Gamma-Ray Bursts

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Basic facts

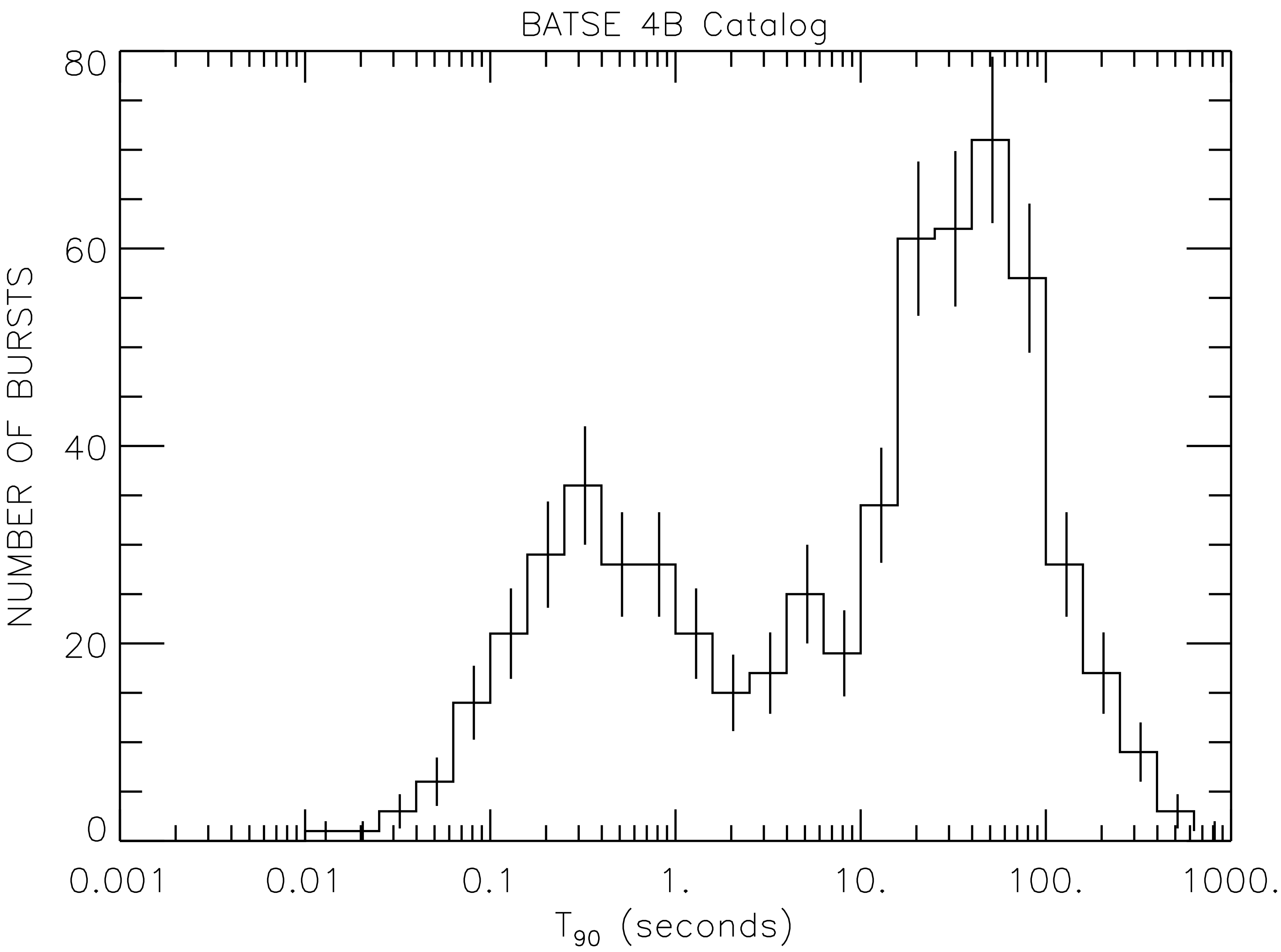
- Unexpectedly discovered in 1967
- Rate $\sim$ 1000 per year
- Isotropic energy release $\sim 10^{52}$ erg

  (up to $\sim 10^{55}$ erg, down to $\sim 10^{49}$ erg)
- Duration: two groups

  ~ 0.3 s (short bursts) and ~ 50 s (long bursts)
- Spectrum:

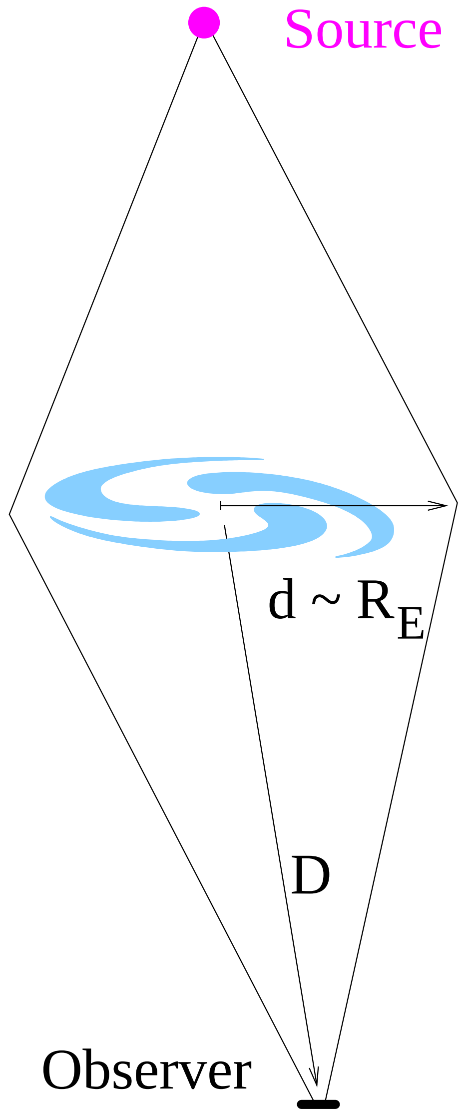
  nonthermal, peaks typically in 10 keV - 1 MeV range
- Redshifts: typically ~ 1, up to 8

Long and short bursts



Data from BATSE 4B catalog at http://gammaray.msfc.nasa.gov/batse/grb/catalog/4b

Gravitational lensing: twin bursts



Deflection angle for a light beam

$$\theta_L = \frac{4\,GM}{dc^2} = \frac{2\,R_g}{d}$$

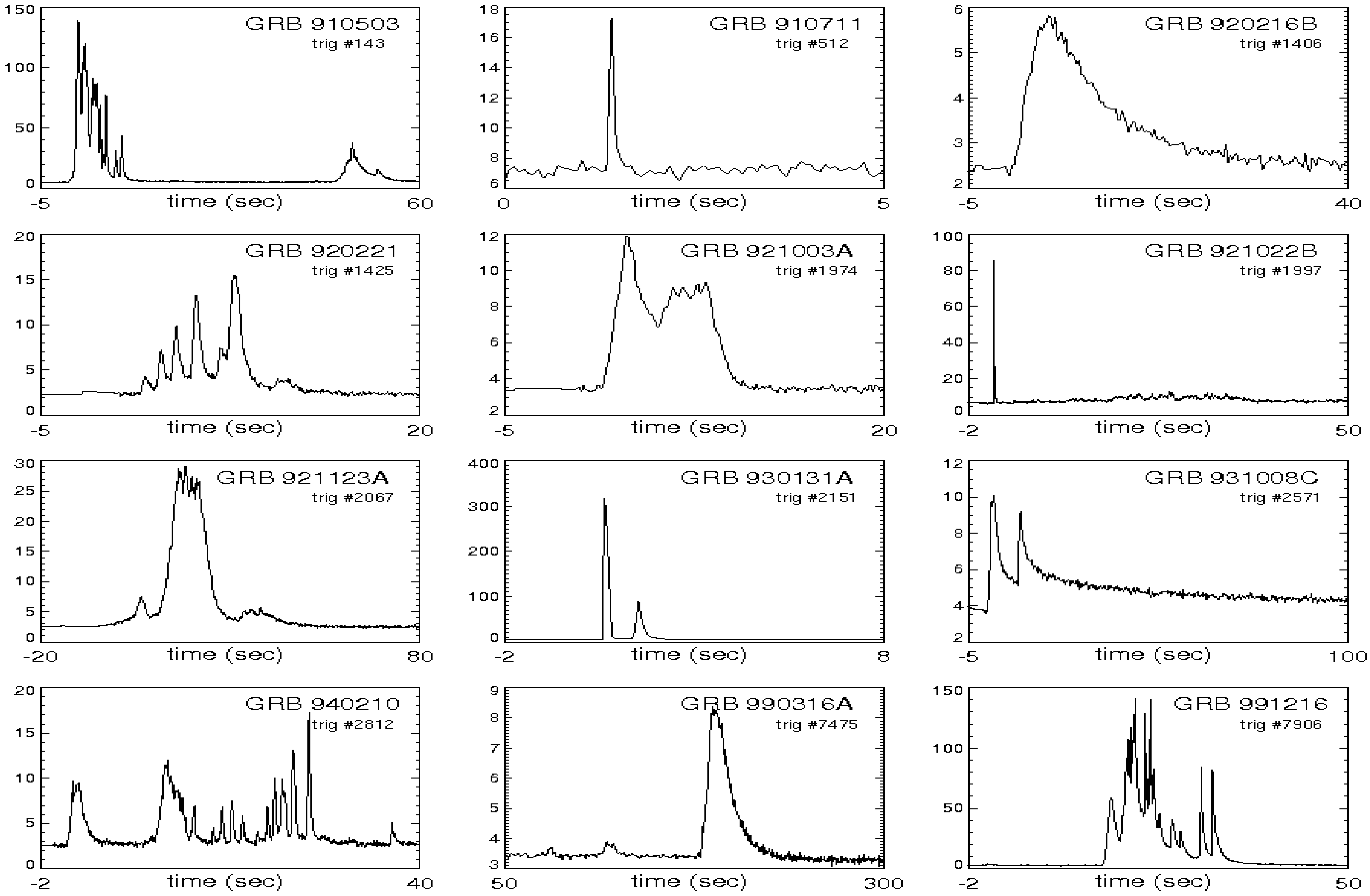
Einstein's radius $\quad R_E \sim \sqrt{R_g D/2}$

Time delay between the images

$$t_L \sim \theta_L^2 D/c \sim R_g/c$$

- **Same spectra**
- **different brightness**
- **(possibly) different lightcurves**
- **delay** $\sim$ **days**
- **probability of lensing** $\sim \Omega_L \sim 0.1\%$

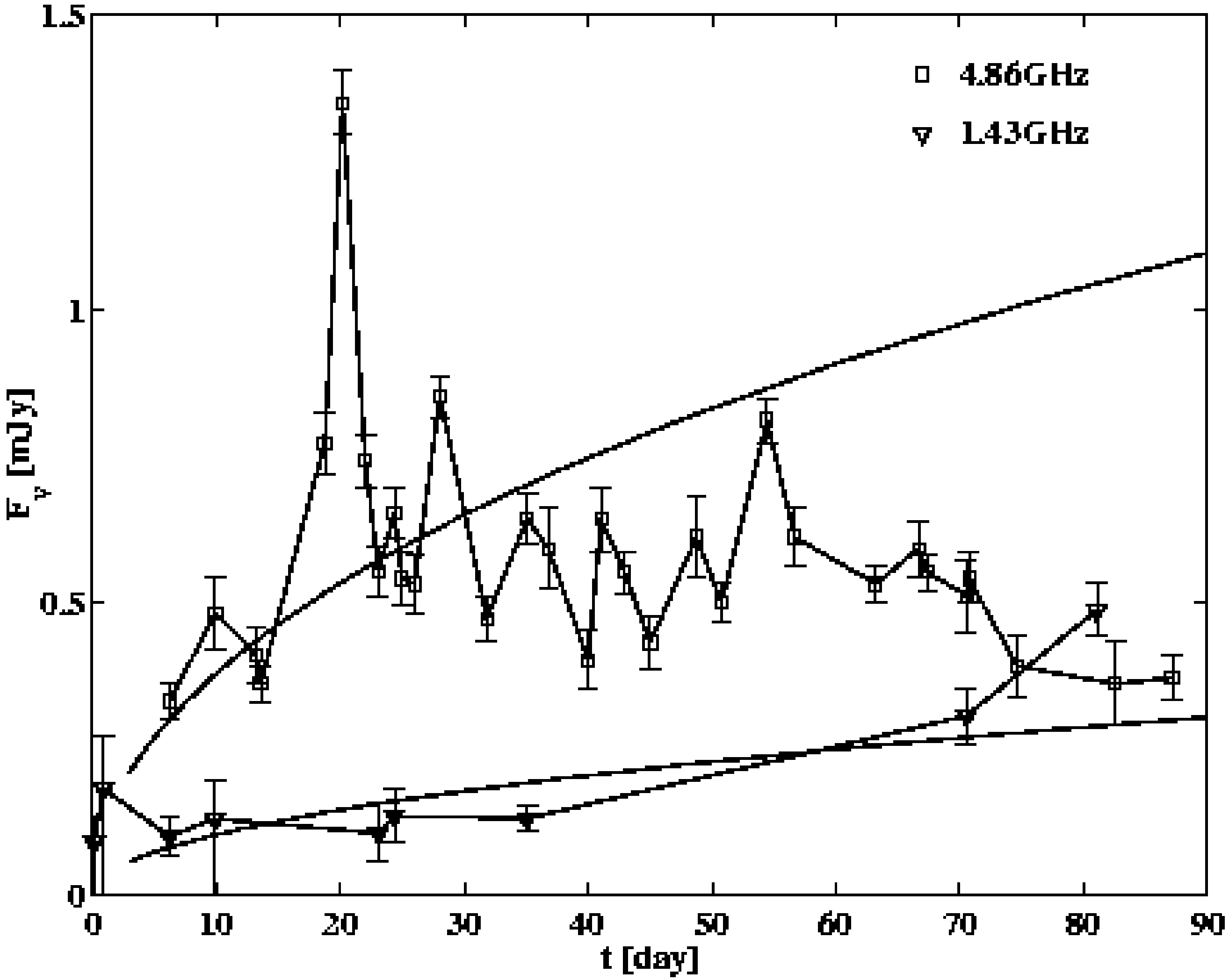
Prompt emission lightcurves



Optical afterglow

- **First detected in 1997 (GRB970228)**
- **Absorption lines in spectra $\Rightarrow$ redshifts**
- **Associated with galaxies and (some GRBs) with supernovae**

Radio afterglow: twinkling



4 weeks after the burst:

