GAMMA-RAY BURSTS: AFTERGLOW EMISSION

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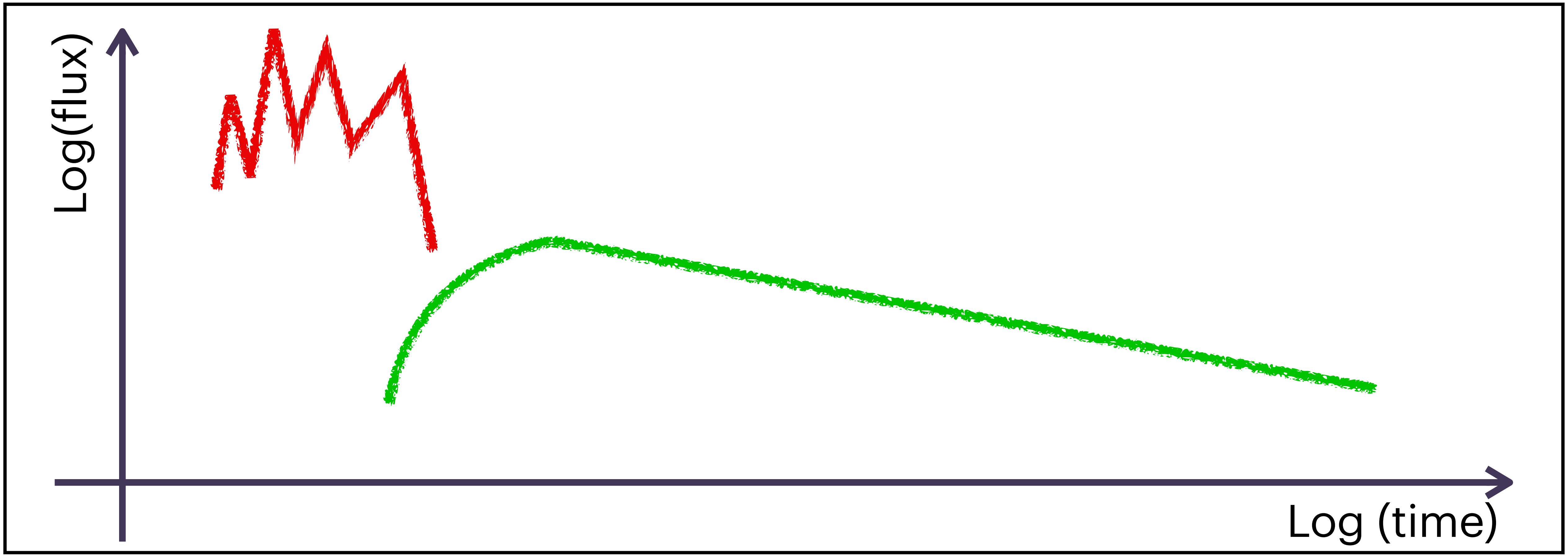
EMISSION FROM GRBS: AN OVERVIEW

TWO DISTINCT EMISSION PHASES



PROMPT

- from 10 keV to 10 MeV
- non-thermal spectra
- 0.1 seconds to 10^3 seconds
- highly variable flux

