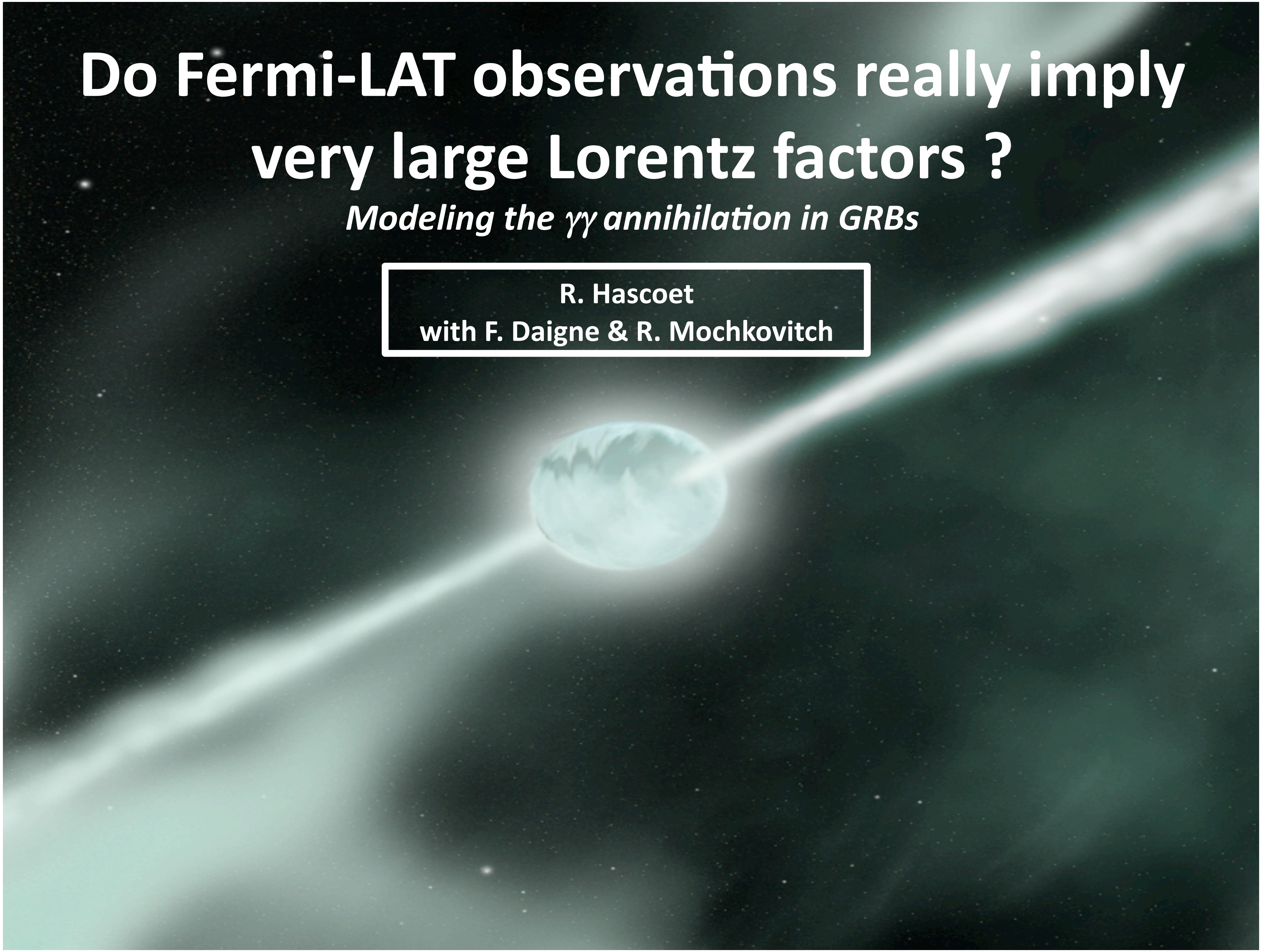
# Do Fermi-LAT observations really imply very large Lorentz factors ?

*Modeling the $\gamma\gamma$ annihilation in GRBs*


R. Hascoet
with F. Daigne & R. Mochkovitch

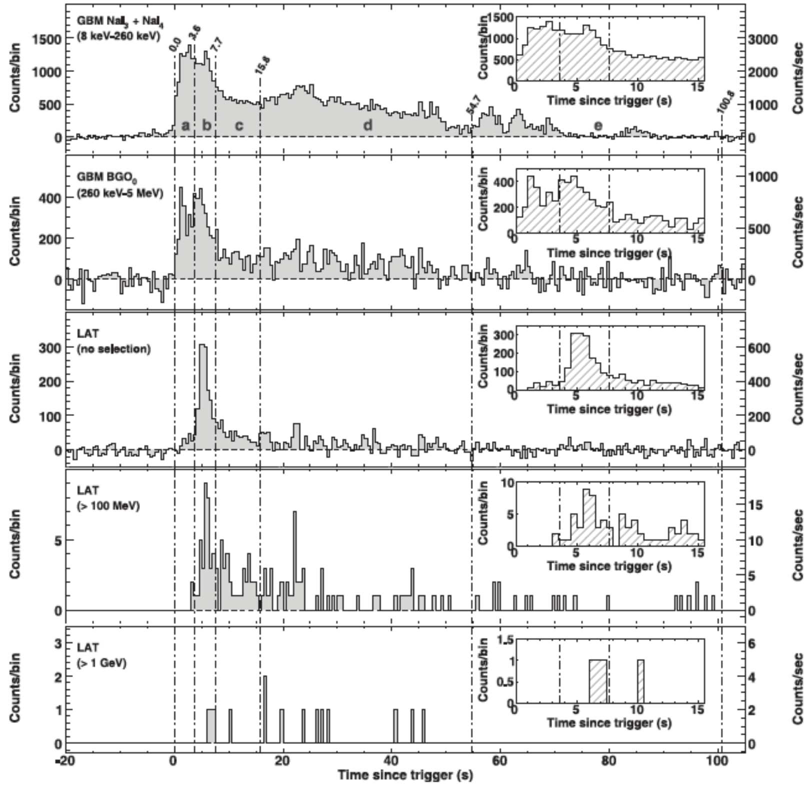
# Recent GeV detections by Fermi-LAT

### Stricter Lorentz factor constraints

- GRB 080916C : $\Gamma_{min} \geq 887$ **(Abdo et al. 2009)**
- GRB 090510 : $\Gamma_{min} \geq 1200$ **(Ackerman et al. 2010)** ($E_{max}$ = 30.1 GeV)

- severe constraints on the central engine physics (baryon load should be strongly limited)

- small deceleration radius $R_{dec}$ for a dense external medium (long GRBs), which limits the radius range for the prompt internal mechanism




*γ observations of GRB 080916C*
**(Abdo et al. 2009)**

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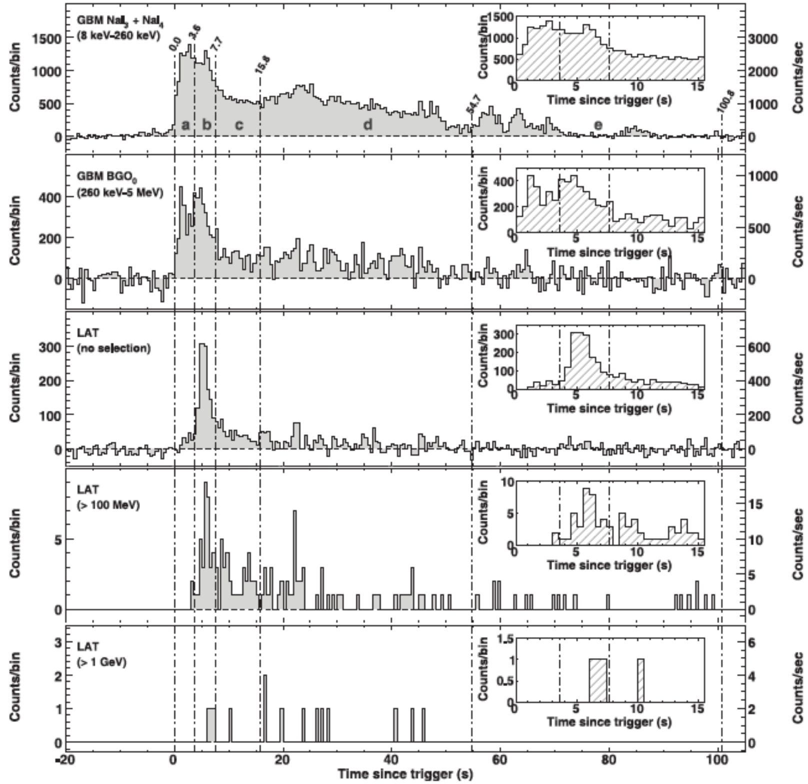