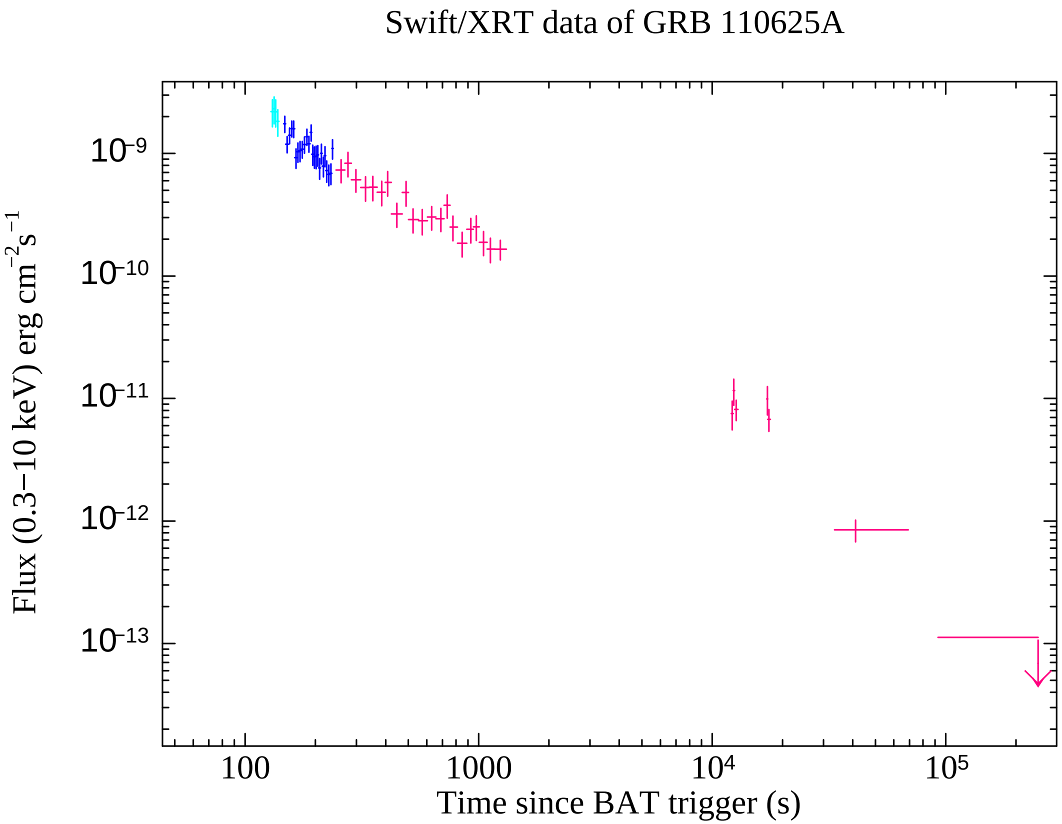
linear size $\sim 10^{17}$ cm

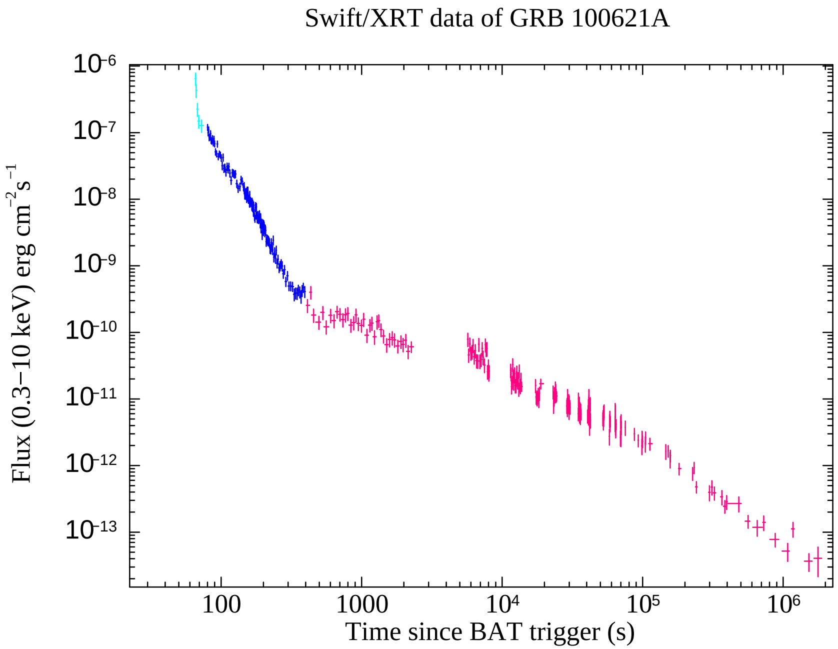
apparent expansion speed $\sim c$

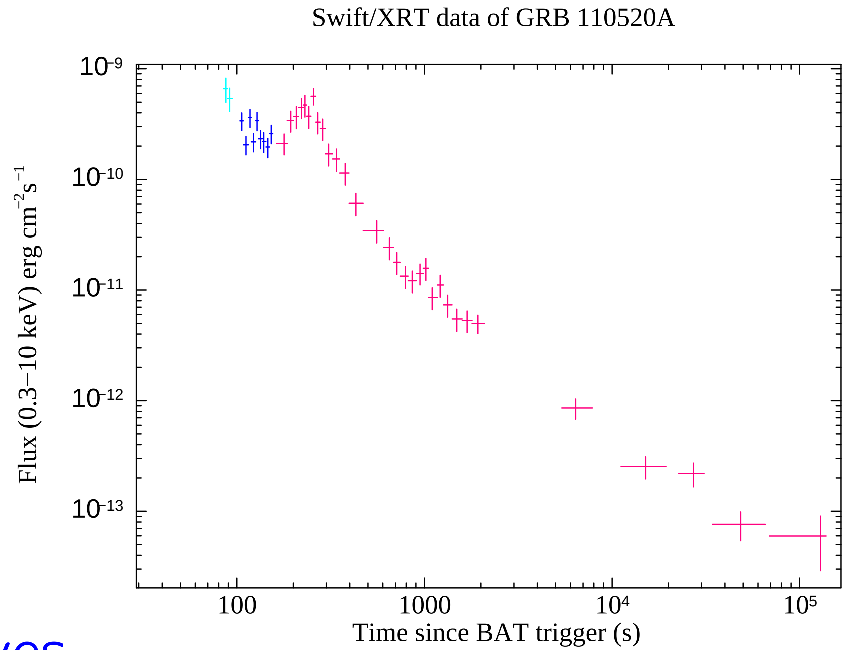
Light curves of the radio afterglow of GRB 970508 at 4.86 and 1.43 GHz, compared to the predictions of the adiabatic firereball model

Waxman, Kulkarni & Frail, ApJ 497 (1998)

X-ray afterglow lightcurves







Data from http://www.swift.ac.uk/xrt_curves

Afterglow lightcurves

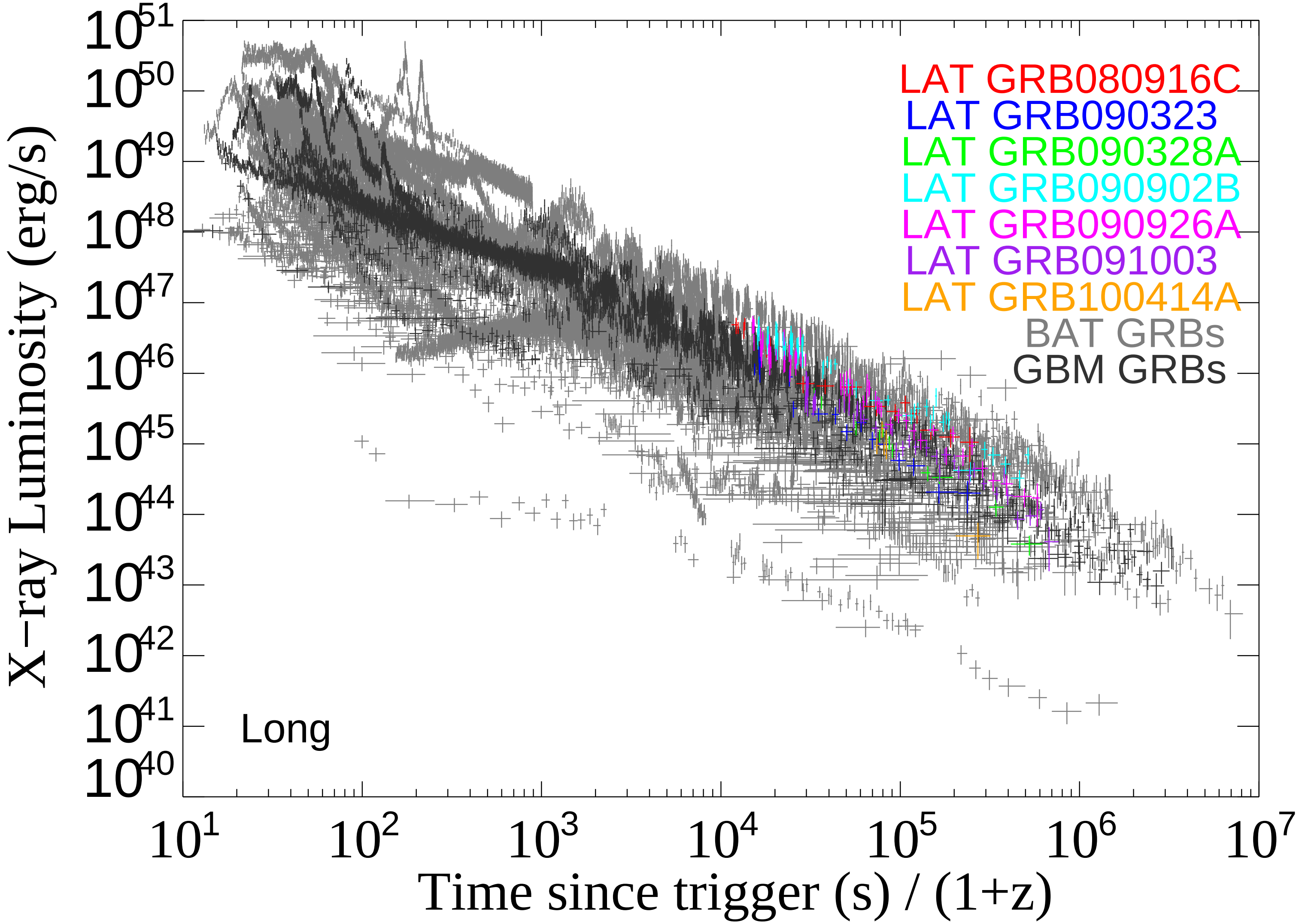
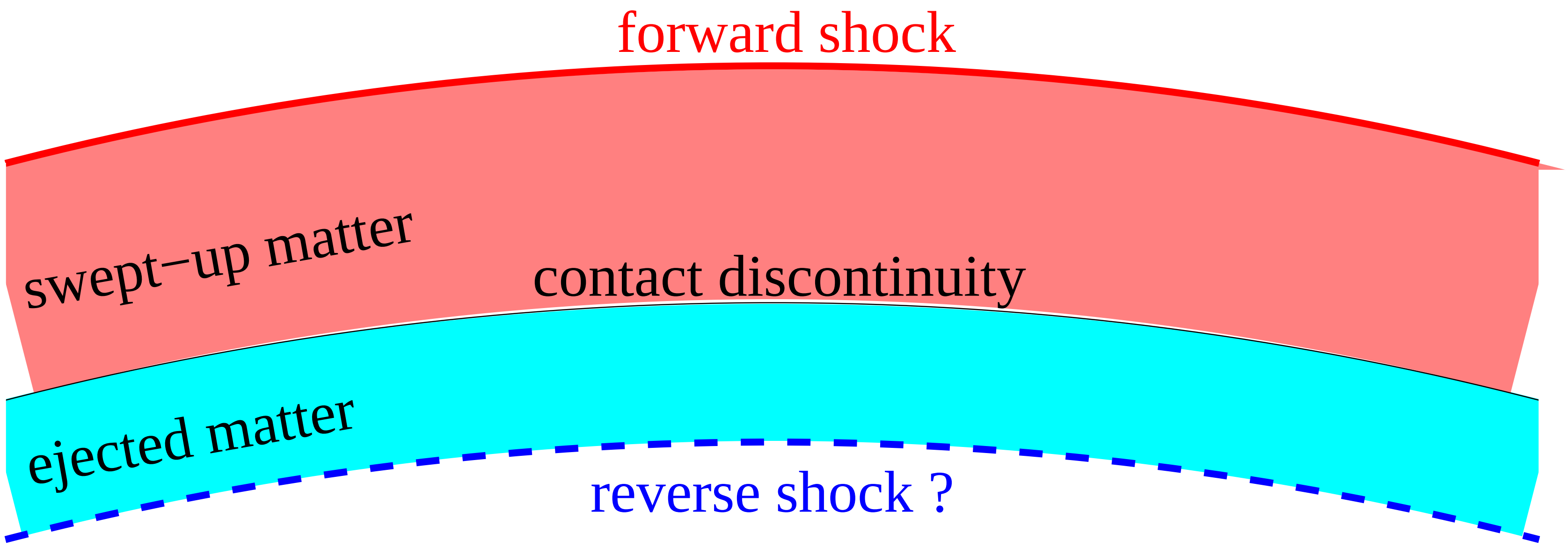


Figure from Racusin et al. arXiv:1106.2469 (2011)

External shock deceleration: afterglows

Blandford & McKee 1976



Adiabatic shock:

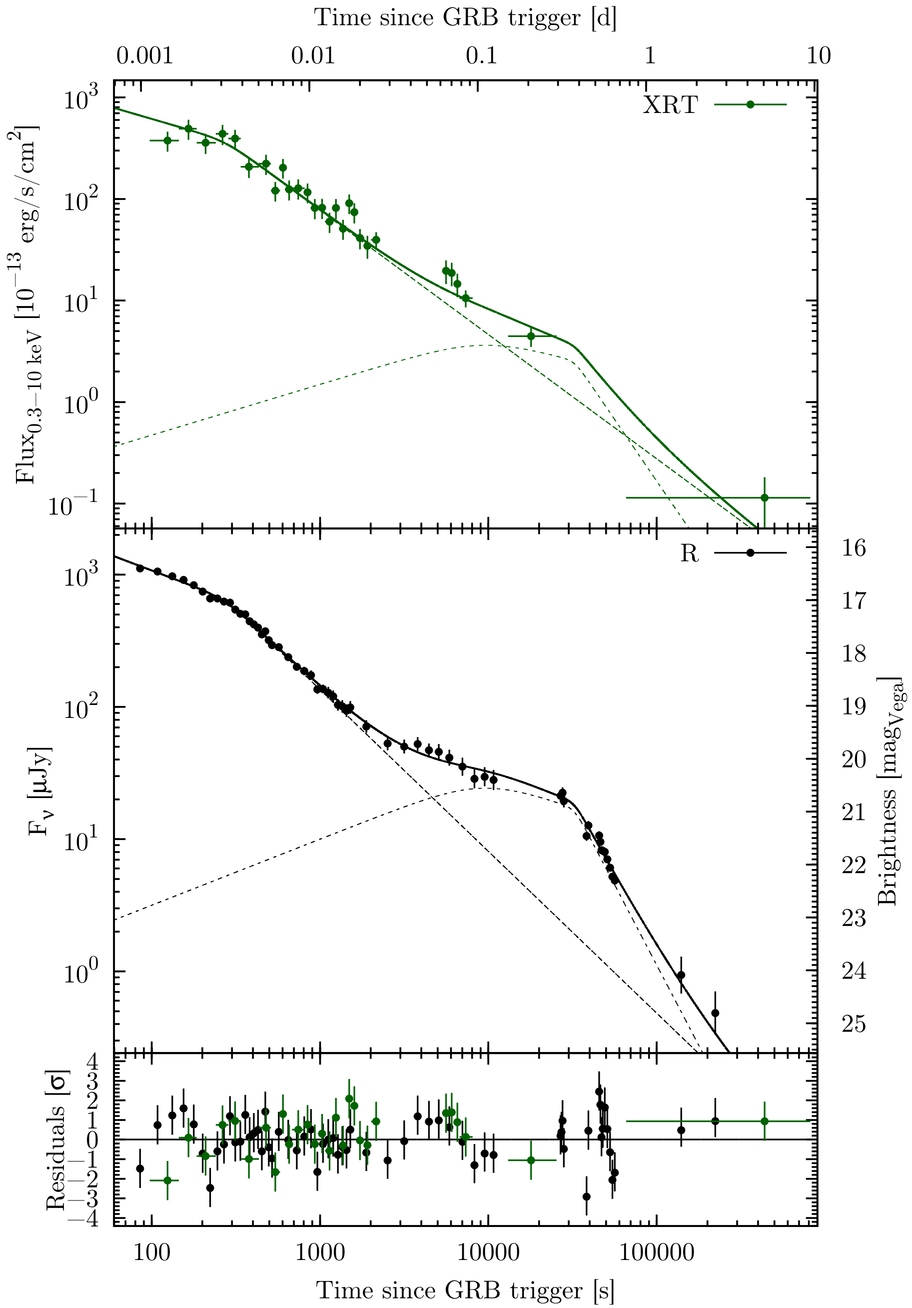
Swept-up mass $M = \dfrac{4\pi}{3} R^3 \rho_{ext}$

Energy $E_{GRB} \sim M c^2 \Gamma^2 \approx const$

Observer's time $t_{obs} \sim R/(\Gamma^2 c)$

$\Gamma \propto R^{-3/2} \propto t_{obs}^{-3/8} \qquad R \propto t_{obs}^{1/4}$

Breaks in afterglow lightcurves



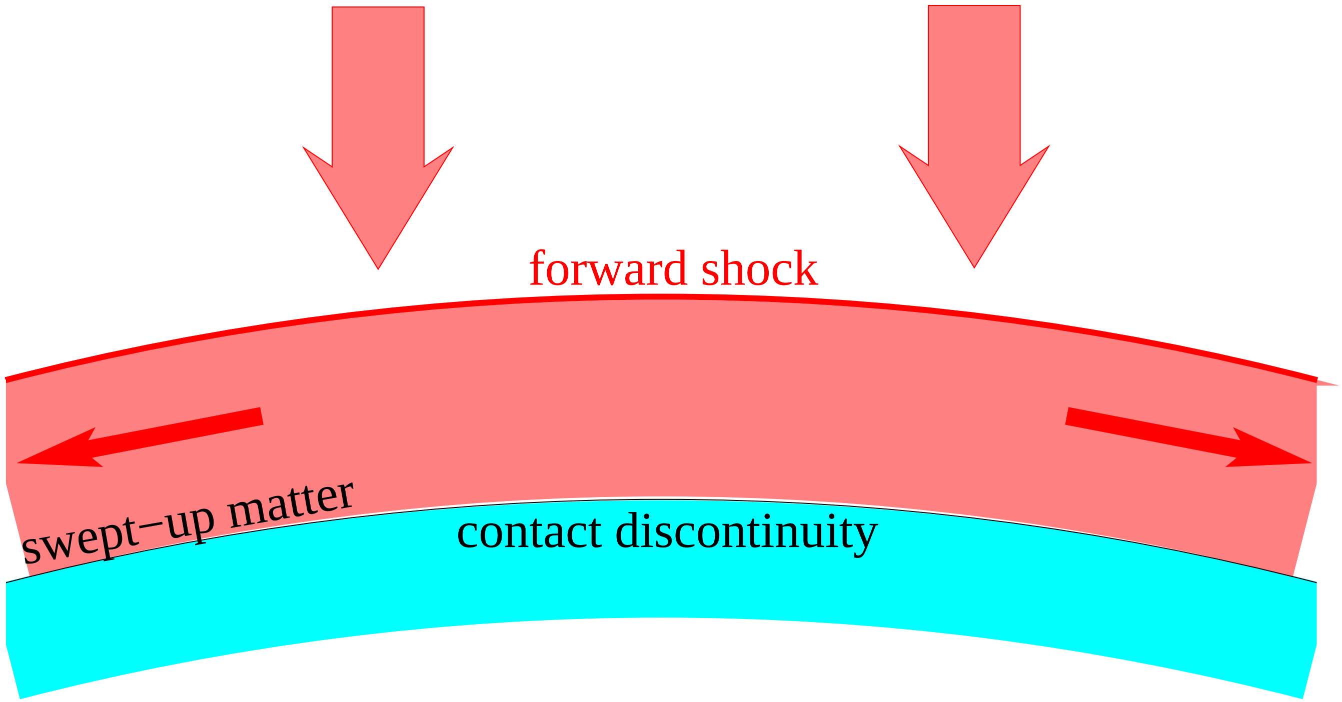
Top: X-ray light curve.