AFTERGLOW

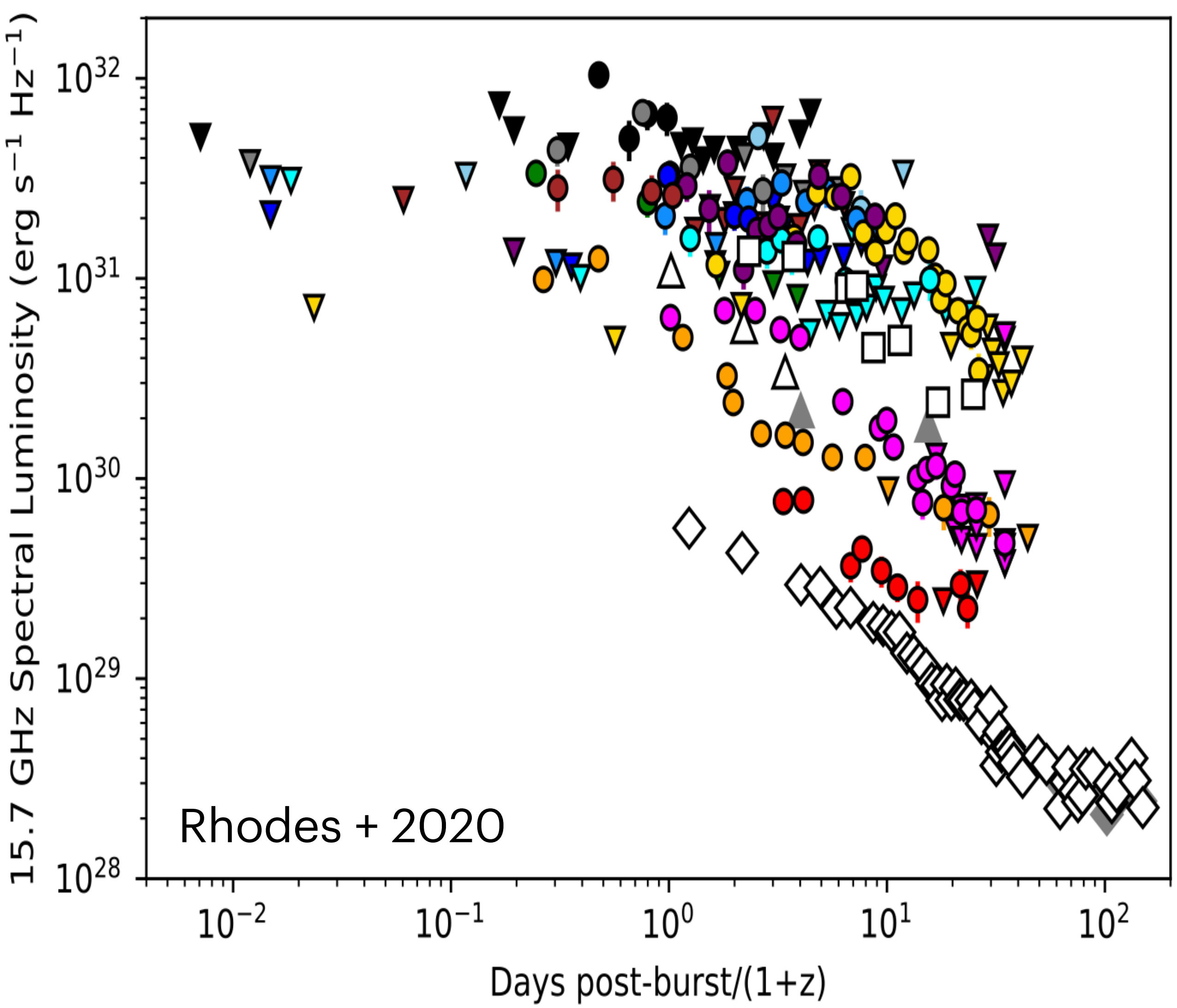
- from radio to TeV
- non-thermal spectra
- days - weeks
- smooth (PL) lightcurve