***However, these lower limits are obtained from simplified single zone models. (no time and space dependencies)***

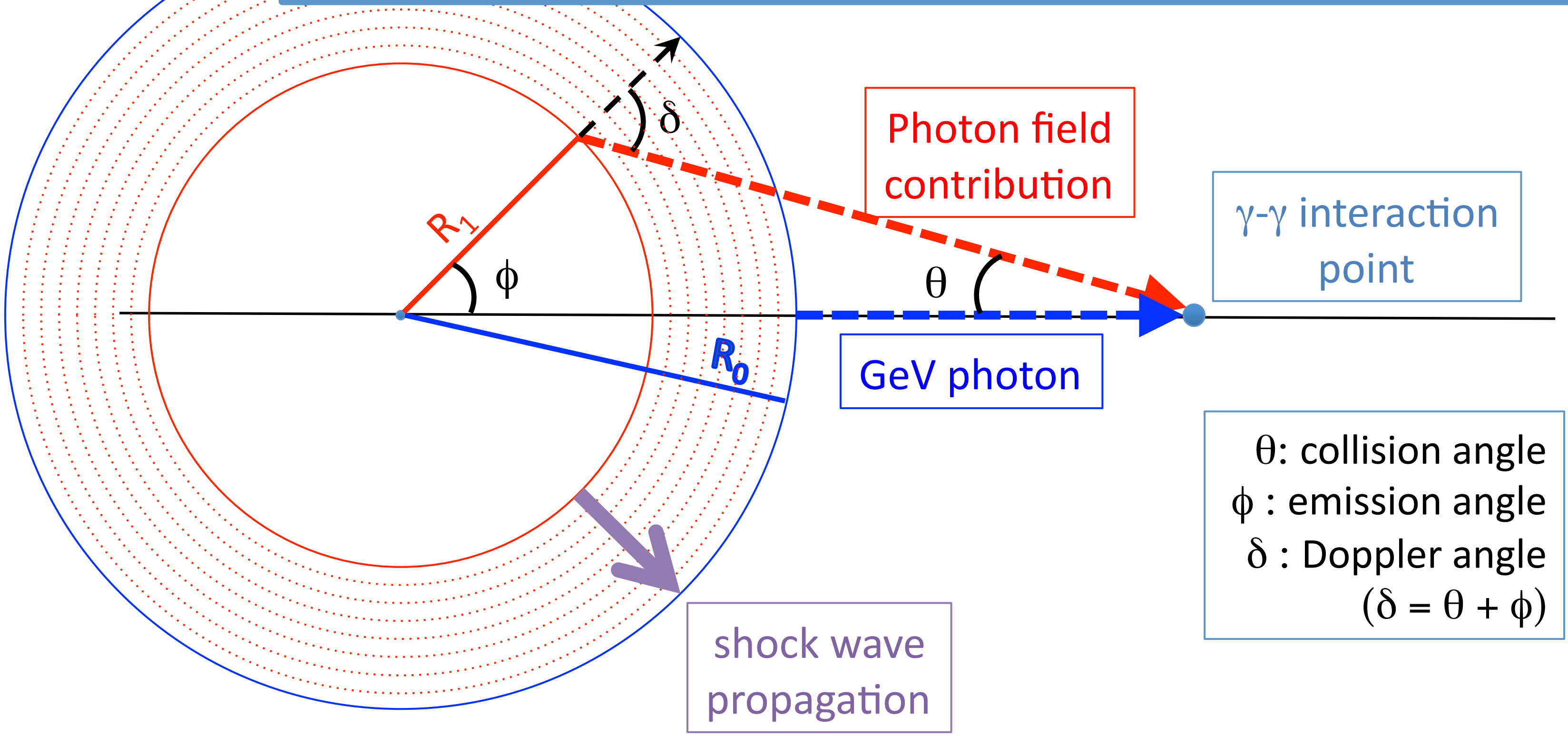
$$\Gamma_{\min} = \left[\sigma_T \left(\frac{d_L(z)}{c\Delta t_{\rm var}}\right)^2 E_c f(E_c) F(\beta)\right]^{\frac{1}{2(1-\beta)}} (1+z)^{-\frac{\beta+1}{1-\beta}} \left(\frac{E_{GeV}E_c}{m_e^2c^4}\right)^{\frac{\beta+1}{2(\beta-1)}}$$

(Abdo et al. 2009)

# Opacity computation

calculation of the γγ opacity which takes into account the ***time, space and direction dependent*** photon field existing in an outflow with ***several*** relativistically moving emitting regions (internal shock framework)

$$\tau_{\gamma\gamma}(E_{HE}) = \int_{R_0}^{\infty} dR \int 2\pi \sin\theta \; d\theta \int_{E_c(E_{HE},\theta)}^{\infty} \frac{dn}{dE\; d\Omega} \sigma_{\gamma\gamma}(E_{HE}, E, \theta)(1 - cos\theta) dE$$



# Minimum Lorentz factor

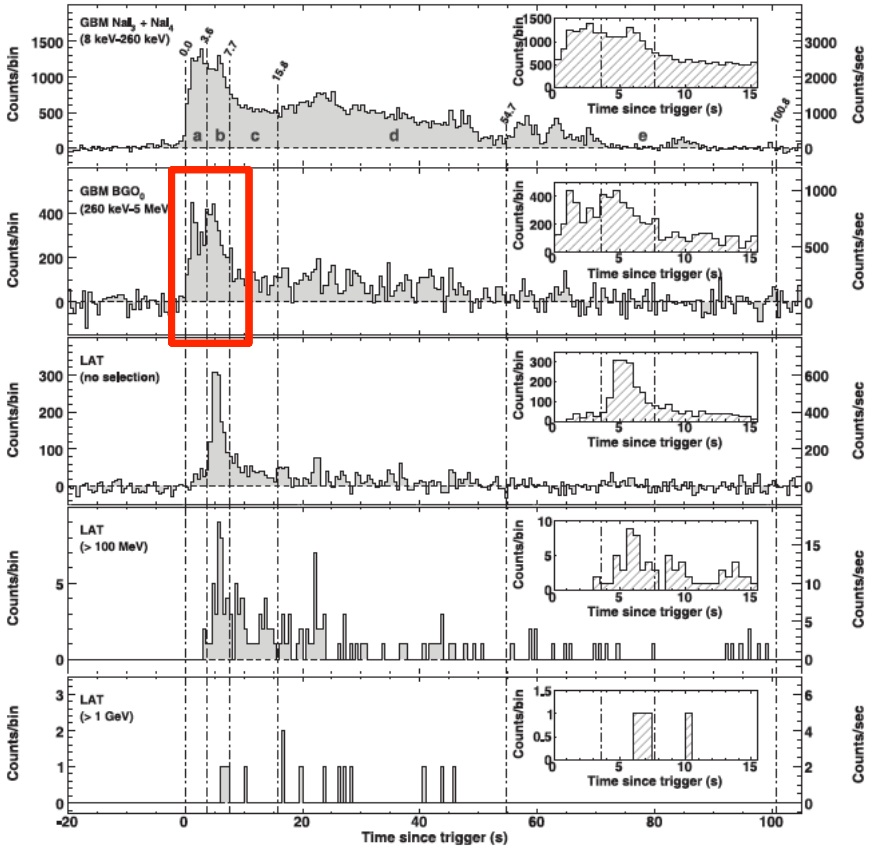
## Example of GRB 080916C

***Observational constraints***

- redshift (z = 4.35)

- $\gamma$-ray energy ($E_{\gamma iso}$ = 8.8 $10^{54}$ erg)
- temporal characteristics
(duration & variability timescale)
- spectral properties: $\alpha$, $\beta$, $E_{peak}$

- We focus on the most constraining time bin
(time bin b)
- Highest photon energy: E = 3 GeV

