GRBs: properties & afterglows

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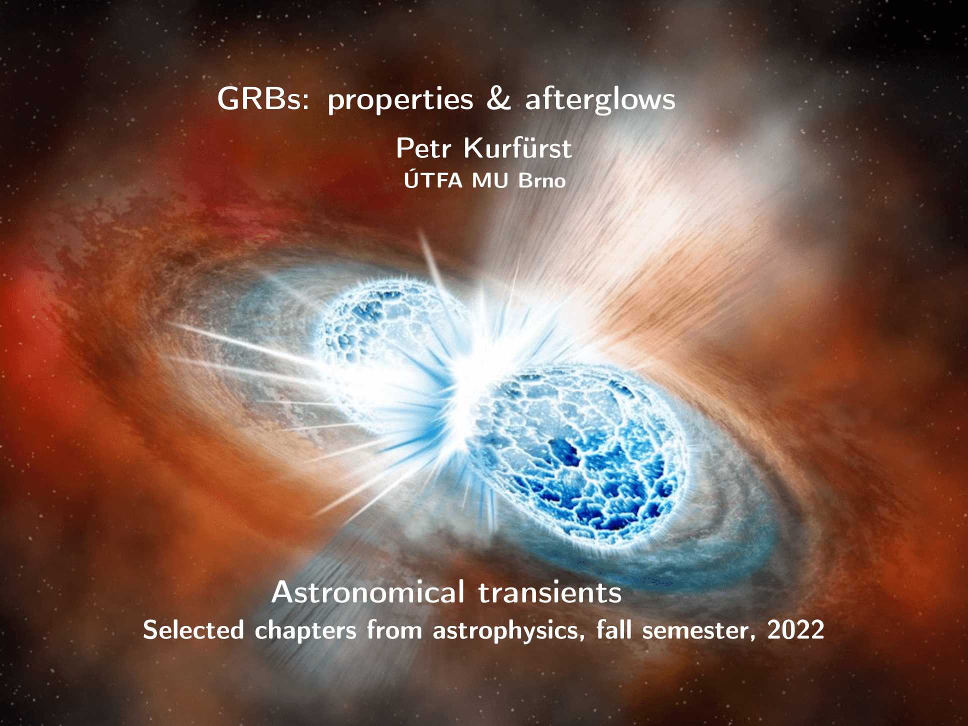


Astronomical transients

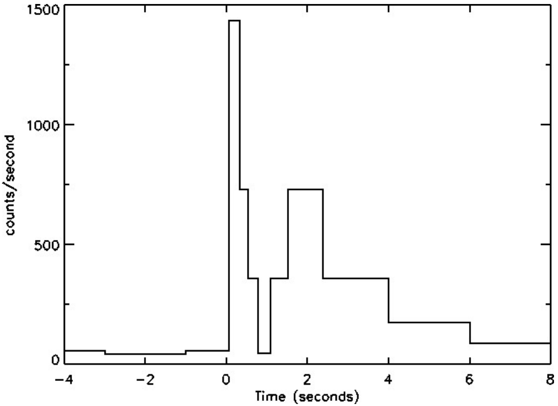
Selected chapters from astrophysics, fall semester, 2022

GRBs: the brightest EM transients

(cf. Tsvi Piran's talk on 35HUJI)

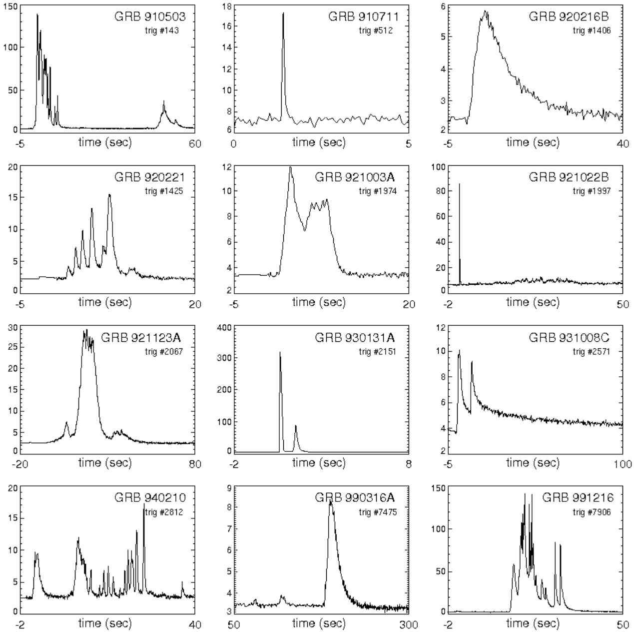
Once or twice a day (Credit: Compton Gamma-Ray satellite)

GRBs: the brightest EM transients



July 2nd 1967: Vela 4a satellite (noticed only in 1969)
(Credit: Klebsadel+ 1973)