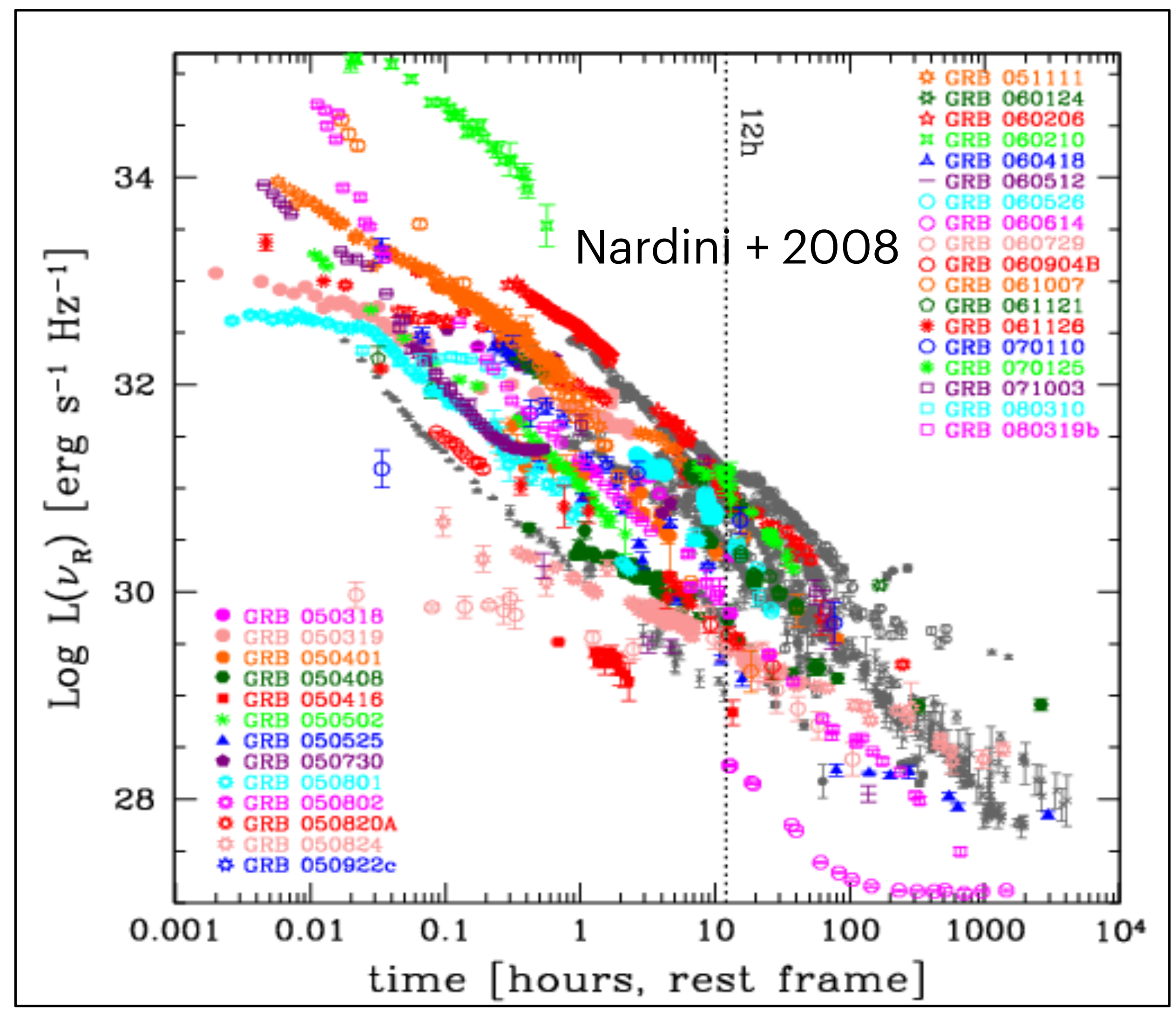
AFTERGLOW EMISSION LIGHTCURVES

OBSERVATIONS AT DIFFERENT FREQUENCIES

