Radiation mechanisms for relativistic jets in Gamma-Ray Bursts

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General requirements to GRB models

- Should produce large energy release and luminosity

- Should explain very rapid (ms scale) variability

- The emitted radiation should be very broad-band (therefore – nonthermal)

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 Poynting-dominated

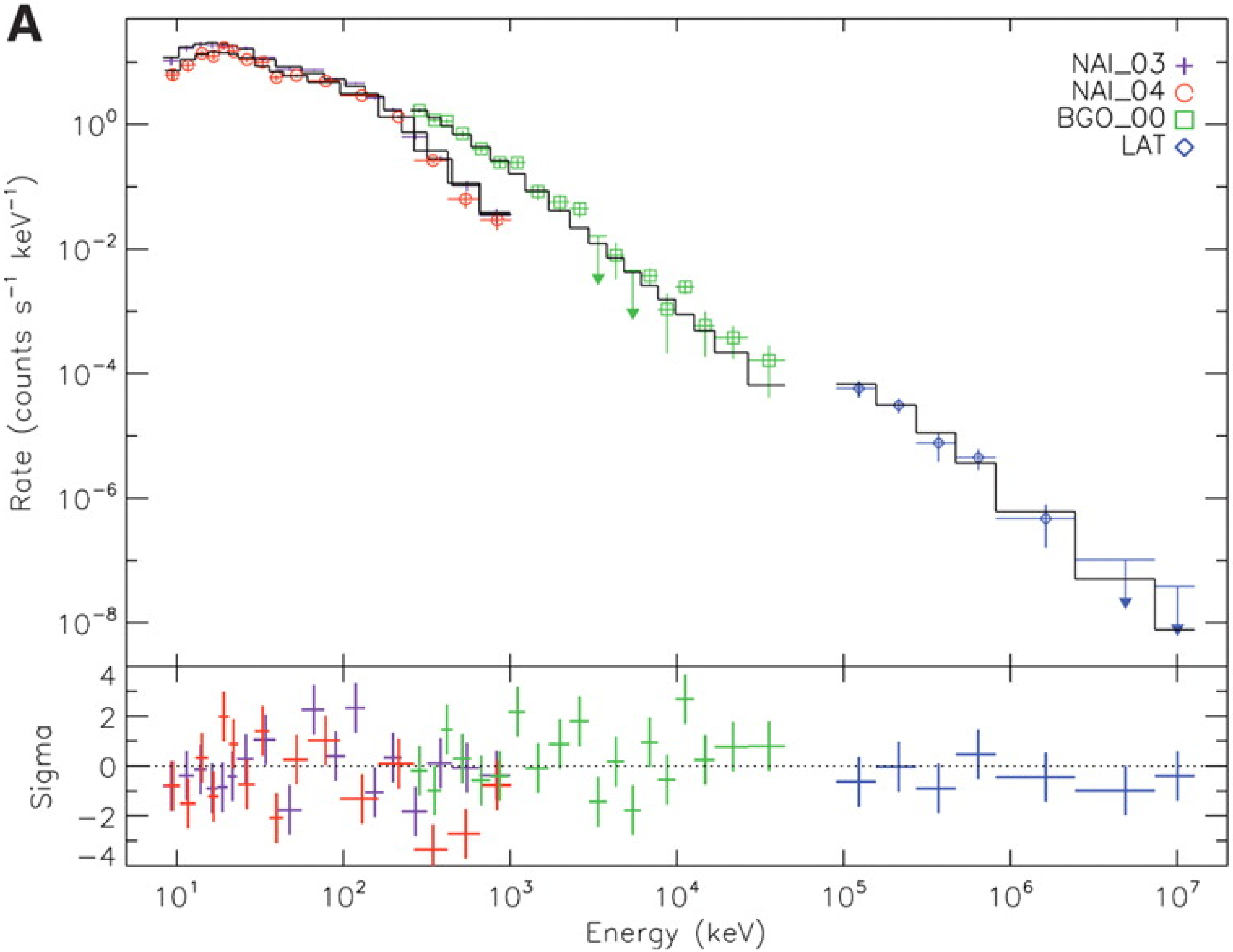
- **Energetic charged particles**

likely electrons and positrons, by maybe protons

- **Neutrons**

produced in many ways, being stable over GRB duration
Derishev et al. 1999

Broad-band GRB spectrum

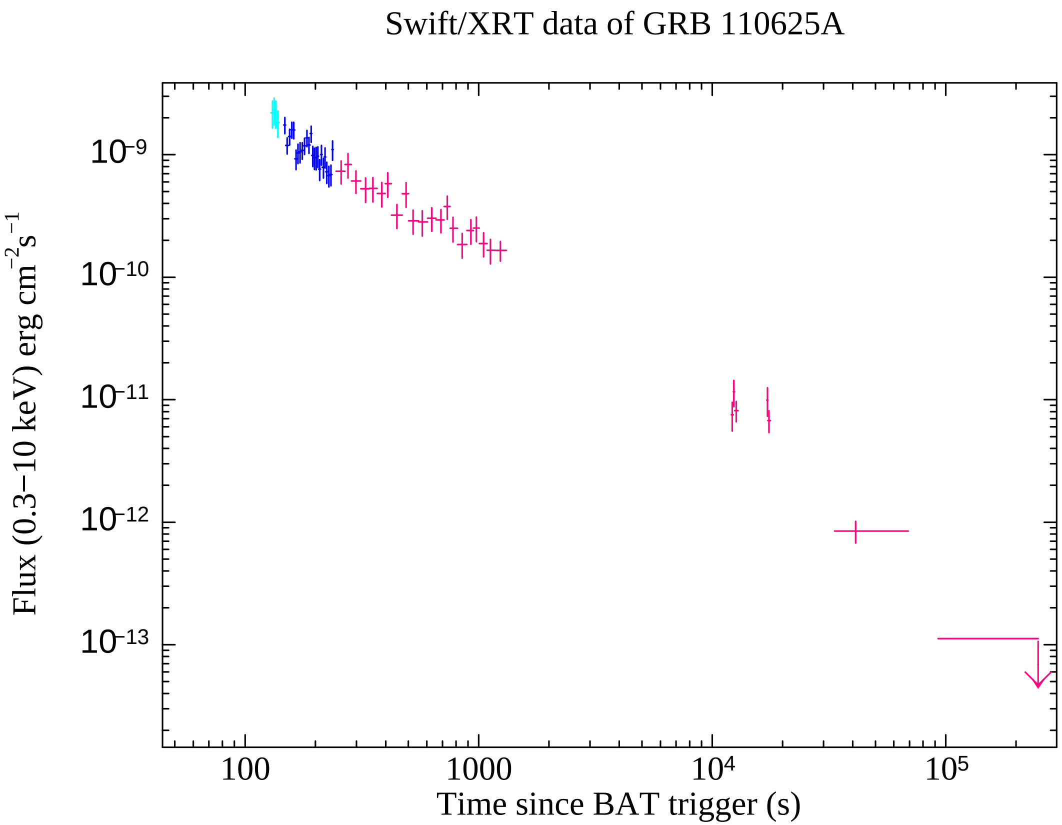


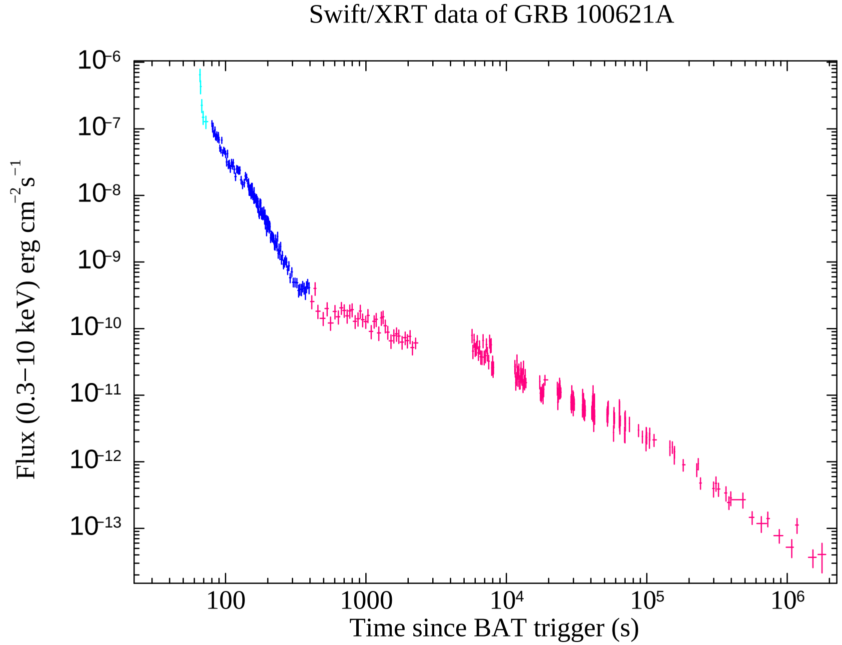
GRB 080916C

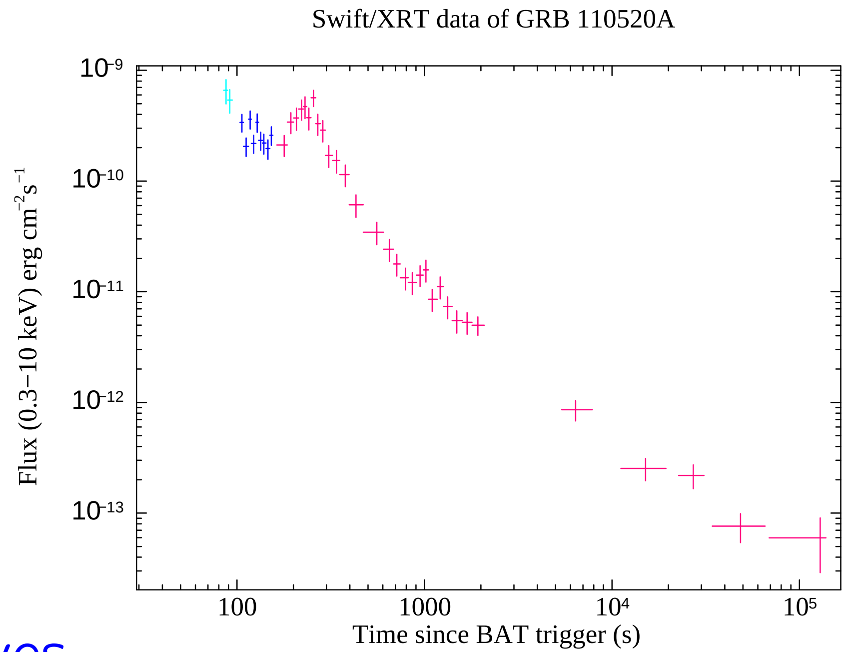
νF_{ν} is nearly flat above 100 keV

Figure from Abdo et al. Science 323 (2009)