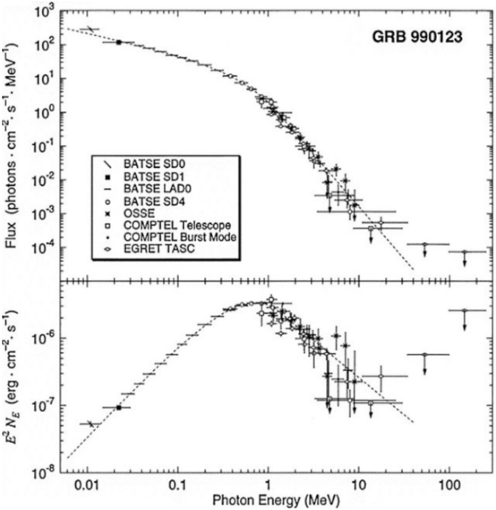
GRBs: the brightest EM transients



BATSE GRB LCs: great diversity

- 'Multimessengers'
- Colgate's model

GRBs: the brightest EM transients



The "Band" function

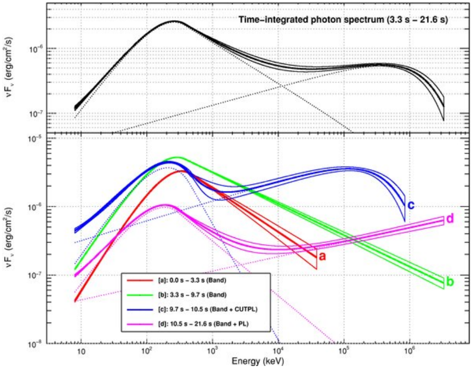
Prompt GRB spectrum → nonthermal!

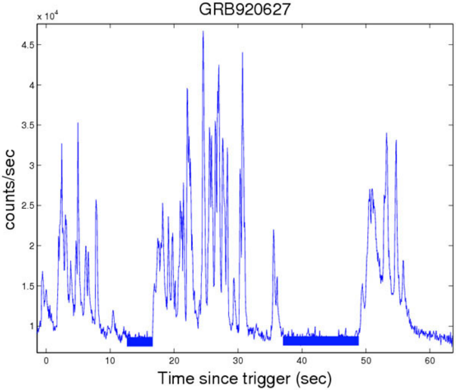
Louis Band (1957 - 2009)

$$N(E) = \begin{cases} A\left(\frac{E}{100\text{ keV}}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right), & E < (\alpha-\beta)E_0 \\ A\left[\frac{(\alpha-\beta)E_0}{100\text{ keV}}\right]^{\alpha-\beta} \exp(\beta-\alpha)\left(\frac{E}{100\text{ keV}}\right)^{\beta}, & E \geq (\alpha-\beta)E_0 \end{cases}$$

(cf. Bing Zhang's talk 2018)

GRBs: the brightest EM transients

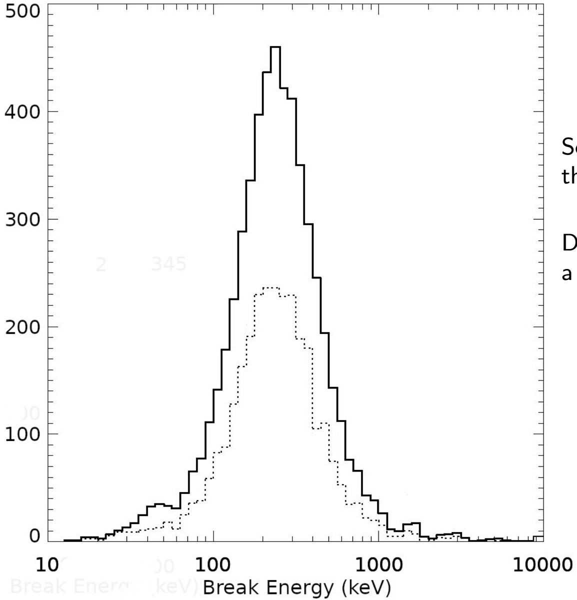




(Credit: Ackermann+ 2011)

(Credit: Piran 2004)

GRBs: the brightest EM transients



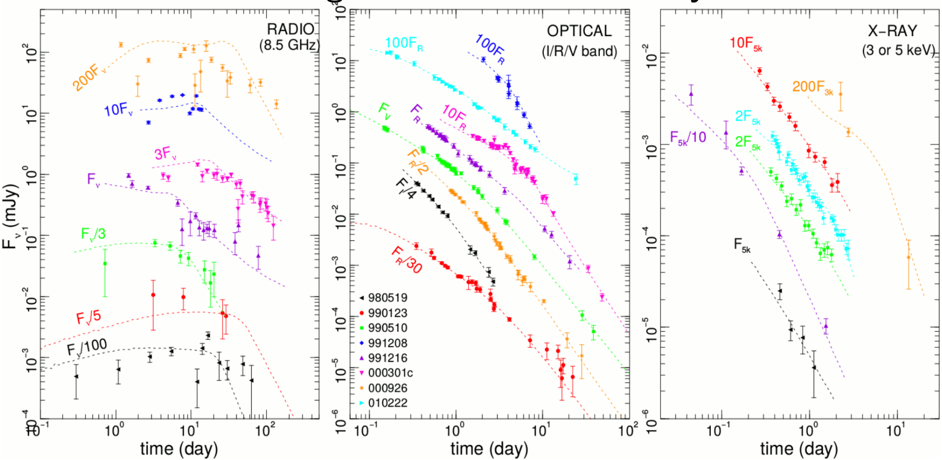
Solid line:
the whole sample

Dashed line:
a subset of the data

(Credit: Piran 2004)