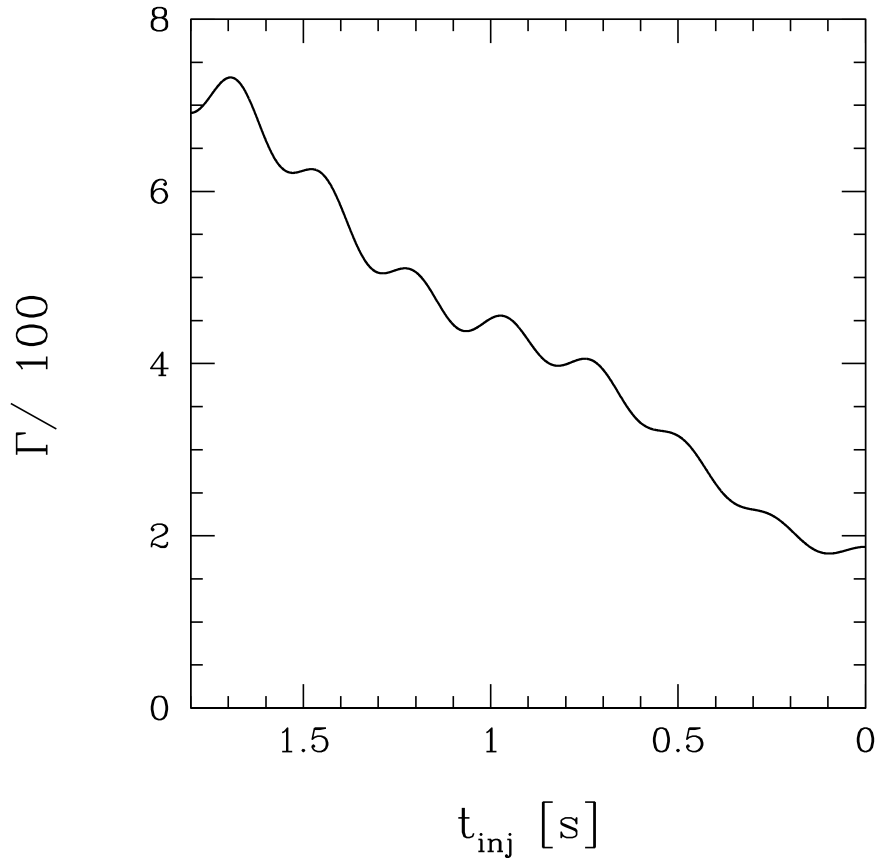



*$\gamma$ observations of GRB 080916C*

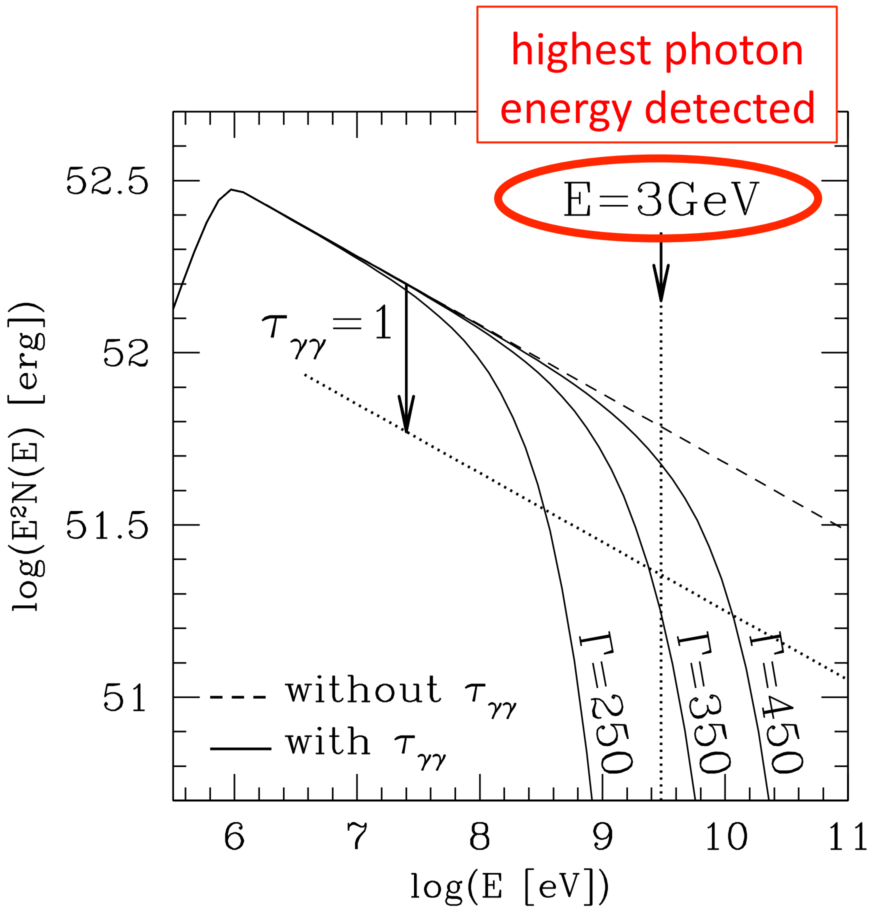
**(Abdo et al. 2009)**

# Minimum Lorentz factor

## Example of GRB 080916C



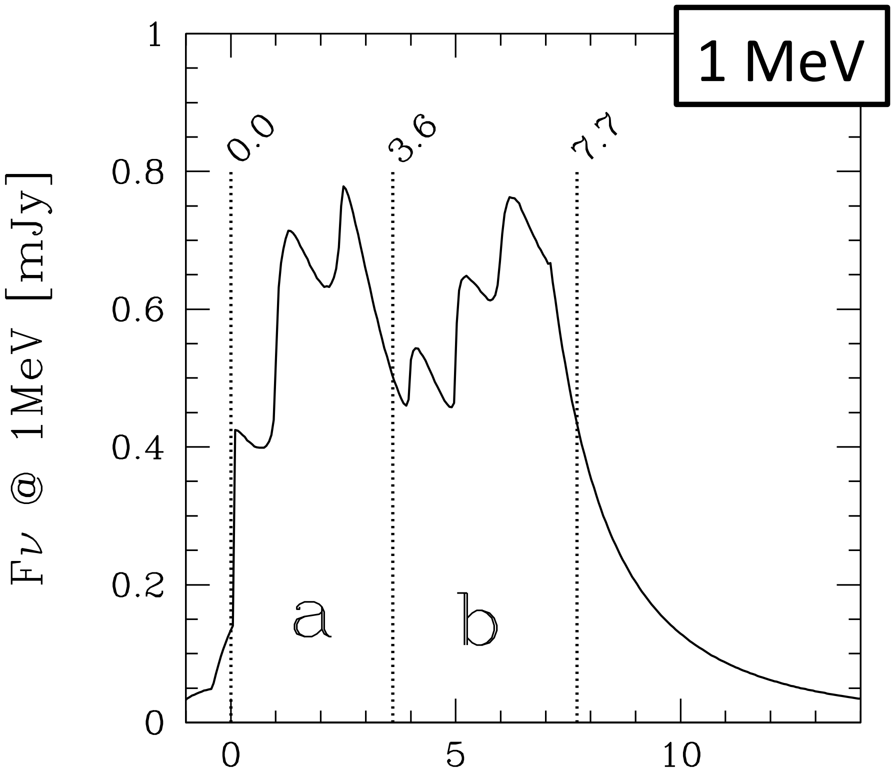

Initial Lorentz factor profile

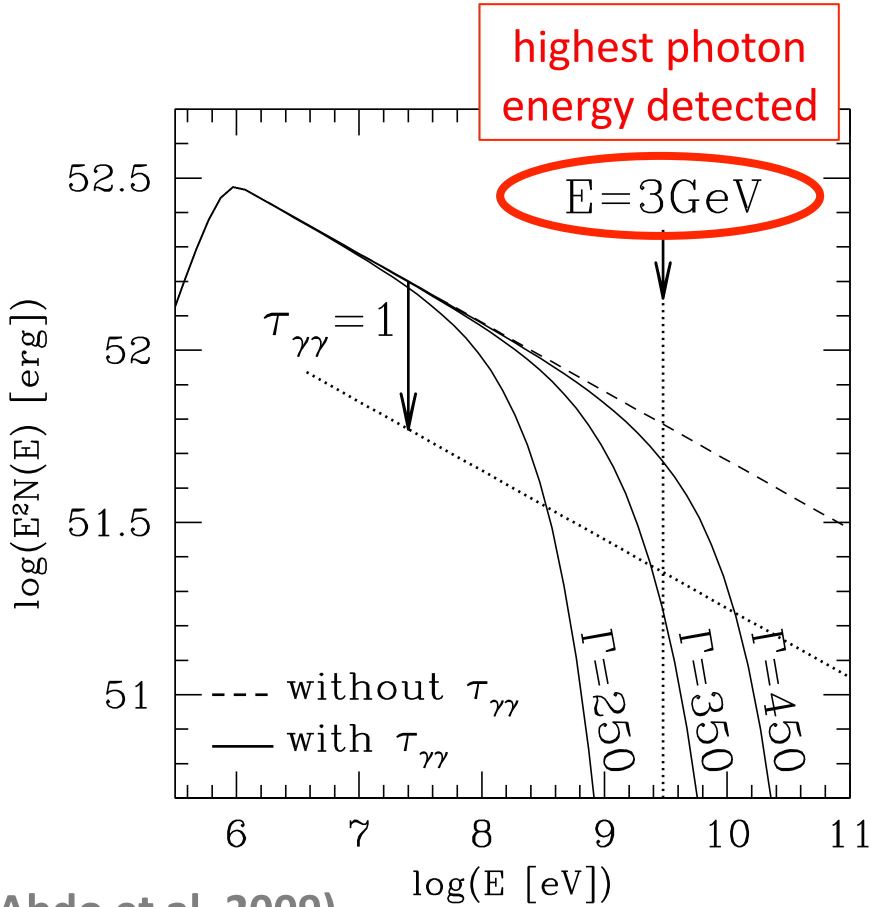



Integrated spectra
time bin ***b***

# Minimum Lorentz factor

## Example of GRB 080916C

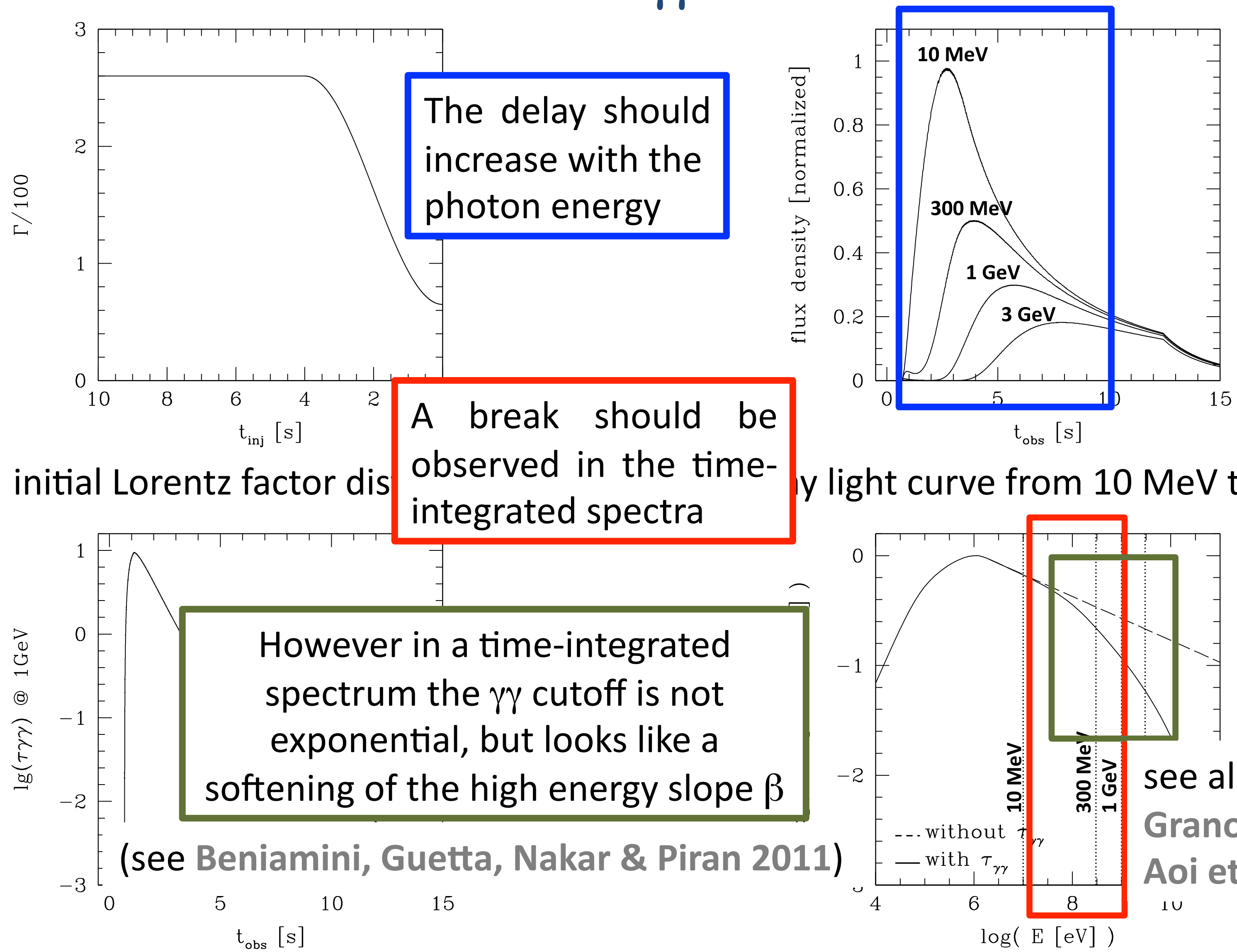



$\overline{\Gamma}_{min} \approx 360$ instead of $\Gamma_{min} \approx 900$ **(Abdo et al. 2009)**

Our detailed model predicts minimum Lorentz factors lower by a factor 2-3
(in agreement with the single-pulse semi-analytical model by **Granot et al. 2008**)