Bottom: combined Rc-band data set.

Guelbenzu et al. A&A 531 (2011)

Jet breaks

Rhoads 1997



Jet deceleration becomes much more efficient when

$$\Gamma < \theta_{in}^{-1}$$

Swept-up mass $M = \frac{4\pi}{3} R^3 \rho_{ext}$

Energy $E_{iso} \sim Mc^2\Gamma^2 \approx const$

Observer's time $t_{obs} \sim R/(\Gamma^2 c)$

$$R_{br} \sim \left(\frac{E_{iso}\,\theta_{in}^2}{\rho_{ext}\,c^2}\right)^{1/3}$$

Broad-band GRB spectrum

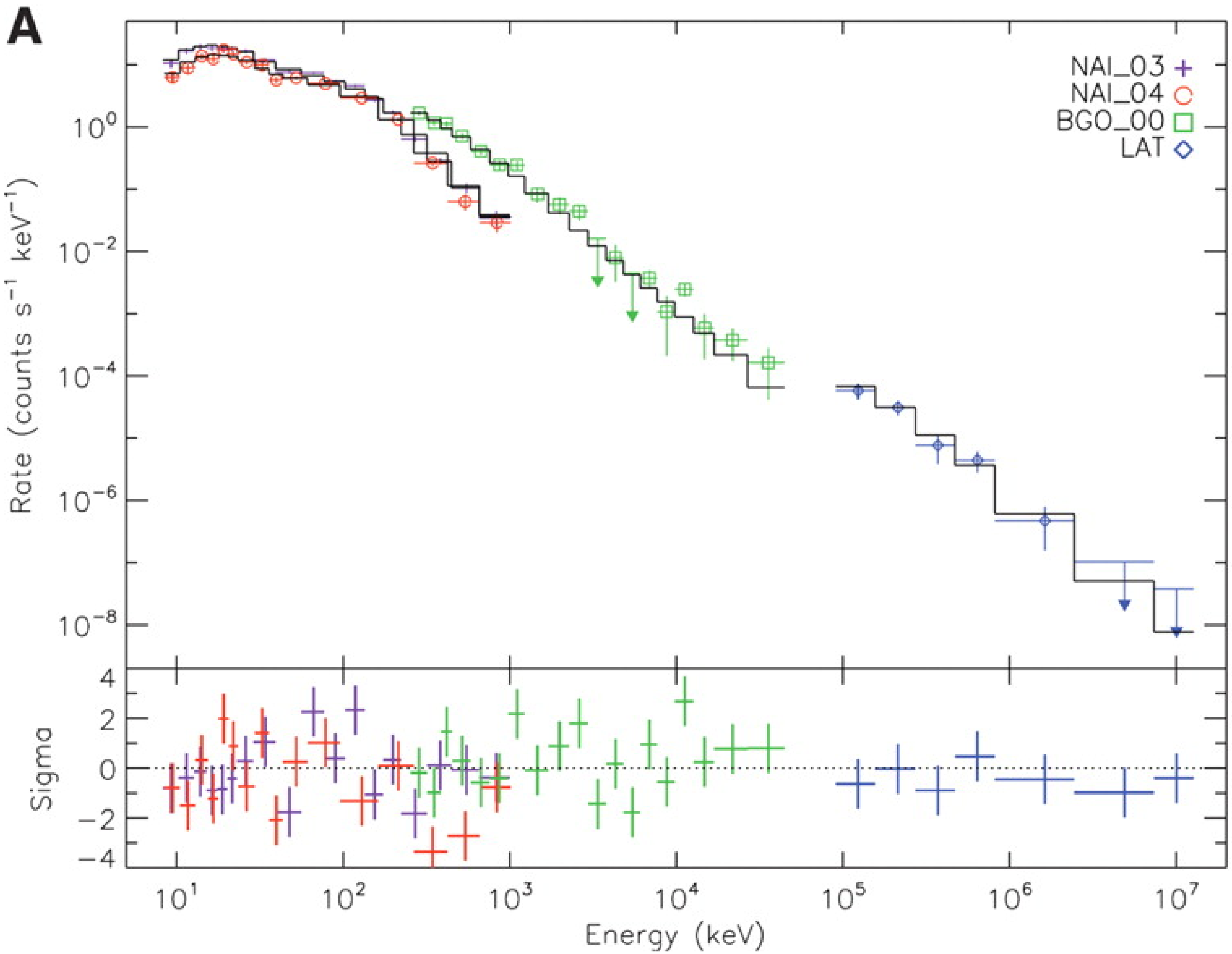
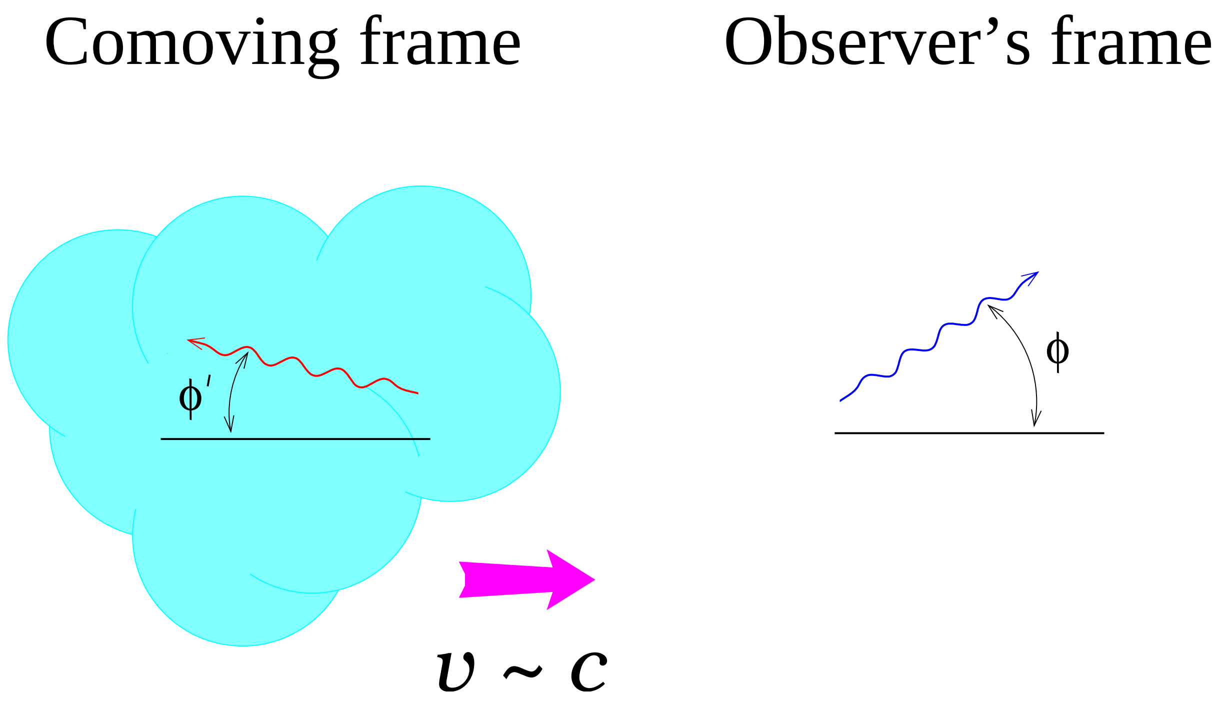


Figure from Abdo et al. Science 323 (2009)

Lorentz transformations

- Angles: $\cos\theta = \dfrac{\beta - \cos\theta'}{1 - \beta\cos\theta'}$; $\cos\theta' = \dfrac{\beta - \cos\theta}{1 - \beta\cos\theta}$
- Intensity: $I'_\omega(\omega') = \delta^3 \times I_\omega(\omega)$
- Frequency: $\omega' = \delta \times \omega$

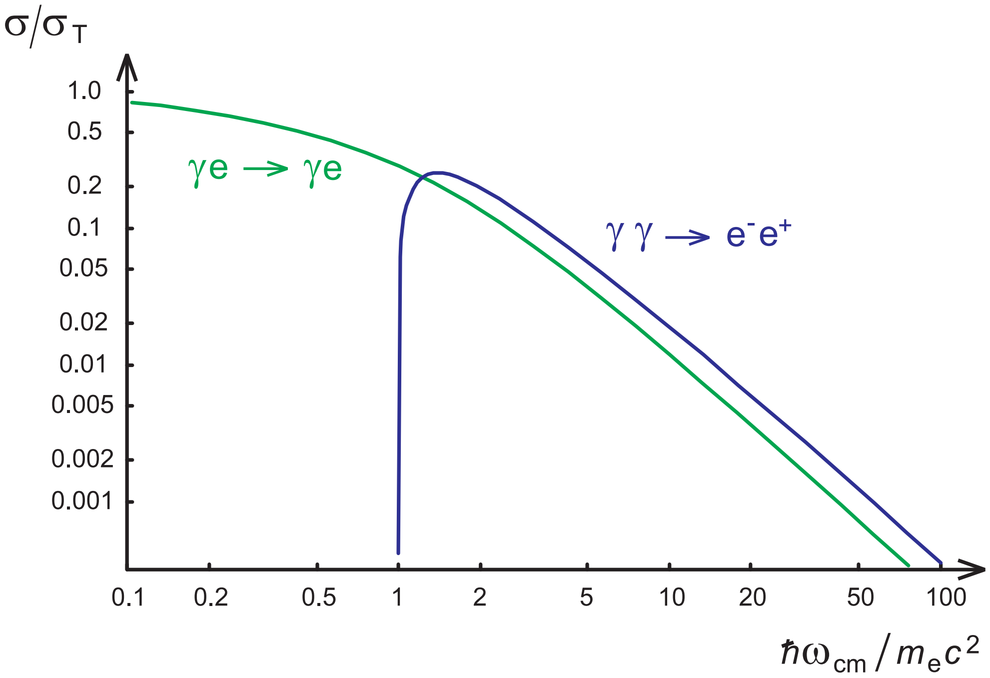
$\delta = \gamma(1 - \beta\cos\theta)$ — *Doppler-factor.*



For small angles approximately

$$\theta \simeq \frac{2}{\sqrt{(\gamma\theta')^2 + 1}} \quad \textit{and} \quad \delta \simeq \frac{(\gamma\theta)^2 + 1}{2\gamma}$$

Two-photon absorption



Baring & Harding 1995

$$\tau_{\gamma\gamma} \sim \sigma_T \frac{\mathcal{L}_{iso}(\varepsilon_*)}{4\pi R^2 c \Gamma \varepsilon_*} \frac{c t_v}{\Gamma}$$

where $\varepsilon_* \sim \frac{m_e^2 c^4}{\varepsilon_{ph}} \Gamma^2$

Two-photon opacity

$$\tau_{\gamma\gamma} = \sigma_{\gamma\gamma}\, n'_{ph}\, R' < 1$$

For brightest GRBs: $\Gamma \gtrsim 10^3$

Delayed high-energy emission

In some cases (GRB940217)

GeV emission lasts

hours after the burst

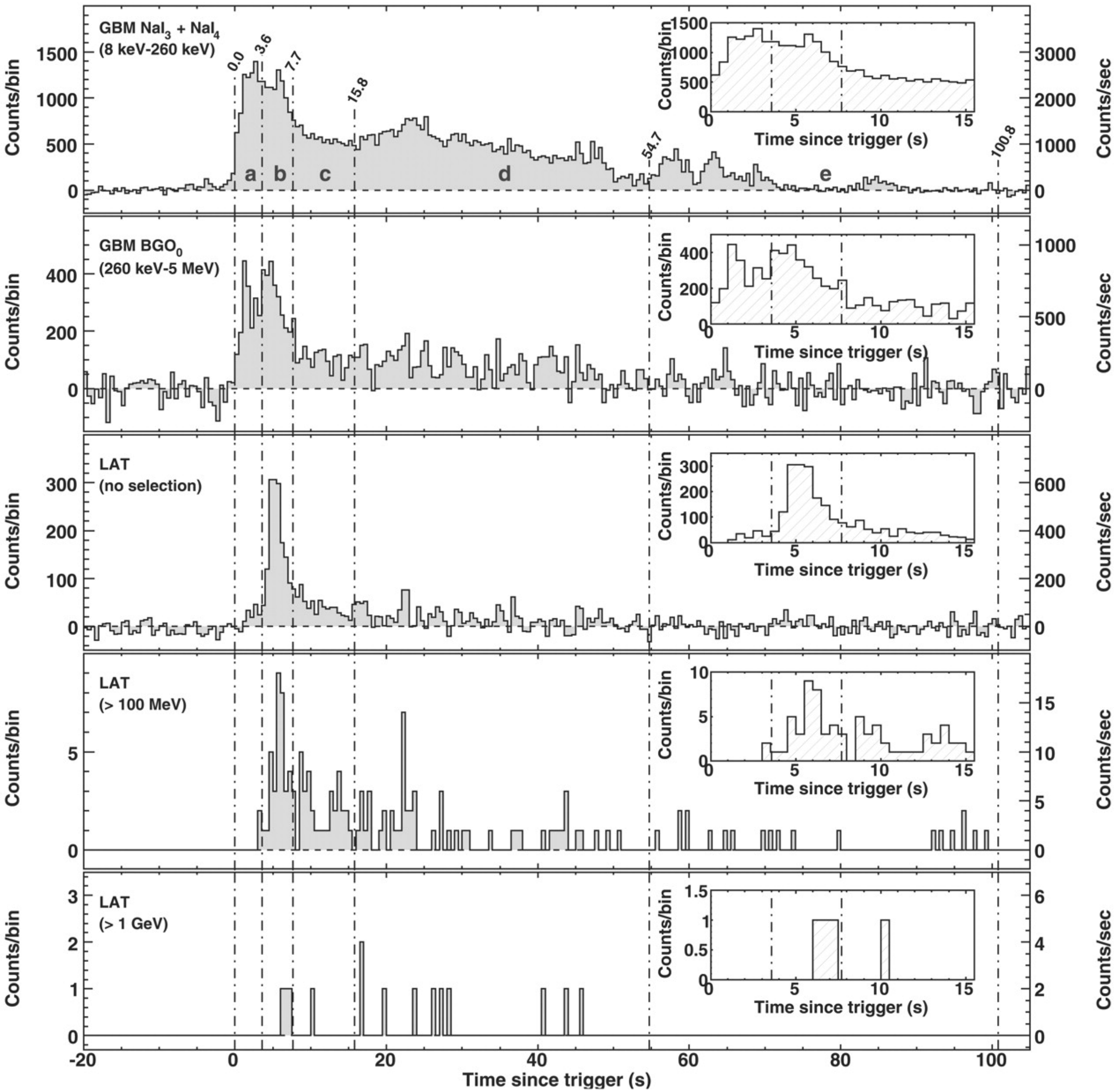


Figure from Abdo et al. Science 323 (2009)