GRBs: the brightest EM transients

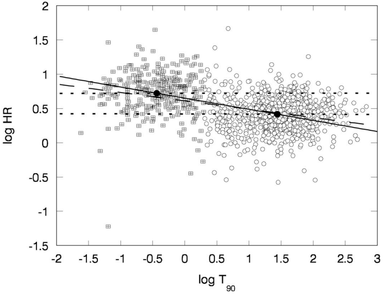
GRB afterglow LCs - Radio to X-ray

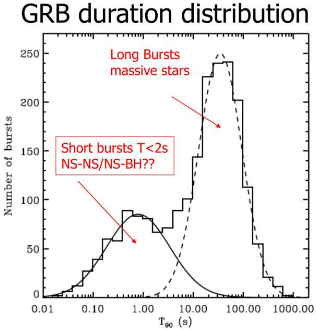


(Credit: Kumar 2003)

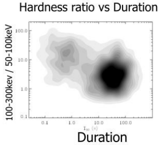
GRBs: the brightest EM transients

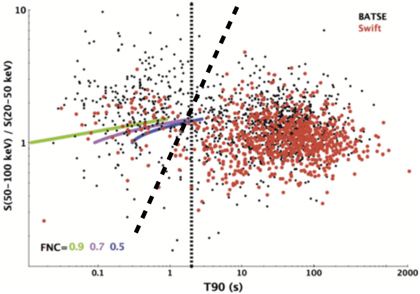
Short & long GRBs





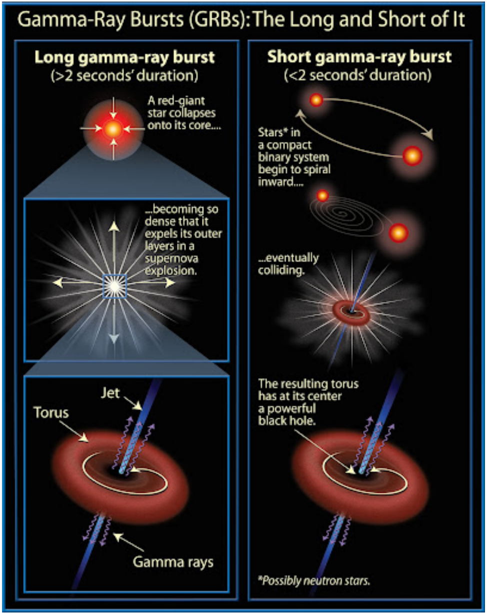
Lazzati and Perna





Mazets et al. 1981, Norris et al. 1984, Kouveliotou et al. 1993

GRBs: the brightest EM transients



Short & long GRBs

different progenitors

different physical mechanism

$< 2\,\mathrm{s}$

ultra long?

short GRB

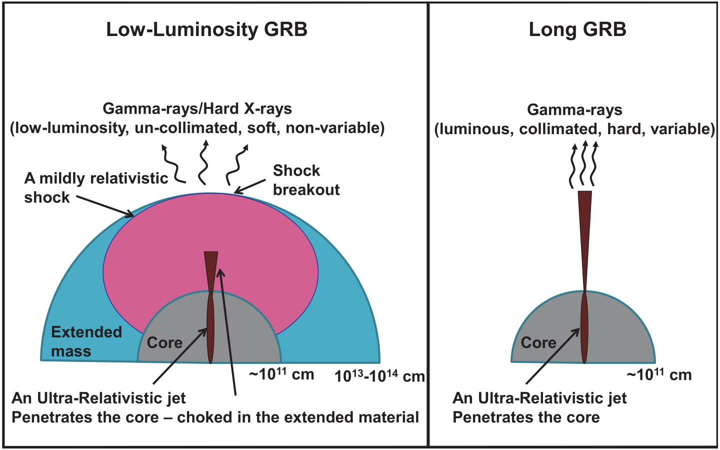
long GRB

low-luminosity short GRB $\rightarrow$ softer & different spectral evolution

low-luminosity long GRB $\rightarrow$ soft and smooth

GRBs: the brightest EM transients

Low luminosity GRBs

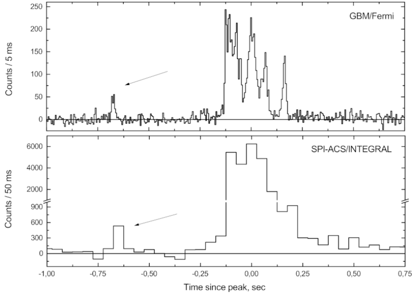


Necessary condition for GRB: the engine working time is long enough to allow the jet to drill through the star

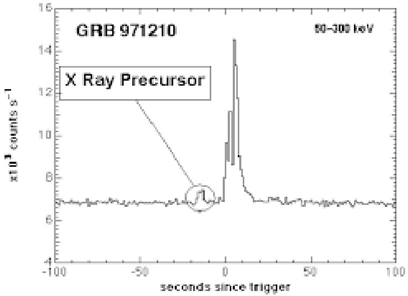
(Credit: Nakar+ 2015, see also Lazzati+ 2012, del Colle+ 2018, etc.)