# delayed GeV onset = $\tau_{\gamma\gamma}$ temporal evolution ?




The delay should increase with the photon energy

A break should be observed in the time-integrated spectra

initial Lorentz factor dis[tribution] … [γ]y light curve from 10 MeV to 3 GeV

However in a time-integrated spectrum the γγ cutoff is not exponential, but looks like a softening of the high energy slope β

(see **Beniamini, Guetta, Nakar & Piran 2011**)

see also
**Granot et al. 2008**
**Aoi et al. 2010**

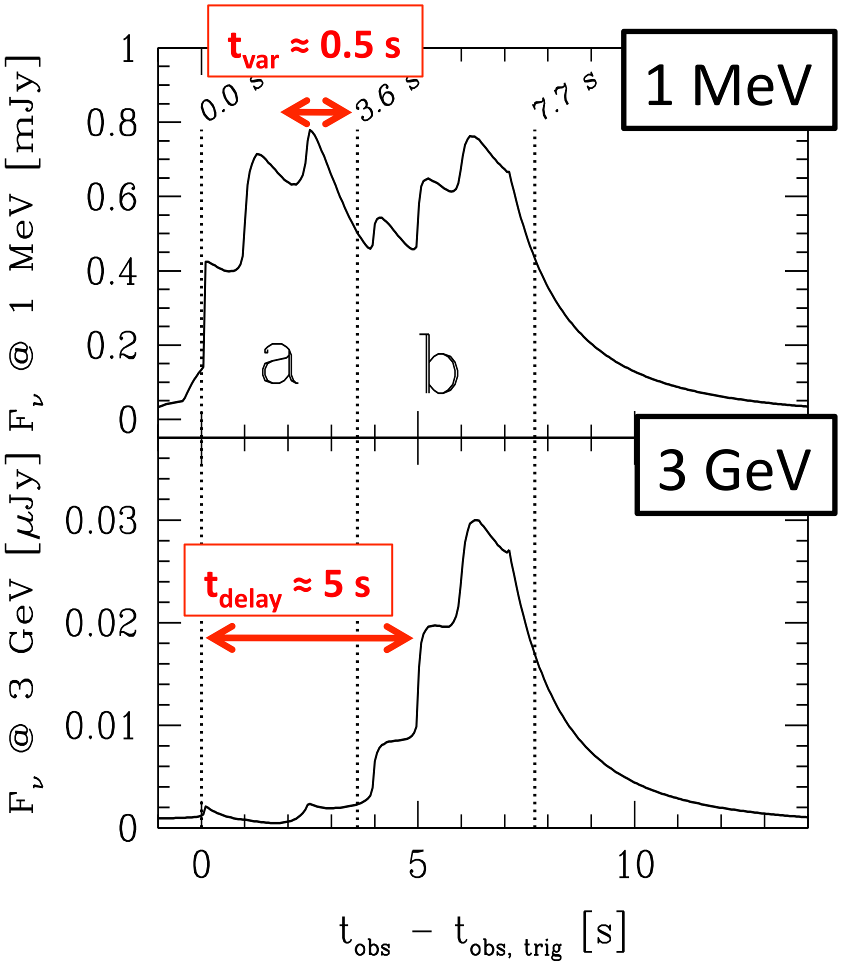
$\tau_{\gamma\gamma}$ for 1GeV photons emitted on-axis

time-integrated spectrum

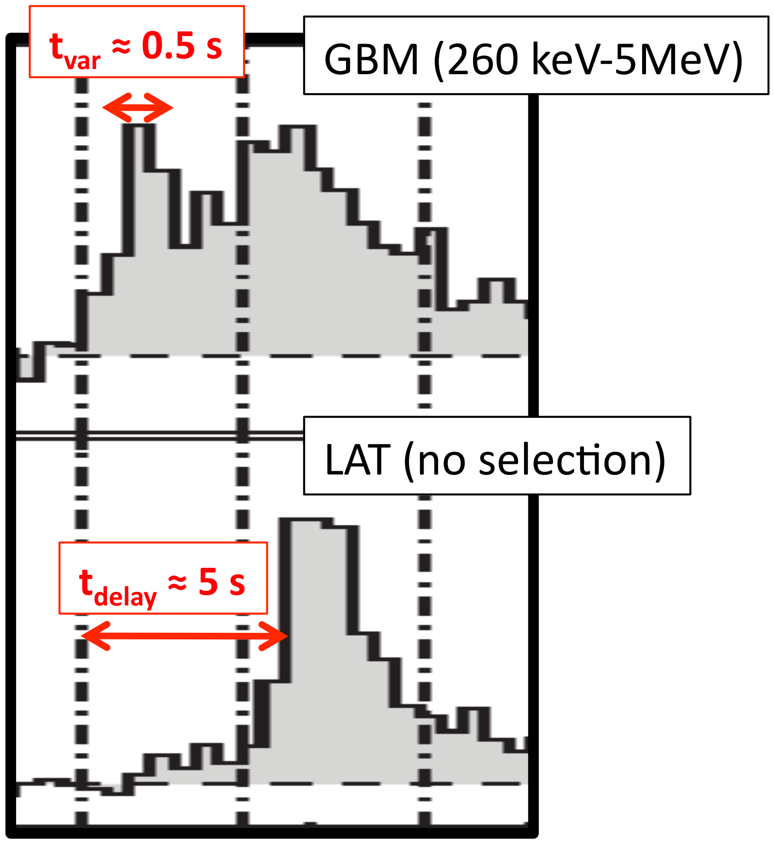
# delayed GeV onset = $\tau_{\gamma\gamma}$ temporal evolution ?