X-ray afterglow lightcurves







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

Afterglow lightcurves

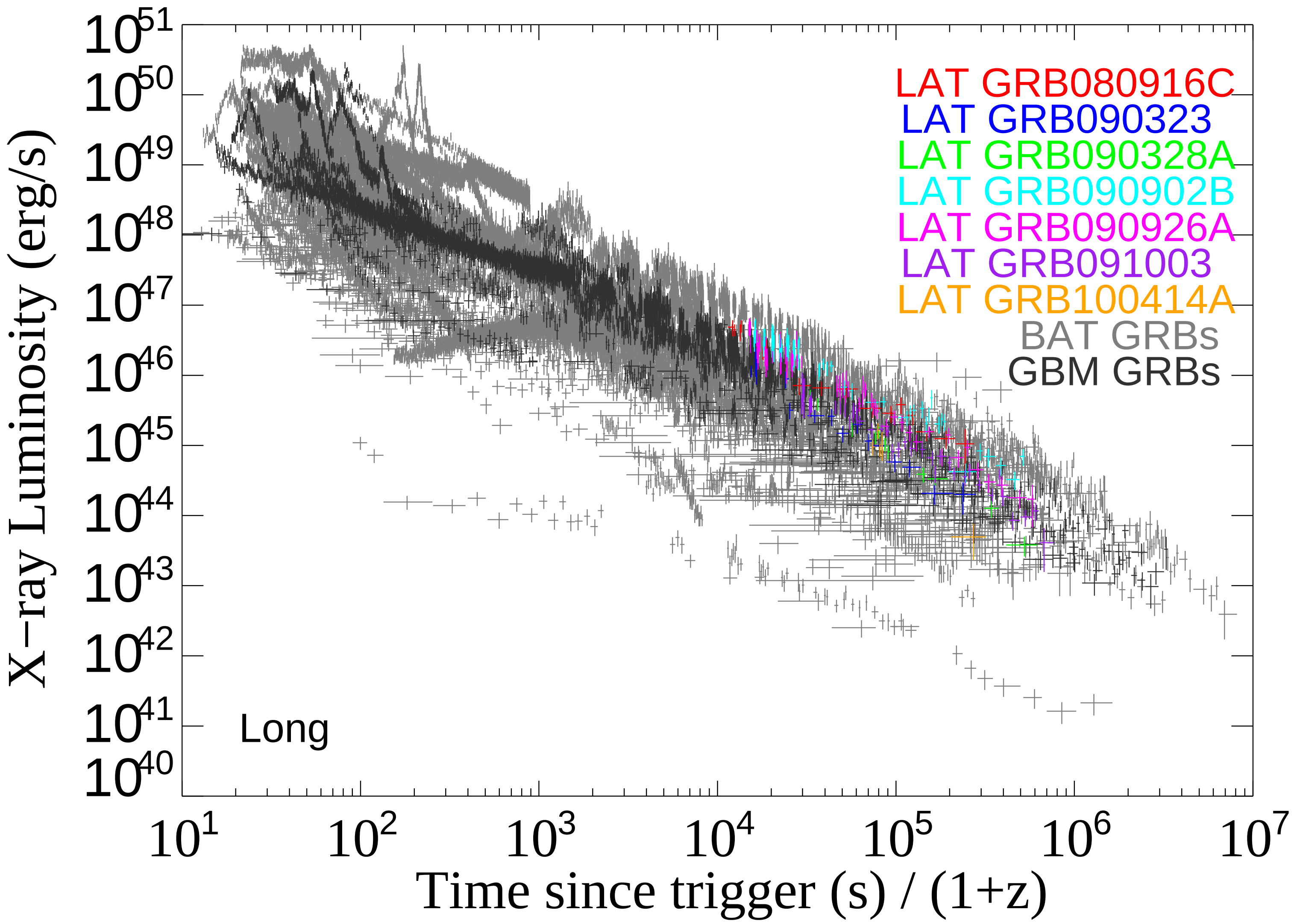


Figure from Racusin et al. ApJ 738 (2011)

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

Low-energy spectral indices

Fast cooling: $\alpha < -1.5$

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

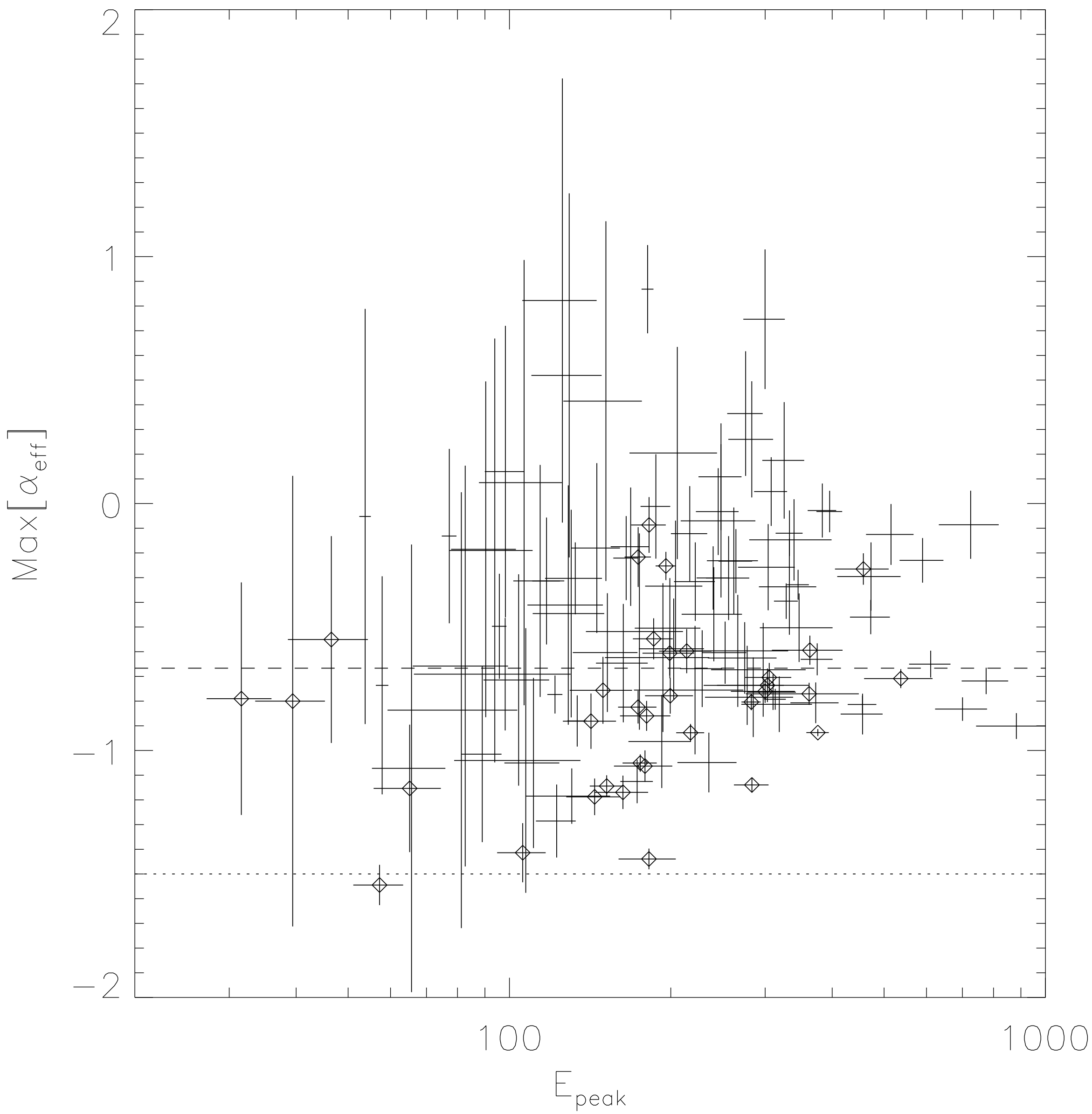


Figure from Preece et al. ApJ 506 (1998)

Radiation mechanisms

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  undulator radiation

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- Bremsstrahlung

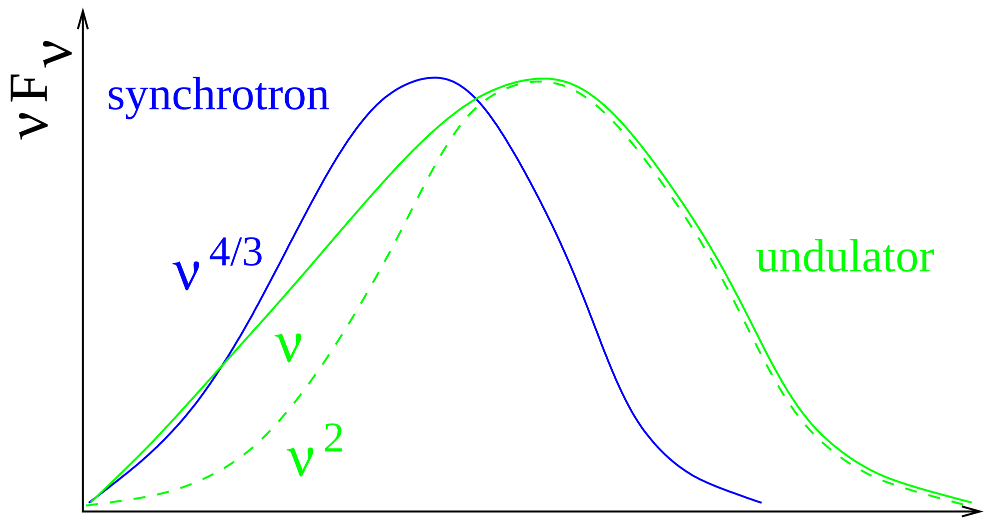
protons

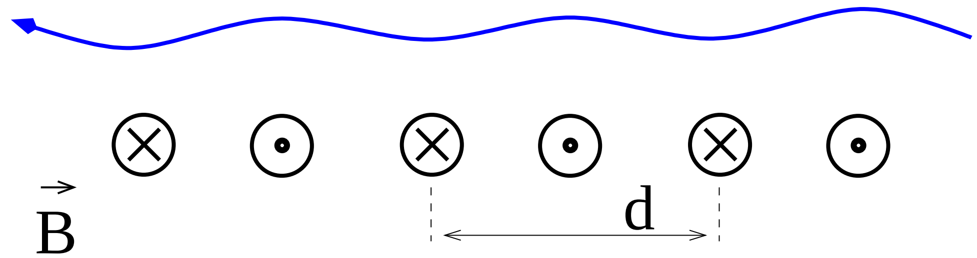
- Synchrotron radiation
- Inelastic nucleon collisions
- Coulomb losses