radio

optical

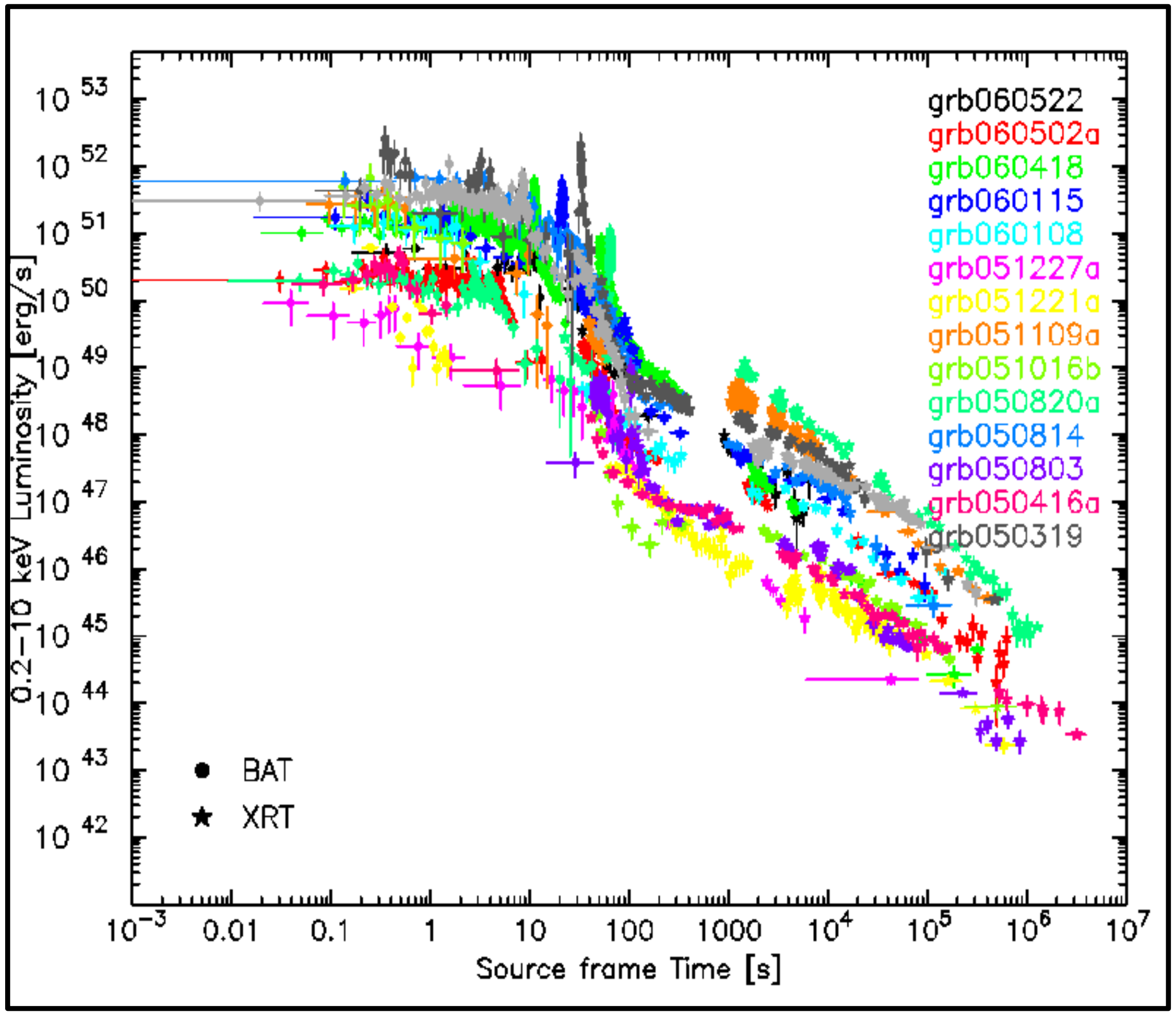




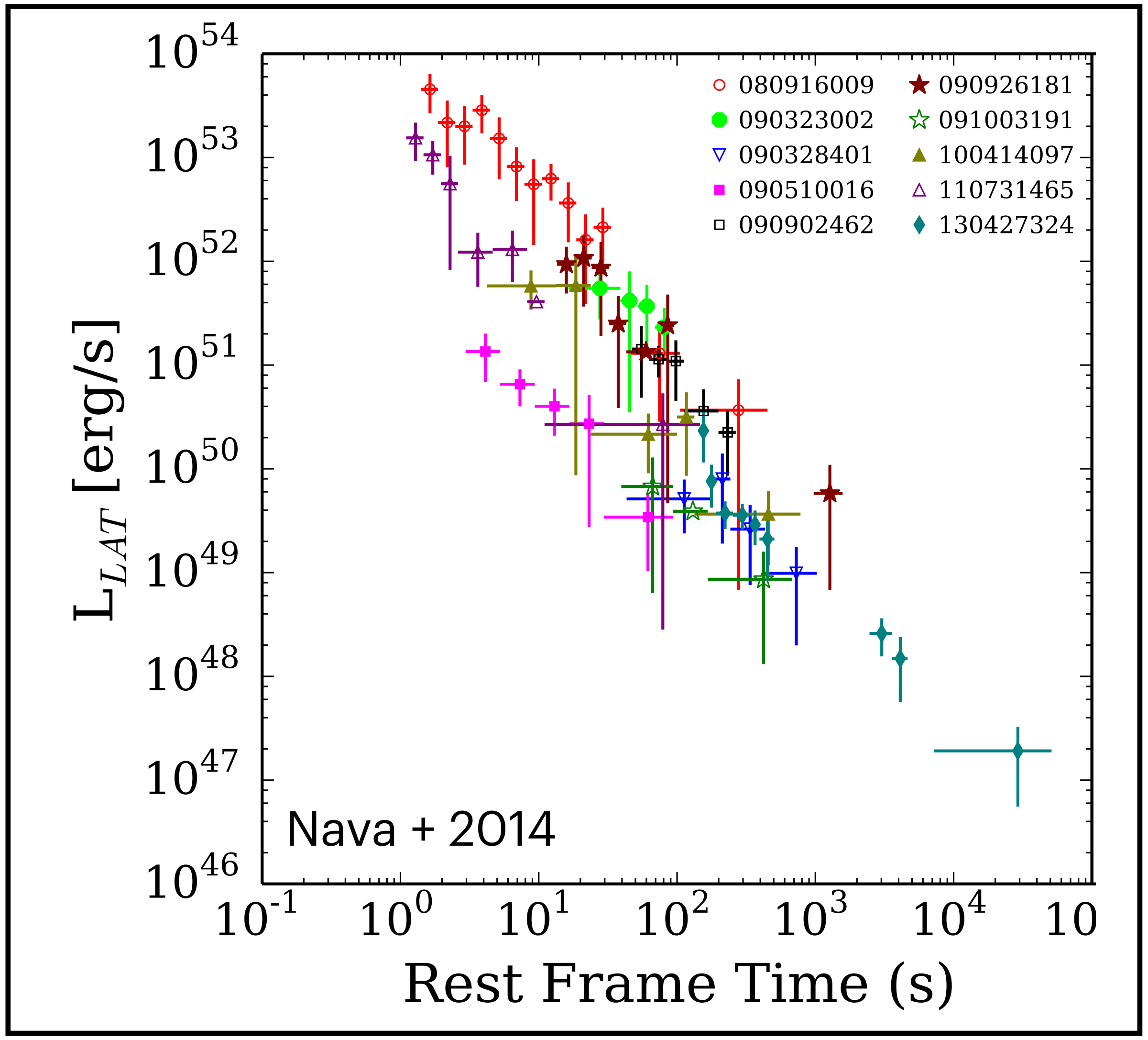