Low-energy spectral indices

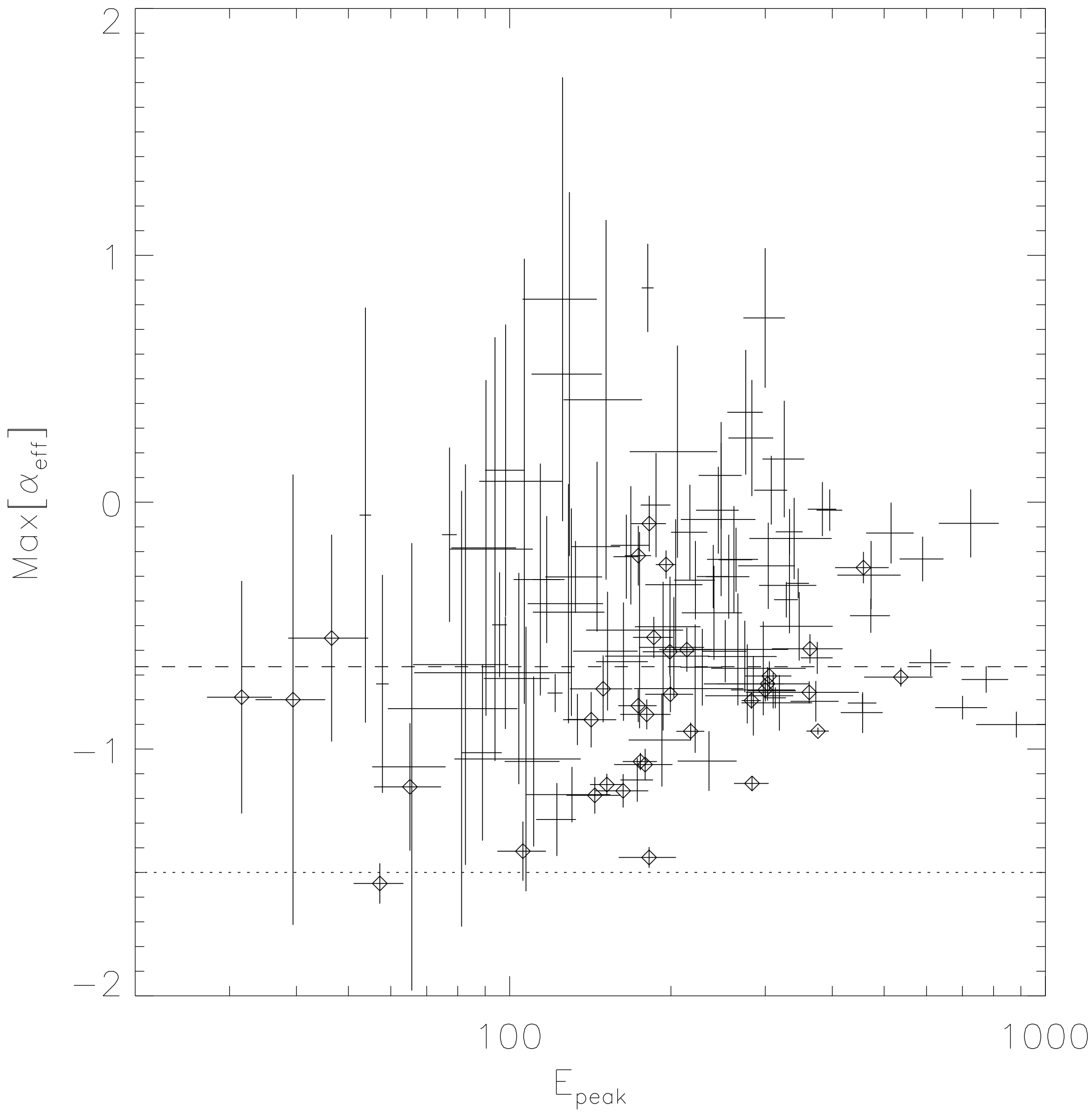


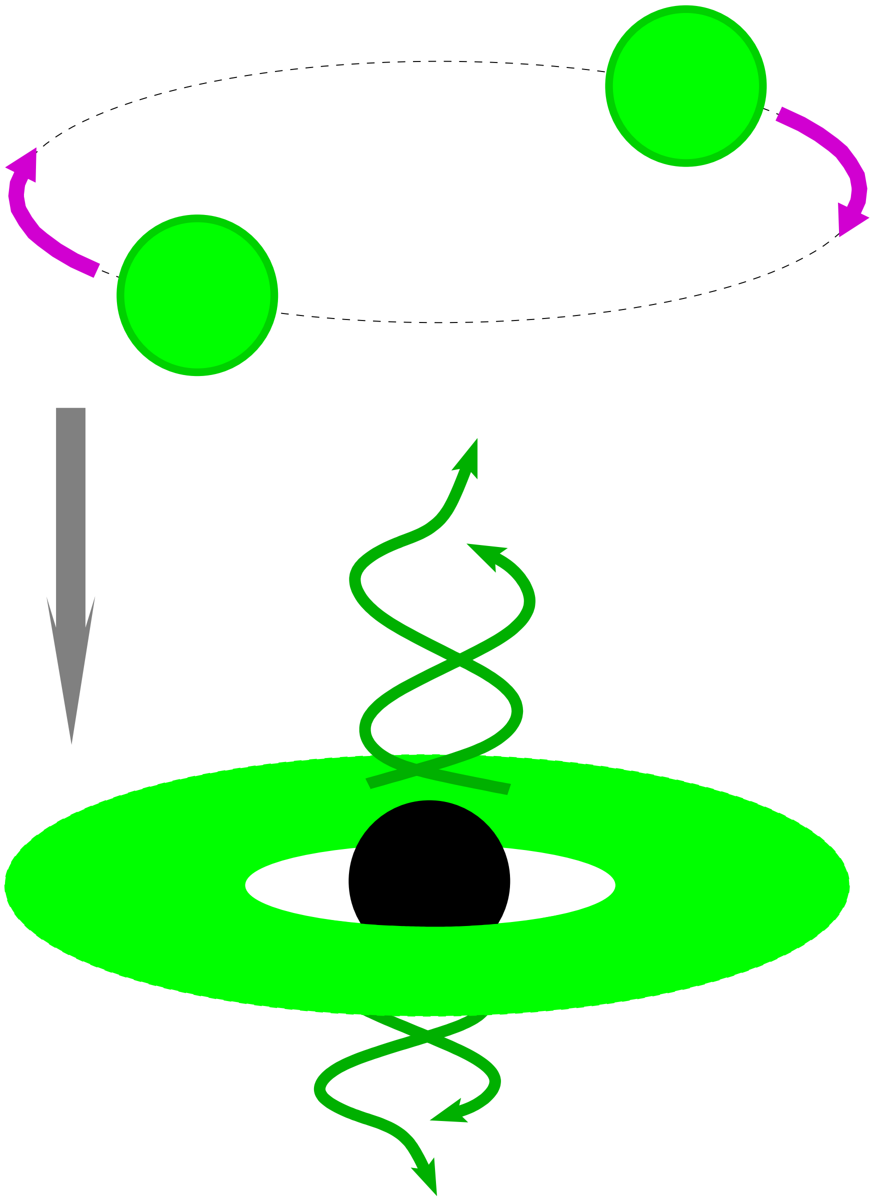
Figure from Preece et al. ApJ 506 (1998)

General requirements to GRB models

- Should produce large energy release and luminosity
- Should explain very rapid (ms scale) variability
- Central engines should be capable of launching highly relativistic outflows
- The emitted radiation should be very broad-band (therefore – nonthermal)

Merger scenario (short GRBs)

B. Paczynski



Starting point:
Two neutron stars or a neutron star and a black hole in a close binary

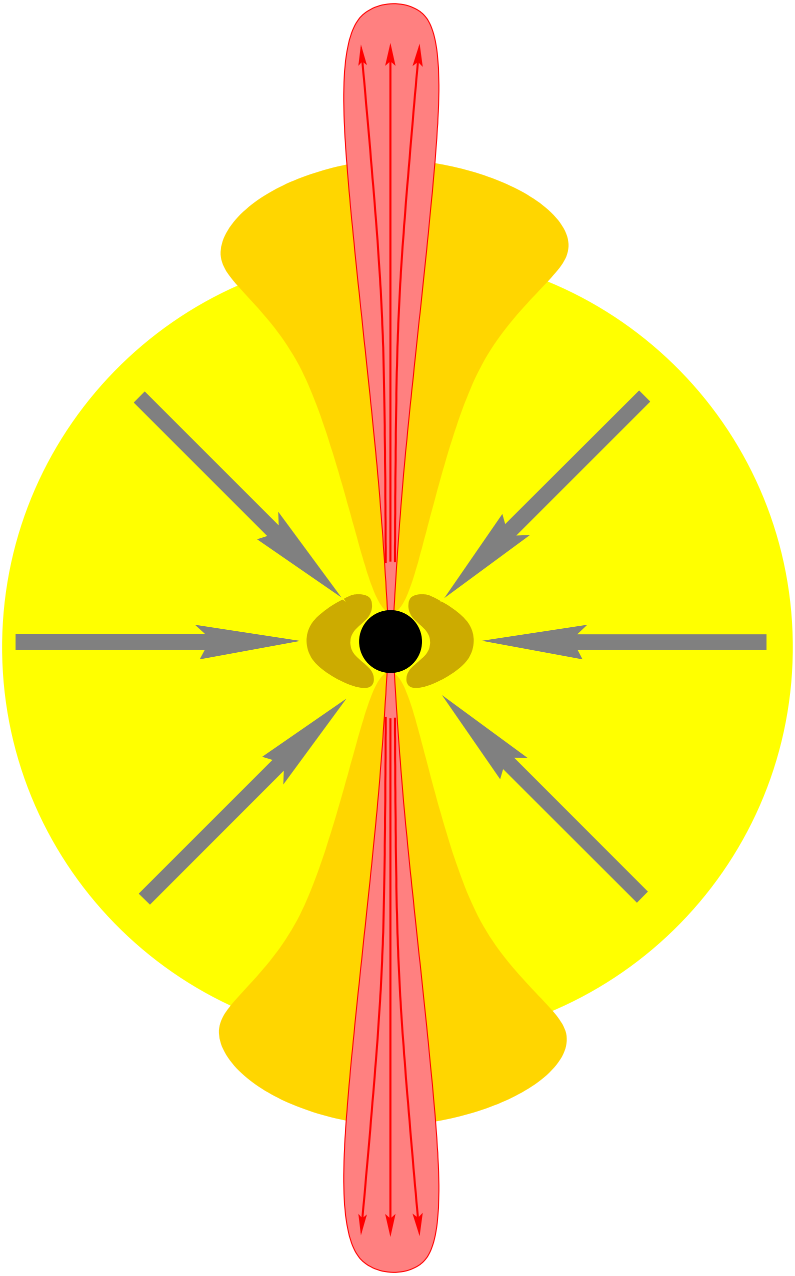
Loss of energy for gravitational radiation eventually causes merger

Features:

Not connected with star-forming regions

Burst of grawitational waves at the time of GRB

Collapsar scenario (long GRBs)



S. Woosley

Starting point:

A rapidly rotating Wolf-Rayet star

The star undergoes core-collapse, forming a black hole surrounded by a massive accretion torus

Features:

Can occur only in star-forming regions

Can be a special type of supernovae

Main characters in GRB play

- **Magnetic fields**

either need to be generated, likely by Weibel instability

Medvedev & Loeb 1999

or need to be dissipated, if the jets are Pointing-dominated

- **Energetic charged particles**

likely electrons and positrons, by maybe protons

- **Neutrons**

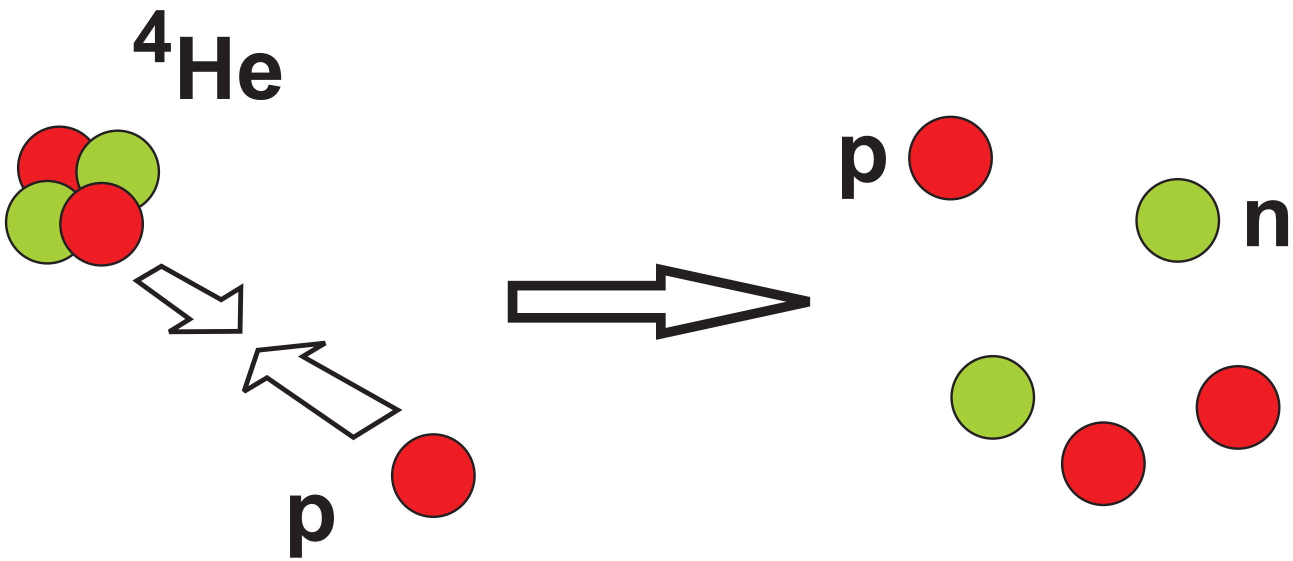
produced in many ways, being stable over GRB duration

Derishev et al. 1999

Sources of free neutrons

1. thermal dissociation of nuclei

$^4\text{He} + p \rightarrow 3p + 2n$ (requires $T > 0.7$ MeV)



^{4}He – helium nucleus

p – proton

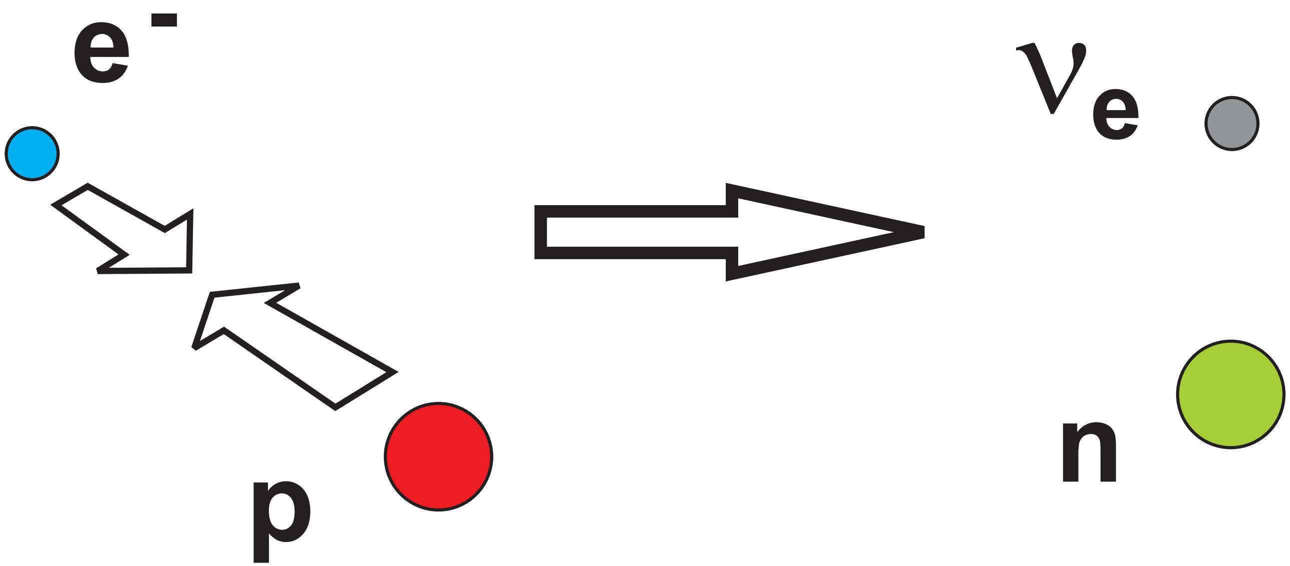
n – neutron

Sources of free neutrons
2. electron capture

$p + e^- \rightarrow n + \nu_e$

requires $\rho > 10^8$ g/cm^3

or $T \gtrsim 5$ MeV



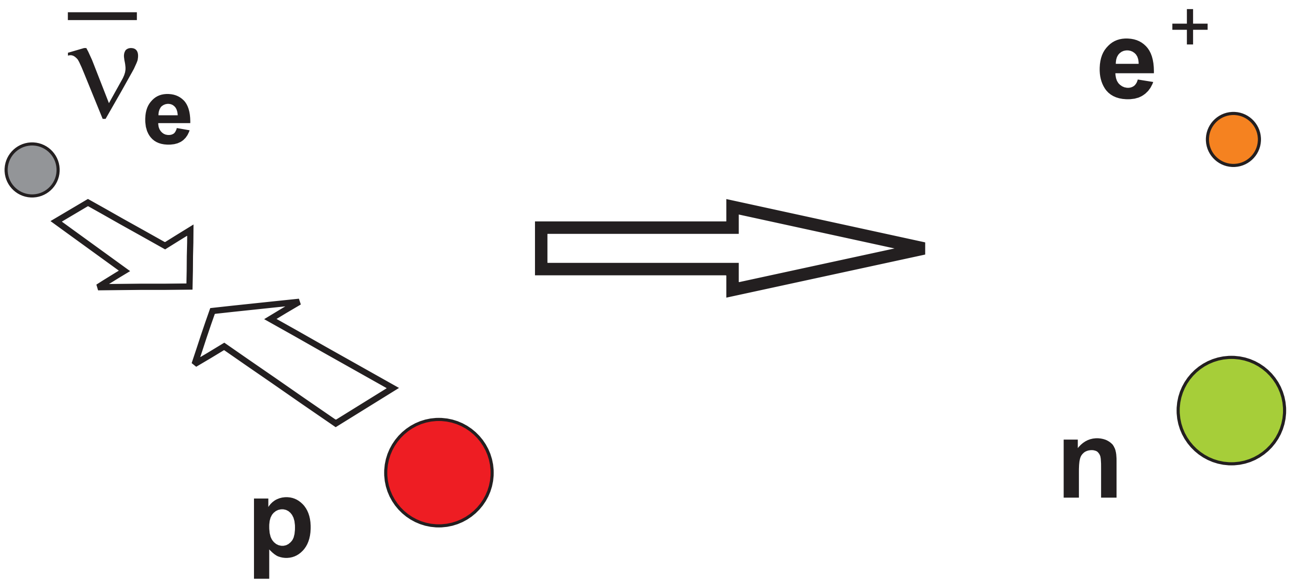
e^- – electron

ν_e – electron neutrino

Sources of free neutrons
3. inverse beta-decay

$$p + \bar{\nu}_e \rightarrow n + e^+ \qquad \sigma = 9.3 \times 10^{-44}\ \mathrm{cm}^2 \left(\frac{\varepsilon_\nu}{1\ \mathrm{MeV}} \right)^2$$