Toptygin & Fleishman 1987, Medvedev 2000

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

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





Radiation mechanisms

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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

Radiation mechanisms

electrons

- Synchrotron radiation

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protons

- Synchrotron radiation

- Inelastic nucleon collisions

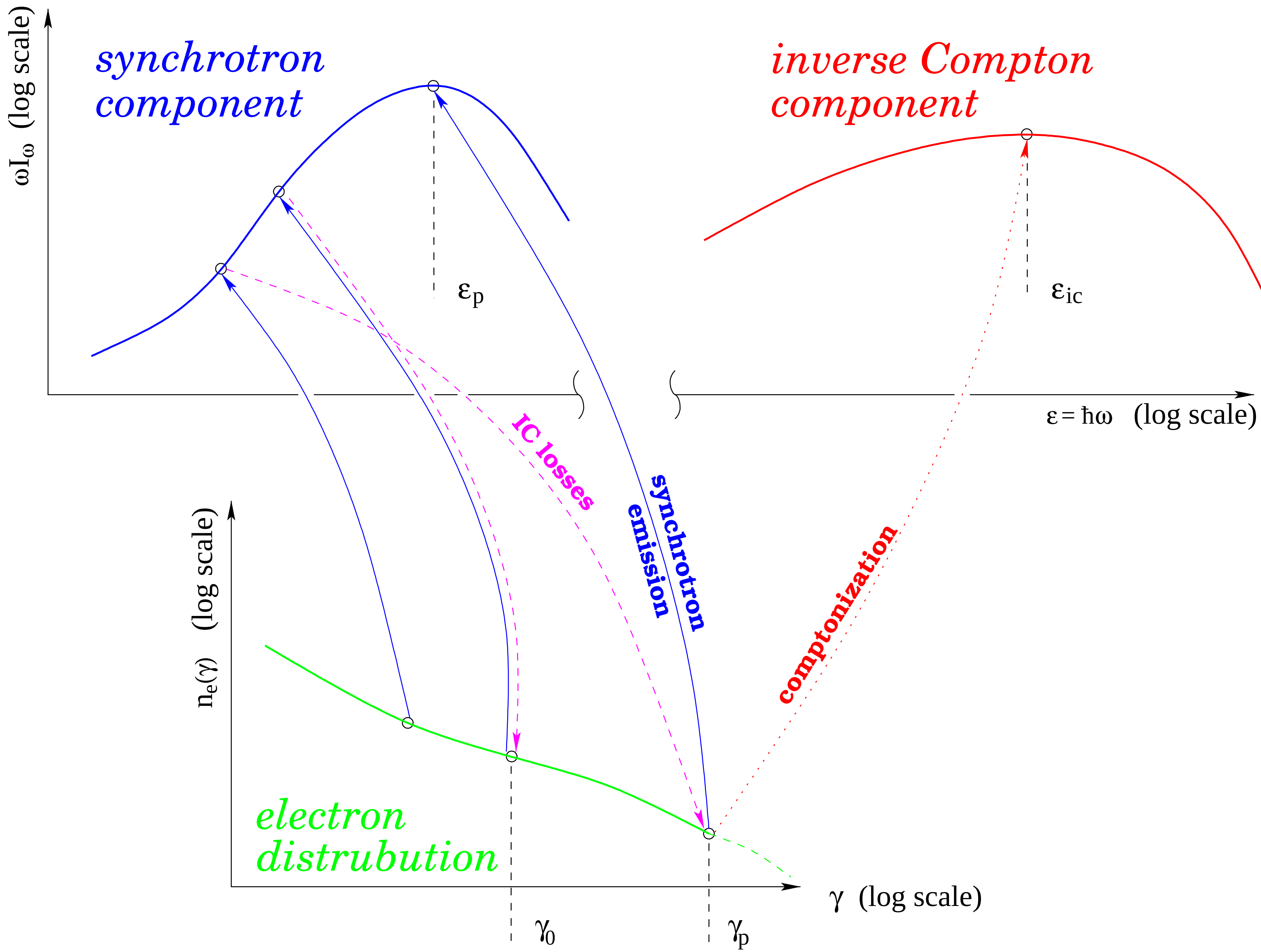
- Coulomb losses

Same problems with fast cooling.

Way out –
comptonize quasi-thermal radiation
talks by Vurm and Levinson

Photon generation takes place well below photosphere at $\Gamma < 20$
Vurm, Lyubarsky & Piran 2013

The synchrotron-self-Compton model



Some hints for physical parameters in GRBs

Derishev et al. 2001

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

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

$\mathcal{D} = \frac{\text{burst duration}}{\text{variability timescale}}$ — 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 $\delta E_{\text{ic}} < 0.5$ follows that:

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

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

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

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 $T \lesssim \alpha_f^2\, m_e c^2 \sim 25\ \mathrm{eV}$