## Example of GRB 080916C

simulation




observations




(Abdo et al. 2009)

# delayed GeV onset = $\tau_{\gamma\gamma}$ temporal evolution ?

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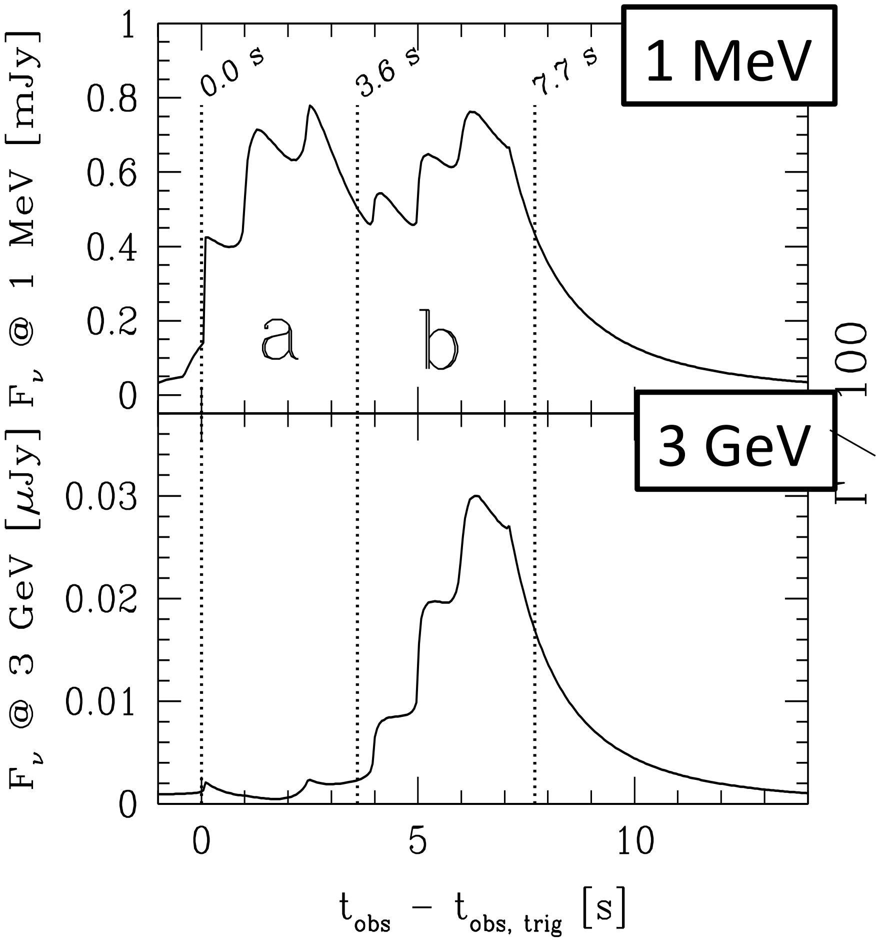
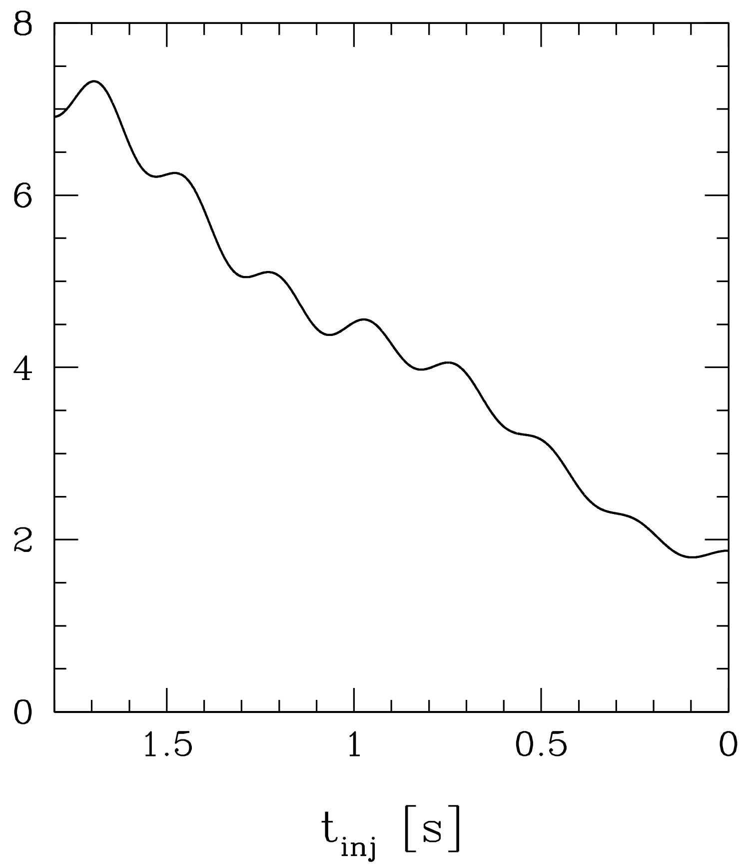
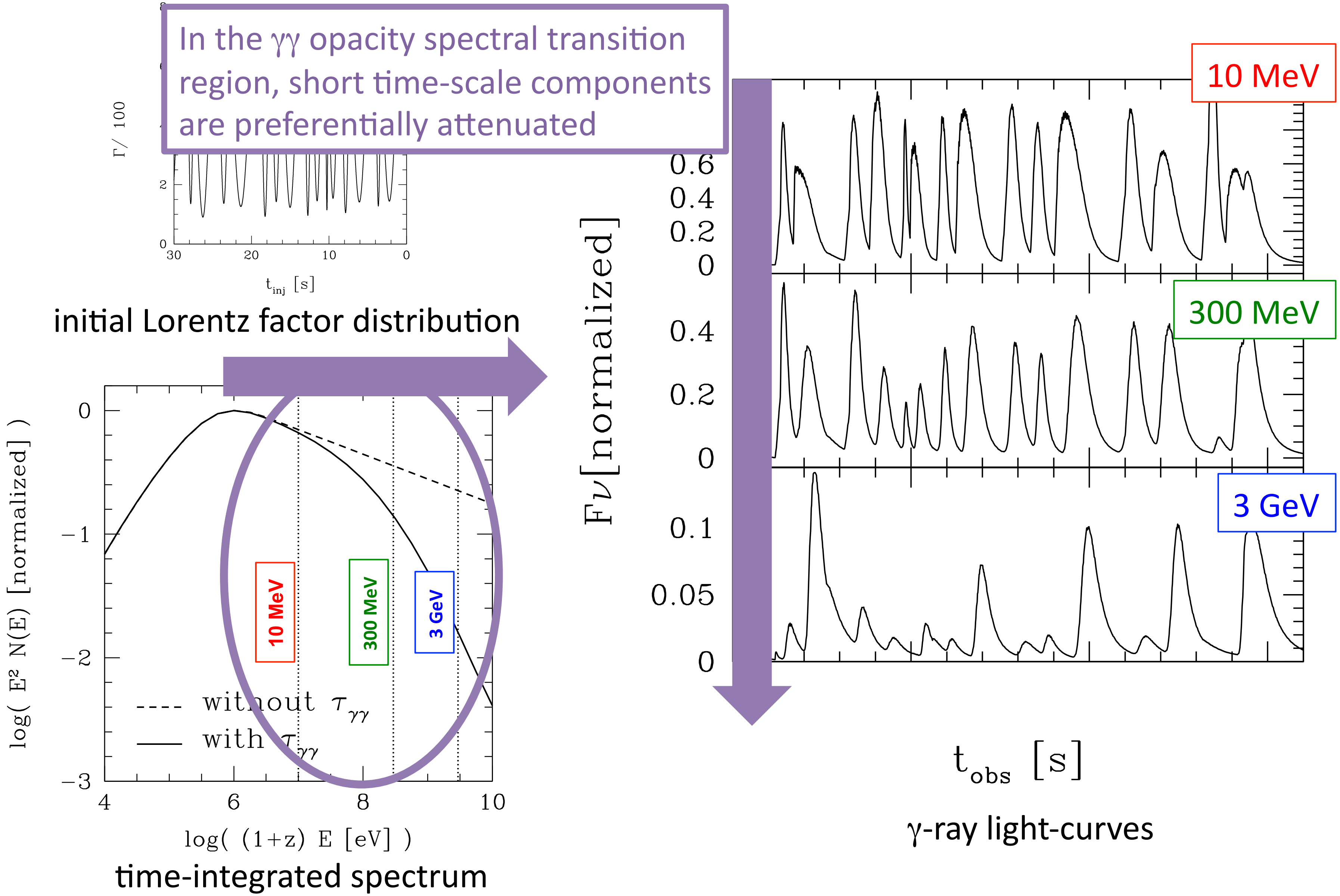