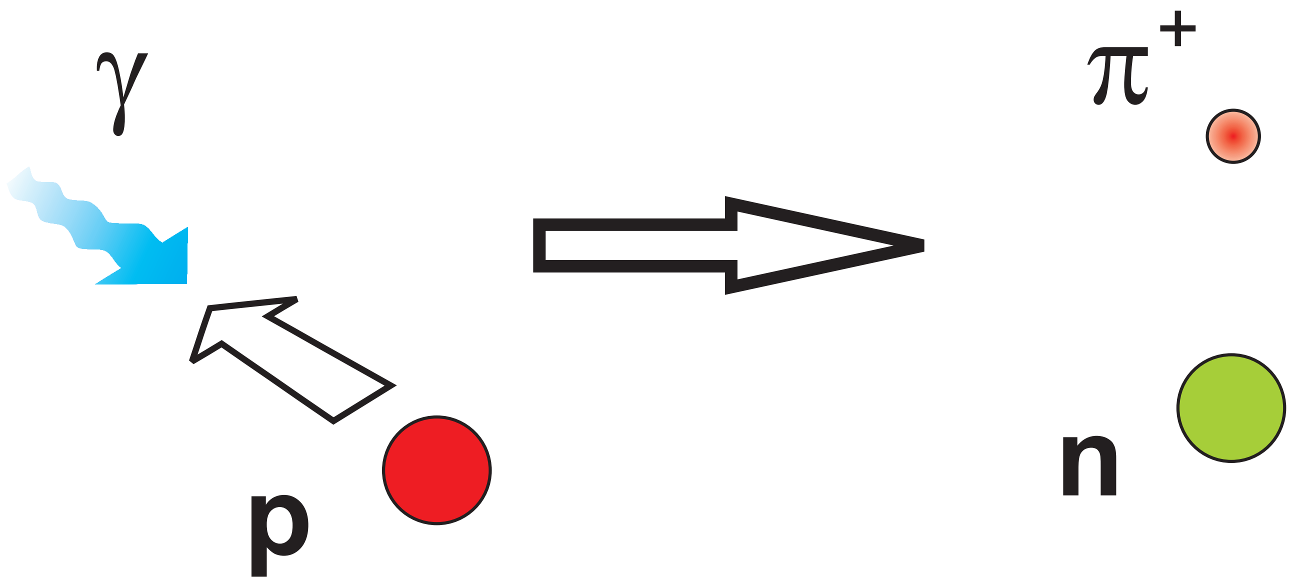
$$\varepsilon_\nu \gg (m_n - m_p)c^2$$



Sources of free neutrons
4. photopion reactions

$$p + \gamma \rightarrow n + \pi^{+}$$

compactness $\ell \gtrsim \dfrac{10^{7}}{\Gamma_{p}}$

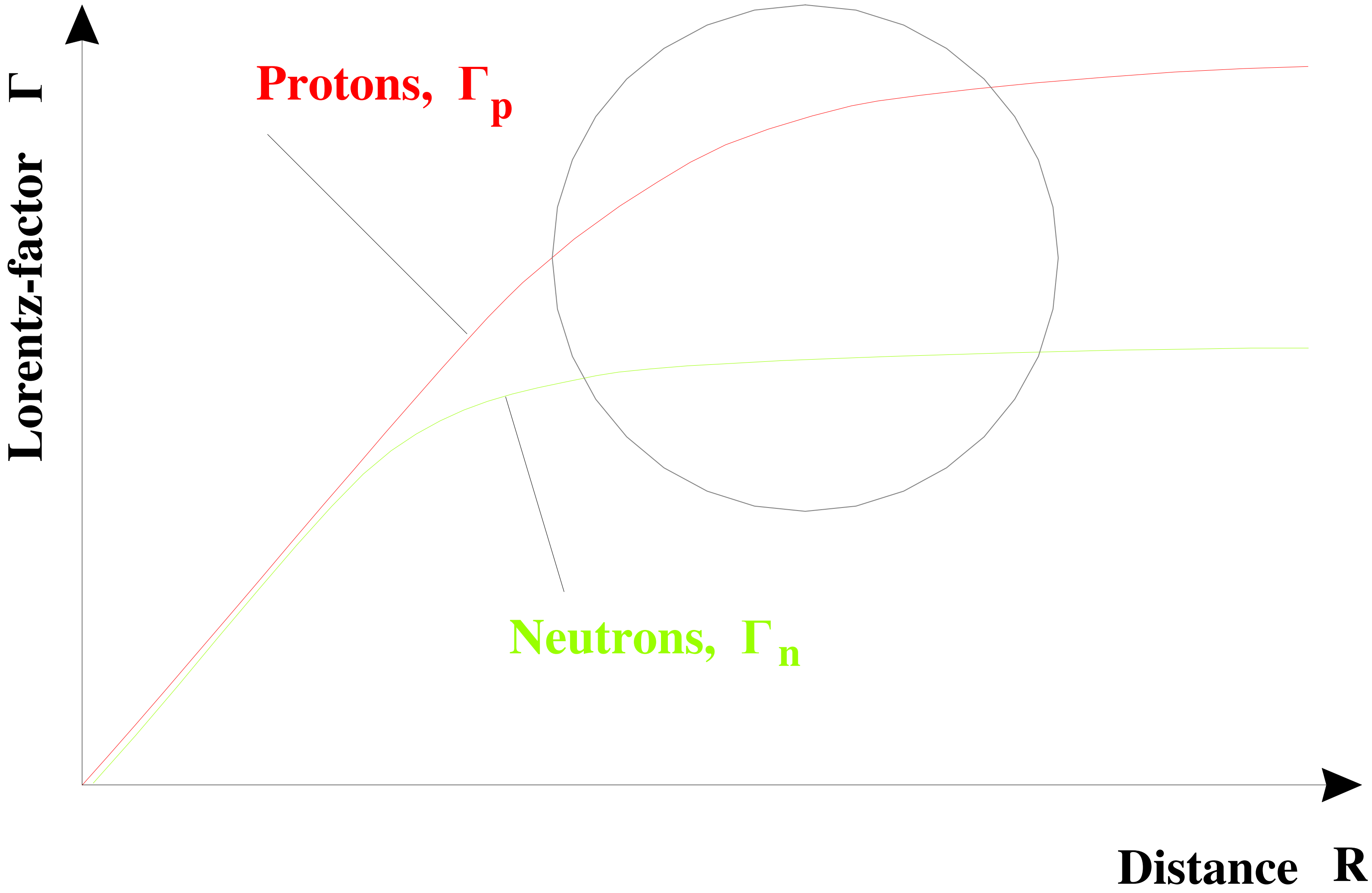


π^{-} – pion

γ – photon

Γ_p – Lorentz-factor of a proton

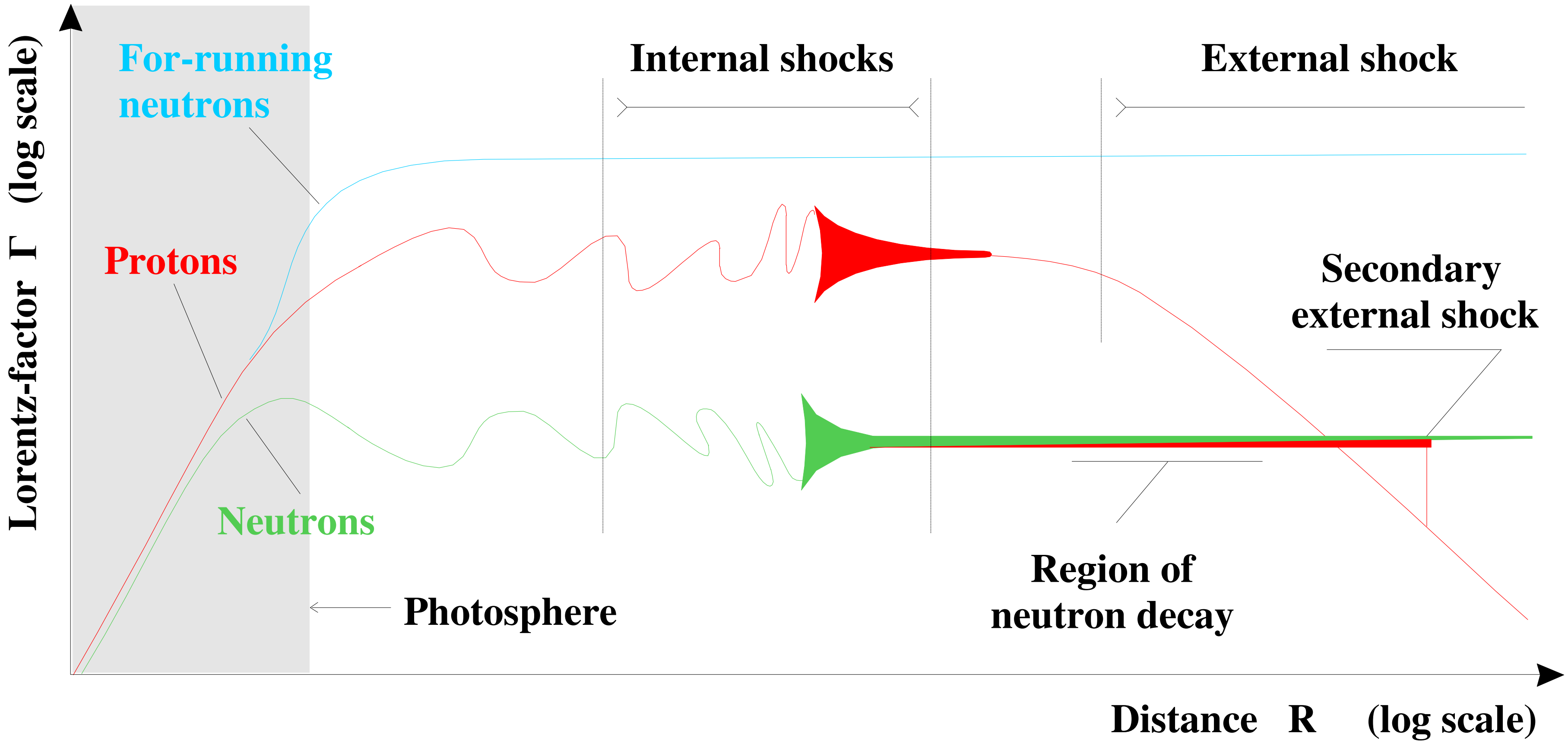
Proton-neutron decoupling



$p + n \to N + N' + X$

$X = \pi^-, \pi^+, \pi^0$ with roughly equal probabilities

GRB evolution over distance



- Secondary dissociation of helium
- Appearance of for-running neutrons
- High-energy neutrino emission
- Electromagnetic cascade; photosphere shift and production of hard gamma-rays
- Secondary external shock(s) due to decay of slow neutrons

Radiation mechanisms

electrons

- **Synchrotron radiation**

  undulator radiation

- Inverse Compton radiation
- Bremsstrahlung

$$L_{sy} = \frac{4}{3}\gamma^2 \sigma_T c \frac{B^2}{8\pi} \qquad \varepsilon_{sy} \sim \gamma^2 \frac{\hbar e B}{m_e c}$$

When coupled to diffusive shock acceleration,

$$\varepsilon_{sy} \lesssim m_e c^2/\alpha_f \sim 70 \text{ MeV}$$

due to radiative losses, that limit acceleration

protons

- Synchrotron radiation
- Inelastic nucleon collisions
- Coulomb losses

Radiation mechanisms

Toptygin & Fleishman 1987, Medvedev 2000

electrons

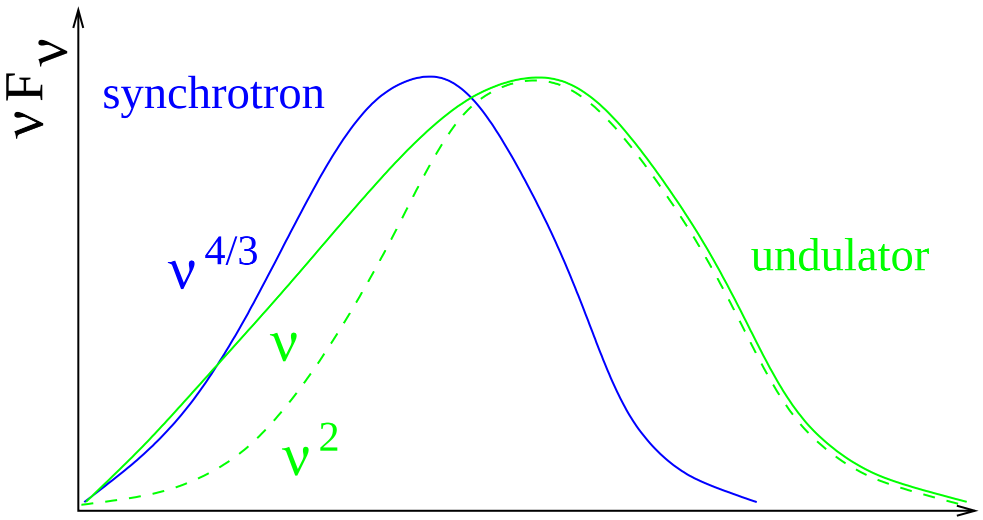
- Synchrotron radiation

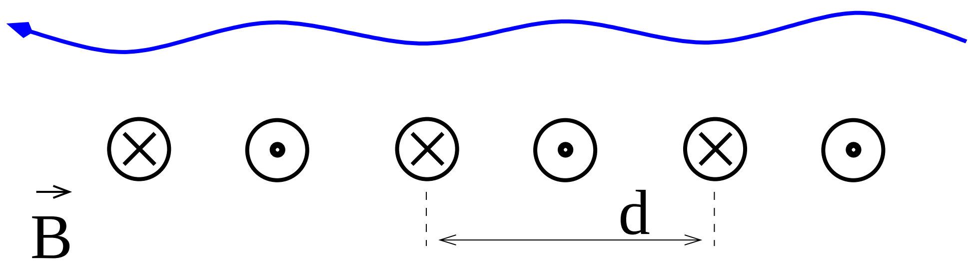
  undulator radiation

- Inverse Compton radiation
- Bremsstrahlung

$$L_{und} = \frac{4}{3}\gamma^2 \sigma_T c \frac{B^2}{8\pi} \qquad \varepsilon_{und} \sim \gamma^2 \frac{\hbar c}{d}$$

differs from synchrotron if $d < m_e c^2/(eB)$





protons

- Synchrotron radiation
- Inelastic nucleon collisions
- Coulomb losses

Radiation mechanisms

electrons

- Synchrotron radiation

  undulator radiation

- **Inverse Compton radiation**

- Bremsstrahlung

protons

- Synchrotron radiation

- Inelastic nucleon collisions

- Coulomb losses

Thomson regime ($\varepsilon_{ph} \ll m_e c^2/\gamma$):

$$L_{IC} = \frac{4}{3}\gamma^2 \sigma_T c w_{ph} \qquad \varepsilon_{IC} \sim \gamma^2 \varepsilon_{ph}$$

Klein-Nishina regime ($\varepsilon_{ph} \gtrsim m_e c^2/\gamma$):

$$L_{IC} < \frac{4}{3}\gamma^2 \sigma_T c w_{ph} \qquad \varepsilon_{IC} \sim \gamma m_e c^2$$

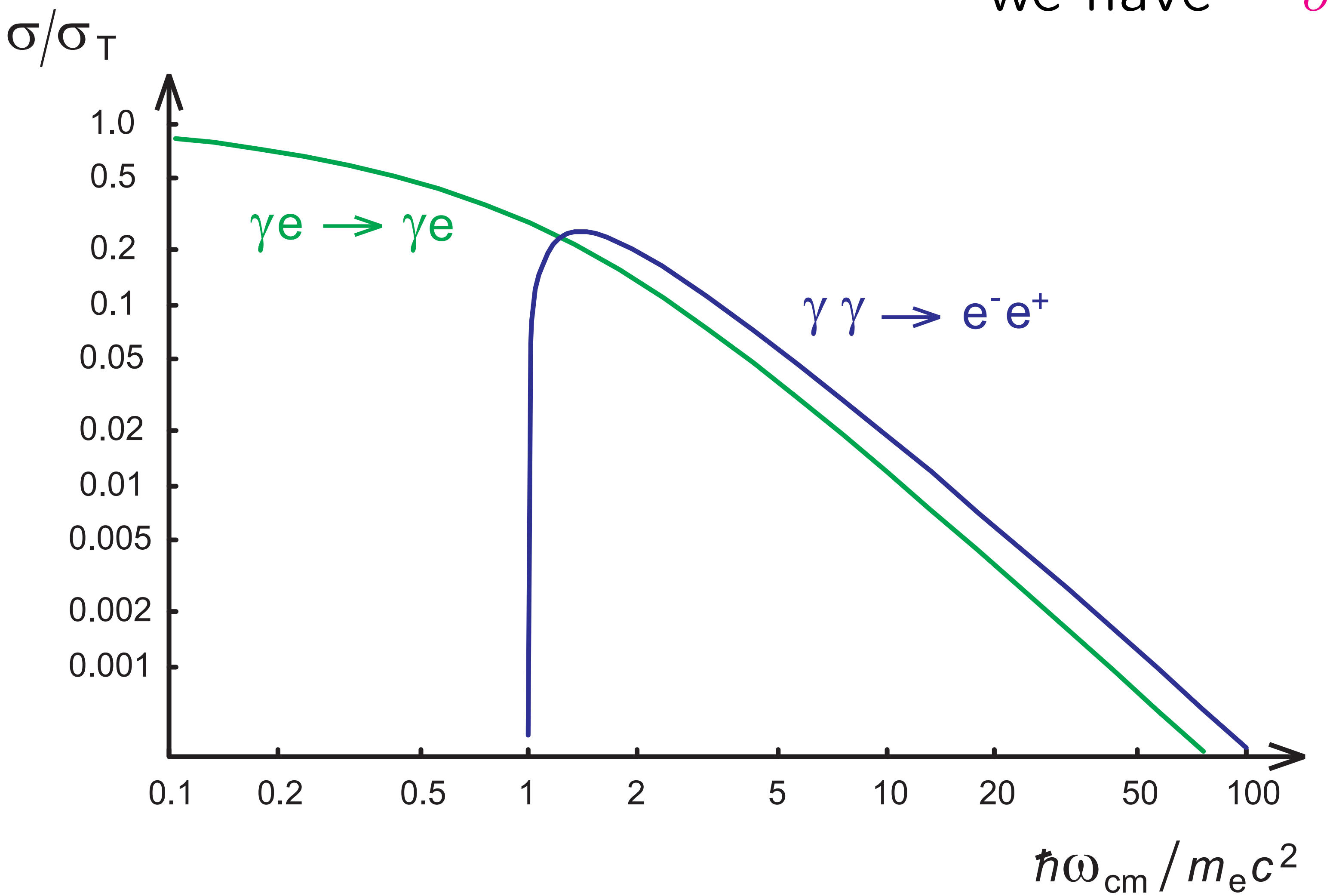
ε_{ph} – background photons' energy

w_{ph} – background radiation energy density

Interlude: Two-photon absorption

In the limit $\varepsilon_\gamma \gg m_e c^2$

we have $\sigma_{\gamma\gamma} \approx 2\,\sigma_{e\gamma}$



Two-photon absorption

Optical depth for two-photon absorption

$$\tau_{\gamma\gamma}(\omega) \simeq \sigma_{\gamma\gamma} \, N_{ph}(\omega_*) \, R$$