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**

Derishev *et al.* 1999
Beloborodov 2010

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

Problem 1:
too soft fast-cooling spectrum

Diffusive shock acceleration

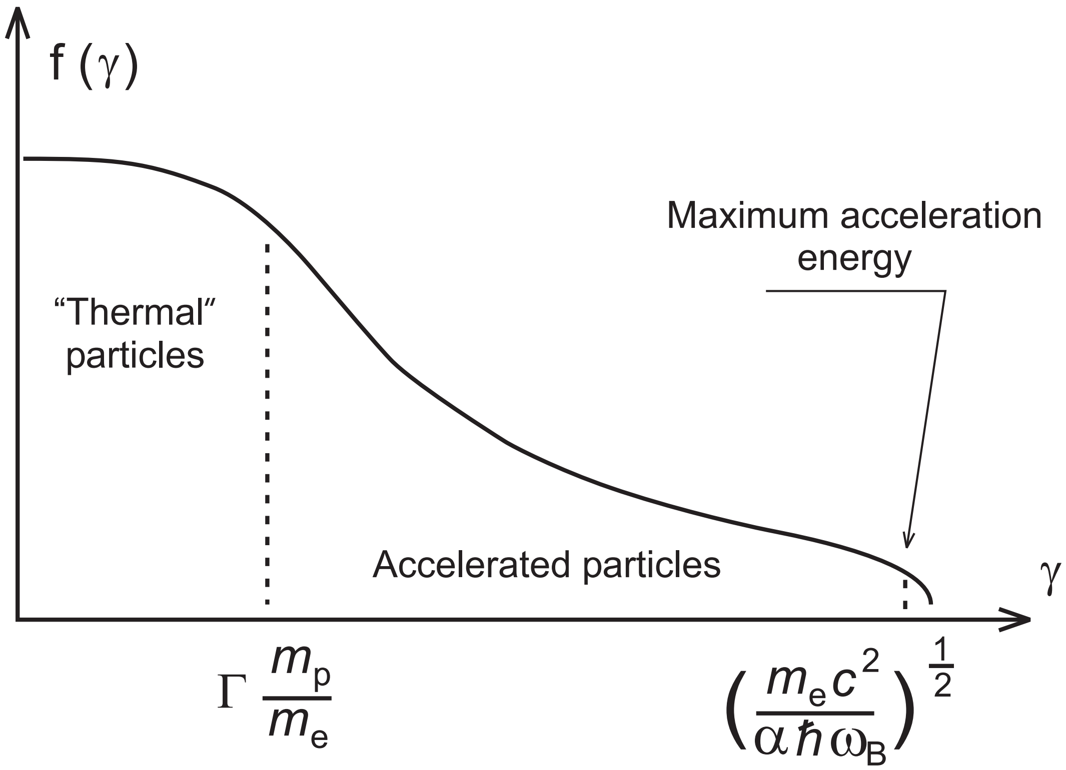
Γ – Lorentz-factor of the shock,

γ – Lorentz-factor of an electron,

$\omega_{\rm B} = eB/m_e c$ – gyrofrequency,

α – fine structure constant,

$f(\gamma)$ – injection function

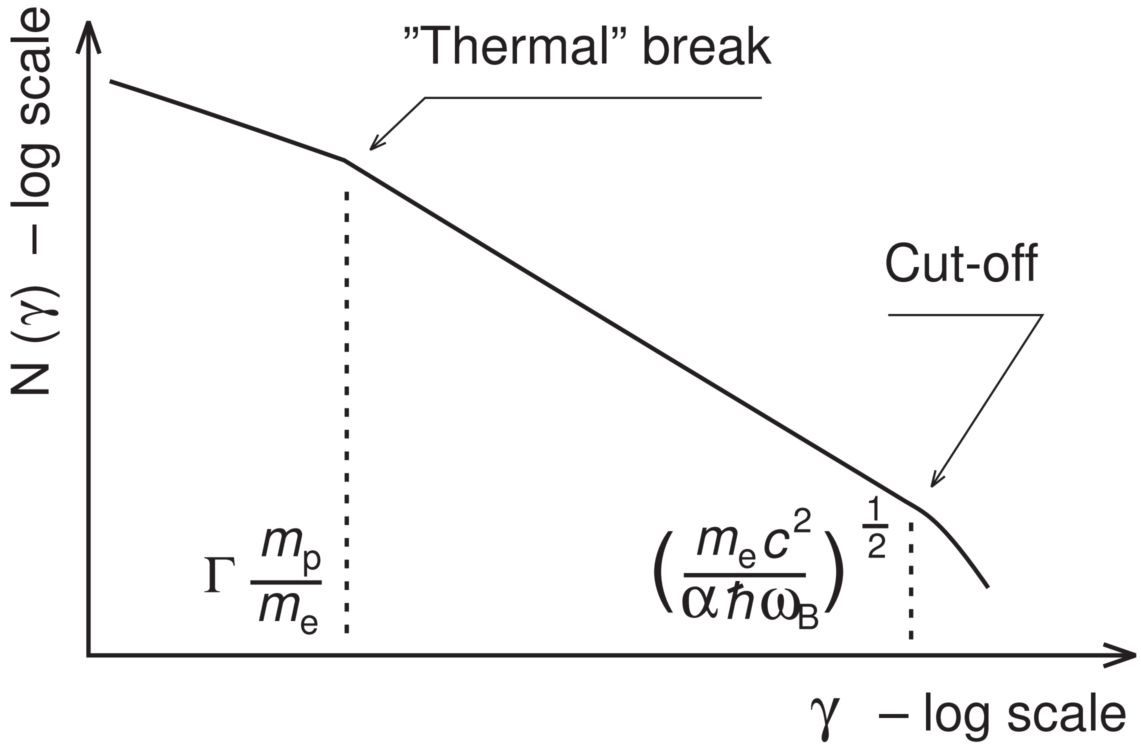


Diffusive shock acceleration gives $f(\gamma) \propto \gamma^{-s}$,

where $s \simeq 2.2$ (universal power-law)

Fast cooling regime

$N(\gamma)$ – electrons' distribution function



Continuity equation

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

gives stationary solution

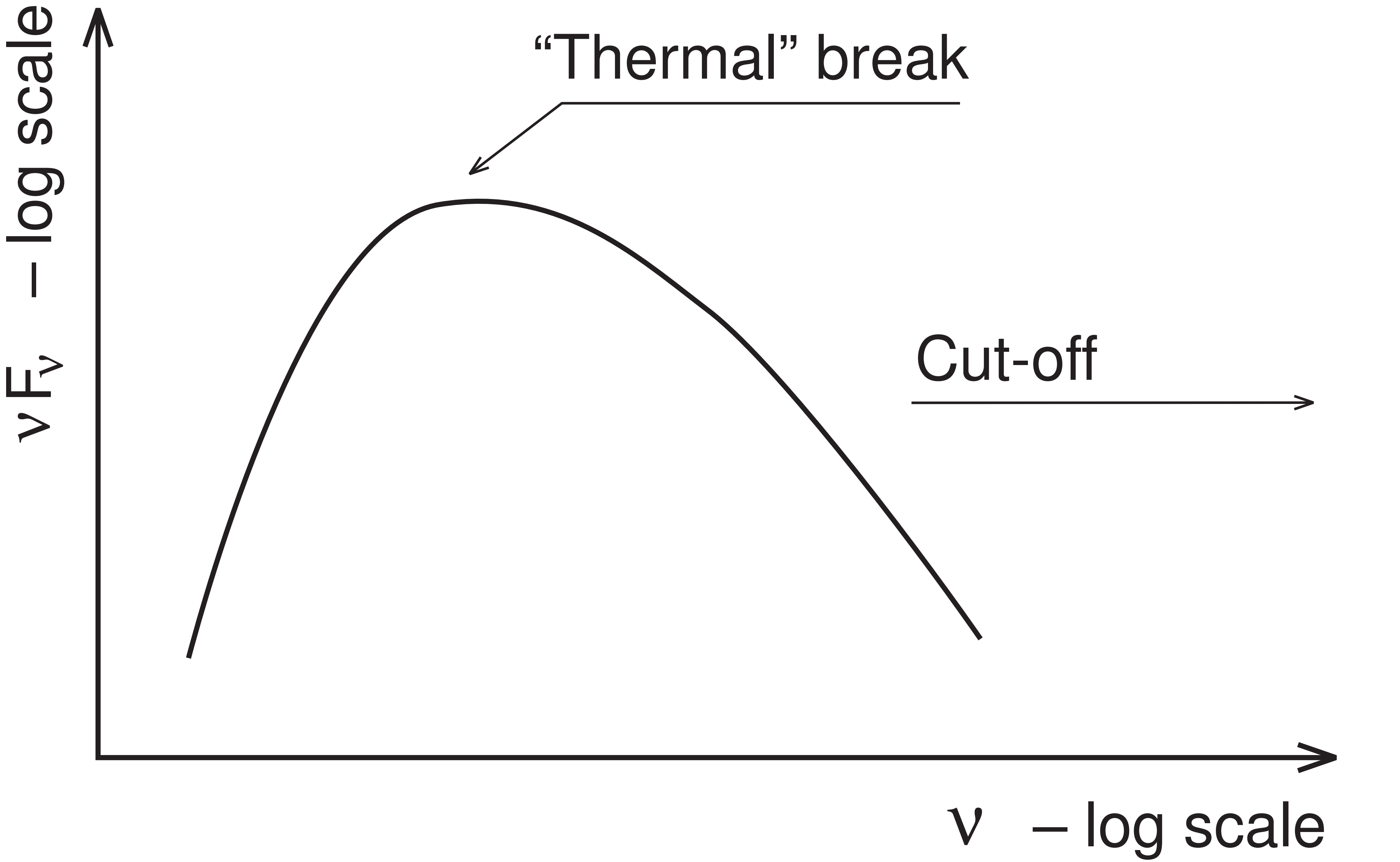
$$N(\gamma) = -\frac{1}{\dot{\gamma}} \int_{\gamma}^{\infty} f(\gamma')\, d\gamma'$$

The corresponding spectrum (provided $\nu \propto \gamma^x$) is :

$$\nu F_\nu \propto \frac{dF}{d\ln\gamma} \propto \gamma\eta \int_{\gamma}^{\infty} f(\gamma')\, d\gamma'$$

$\eta(\gamma)$ – the fraction of electron's energy transferred to the observed radiation

Standard assignment of spectral features –



... – standard problems

- **Position of the peak is too sensitive to the shock Lorentz-factor**

  Photon energy at the peak in the comoving frame

$$\varepsilon'_{\mathrm{peak}} \sim \left(\Gamma \frac{m_p}{m_e}\right)^2 \frac{\hbar e B}{m_e c}$$

in the laboratory frame $\varepsilon_{\mathrm{peak}} \propto \Gamma^4$ (since $B \propto \Gamma$)

- **The spectrum well above the peak frequency is universal and too hard**

$N_\gamma \propto \gamma^{-3.2} \quad \Rightarrow \quad \nu F_\nu \propto \nu^{-0.1}$

... – standard problems

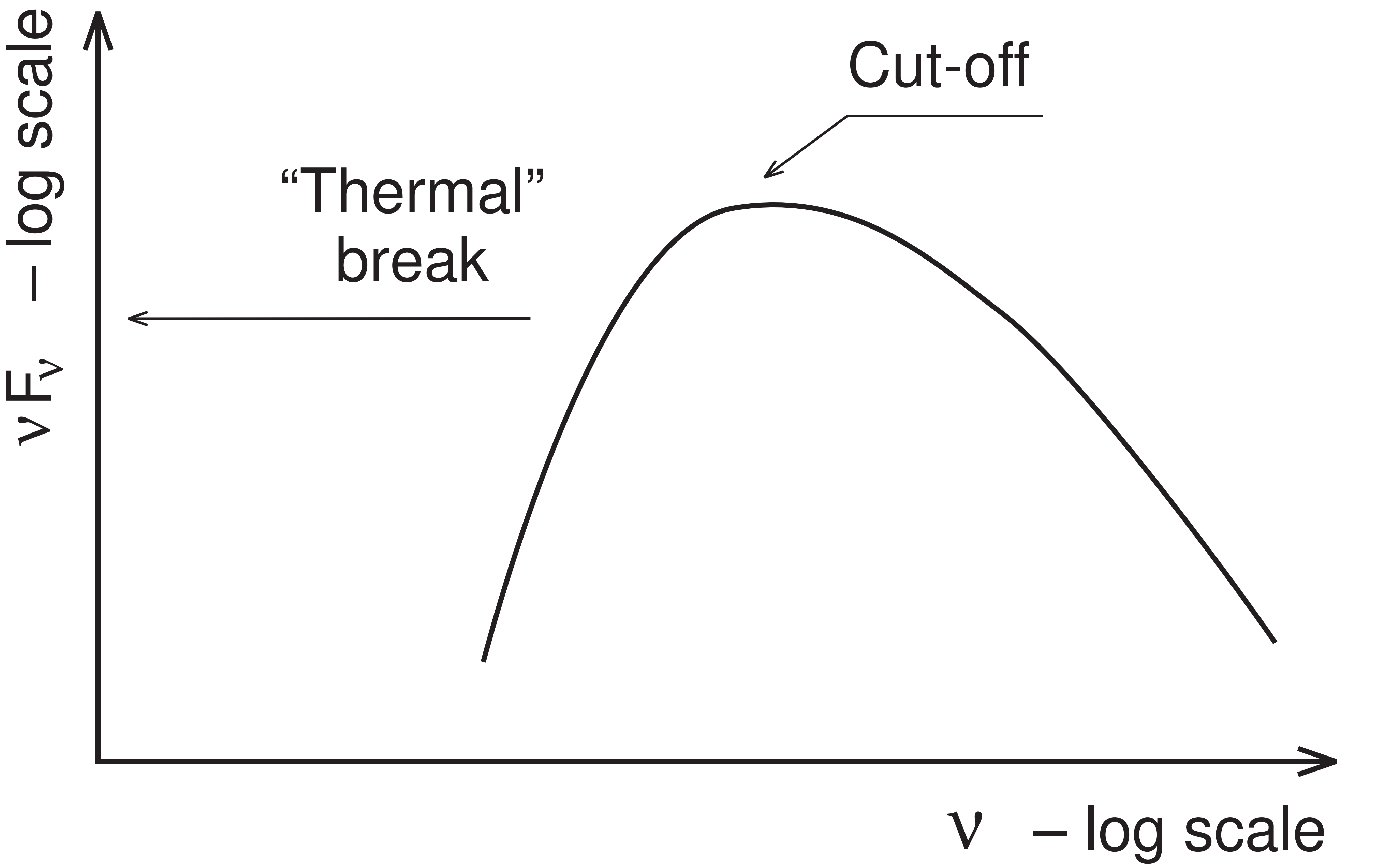
- **Low-frequency asymptotics in the fast-cooling regime is too soft**