(cf: Alessandra Corsi's talk)

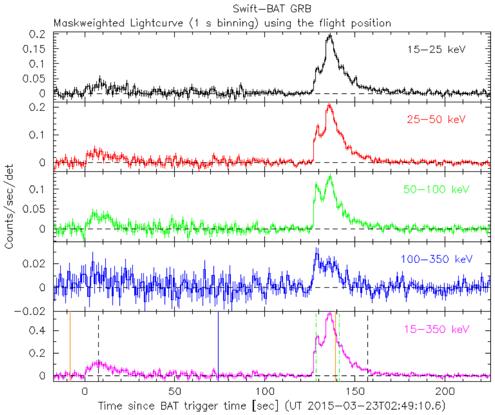
GRBs: the brightest EM transients



Credit: Minaev & Pozanenko



Precursors of GRB



GRBs: the brightest EM transients

- **Time vs. energy $\Rightarrow$ a compact object $\Rightarrow$ BH or NS**
- **Size of a GRB engine**: $\lesssim 10^6$ cm
- **Energy density**: $\sim 10^{33}\,\mathrm{erg\,cm^{-3}} \Leftrightarrow$ mass density $\sim 10^{13}\,\mathrm{g\,cm^{-3}}$
- **Temperature**: $\sim 10^{11}$ K $\rightarrow$ much higher then T threshold for e^+e^- pair production $\Rightarrow$ almost equal number of photons and pairs
- Pair dominated plasma or Poynting flux?
- $\Rightarrow$ **BH with accretion disk**?
- $\Rightarrow$ **Magnetars**?
- Indication for the collapsar models $\rightarrow$ several long GRBs detected in 1997 in SF galaxies?
- We detect short GRBs in all types of galaxies

The compactness problem:

- **Energy**: $\sim \mathbf{10^{51}}$ **erg**
- **Time variability**: $\delta t \cong \mathbf{0.1}$ **s** (or less!)
- Let's evaluate the **size of the emitting region**:
  $R \leq c\,\delta t \lesssim 3 \times 10^{9}\,\mathrm{cm} \approx 10^{10}\,\mathrm{cm}$
- We see **photon energies**: $\sim$ **300 keV - 1 Mev** with high energy tail **far beyond it** (1 Mev $\approx 10^{-6}$ erg)

  $\Downarrow$

- Now let's estimate the **# density of photons** within the source object as $\sim E/R^{3} \rightarrow 10^{51+6}/(10^{10})^{3} \approx 10^{27}$ photons cm^{-3}
- **Cross-section** for $\gamma\gamma \rightarrow e^{+}e^{-}$ is of the order of $\sigma_T \sim 10^{-24}\,\mathrm{cm}^{2}$
- **Optical depth** $\tau_{\gamma\gamma\rightarrow e^{+}e^{-}} \sim n_{e}\sigma_{t}R \cong 10^{27} \times 10^{-24} \times 10^{10} \approx \mathbf{10^{13}}$
- That is: the optical depth for these photons to escape from this "fireball soup" will be also 10^{13} (likely even more) $\rightarrow$ they **cannot escape**
- **This means**: the **spectrum** must be **thermal!**

The compactness problem:

- **But**: we observe clearly **nonthermal spectrum** (synchrotron)!
- Need a "new physics" for explanation? Yes, but the "new physics" was invented in 1905: **special relativity!**
- $E_{\rm ph}\,(\text{observed}) = \Gamma E_{\rm ph}\,(\text{emitted}), \quad R \leq \Gamma^2 c\,\delta t$ (explain later)
- An integrated power law energy spectrum $\mathrm{d}n(\epsilon)/\mathrm{d}\epsilon \sim \epsilon^{-\alpha}$ reduces the # of photons $N_{\rm ph}$ above the $\gamma\gamma \to \mathrm{e}^+\mathrm{e}^-$ pair production threshold by $\epsilon^{-\alpha+1} = \Gamma^{-2\alpha+2} \Rightarrow \tau_{\gamma\gamma\to\mathrm{e}^+\mathrm{e}^-} \sim \frac{N_{\rm ph}}{R^3}\sigma_t R$
- In that case: the optical depth will be transformed as

$$\tau_{\gamma\gamma\to\mathrm{e}^+\mathrm{e}^-} \sim \Gamma^{-(2+2\alpha)} n_{\rm e}\sigma_t R \approx 10^{13}/\Gamma^{2+2\alpha}$$

- The power index $\alpha \sim 2 \to \Gamma \gtrsim 100$ - 150 **solves this mystery!**
- Calculations may give the **constraints on** Γ for long and short GRBs
- Occurrence of high Γ **jets** with a large beaming factor explain $E \gtrsim 10^{52}$ ergs

GRB afterglows

(cf. Re'em Sari's lecture on 35HUJI)

- **GRB source:** mass M, energy E
- **Pre-existing GRB source** surroundings:

$$\rho \sim r^{-w} \quad (\textbf{wind}: w = 2) \quad \Rightarrow \quad \dot{M} = 4\pi r^2 \rho v \quad (\text{everything const. in time})$$