Inverse Compton energy losses per particle

$$\dot{\varepsilon} \simeq \frac{1}{2} \varepsilon \, \sigma_{e\gamma} \, N_{ph}(\omega_*) \, c$$

Under assumption of high radiation efficiency $(\dot{\varepsilon} > \varepsilon / t_v)$

the optical depth of a source with size $R \simeq c t_v$ is

$$\tau_{\gamma\gamma} > 2 \, \frac{\sigma_{\gamma\gamma}(\varepsilon/2)}{\sigma_{e\gamma}(\varepsilon)} \gg 1$$

$N_{ph}(\omega_*)$ – number density of photons with frequency $\sim \omega_*$

Klein-Nishina effect

Inverse Compton power

$$P_{IC} = c \int_0^\infty \sigma_{tr}(\omega') W'_{em,\omega'} \, \mathrm{d}\omega'$$

$\sigma_{tr}(\omega)$ – transport cross-section

High-energy limit ($\hbar\omega' \gg m_e c^2$)

$$\langle \hbar\omega_{sc} \rangle \sim \frac{1}{2} \gamma m_e c^2 \qquad\qquad \sigma_{tr} \propto \omega^{-2} \ln \omega$$

In most cases, a simple approximation works

$$P_{IC} = \frac{4}{3} \gamma^2 \sigma_T c \int_0^{\frac{m_e c^2}{\gamma \hbar}} W_{em,\omega} \, \mathrm{d}\omega$$

Radiation mechanisms

electrons

- Synchrotron radiation

  undulator radiation

- Inverse Compton radiation
- **Bremsstrahlung**

protons

- Synchrotron radiation
- Inelastic nucleon collisions
- Coulomb losses

emission power density:

$$\dot{w}_{ff} = \frac{2}{\pi} \alpha_f \sigma_T c\, n_e^2 \sqrt{T m_e c^2}\, G(n_e, T)$$

At an optical depth τ
each electron on average radiates

$$\frac{w_{ff}}{n_e} = \frac{2}{\pi} \alpha_f \tau \sqrt{T m_e c^2}\, G(n_e, T)$$

inefficient unless $T \lesssim \alpha_f^2 m_e c^2 \sim 25$ eV

Radiation mechanisms

electrons

- Synchrotron radiation

  undulator radiation

- Inverse Compton radiation
- Bremsstrahlung

protons

- **Synchrotron radiation**
- Inelastic nucleon collisions
- Coulomb losses

At a given energy

$$L_{sy}^{(p)} = \left(\frac{m_e}{m_p}\right)^4 L_{sy}^{(e)} \sim 10^{-13} L_{sy}^{(e)}$$

Although relatively slow, the mechanism works in multi-GeV range!

Radiation mechanisms

electrons

- Synchrotron radiation

  undulator radiation

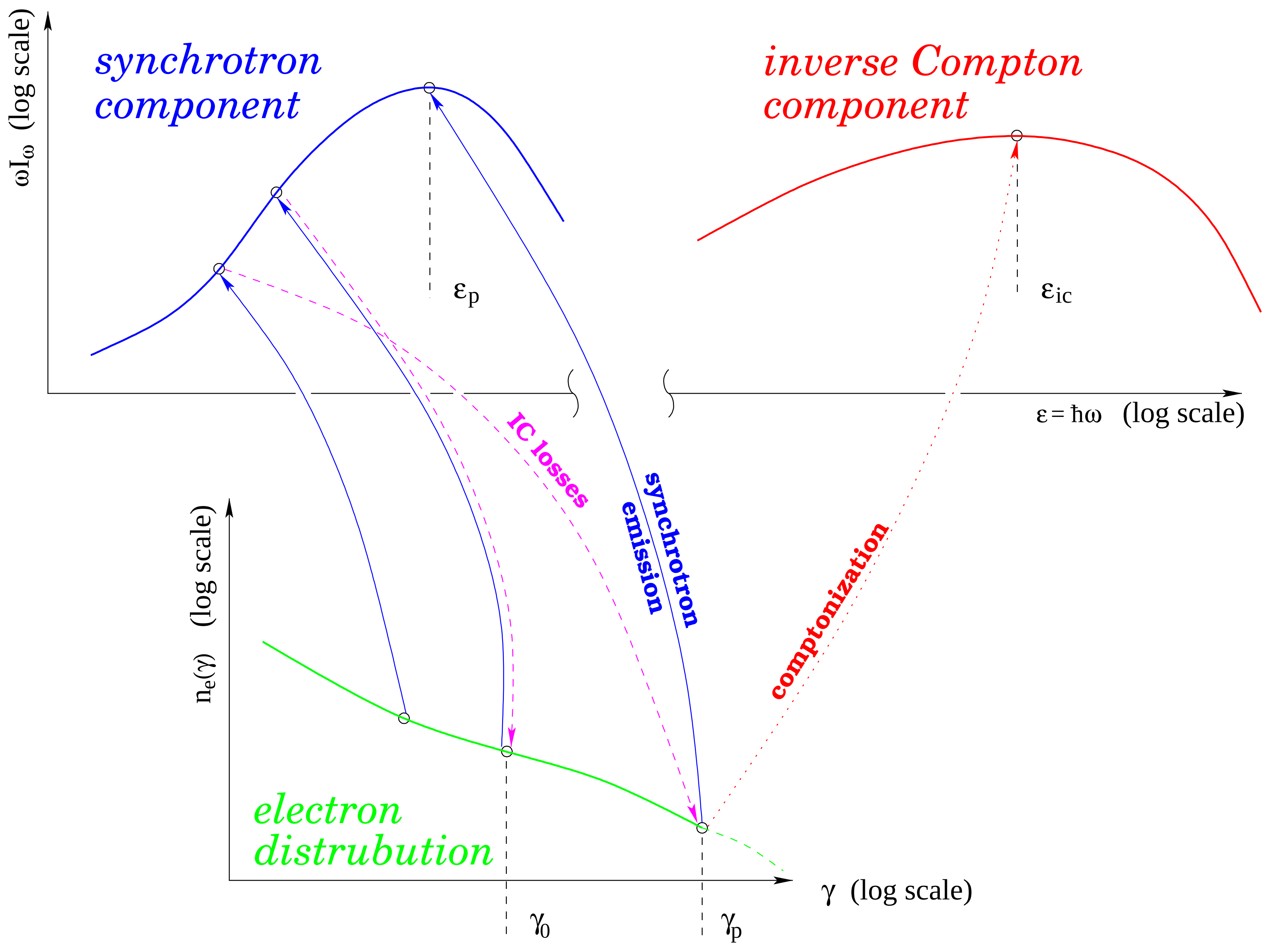
- Inverse Compton radiation
- Bremsstrahlung

protons

- Synchrotron radiation
- **Inelastic nucleon collisions**
- **Coulomb losses**

end up with energetic electrons, which radiate by either of the electron mechanisms

The synchrotron-self-Compton model



Fast cooling regime

Continuity equation $$\frac{\partial N}{\partial t} + \mathrm{div}\,(\dot{\gamma} N) = f(\gamma)$$

$f(\gamma)$ – injection function,

for accelerated particles usually $f(\gamma) \propto \gamma^{-s}$, where $s \simeq 2$

$N(\gamma)$ – electron distribution function

gives stationary solution $$N(\gamma) = -\frac{1}{\dot{\gamma}} \int_{\gamma}^{\infty} f(\gamma')\, d\gamma',$$

the corresponding spectrum is

(under the condition $\omega \propto \gamma^x$) $$\omega L_\omega \propto \frac{dL}{d\ln\gamma} \propto \gamma\eta \int_{\gamma}^{\infty} f(\gamma')\, d\gamma'$$

$\eta(\gamma)$ – fraction of electron's energy, which goes into observed radiation

Low-energy spectral indices

Fast cooling: $\alpha < -1.5$

Synchrotron from a single electron: $\alpha < -2/3$

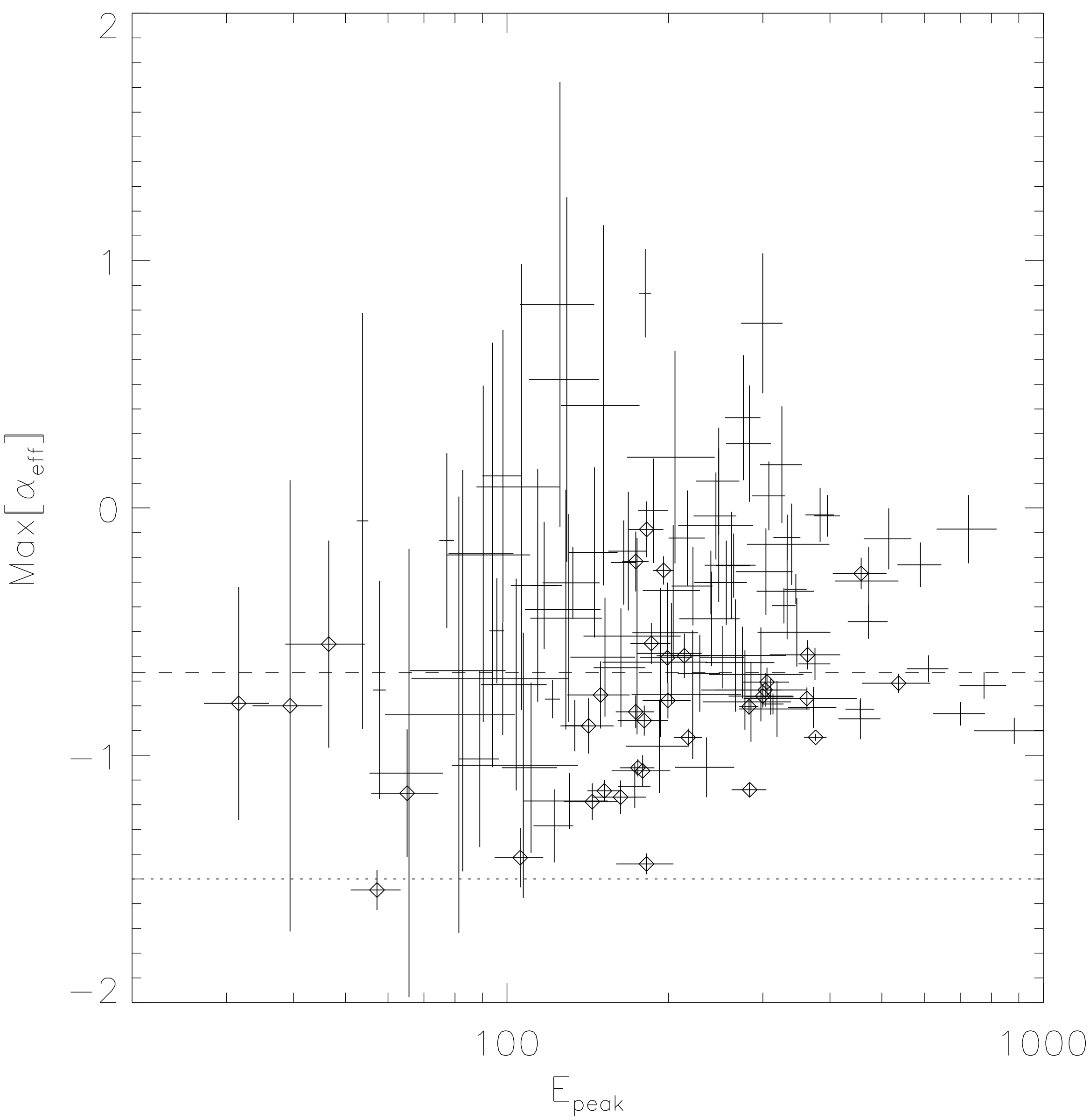


Figure from Preece et al. ApJ 506 (1998)

Equation for synchrotron efficiency

Derishev et al. 2001

$$\frac{1}{\eta(x)} = 1 + \mathcal{K} \int_0^{1/\sqrt{x}} p(x')\eta(x')\,\mathrm{d}x'$$

$\eta(\gamma) = \dfrac{\mathcal{L}_{\mathrm{sy}}}{\mathcal{L}_{\mathrm{ic}} + \mathcal{L}_{\mathrm{sy}}}$ — synchrotron efficiency

$\mathcal{L}_{\mathrm{sy}}$ $\mathcal{L}_{\mathrm{ic}}$ — synchrotron and Compton powers of an electron

$\mathcal{K} = \tau_{\mathrm{ic}} / (\bar{\eta} x_{\mathrm{i}})$ — Compton potential

$x = \gamma/\gamma_0$ — normalized Lorentz-factor of electrons

$p(x)$ — probability that an electron is injected with the Lorentz factor $> x$

τ_{ic} — optical depth for Comptonization ($\approx$ Compton y parameter)

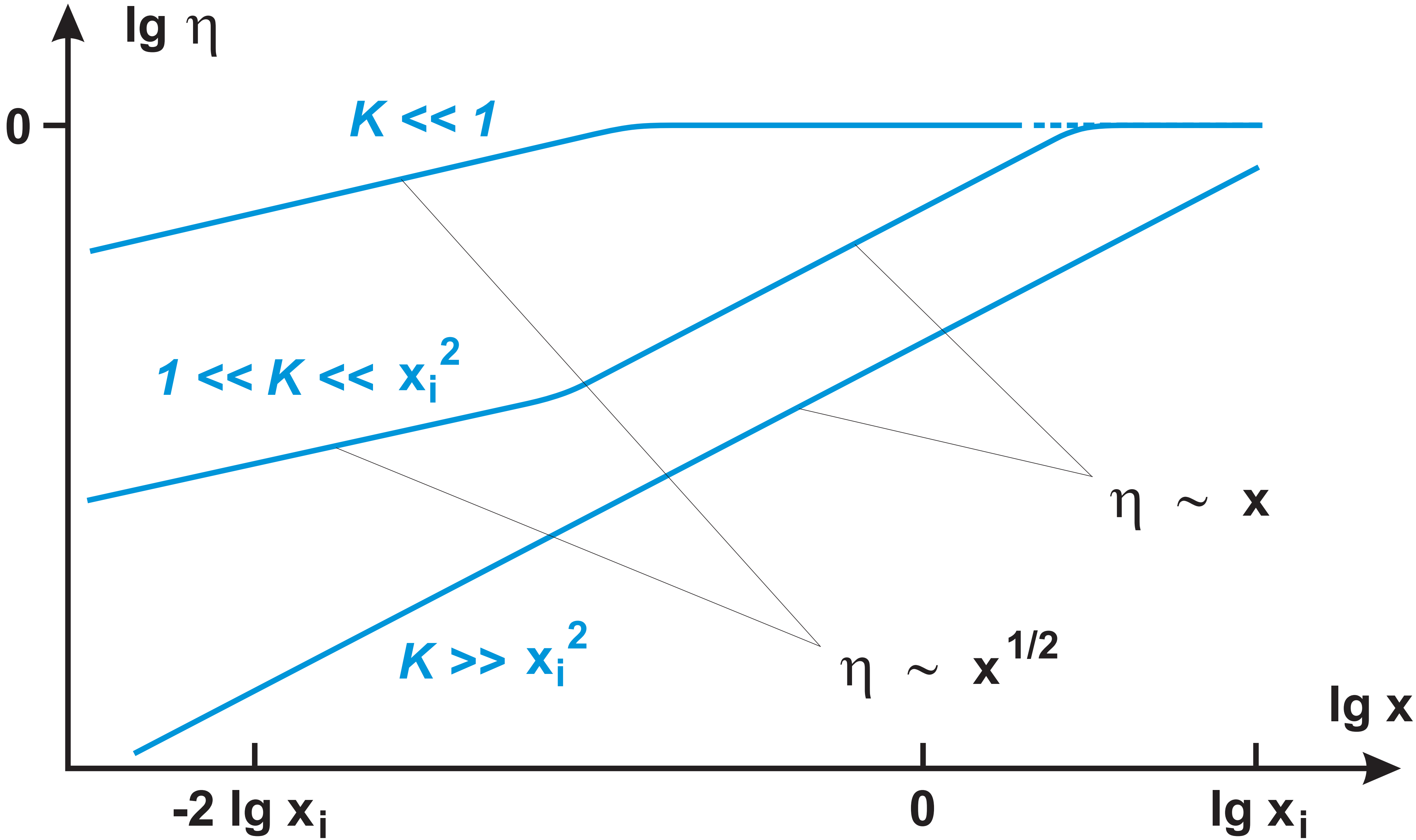
$$\gamma_0 = \left(\frac{2m_e^2c^3}{\hbar e B}\right)^{1/3} \simeq \left(\frac{10^{14}\,\mathrm{G}}{B}\right)^{1/3}; \quad \gamma_{\mathrm{i}} = \int_1^{\infty} p(\gamma)\,\mathrm{d}\gamma + 1 \;; \quad \bar{\eta} = \frac{1}{\gamma_{\mathrm{i}}}\int_1^{\infty} p\,\eta\,\mathrm{d}\gamma$$

✓ Electron distribution function: $f(\gamma) \propto \eta(\gamma)\,p(\gamma)\,\gamma^{-2}$

✓ Spectrum of synchrotron component: $\nu F_\nu^{\mathrm{sy}} \propto x\,p(x)\,\eta(x)$, $x \propto \sqrt{\nu}$

✓ Spectrum of IC component: $\nu F_\nu^{\mathrm{ic}} \propto x\,p(x)\,(1-\eta)$, where $x \propto \nu$

Solutions for different Compton potentials



Some hints for physical parameters in GRBs

Magnetic field in the emitting region $B \sim \dfrac{E_{52}^{1/2}}{t_1^{3/2}\tau_{\rm ic}^{1/2}}\,\mathcal{D}\,\dfrac{10^9}{\Gamma^3}$ G

Lorentz factor of accelerated electrons $\gamma_{\rm i} \sim 200\ \tau_{\rm ic}^{1/4}\Gamma\,\dfrac{t_1^{3/4}}{E_{52}^{1/4}}\,\mathcal{D}^{-1/2}$

Inverse Compton peak at $\varepsilon_{\rm ic} \sim 10^{-4}\ \Gamma^2\,\dfrac{t_1^{3/4}}{E_{52}^{1/4}}\,\mathcal{D}^{-1/2}$ TeV

Fraction of inverse Compton losses $\delta E_{\rm ic} \gtrsim \left[0.01\,\dfrac{E_{52}^{1/4}}{t_1^{3/4}}\,\mathcal{D}^{1/2}\right]^{\alpha}$

$\mathcal{D} = \dfrac{\text{burst duration}}{\text{variability timescale}}$ — variability parameter

t_1 — burst duration in units 10 s

E_{52} — burst energy in units 10^{52} erg

α $(0 < \alpha < 1)$ — low-frequency spectral index

From the condition $\delta E_{\rm ic} < 0.5$ follows that:

$\tau_{\rm ic} \sim 1 \div 10$

burst duration $t_{\rm grb} \gtrsim 0.03$ s

variability timescale $\gtrsim 10^{-3}$ s

What limits acceleration?