  The hardest possible injection $f(\gamma) = \delta(\gamma - \gamma_0)$ gives

  $\nu F_\nu \propto \gamma\eta$ for $\gamma < \gamma_0$;

  $\Rightarrow$ $\nu F_\nu \propto \nu^{1/2}$, if $\eta = const$

Another assignment of spectral features –



… – other problems

- **The synchrotron cut-off frequency is too high**

  At the maximum energy, the scattering length (gyroradius) equals to the radiation length:

$$\eta \left(\frac{4}{3} \gamma \sigma_{\mathsf{T}} \frac{B^2}{8\pi} \right)^{-1} = \frac{\gamma m_e c^2}{eB}$$

So that $\gamma_{\mathsf{max}}^2 \frac{\hbar e B}{m_e c} \simeq \eta \frac{m_e c^2}{\alpha}$ σ_{T} – Thomson cross-section

- **Low-frequency asymptotics in the fast-cooling regime is too soft**

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Chaotic magnetic field

Derishev Ap&SS 2007

Scattering length: $\ell_{\mathrm{s}} = \ell_{\mathrm{c}} \left(\frac{r_g}{\ell_{\mathrm{c}}} \right)^2 = \frac{\left(\gamma m_e c^2 \right)^2}{e^2 B^2 \ell_{\mathrm{c}}}$

ℓ_{c} – correlation length

$r_g = \frac{\gamma m_e c^2}{eB}$ – gyroradius

Acceleration limit: $\ell_{\mathrm{s}} = \eta \left(\frac{4}{3} \gamma \sigma_{\mathrm{T}} \frac{B^2}{8\pi} \right)^{-1}$

Consequently, $\gamma_{\mathrm{max}}^3 \simeq \eta \frac{\ell_{\mathrm{c}}}{r_e}$

r_e – classical radius of the electron

Typical energy of synchrotron photons:

$$\gamma_{\mathrm{max}}^2 \frac{\hbar e B}{m_e c} \simeq \left(\eta \frac{\ell_{\mathrm{c}}}{r_{\mathrm{g0}}} \right)^{2/3} \left(\frac{\alpha B}{B_{\mathrm{cr}}} \right)^{1/3} \frac{m_e c^2}{\alpha}$$

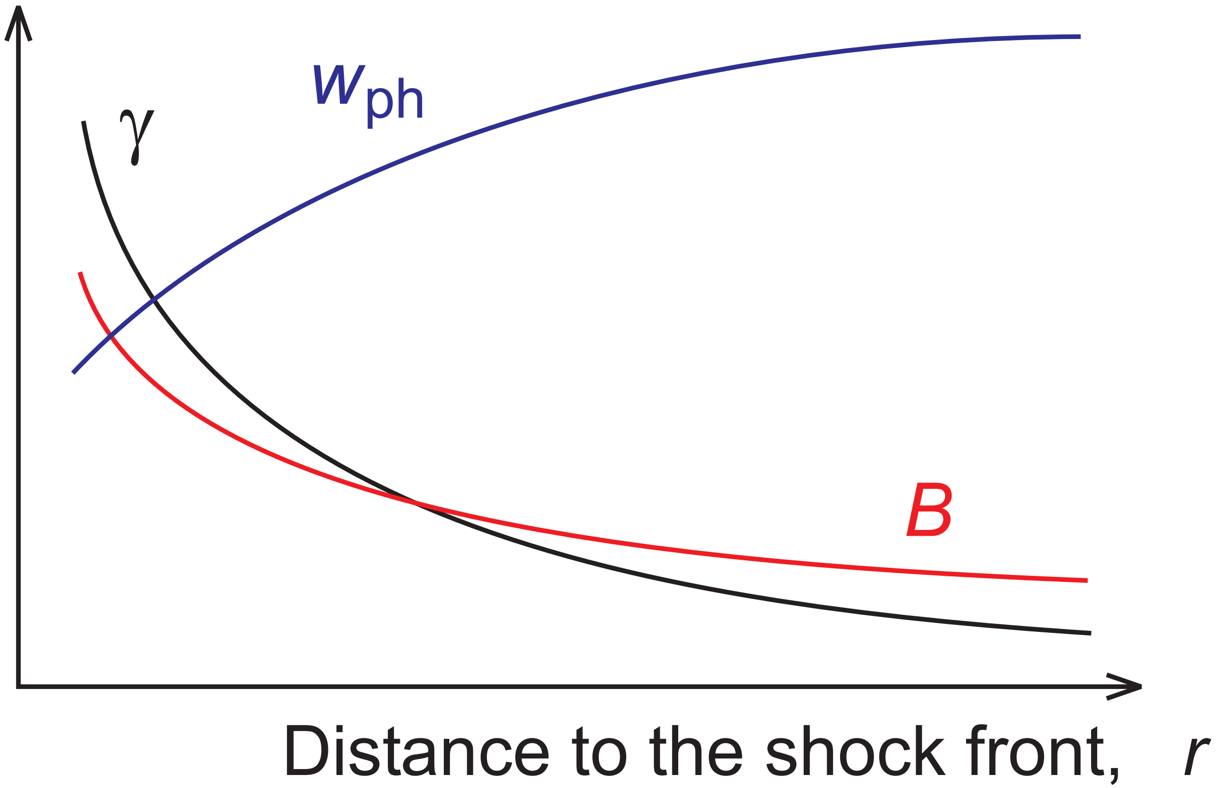
$B_{\mathrm{cr}} \simeq 4.5 \times 10^{13}$ G – Schwinger magnetic field

$r_{\mathrm{g0}} = \frac{m_e c^2}{eB}$ – "cold" gyroradius

Decaying magnetic field

Derishev Ap&SS 2007

Zhao *et al.* arXiv:1310.0551



$w_{\rm ph}$ – effective energy density of photons

$$w_{\rm ph}(\gamma) = \int_0^{\frac{m_e c^2}{h\gamma}} w_\nu \, d\nu$$

The electrons are advected $\Rightarrow$ $\frac{d\gamma}{dr} = \frac{3}{c}\frac{\partial\gamma}{\partial t} = -4\gamma^2 \sigma_{\rm T}\left(w_{\rm ph} + \frac{B^2}{8\pi}\right)$

For a power-law photon spectrum $w_\nu \propto \nu^q$ $(-1 < q < 0)$: $w_{\rm ph}(\gamma) \propto \gamma^{-1-q}$

Decaying magnetic field

Derishev Ap&SS 2007

- **Let** $\eta \ll 1$ **and** $w_\nu \propto \nu^q$

$$\frac{d\gamma}{dr} \propto -\gamma^{1-q} \qquad \Rightarrow \qquad \gamma = \left(\frac{r}{r_0}\right)^{\frac{1}{q}} \qquad \text{for} \qquad \gamma \ll \gamma_0$$

Injecting delta-function gives: $N(\gamma) \propto \gamma^{q-1}$ for $\gamma < \gamma_0$

- **Let** $B \propto r^{-y}$

The synchrotron efficiency: $\eta \simeq \frac{B^2}{8\pi w_{\rm ph}} \propto r^{-2y}\gamma^{1+q} \propto \gamma^{1+q-2qy}$

Typical synchrotron frequency: $\nu \propto \gamma^2 B \propto \gamma^{2-qy}$

Emerging spectrum:

$$\nu F_\nu \propto \gamma\eta \propto \nu^{\frac{2+q-2qy}{2-qy}}$$

$q = -1$: $\nu F_\nu \propto \nu^{\frac{1+2y}{2+y}}$

$q = 0$: $\nu F_\nu \propto \nu$

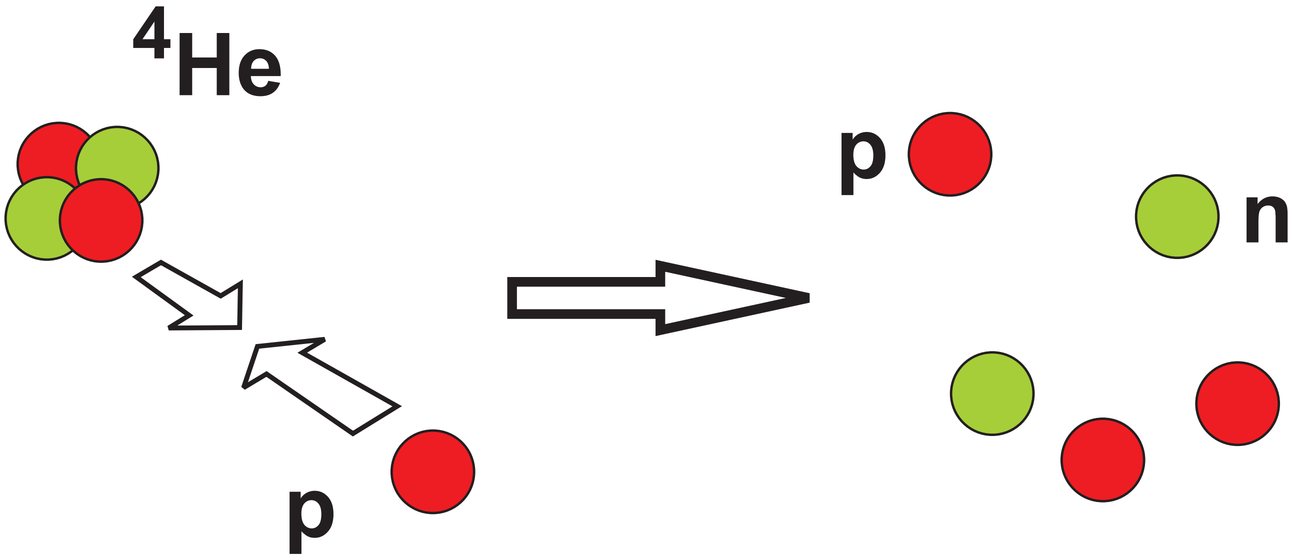
$\eta = 1$: $\nu F_\nu \propto \nu^{\frac{1-2y}{2-3y}}$