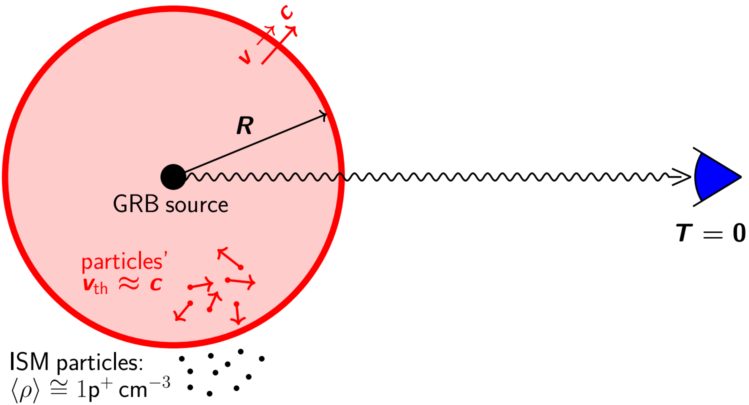
- **Spherical explosion**: after a time $t \to$ **mass** m encountered by the expansion shock wave $\gg M$
- (Analogy: a-bomb in the atmosfere $\to$ a few (few tens) kgs of explosive material $\to$ after a time the shock wave encounters much higher mass of the air)
- The whole system is thus **independent of an explosive mass** $M \to$ depends only on **surrounding density** ρ and **energy** E (conserved quantity)
- **Estimate of a size R of the shock wave at any time t:**

$$\sim \rho R^3 \left(\frac{R}{t}\right)^2 = E \quad \Rightarrow \quad R \propto t^{2/(5-w)} \quad (\textit{Sedov - Taylor solution})$$

- $R \propto t^{2/5}$ for $\rho = \text{const.}$, $R \propto t^{2/3}$ for wind, conserved $E_k \to v$ may decelerate

GRB afterglows

- **Now: what is the (ultra)relativistic analog** of the previous ($v_{\text{shock}} \to c$)?
- **Shocked sphere at time** t (in observer's frame) with the "size" $\boldsymbol{R}$ and the expansion velocity $\boldsymbol{v}=$ (almost) $\boldsymbol{c}$:



GRB afterglows

- **Now: what is the (ultra)relativistic analog** of the previous ($v_{\text{shock}} \to c$)?
- Reminder of the **STR** formalism **(primed = particle's rest frame)**:

$$E = \Gamma m_0 c^2, \quad \text{where } \Gamma = \frac{1}{\sqrt{1-\beta^2}} \text{ with } \beta = \frac{v}{c}, \text{ and } m_0 = m \text{ at rest}$$

- **The size of the shock wave now becomes** (*Blandford - McKee solution*):

$$\sim \rho R^3 c^2 \Gamma^2 = E \quad \rightarrow \quad \Gamma \propto R^{-3/2} \text{ for } \rho = \text{const.} \quad (\Gamma^2 \text{ due to } v_{\text{th}})$$

- From the *aberration of light* (a 4-velocity with $u' \equiv u \equiv c$):

$$\sin\theta = \frac{\sin\theta'}{\Gamma\,(1+\beta\cos\theta')} \Rightarrow \text{for } \theta' = \pi/2 \text{ (a photon emitted } \perp \text{ to } v \text{ in } \mathcal{K}') \rightarrow$$

$$\sin\theta = \frac{1}{\Gamma} \Rightarrow \text{for } \Gamma \gg 1 \rightarrow \theta \sim \frac{1}{\Gamma}$$

- **Beaming effect**: if photons are emitted in $\mathcal{K}'$ isotropically $\rightarrow$ for half of them $\theta' < \pi/2 \Rightarrow$ in $\mathcal{K}$ half of them lying within a cone of half-angle $1/\Gamma$, while for a minority $\theta \gg 1/\Gamma$

GRB afterglows

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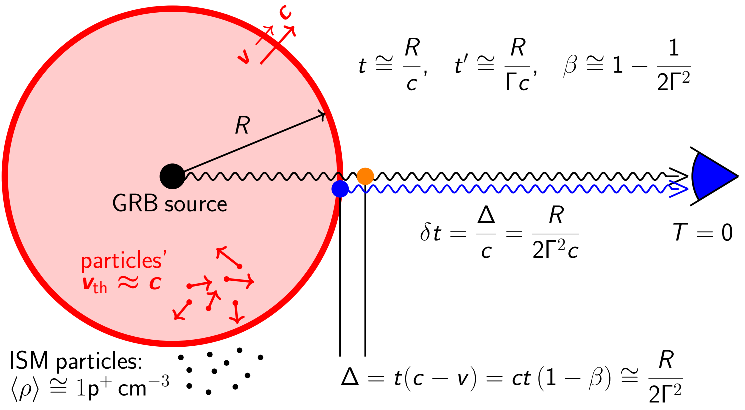
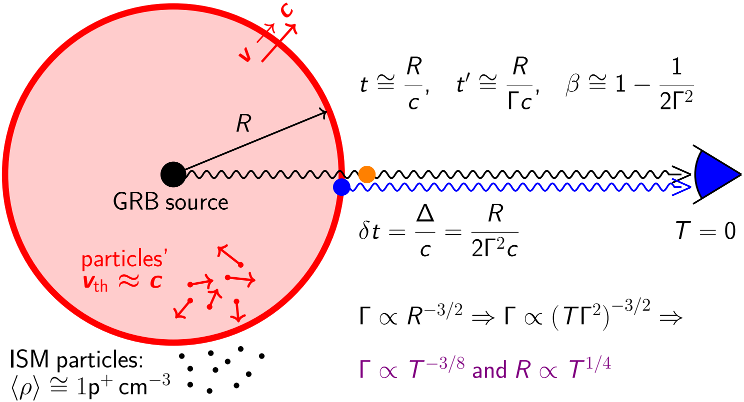