***with a short time-scale variability***



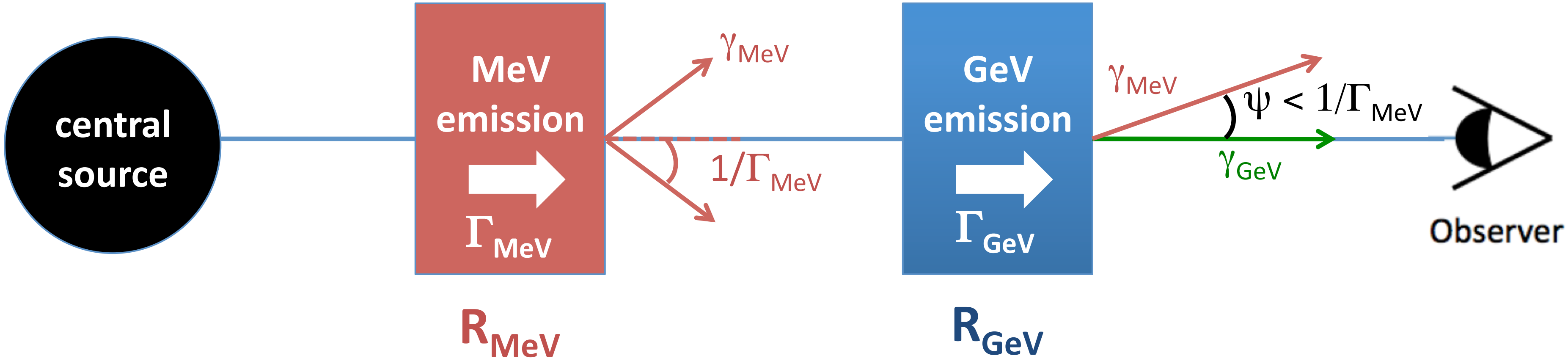

Initial Lorentz factor profile

# smoothing the GeV light curves with $\tau_{\gamma\gamma}$



# 2 distinct emission zones

Zou, Fan & Piran (2011)




- The MeV component is produced at a typical radius $R_{MeV}$ ($\Delta t_{obs,MeV} > R_{MeV}/2\Gamma_{MeV}^2 c$)
- If GeV photons are produced at a larger radii $R_{GeV}$ ($\Delta t_{obs,GeV} > R_{GeV}/2\Gamma_{GeV}^2 c$):
  - the interacting MeV photon field will have a smaller density
  - the collision angles between MeV and GeV photons will be smaller than $1/\Gamma_{MeV}$

➡ $\tau_{\gamma\gamma}$ is smaller and the constraint on $\Gamma_{min}$ is loosened

# How to produce MeV and GeV photons in 2 distinct zones

**External forward shock emission (Kumar & Barniol Duran 2010, Ghisellini et al. 2010)**

- MeV emission produced by internal mechanisms
- The whole GeV emission is made by the external forward shock

**Internal leptonic model (e.g. Bošnjak, Daigne & Dubus 2009)**

Within the internal shock framework

- Band component: synchrotron
- Extra component at HE (not dominant): IC (in Klein-Nishina) rising with a delay

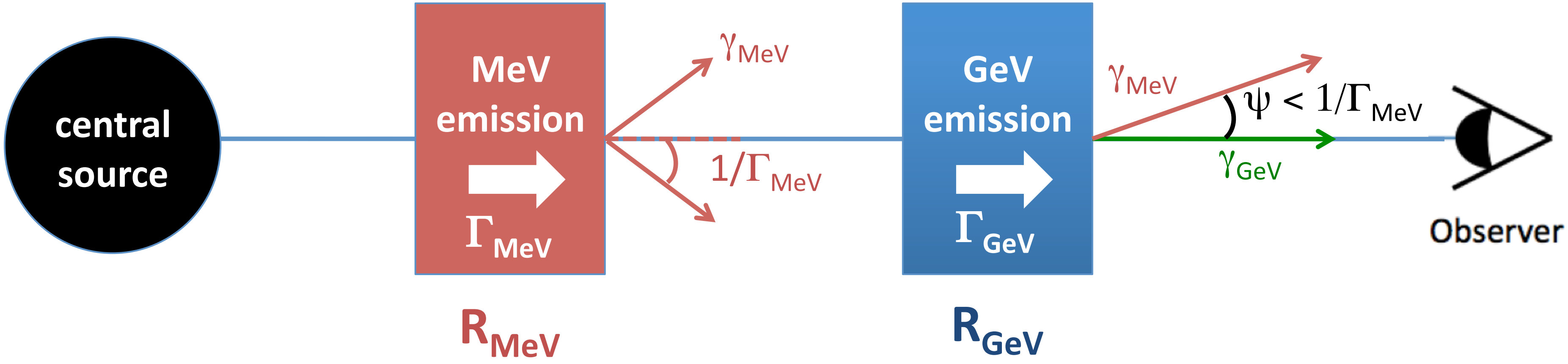
**Internal hadronic model (e.g. Asano, Guiriec & Mészáros 2009)**

Within the internal shock framework

- Band component: leptonic origin
- Extra component at HE (not dominant): proton synchrotron or IC off pairs (produced by photon-hadronic interactions). The acceleration time implies a delay.

# 2 distinct emission zones

Zou, Fan & Piran (2011)

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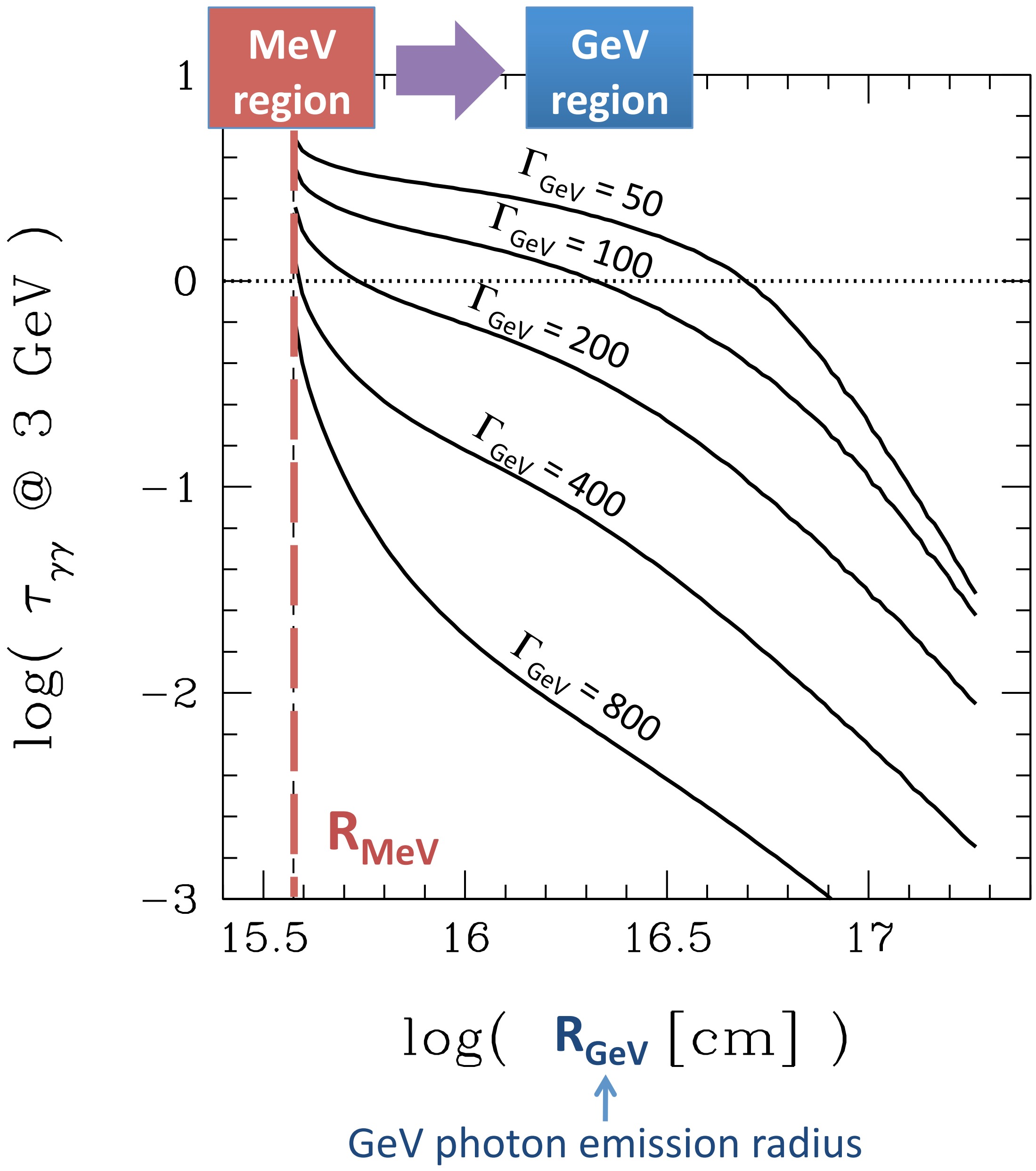
# 2 distinct emission zones

Example of GRB 080916C

The delay for the GeV photon is fixed:

$\delta t_{obs} = (t_{obs,GeV} - t_{trigger})/(1+z) = 0.67s$



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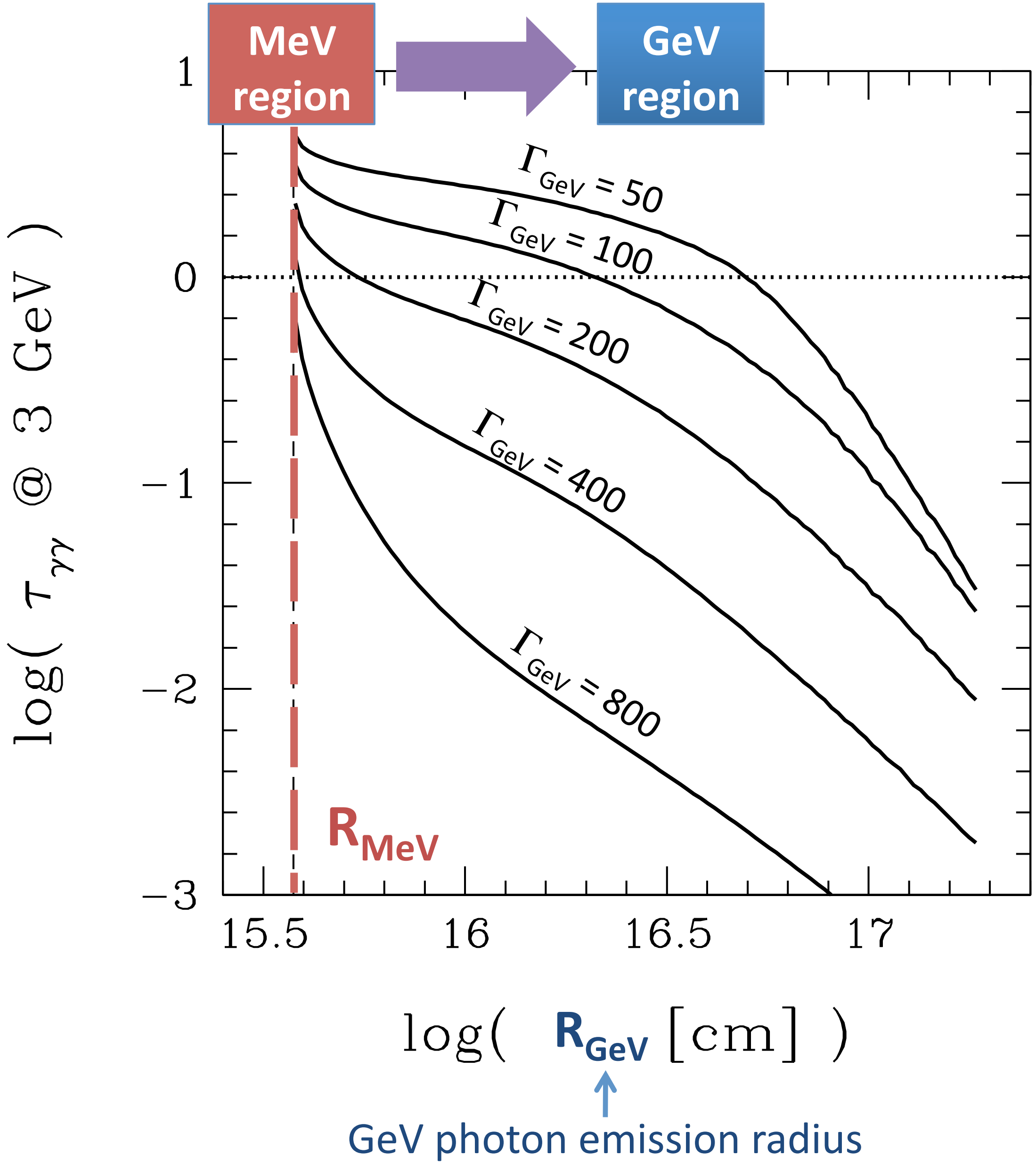

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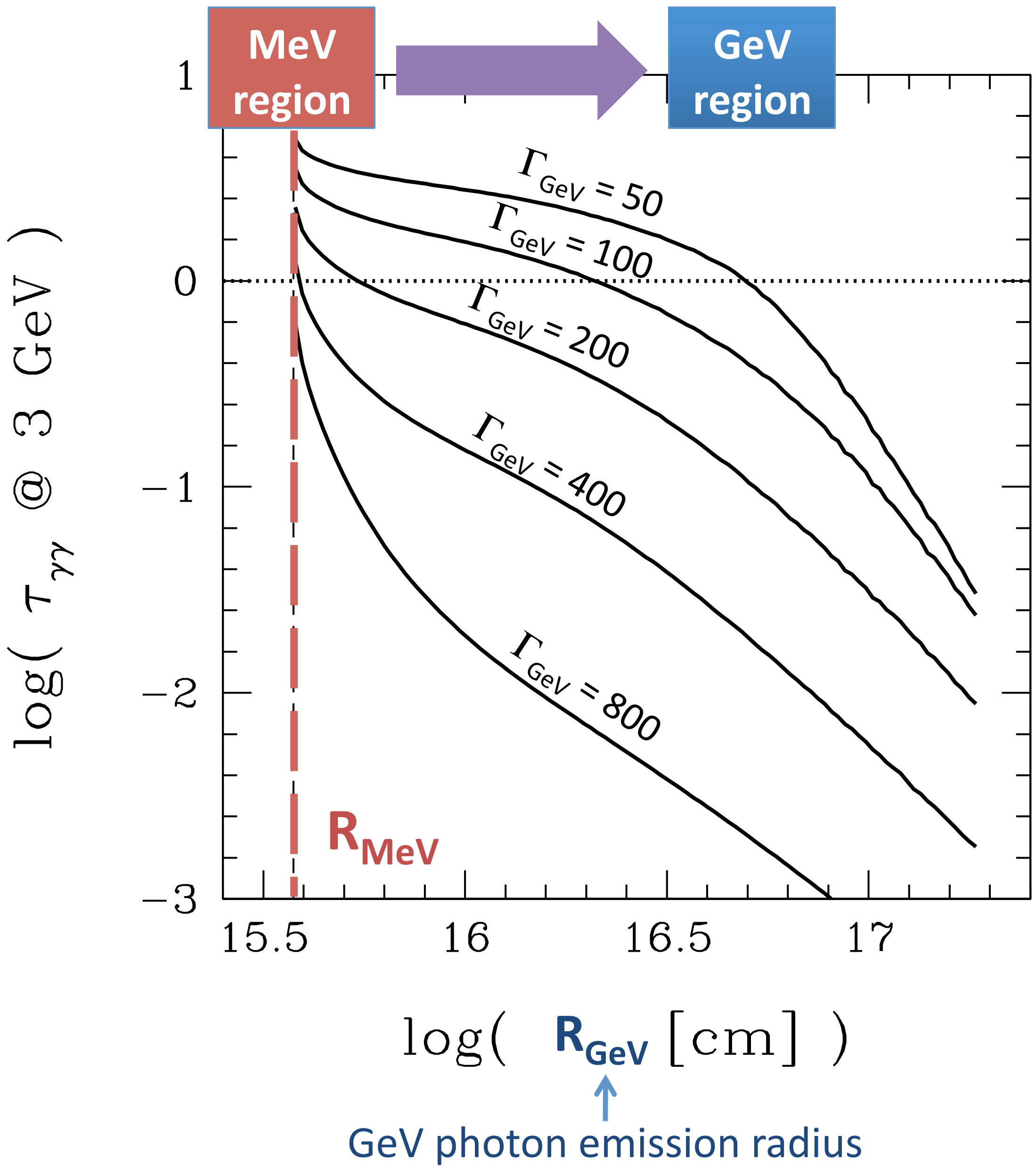

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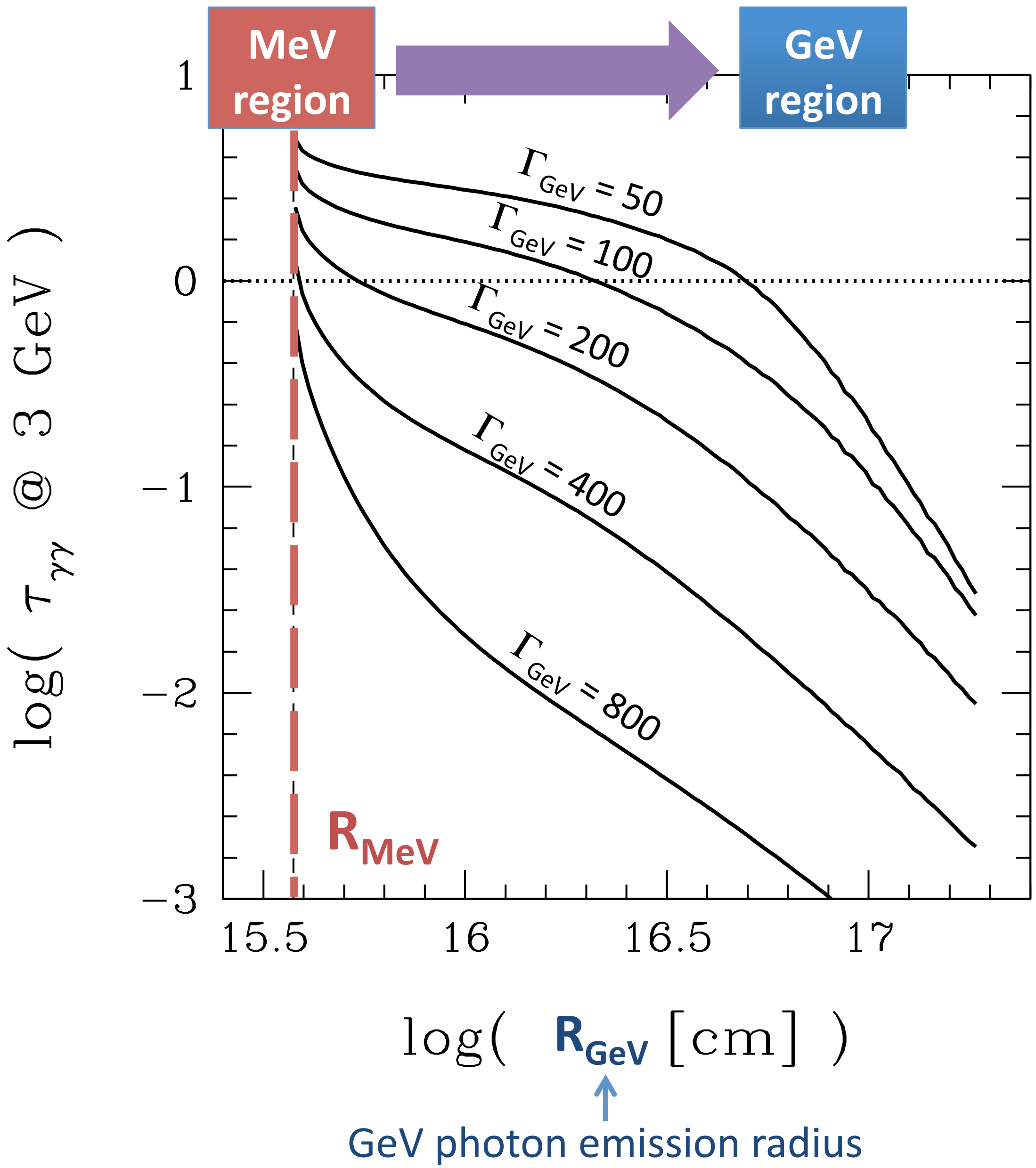