Problem 2:
energy transfer to radiating particles

Sources of free neutrons

1. thermal dissociation of nuclei

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



^{4}He – helium nucleus

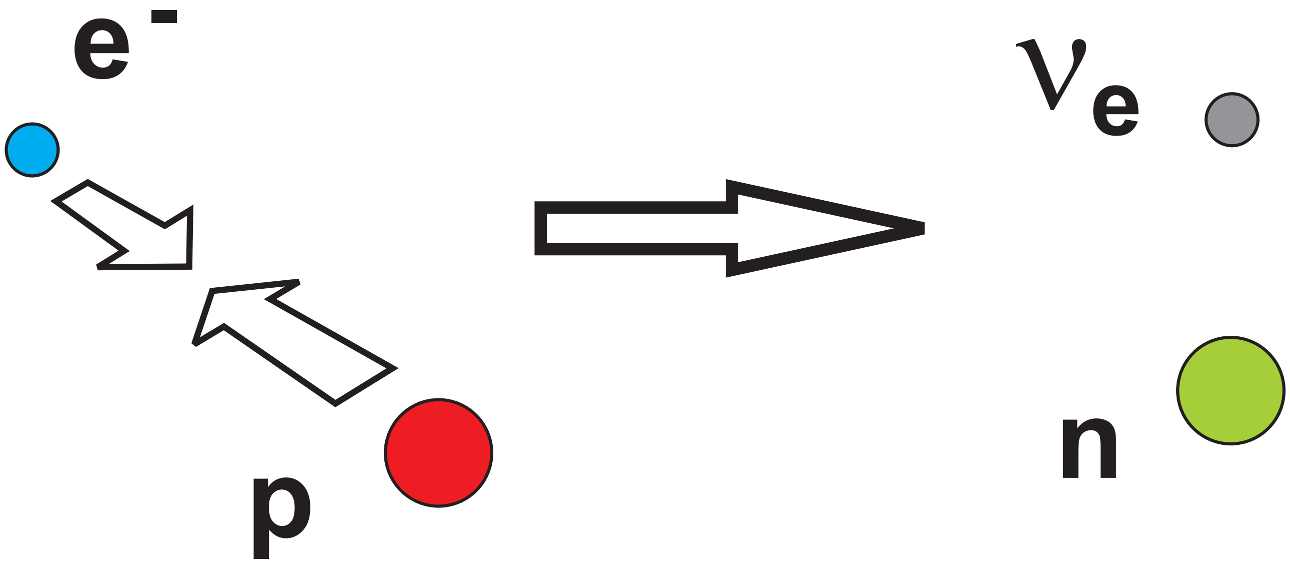
p – proton

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



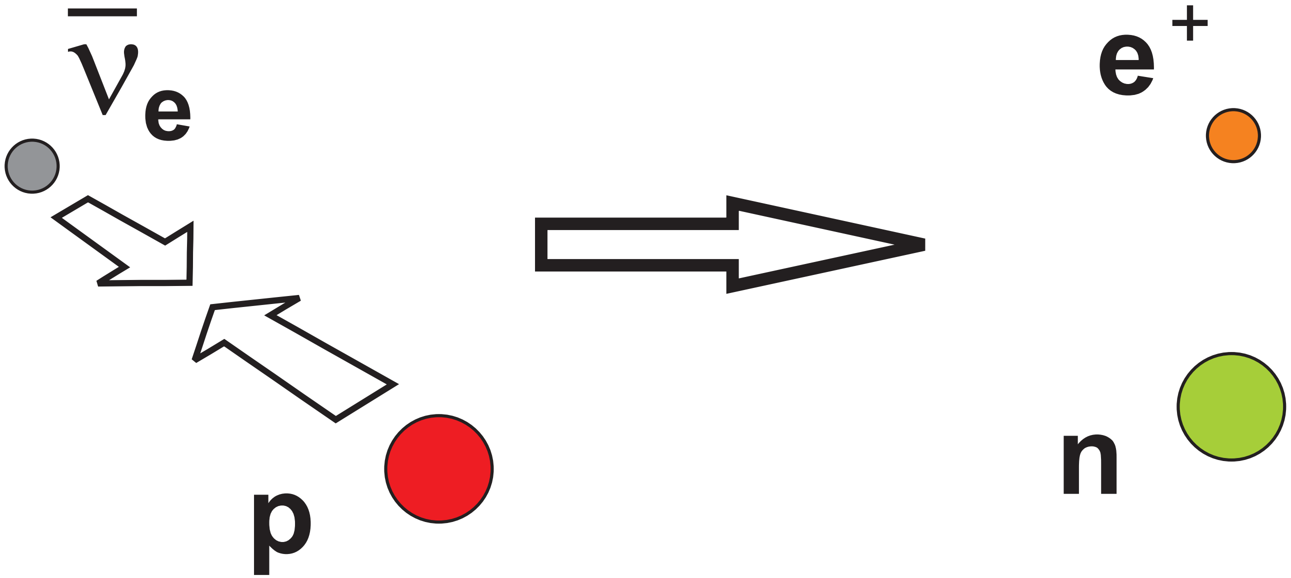
e^- – electron

ν_e – electron neutrino

Sources of free neutrons
3. inverse beta-decay

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

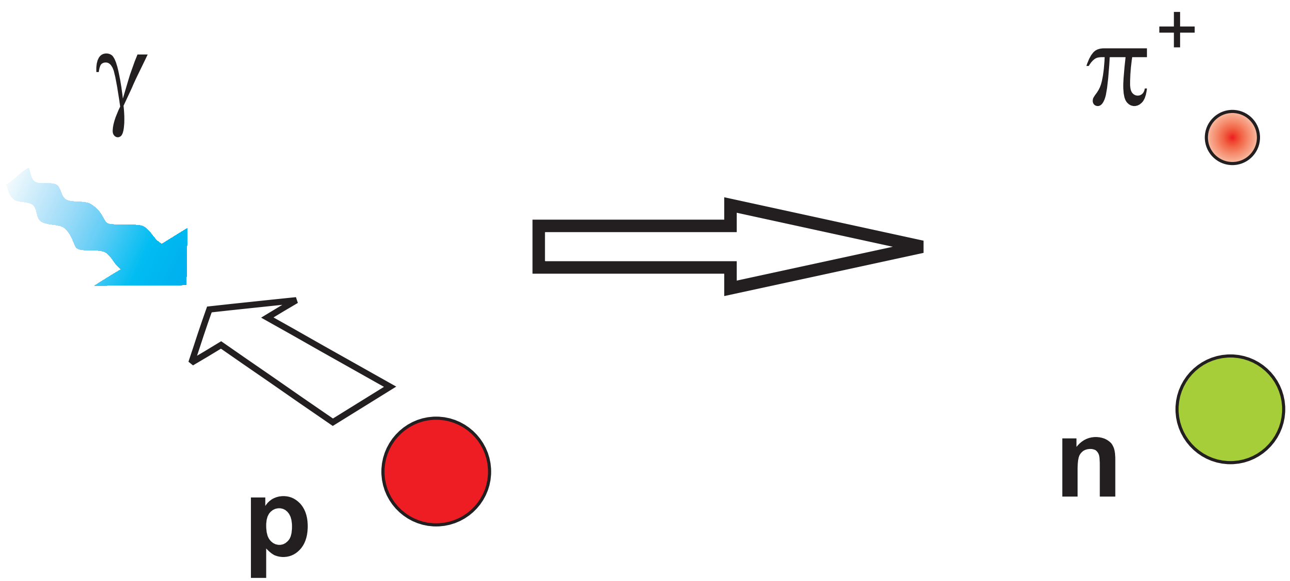
$$\varepsilon_\nu \gg (m_n - m_p)c^2$$



Sources of free neutrons
4. photopion reactions

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

compactness $\ell \gtrsim \dfrac{10^7}{\Gamma_p}$

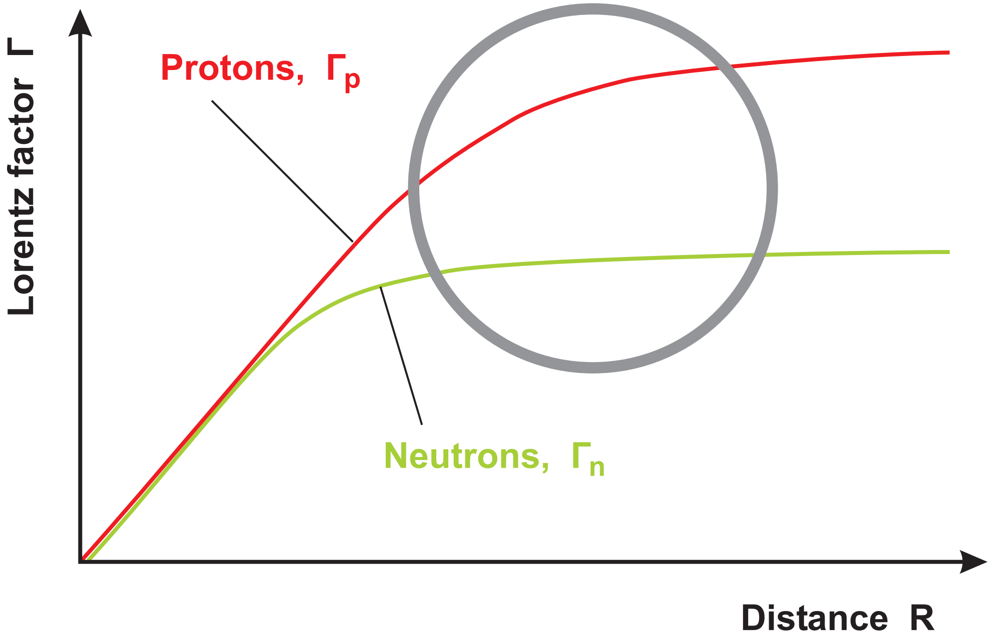


π^- – pion

γ – photon

Γ_p – Lorentz-factor of a proton

Jet's own neutrons, carried from central engine



Protons and neutrons decouple when they collide less than once on their way out

p-n decoupling radius

$$R_{dec} = \frac{1}{\eta_0} \frac{P_j}{m_N c^2} \frac{\sigma_{coll}}{\pi c}$$

photospheric radius

$$R_{ph} = \frac{1}{\eta_0} \frac{P_j}{m_N c^2} \frac{\sigma_T}{\pi c} = \frac{\sigma_T}{\sigma_{coll}} R_{dec}$$