Particle escape from the accelerator

Degradation of particles' energy

- Sinchrotron radiation
- Inelastic collisions
- Inverse Compton losses (for electrons)
- Photomeson interactions and creation of e^-e^+ pairs (for protons and nuclei)

The probability of photon-induced reaction is usually small, $\ll 1$

How small has to be "small" to become dynamically negligible?

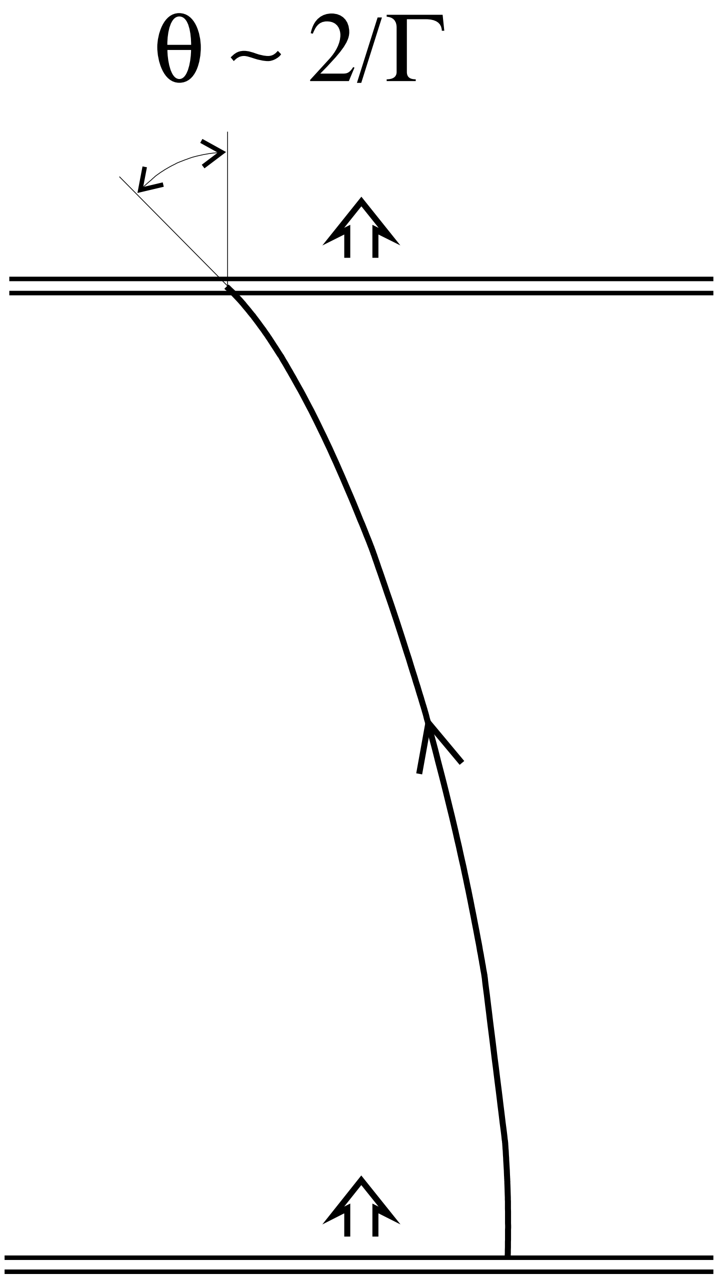
For a non-relativistic shock, a probability $\ll 1$ is always small

For a relativistic flow, the answer is either $\ll 1$ or $\ll 1/\Gamma^2$, depending on what you are talking about

If some energy leaks from downstream to upstream and mixes up with the upstream particles, we feed back to the shock Γ^2 time the initial energy!

Γ is the Lorentz factor of the flow

When "small" is large (standard acceleration)



The distribution of accelerated particles remains highly collimated.

The energy gain factor $g = (1/2)\,(\Gamma\theta)^2 \simeq 2$

The probability of particle injection back to upstream must be ~ 1 to get efficient acceleration. The actual probability depends on the (unknown) magnetic field geometry.

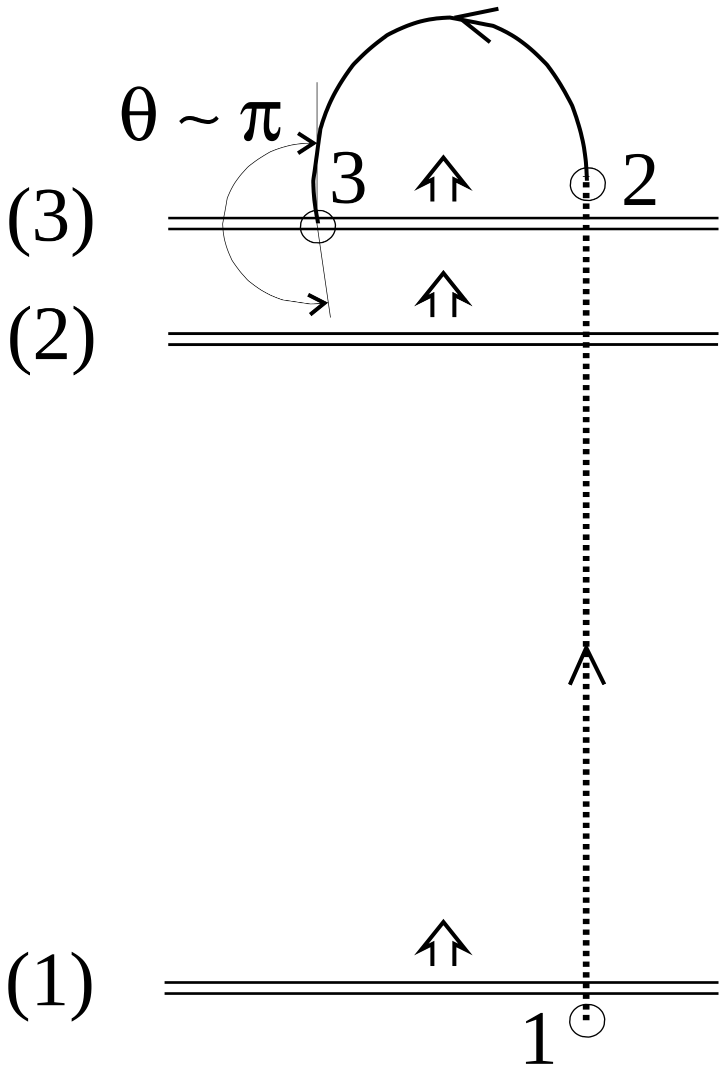
Favorable geometry gives, e.g., $\dfrac{\mathrm{d}N}{\mathrm{d}\varepsilon} \propto \varepsilon^{-\frac{22}{9}}$

(Keshet & Waxman, PRL 2005)

"Realistic" geometry leads to very soft particle distributions, with energy concentrated near $\Gamma^2 mc^2$

(Niemiec & Ostrowski, ApJ 2006;

When "small" is REALLY small



Full isotropization in the upstream ($\theta \sim 1$)

gives the energy gain factor $g = \frac{1}{2}(\Gamma\theta)^2 \sim \Gamma^2$

in each shock-crossing cycle

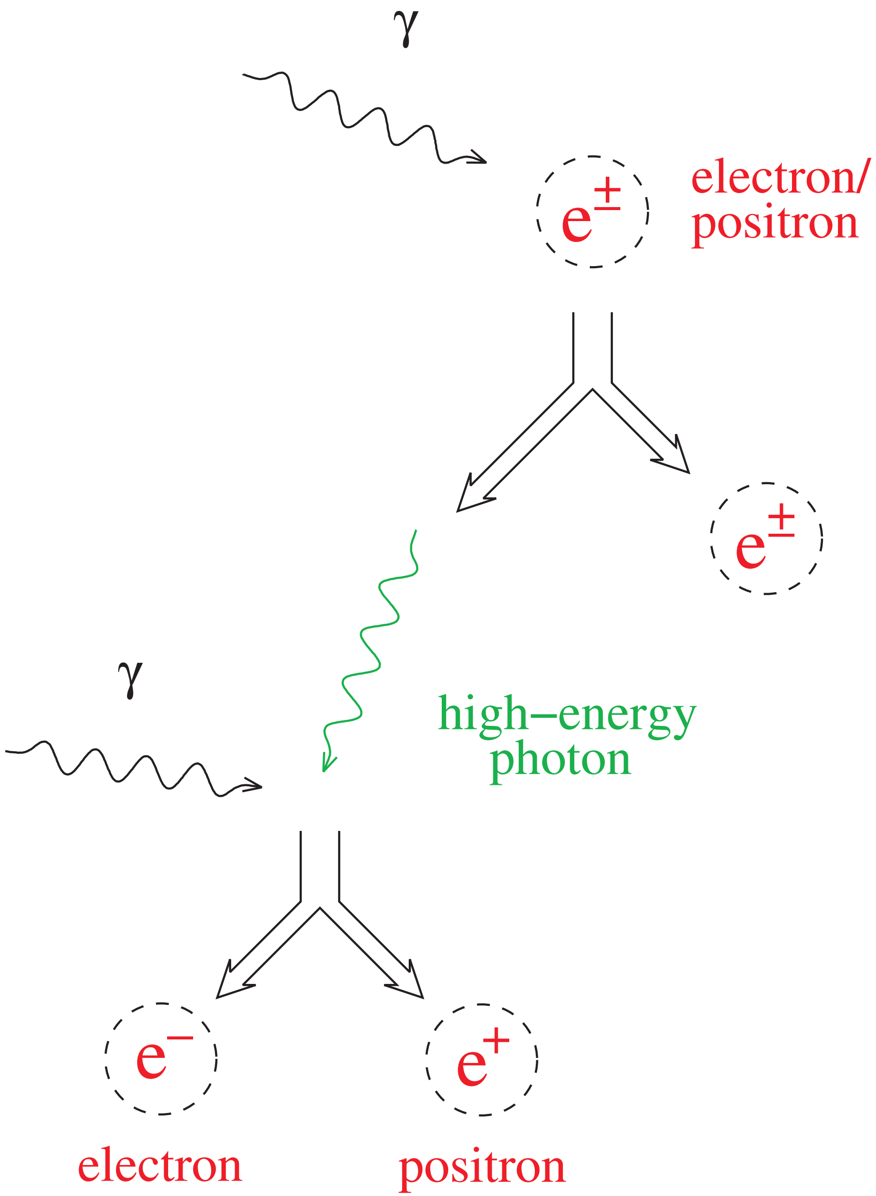
Photon-induced reactions reversibly "convert" accelerated particles to neutrals

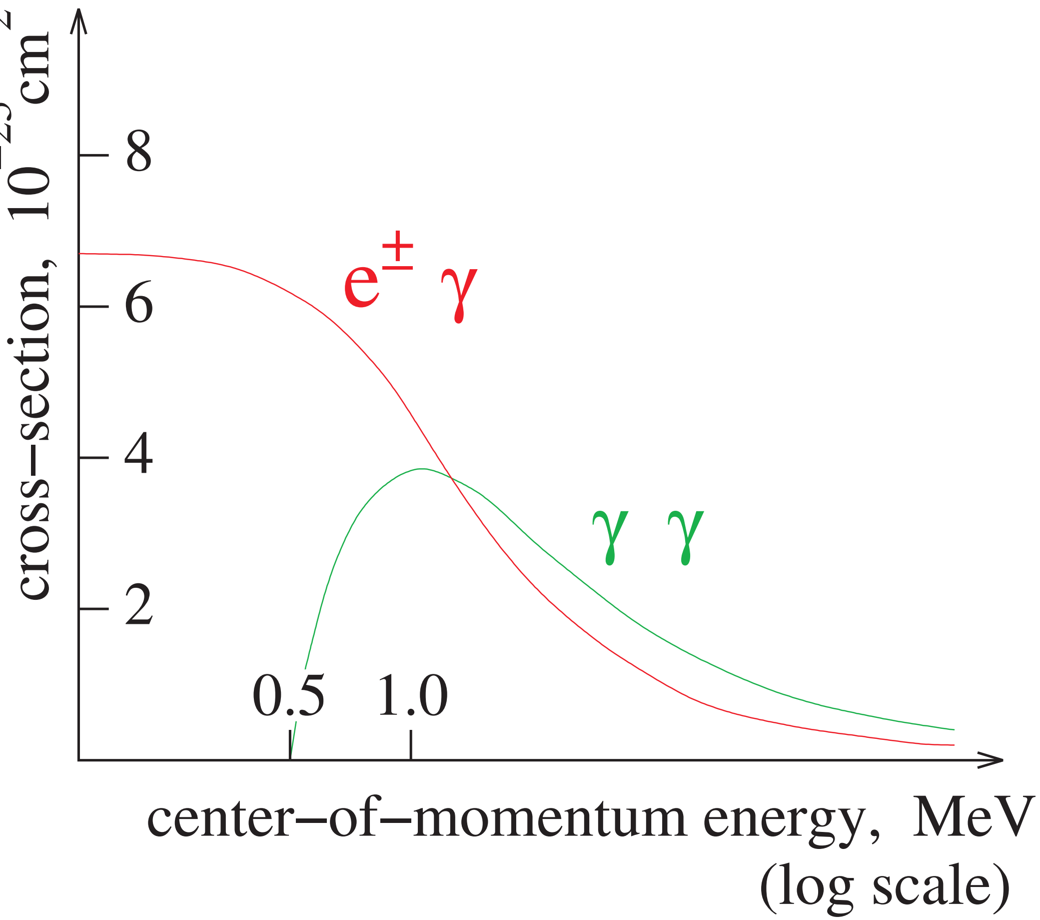
$\Rightarrow$ **Converter acceleration mechanism**

Derishev, Aharonian, Kocharovsky & Kocharovsky, PRD 2003;