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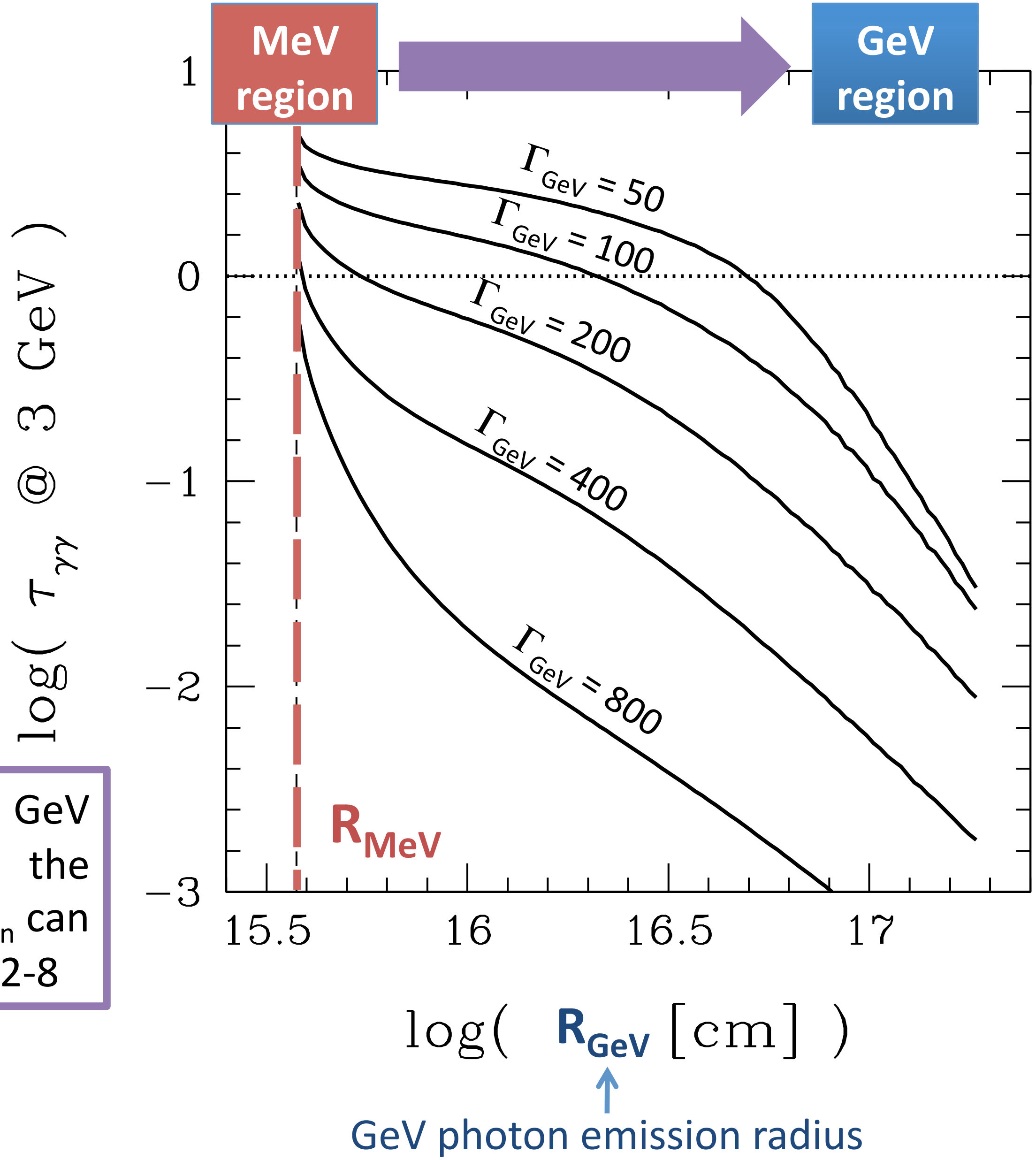


**Example of GRB 080916C**

The delay for the GeV photon is fixed:
**$\delta t_{obs} = (t_{obs,GeV} - t_{trigger})/(1+z) = 0.67s$**

if the main MeV component and GeV photons are not produced at the same place, the constraint on $\Gamma_{min}$ can be further loosened by a factor ≈ 2-8

# Conclusions

**Do Fermi-LAT observations really imply very large Lorentz factors ?**

NO

***not as large as 1000***

# Conclusions

***Minimum Lorentz factor in GRB outflows***

**If MeV and GeV photons are produced at the same place**

- detailed modeling vs. simple modeling: $\Gamma_{min}$ lower by a factor 2-3
  - less severe constraint on the central engine physics
  - prompt internal mechanism radius less constrained (larger deceleration radius)

**If MeV and GeV photons are produced in 2 distinct regions**

- can further weaken the constraint on $\Gamma_{min}$ (another factor 2-8)

(Except for the FS model for the GeV emission: a large Lorentz factor is needed for an early deceleration, **Kumar & Barniol Duran 2010**, **Ghisellini et al. 2010**)

# New approximate formula

## more precise, more general

$$K(\beta) \approx \frac{1}{3}$$

correction factor
(detailed modeling)

single zone formula
(Abdo et al. 2009)

$$\Gamma_{\rm min} \approx K(\beta) \left\{ \left[ \sigma_T \left( \frac{d_L(z)}{c\Delta t_{\rm var}} \right)^2 E_c f(E_c) F(\beta) \right]^{\frac{1}{2(1-\beta)}} (1+z)^{-\frac{\beta+1}{1-\beta}} \left( \frac{E_{GeV} E_c}{m_e^2 c^4} \right)^{\frac{\beta+1}{2(\beta-1)}} \right\}$$

$$\times \left[ \frac{1}{2} \left( 1 + \frac{R_{GeV}}{R_{MeV}} \right) \frac{R_{GeV}}{R_{MeV}} \right]^{-1/2}$$

additional correction factor,
if different emitting regions for MeV and GeV photons

- = 1, if $R_{GeV} = R_{MeV}$
- < 1, if $R_{GeV} > R_{MeV}$

Estimation of $R_{MeV}$: $R_{MeV} \approx \Gamma^2 c\Delta t_{var}/(1+z)$

# Conclusions

***Minimum Lorentz factor in GRB outflows***

**New approximate formula**

$$\Gamma_{\min} \approx \frac{1}{3} \cdot \left\{ \left[ \sigma_T \left( \frac{d_L(z)}{c\Delta t_{\rm var}} \right)^2 E_c f(E_c) F(\beta) \right]^{\frac{1}{2(1-\beta)}} (1+z)^{-\frac{\beta+1}{1-\beta}} \left( \frac{E_{GeV} E_c}{m_e^2 c^4} \right)^{\frac{\beta+1}{2(\beta-1)}} \right\} \times \left[ \frac{1}{2} \left( 1 + \frac{R_{GeV}}{R_{MeV}} \right) \frac{R_{GeV}}{R_{MeV}} \right]^{-1/2}$$

***Other results (Within the internal shock framework)***

- $\gamma\gamma$ cutoff in a time-integrated spectrum: softening of the HE slope $\beta$ instead of an exponential shape
  ➜ could make the gamma-gamma cutoff characterization more difficult
- the $\tau_{\gamma\gamma}$ temporal evolution can produce a delayed onset for the GeV emission
  ➜ $t_{delay}$ can be significantly larger than $t_{var}$
- $\tau_{\gamma\gamma}$ can smooth the shortest time-scales of HE light-curves
  ➜ temporal variability analysis to discriminate between an internal or external origin could be biased ?