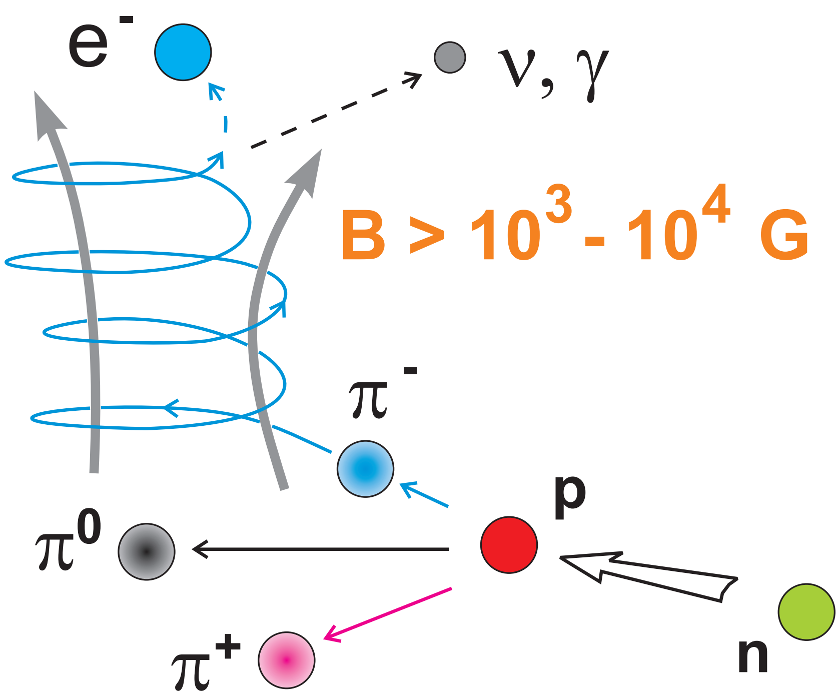
P_j – jet's power

η_0 – initial magnetization parameter (denoted as σ for pulsar winds)

$\sigma_{coll} \simeq 3 \times 10^{-26}$ cm^2 – p-n collision cross-section

$\sigma_T \simeq 7 \times 10^{-25}$ cm^2 – Thomson cross-section

Collective recoil



Inelastic nucleon collisions

$$p + n \rightarrow 2p + X$$
$$p + n \rightarrow 2n + X$$
$$p + n \rightarrow p + n + X$$

X – mostly pions (π^0, π^-, π^+)

all branches have equal probabilities

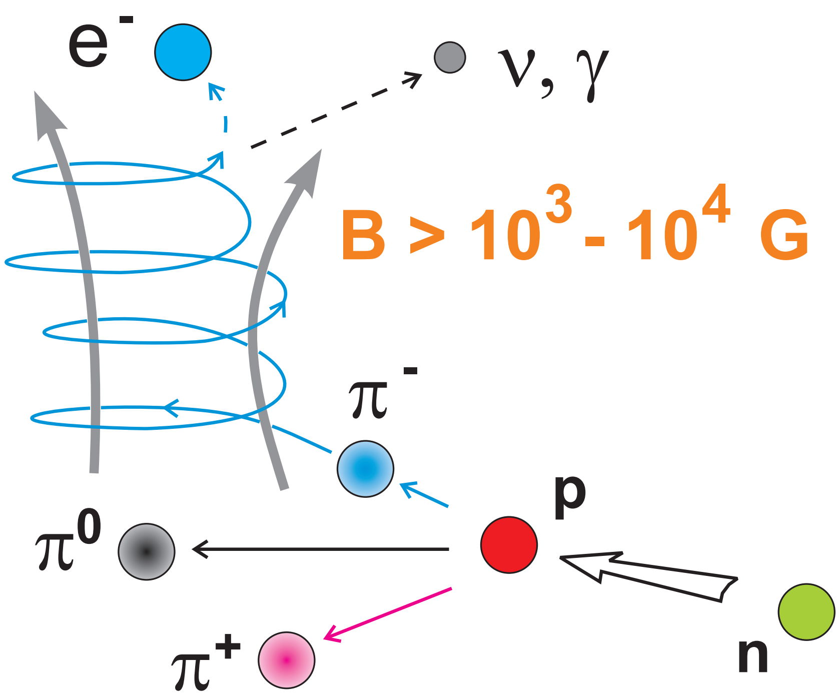
Decay of charged and neutral pions:

$$\pi^- \xrightarrow{2.6\times10^{-8}\text{s}} \mu^- + \bar{\nu}_\mu \xrightarrow{2.2\times10^{-6}\text{s}} e^- + \bar{\nu}_\mu + \nu_\mu + \bar{\nu}_e$$

$$\pi^+ \xrightarrow{2.6\times10^{-8}\text{s}} \mu^+ + \nu_\mu \xrightarrow{2.2\times10^{-6}\text{s}} e^+ + \nu_\mu + \bar{\nu}_\mu + \nu_e$$

$$\pi^0 \xrightarrow{10^{-16}\text{s}} 2\gamma \rightarrow e^\pm \text{ pairs}$$

Collective recoil



Thermal energy transferred to the jet:

$$dQ \simeq \frac{1}{2} \Delta_{pn} m_N c^2$$

Radiated energy (lab frame):

$$\varepsilon_{rad} \simeq \frac{1}{2} \Gamma dQ \sim \frac{\Gamma_p}{8\Gamma_n} \varepsilon_p$$

Lorentz factor of secondary electrons:

$$\gamma_e \simeq 70 \Delta_{pn}$$

ε_p – lab-frame proton energy

Γ_p, Γ_n – Lorentz factors of protons and neutrons

Δ_{pn} – relative Lorentz factor of protons and neutrons

m_N – nucleon mass

Radiation initiated by jet's own neutrons

Parabolic jet: $\Gamma = \sqrt{R/R_0}$ $\Rightarrow$ $\Delta_{pn}^{(ph)} = \sqrt{\sigma_T/\sigma_{coll}}$

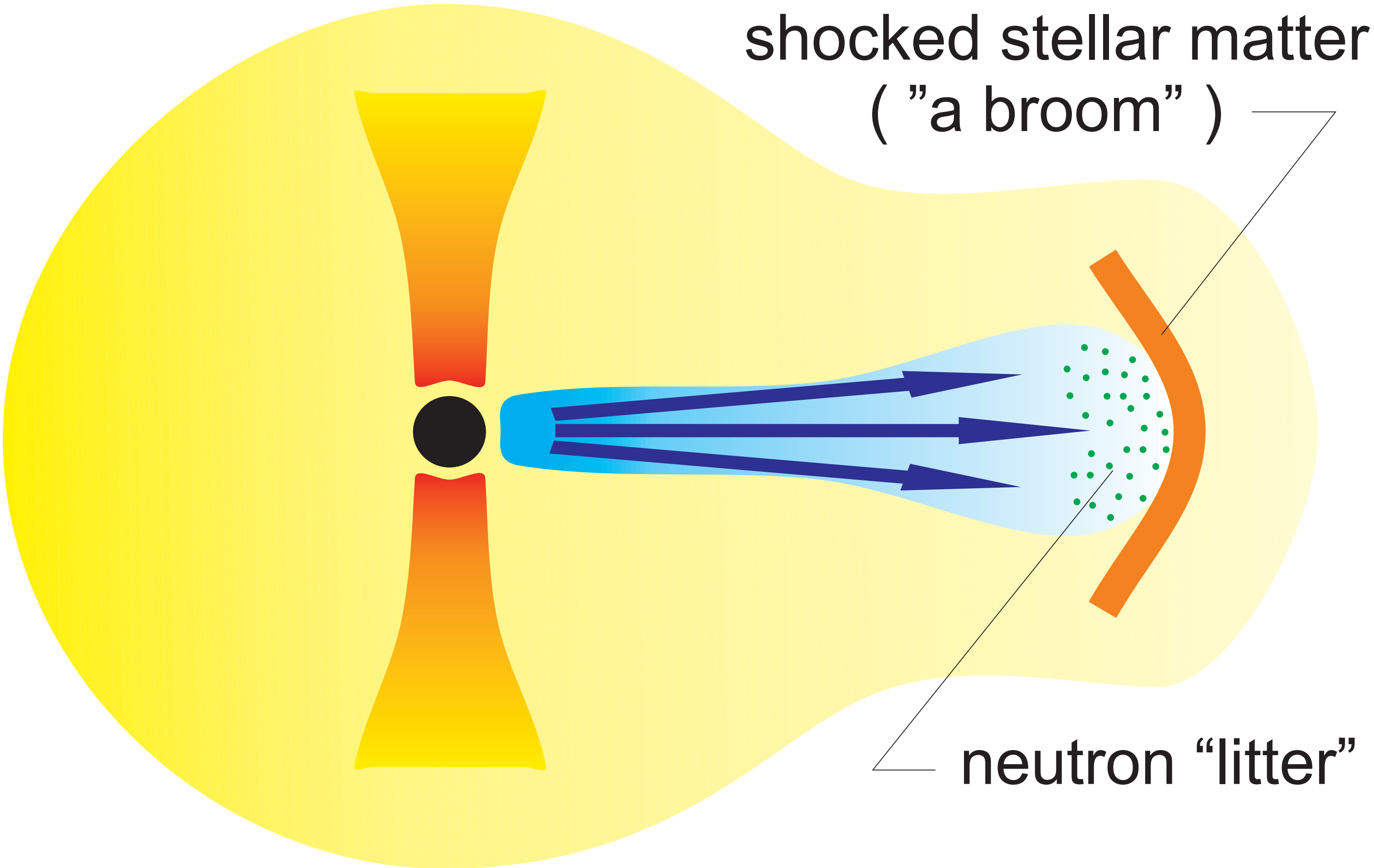
Efficiency: $q = \eta_{dec}^{-1}\sqrt{\sigma_{coll}/\sigma_T}$