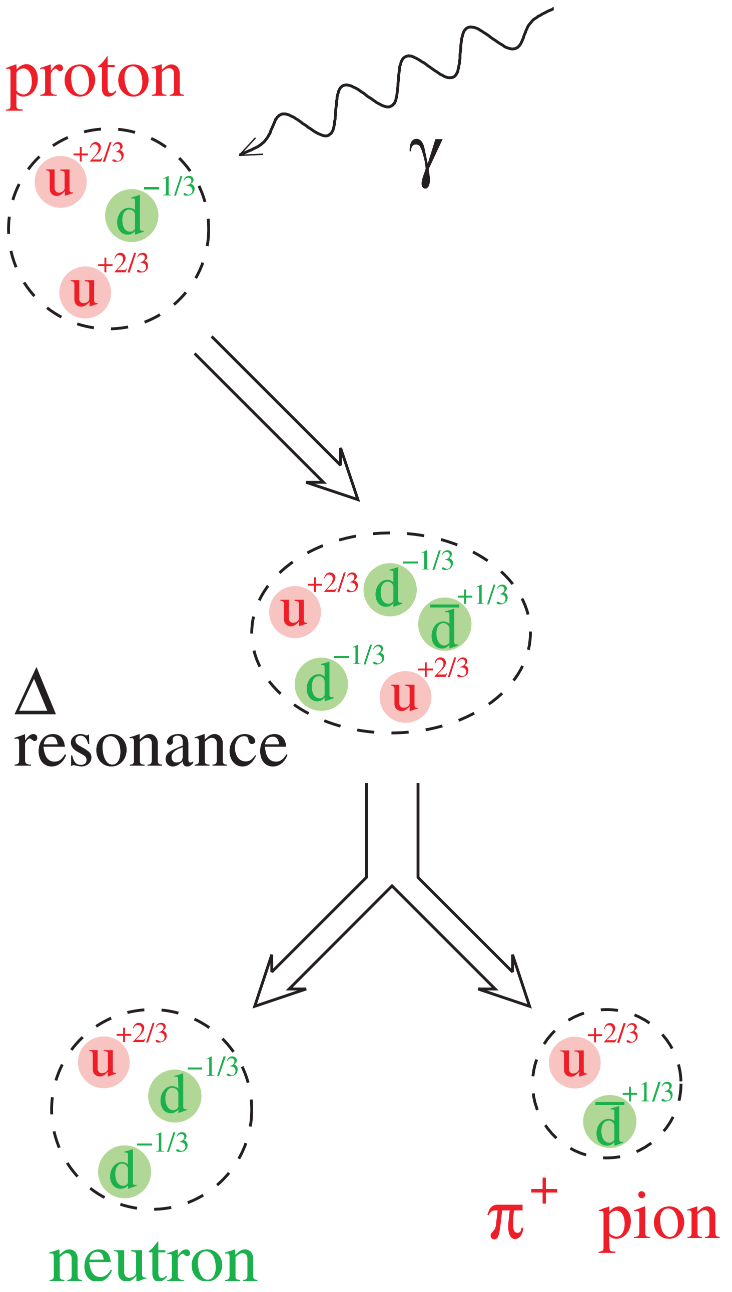
Stern, MNRAS 2003

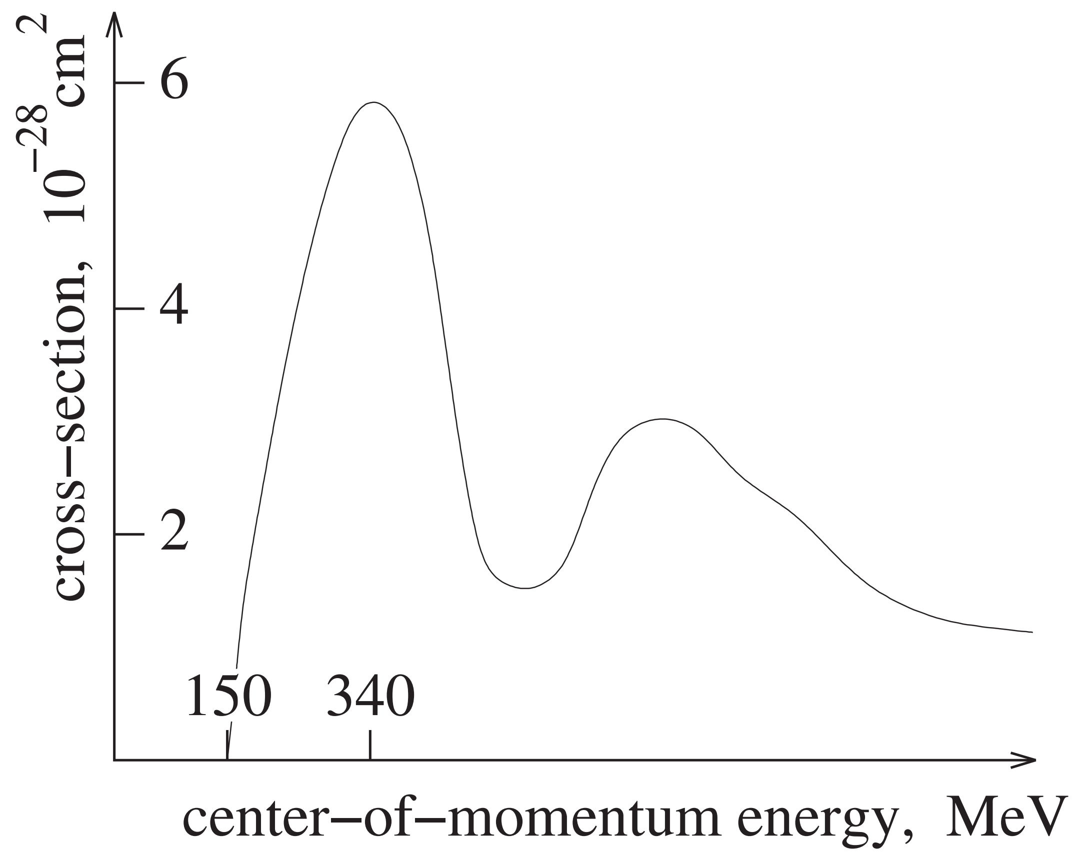
Conversion to neutrals for electrons/positrons



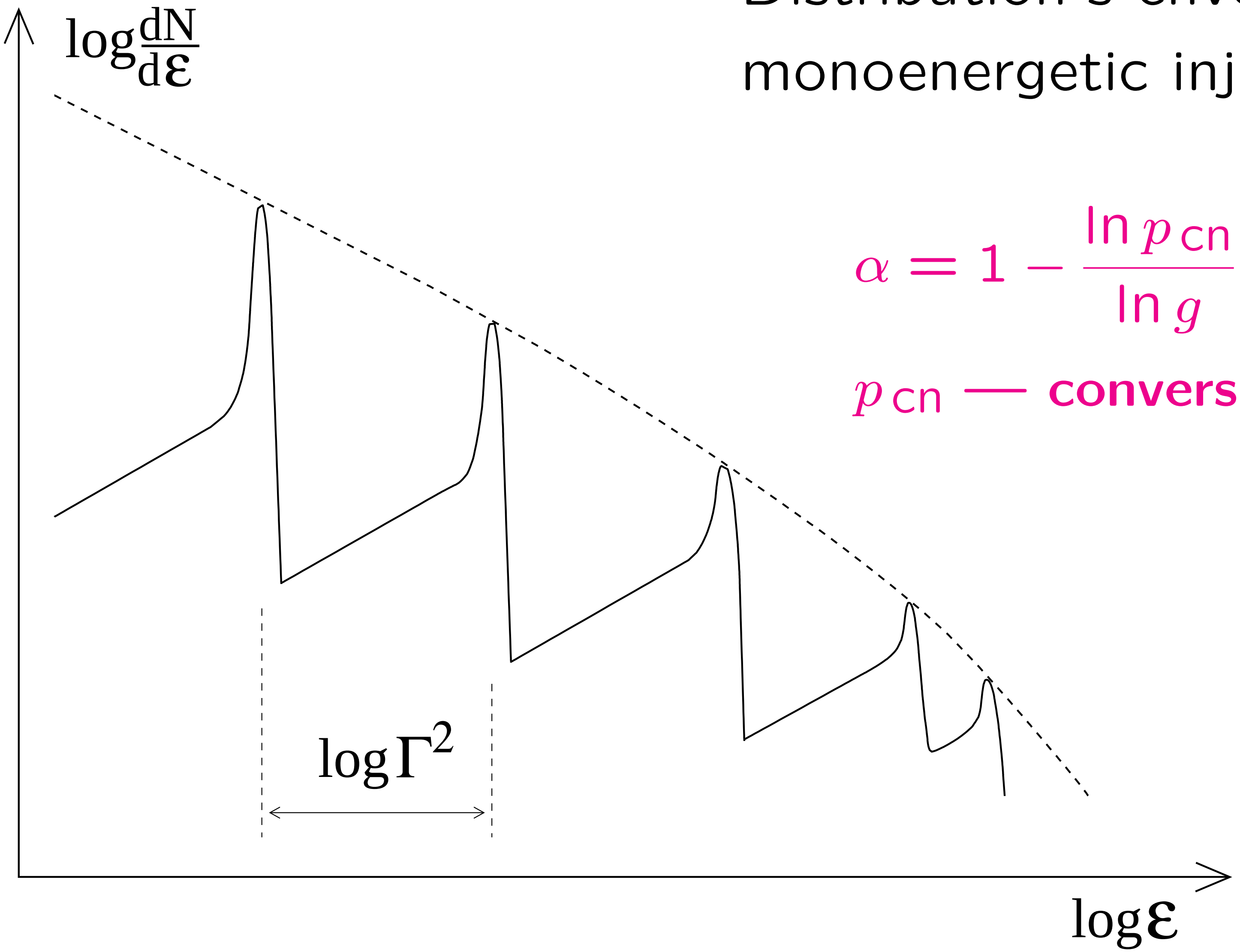


Conversion to neutrals for protons





Emerging particle distribution



Distribution's envelope for monoenergetic injection: $\frac{dN}{d\varepsilon} \propto \varepsilon^{-\alpha}$

$\alpha = 1 - \frac{\ln p_{\mathrm{cn}}}{\ln g}$ — **spectral index**

p_{cn} — **conversion probability**

Distinctive features of the converter mechanism

- **Protons are accelerated, but not nuclei**

- **Accelerated particles reach supercritical energies, so that the spectrum of their synchrotron emission extends to much higher frequencies (up to Γ^2 times higher compared to the standard acceleration mechanism)**

- **Broadening of beam pattern (up to becoming nearly isotropic) for high-energy emission in the sub-GeV − TeV range.**

prolonged GeV emission from Gamma-Ray Bursts = geometrically retarded off-axis emission?

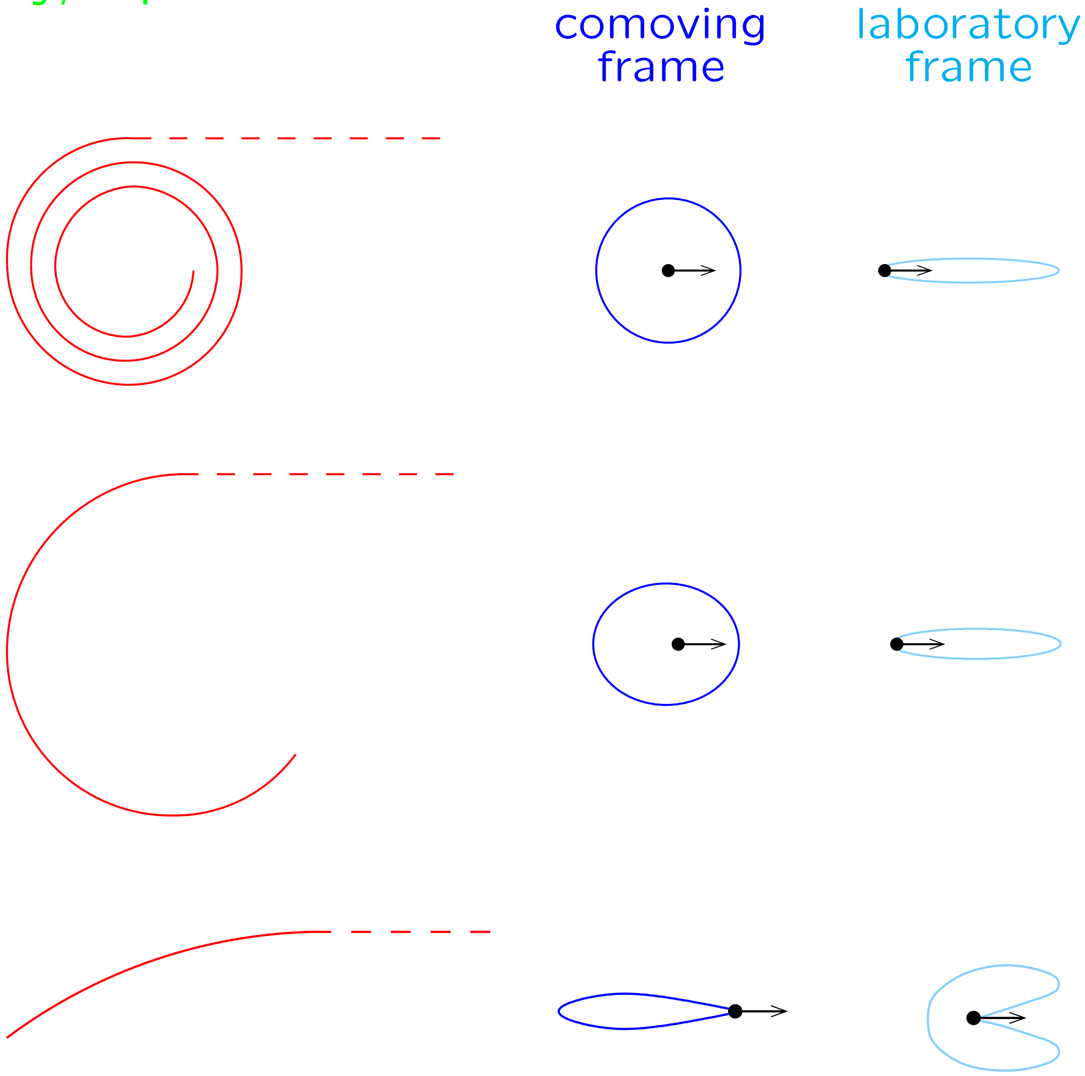
Changes in the beam-pattern

Derishev, Aharonian & Kocharovsky, ApJ 2007

- **Low-energy particles**
  $\varepsilon \ll \varepsilon_{\rm cr}$

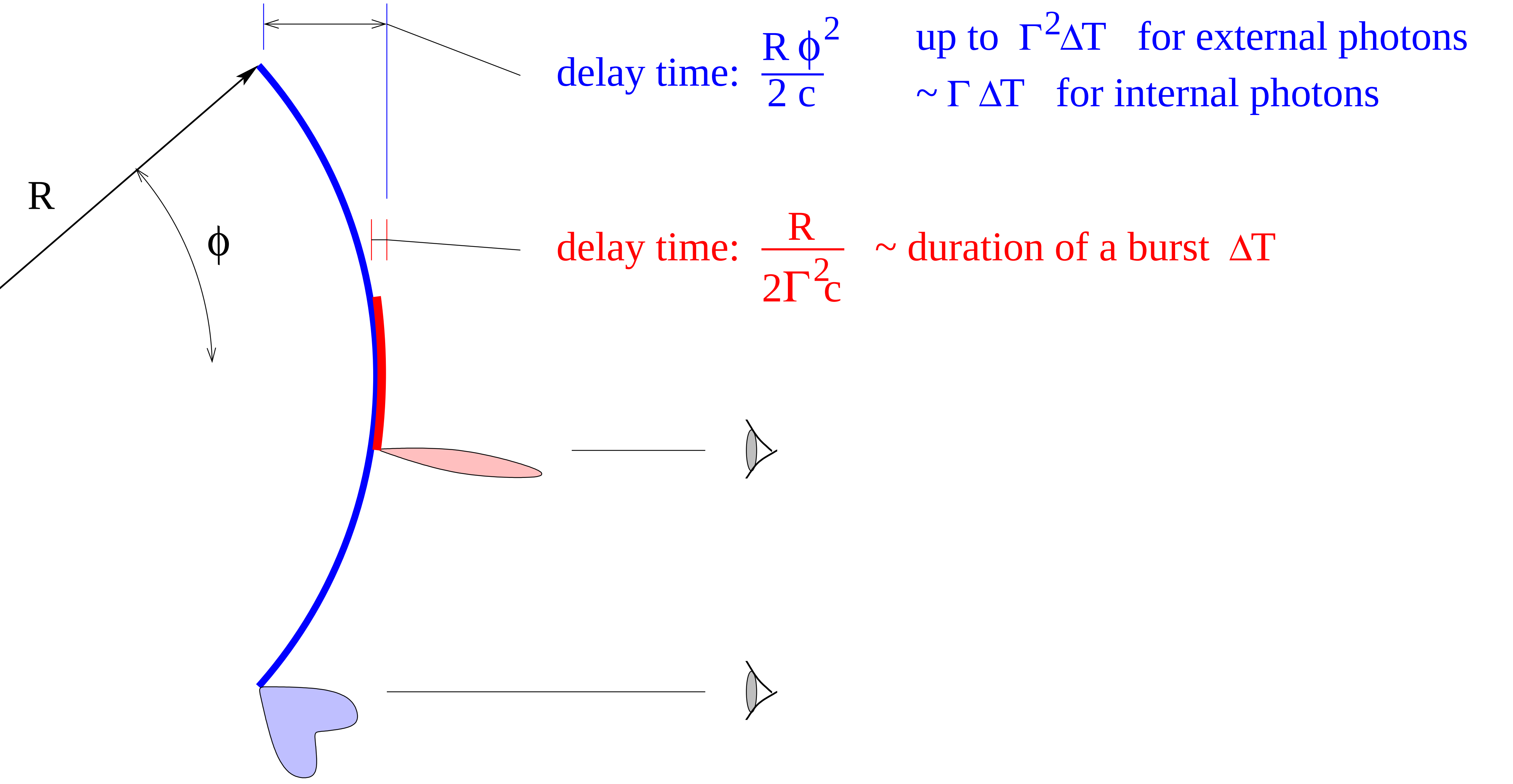
- **Critical-energy particles**
  $\varepsilon \simeq \varepsilon_{\rm cr}$

- **High-energy particles**
  $\varepsilon \gg \varepsilon_{\rm cr}$



$\varepsilon_{\rm cr} = \frac{3}{2}\frac{\left(m_e c^2\right)^2}{e^{3/2} B^{1/2}}$; $h\nu \sim 100 \times \Gamma$ MeV — for synchrotron losses

Delayed hard emission (GeV-TeV afterglow)



Problems for the near future

- What would a GRB look like when observed off-axis?
  where are orhan afterglows?

- What would a GRB remnant look like?

- Where are gravitationally lensed GRBs?

- If the jets are Pointing-flux dominated, then
  how the magnetic energy is converted into kinetic one?
  if not, then how to get such a large Lorentz factor in jets?

- What is the prompt radiation mechanism?
  is there a way to solve low-frequency spectral index puzzle?

- Where is the inverse Compton peak, why there are
  no clear signs for it?