AFTERGLOW EMISSION LIGHTCURVES

OBSERVATIONS AT DIFFERENT FREQUENCIES

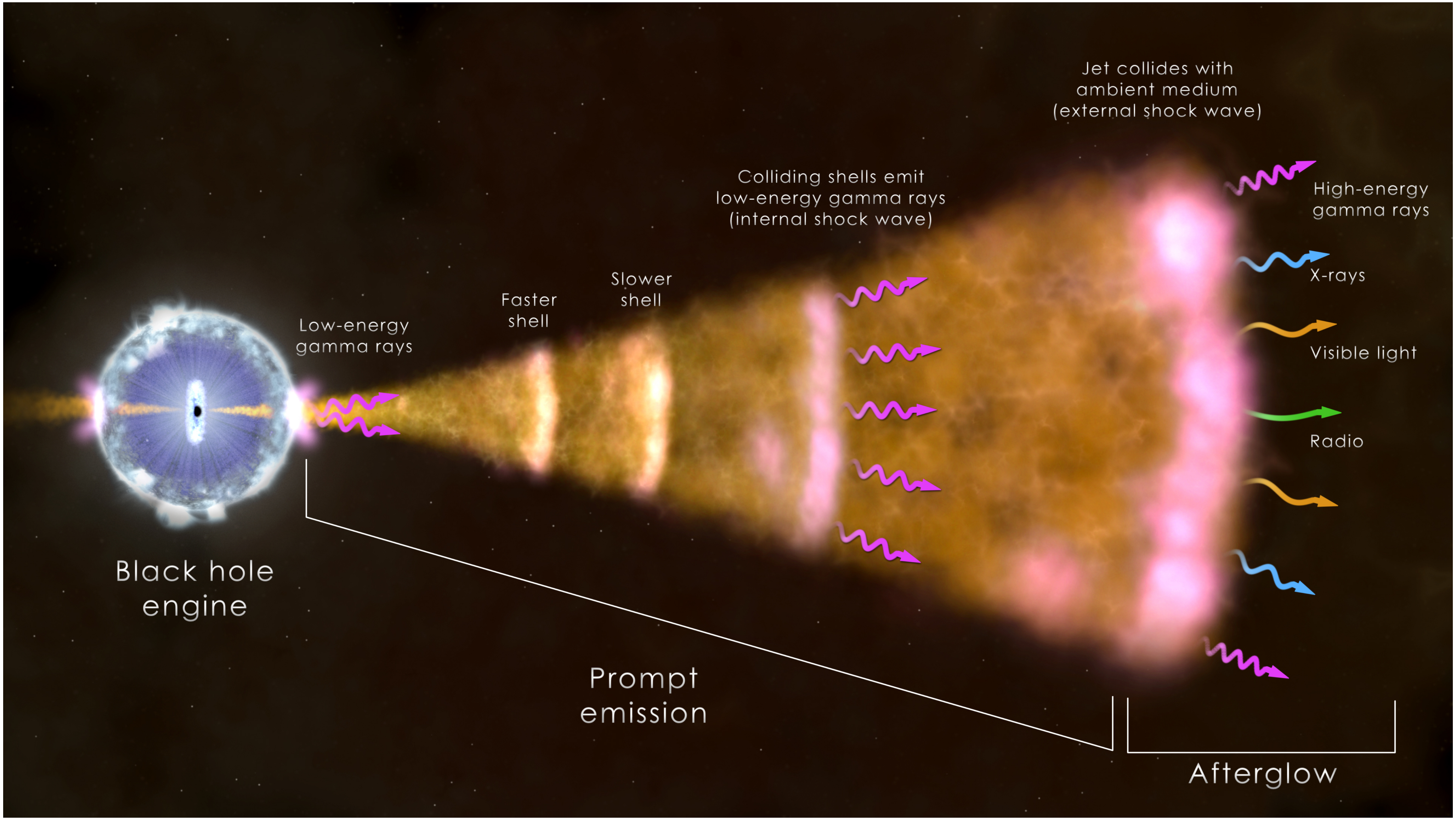
X-ray



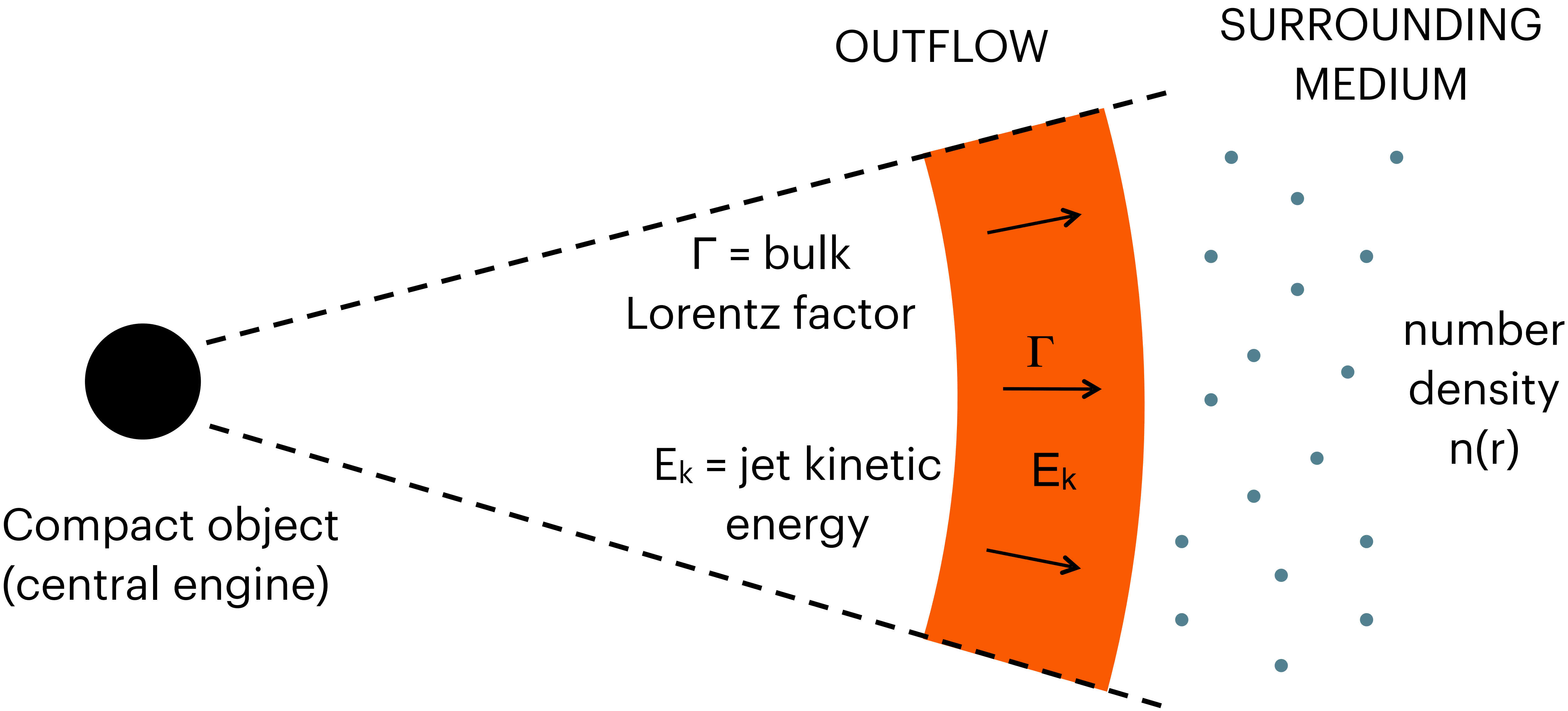
GeV (0.1-10 GeV)