Lorentz factor of secondary electrons and positrons: $\gamma_e^2 \simeq 5 \times 10^3 \dfrac{\sigma_T}{\sigma_{coll}} \simeq 10^5$

Synchrotron peak at $\varepsilon_{sy} \simeq \dfrac{\hbar e}{m_e c}\gamma_e^2 B,$ where $B = \left(\dfrac{4P_j\Gamma^2}{R^2 c}\right)^{1/2}$

$$\varepsilon_{sy} = \frac{1}{\alpha_f}\gamma_e^2\left(\frac{3}{2}\eta_0\frac{m_N}{m_e}\frac{r_e}{R_0}\right)^{1/2} m_e c^2 \simeq \left(\frac{\eta_0}{300}\right)^{1/2}\left(\frac{3\times 10^7\,\mathrm{cm}}{R_0}\right)^{1/2} m_e c^2$$

Hypernova-type model of Gamma-Ray Bursts



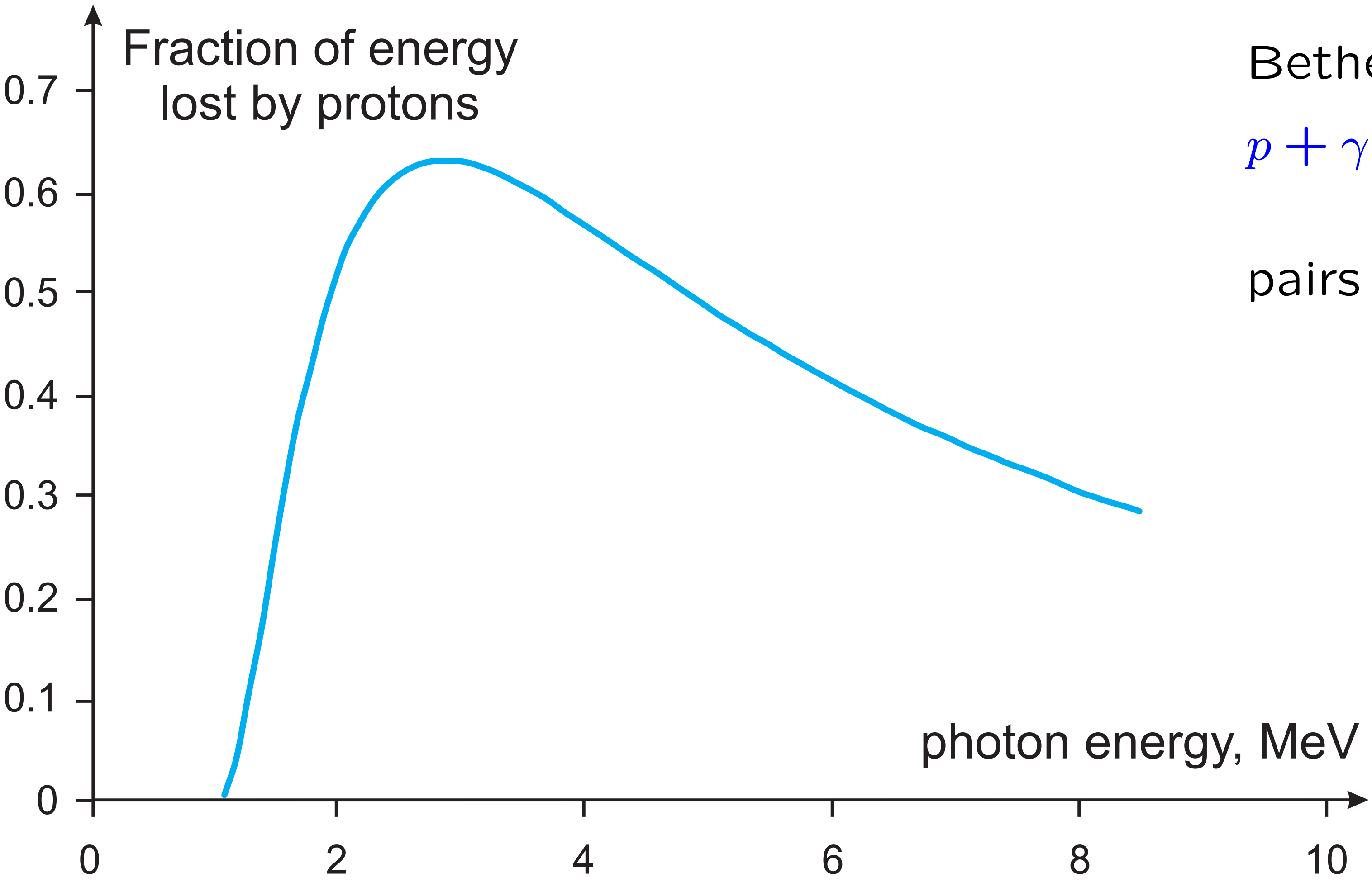
Distance to the "neutron wall"

$R_n \sim 3 \times 10^{12}$ cm

Neutron surface density: $\Sigma_n \gtrsim \sigma_{coll}^{-1} \simeq 3 \times 10^{25}$ cm^{-2}

Available energy (isotr. equivalent): $\gtrsim 2\pi R_n^2 \Sigma_n \Gamma^2 m_N c^2 \simeq 10^{54} \left(\frac{\Gamma}{500}\right)^2$ erg

In powerful bursts even protons radiate



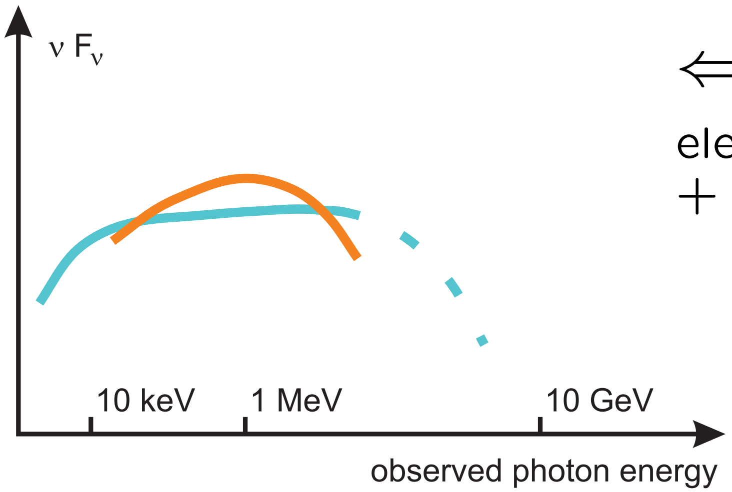
Bethe-Heitler process

$p + \gamma \rightarrow p + e^+ + e^-$

pairs radiate synchrotron

GRB parameters: $L_\gamma^{\text{iso}} = 10^{54}$ erg/s, $\Gamma = 300$, $R = 3 \times 10^{12}$ cm

Spectral sequence for Gamma-Ray Bursts

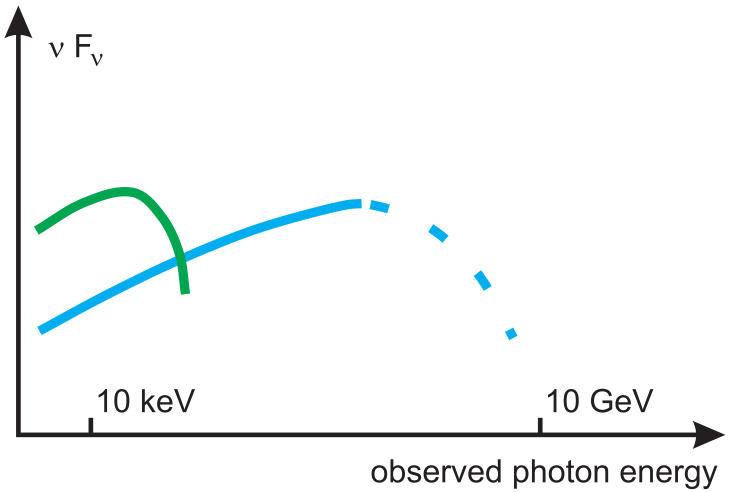


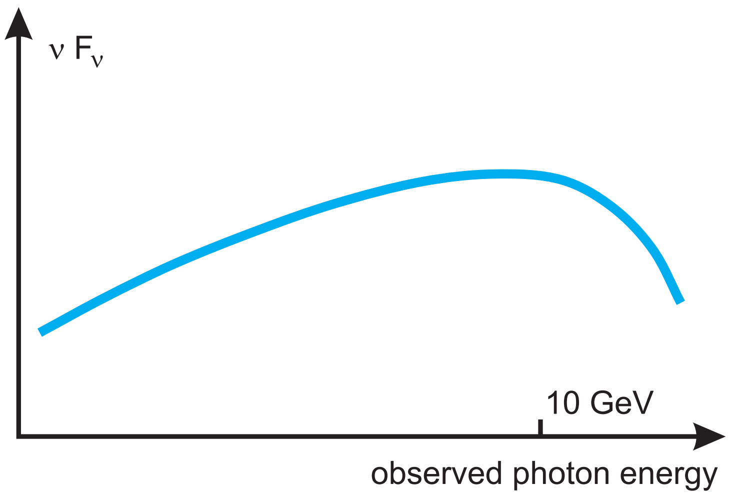
⇐ Very bright GRBs ($L_\gamma^{\rm iso} > 10^{54}$ erg/s)

electromagnetic cascade from primary electrons
+ synchrotron peak from Bethe-Heitler electrons

Moderately bright GRBs ⇒

absorbed synchrotron peak from primary electrons
+ X-ray synchrotron from secondary electrons





⇐ Weak GRBs ($L_\gamma^{\rm iso} < 10^{52}$ erg/s)

single synchrotron peak from primary electrons

Problems for the near future

- 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?

- If the jets are Poynting-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?