GRB afterglows

- **Connecting NR and UR regimes** ($v \ll c / v \approx c$): $\beta\Gamma \propto R^{-3/2}$
- NR: $\Gamma \sim 1$ / UR: $\beta \sim 1$ $\Rightarrow$ smooth relation covering both the extreme cases
- Accurate SSS $\rightarrow$ proper coefficients, now an estimate, **but**: exact coefficient do not differ much $\Rightarrow$ not bad approach (**we now follow the UR case**):



$$t \cong \frac{R}{c}, \quad t' \cong \frac{R}{\Gamma c}, \quad \beta \cong 1 - \frac{1}{2\Gamma^2}$$

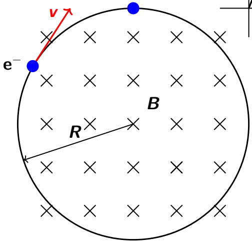
$$\delta t = \frac{\Delta}{c} = \frac{R}{2\Gamma^2 c}$$

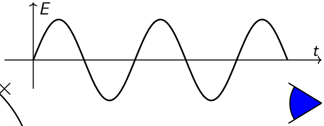
$$\Gamma \propto R^{-3/2} \Rightarrow \Gamma \propto \left(T\Gamma^2\right)^{-3/2} \Rightarrow$$

$$\Gamma \propto T^{-3/8} \text{ and } R \propto T^{1/4}$$

Interlude: synchrotron radiation

- Most o the GRB afterglows go as the **synchrotron** or the **IC radiation**





- NR: cyclotron radiation

- $\frac{m_e v^2}{R} = \frac{v}{c} q_e B \Rightarrow \omega_{cyc} = \frac{v}{R} = \frac{q_e B}{m_e c}$

Interlude: synchrotron radiation

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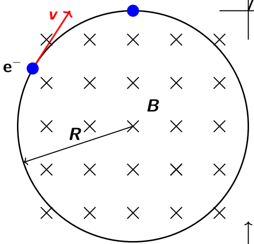

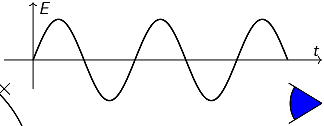

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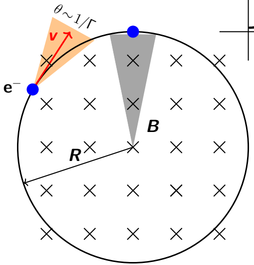
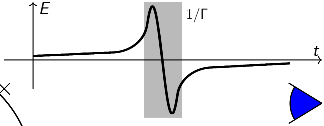




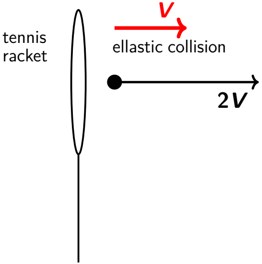
- UR: synchrotron radiation
  $\omega_{syn} = \frac{q_e B}{\Gamma_e m_e c} \; (< \omega_{cyc})$

- **But**: the significant emission duration of an E field narrowed by the ratio $1/\Gamma$ + the electron is chasing the E field by $\sim v \to c$, then the observer sees:

- $\omega_{syn}(\text{grey zone}) = \frac{q_e B}{\Gamma_e m_e c} \Gamma_e^3 \;\to\; \nu_{syn} \sim \nu_{cyc} \Gamma_e^2$

Interlude: synchrotron radiation

- Heuristic estimate of the **synchrotron emission power** $\boldsymbol{P}$ (per unit time): (exact solution using the Larmor formula, etc., too complicated for now)



- **IC scattering** by relativistic electrons:

- NR analog: $\Delta \boldsymbol{V}$ of the ball $\rightarrow$ $\boldsymbol{2V}$ (let's prove it in the restframe of a racket)

- UR IC scattering by a head-on coming e^- with $v \rightarrow c$: incoming photon frequency $h\nu$ $\rightarrow$ backward scattered photon energy $h\nu = \Gamma_e^2 \, h\nu'$ (same Γ^2 as in the previous energy equation)

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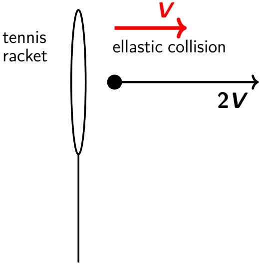

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- Cross sectional "cylinder" volume (between relativistic e^- and ph, per unit time): $\beta c \sigma_T \Rightarrow E_{IC} = \beta c \sigma_T U_{ph} \Gamma_e^2$ (U_{ph} is the photons' energy density inside $\beta c \sigma_T$)
- We may think of a synchrotron radiation as if U_{ph} is the energy density of the B-field: $P_e = \beta c \sigma_T \, \Gamma_e^2 B^2/(8\pi)$ (UR electron's emitted power per unit of time)