GAMMA-RAY BURSTS - THE STANDARD MODEL



AFTERGLOW EMISSION: EXTERNAL SHOCK MODEL



AFTERGLOW EMISSION

To predict and model the radiative output, it is necessary to model the following three processes:

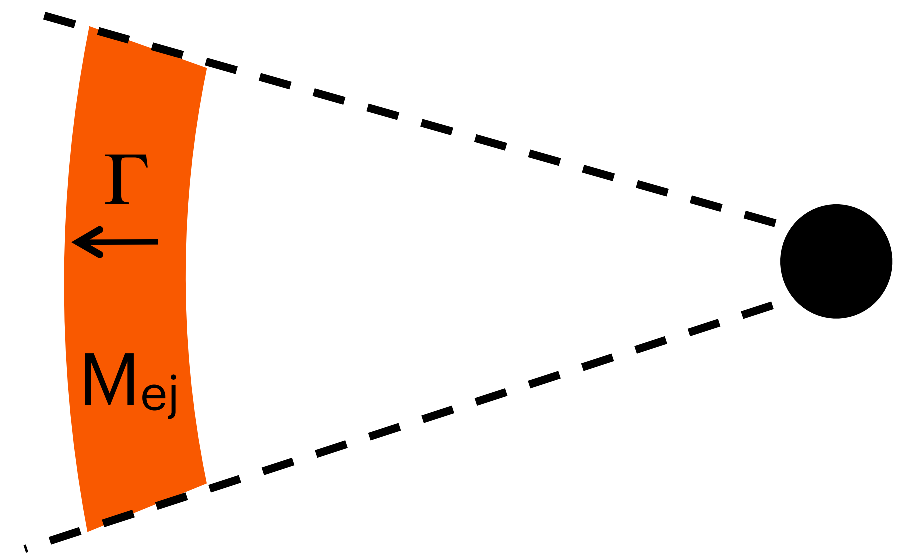
- Dynamics
  how Γ evolves as a function of distance r and time

- Relativistic collisionless shocks
  particle acceleration and B amplification

- Radiative process(es)
  how the radiative output is produced

DYNAMICS

Collision between jet of kinetic energy $E_k = \Gamma_0 M_{ej} c^2$ and the external medium with number density $n(r) = A\, r^{-s}$



At distance r, the collected mass is

$$m(r) = \int 4\pi\, r^2\, n(r)\, m_p\, dr \propto r^{3-s}$$

Conservation of energy and momentum

BEFORE COLLISION		AFTER THE COLLISION
$\Gamma_0 M_{ej}\, c^2 + m(r) c^2$	$=$	$\Gamma(r)\, [M_{ej} + m(r) + \epsilon'(r)/c^2]\, c^2$
$\Gamma_0 \beta_0 M_{ej}\, c$	$=$	$\Gamma(r)\beta(r)[M_{ej} + m(r) + \epsilon'(r)/c^2]\, c$

DYNAMICS

$$\Gamma(r) = \frac{\Gamma_0 M_{ej} + m(r)}{\sqrt{m^2(r) + 2\Gamma_0 M_{ej} m(r) + M_{ej}^2}}$$

- $m(r) < \frac{M_{ej}}{2\,\Gamma_0}$ $\quad \Gamma(r) = \Gamma_0$ $\quad$ coasting phase
- $\frac{M_{ej}}{\Gamma_0} < m(r) < M_{ej}\Gamma_0$ $\quad \Gamma(r) \simeq \sqrt{\frac{E_k}{m(r)}}$ $\quad$ deceleration phase
  see Blandford & McKee 1976
- $m(r) > M_{ej}\Gamma_0$ $\quad \Gamma(r) \to 1$ $\quad$ non-relativistic phase