Interlude: synchrotron radiation

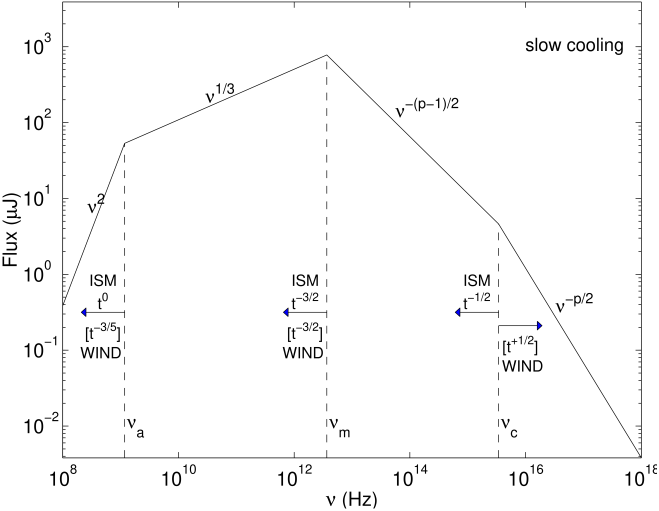
- What is the emission from a distribution of electrons?
- Assuming a **shock wave** that accumulates mass $\sim \rho R^3$, accelerating the collected electrons to all kinds of energies:
- Let's have a decreasing power-law distribution of a # of electrons per Γ_e (dependence of the quantity $\frac{dn_e}{d\Gamma_e}$ on Γ_e): $\frac{dn_e}{d\Gamma_e} \sim \Gamma_e^{-p}$
- The same distribution as a **function of a frequency** ν: # of electrons in a certain Γ_e range $\rightarrow \Gamma_e \frac{dn_e}{d\Gamma_e}$
- Multiplying this by power and divide by the frequency for this Γ_e:

$$\frac{\Gamma_e \frac{dn_e}{d\Gamma_e} \beta c \, \sigma_T \, \Gamma_e^2 \frac{B^2}{8\pi}}{\frac{q_e B}{m_e c} \Gamma_e^2} \sim \Gamma_e \frac{dn_e}{d\Gamma_e} = \text{power (energy per unit time) per unit frequency}$$

- Recalling $\Gamma_e \sim \nu^{1/2}$: $\boldsymbol{F_\nu \sim \nu^{-(p-1)/2}}$

Interlude: synchrotron radiation

- Broad-band synchrotron spectrum of the afterglow from a spherical fireball with constant density (“ISM” model) and $\rho \propto r^{-2}$ medium (“wind” model) :



Credit: Kulkarni+ 2000

Representative of the observed spectrum few days after the burst

Interlude: synchrotron radiation

- Evaluation of an efficient cooling time from the previous:

$$t_{\rm cool} \sim \frac{E_{\rm e}}{P_{\rm e}} \sim \frac{\Gamma_{\rm e} m_{\rm e} c^2}{\beta c\, \sigma_T\, \Gamma_{\rm e}^2 B^2/(8\pi)} \sim \frac{1}{\Gamma_{\rm e}} \sim \frac{1}{\sqrt{\nu}}$$

- Electrons between $\boldsymbol{\nu_{\rm m} < \nu < \nu_{\rm c}}$ "live" forever (= longer than the system)
- Electrons with $\boldsymbol{\nu > \nu_{\rm c}}$ are so efficiently cooled that they "live" for a shorter time than the system: $F_\nu \sim \nu^{-(p-1)/2} \cdot \nu^{-1/2} \propto \boldsymbol{\nu^{-p/2}}$
- The yet simpler consideration may use the fact that during their short "life" the electrons emit all their energy:

$$\left(\Gamma_{\rm e} \frac{{\rm d}n_{\rm e}}{{\rm d}\Gamma_{\rm e}}\, \Gamma_{\rm e} m_{\rm e} c^2\right) \Big/ \left(\frac{q_{\rm e} B}{m_{\rm e} c} \Gamma_{\rm e}^2\right) \sim \Gamma_{\rm e}^{-p} \propto \nu^{-p/2}$$

- Electrons between $\boldsymbol{\nu_{\rm a} < \nu < \nu_{\rm m}}$ (low energy tail, a bit complicated to derive): $F_\nu \propto \boldsymbol{\nu^{1/3}}$ → even for "monoenergetic" electrons
- At the yet more lower frequencies, $\boldsymbol{\nu < \nu_{\rm a}}$, the synchrotron emission is so efficient that it absorbs the photons that it emits: self-absorption (blackbody) spectrum → $F_\nu \sim \frac{\boldsymbol{\nu^2}}{c^2}\, \Gamma_{\rm min} m_{\rm e} c^2 \frac{R^2}{D^2}$ (E instead of kT → not really thermal)

Interlude: synchrotron radiation

- **What we need to know for actual calculations**:
  - # of electrons
  - What is the Γ_{min}
  - Parameters of the B-field
  - Energy distribution p of electrons

- $n_{\mathrm{e}} \sim \dfrac{\rho R^3}{m_{\mathrm{p}}}$

- $\Gamma_{\mathrm{min}} \to \varepsilon_{\mathrm{e}} \Gamma m_{\mathrm{p}} c^2 \Rightarrow \Gamma_{\mathrm{e}} m_{\mathrm{e}} c^2 = \Gamma m_{\mathrm{p}} c^2$ (equipartition between e^- and p^+?) $\Rightarrow$ $\Gamma_{\mathrm{min}} \sim \varepsilon_{\mathrm{e}} \dfrac{m_{\mathrm{p}}}{m_{\mathrm{e}}} \Gamma$ (ε_{e} is the "fudge" factor, Γ is the Lorentz factor of the shock)

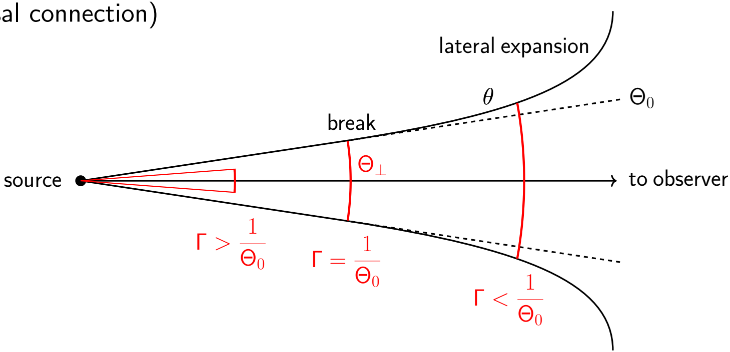
- $R^3 \dfrac{B^2}{8\pi} \sim \varepsilon_{\mathrm{B}} E$

- However: everything evolves in time, the values change; the picture introduced here may fit only for early times (cf. Granot+ 2000)

- Even the ordering of the limiting frequencies may change, e.g., ν_{c} becomes lower than ν_{m}, then the power law is $\nu^{-p/2}$ for $\nu > \nu_{\mathrm{m}}$ and $\nu^{-1/2}$ for $\nu_{\mathrm{c}} < \nu < \nu_{\mathrm{m}}$, etc.

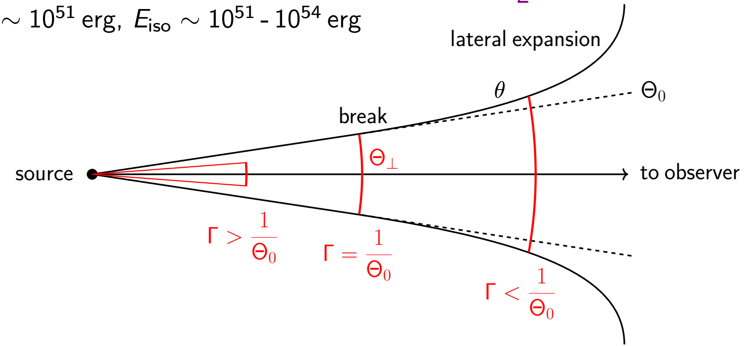
GRBs: the brightest EM transients

- **What if the explosion is not spherical $\rightarrow$ only jet with an initial opening angle** Θ_0: (observational constraints for the geometry)
- If $\Gamma \gg 1 \rightarrow$ the center of the jet does not "know" about edges; only limited amount of material that "knows" about the empty space outside the jet
- The time of the jet expansion in the local frame: $t = R/\Gamma c$
- "Arrival distance" of a photon from edges towards the center: $R_\perp = ct = \dfrac{R}{\Gamma}$ (causal connection)

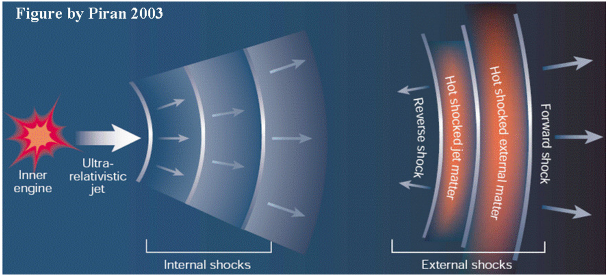


GRBs: the brightest EM transients

- **What if the explosion is not spherical $\rightarrow$ only jet with an initial opening angle** Θ_0: (observational constraints for the geometry)
- Corresponding "arrival angle": $\Theta_\perp = \dfrac{R_\perp}{R} = \dfrac{1}{\Gamma}$; if $\Theta_\perp \geq \Theta_0 \rightarrow$ the jet begins to "feel" the edges $\rightarrow$ spreads and slows down faster; the time when this happens $\approx 6\,\mathrm{hrs}\left(E_{52}/\rho\,[\mathrm{p}^+\,\mathrm{cm}^{-3}]\right)^{1/3}\Theta_0^{8/3}$, ($\Theta_0$ between 1 - 10 degs)
- Spherical explosion energy $E_{\rm iso}$, jet energy $E_{\rm jet} = \dfrac{\Theta_0^2}{2} E_{\rm iso}$, canonical values: $E_{\rm jet} \sim 10^{51}$ erg, $E_{\rm iso} \sim 10^{51}$ - 10^{54} erg



GRBs: the brightest EM transients



GRB engines