DYNAMICS

A closer look to the deceleration phase

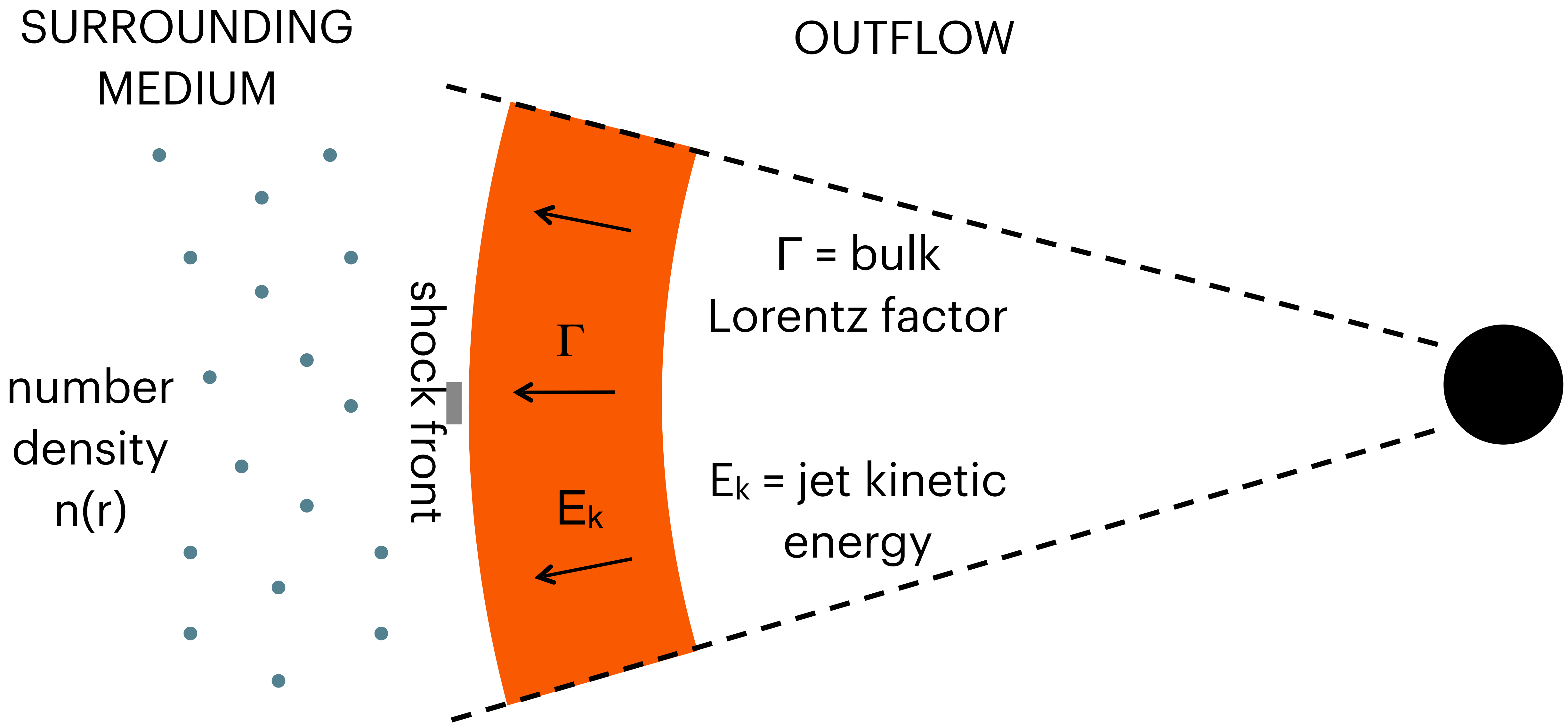
see Blandford & McKee 1976

$$\frac{M_{ej}}{\Gamma_0} < m(r) < M_{ej}\Gamma_0 \quad \rightarrow \quad \Gamma(r) \simeq \sqrt{\frac{E_k}{m(r)}} \propto r^{-\frac{(3-s)}{2}}$$

Given the relation between radius and time:

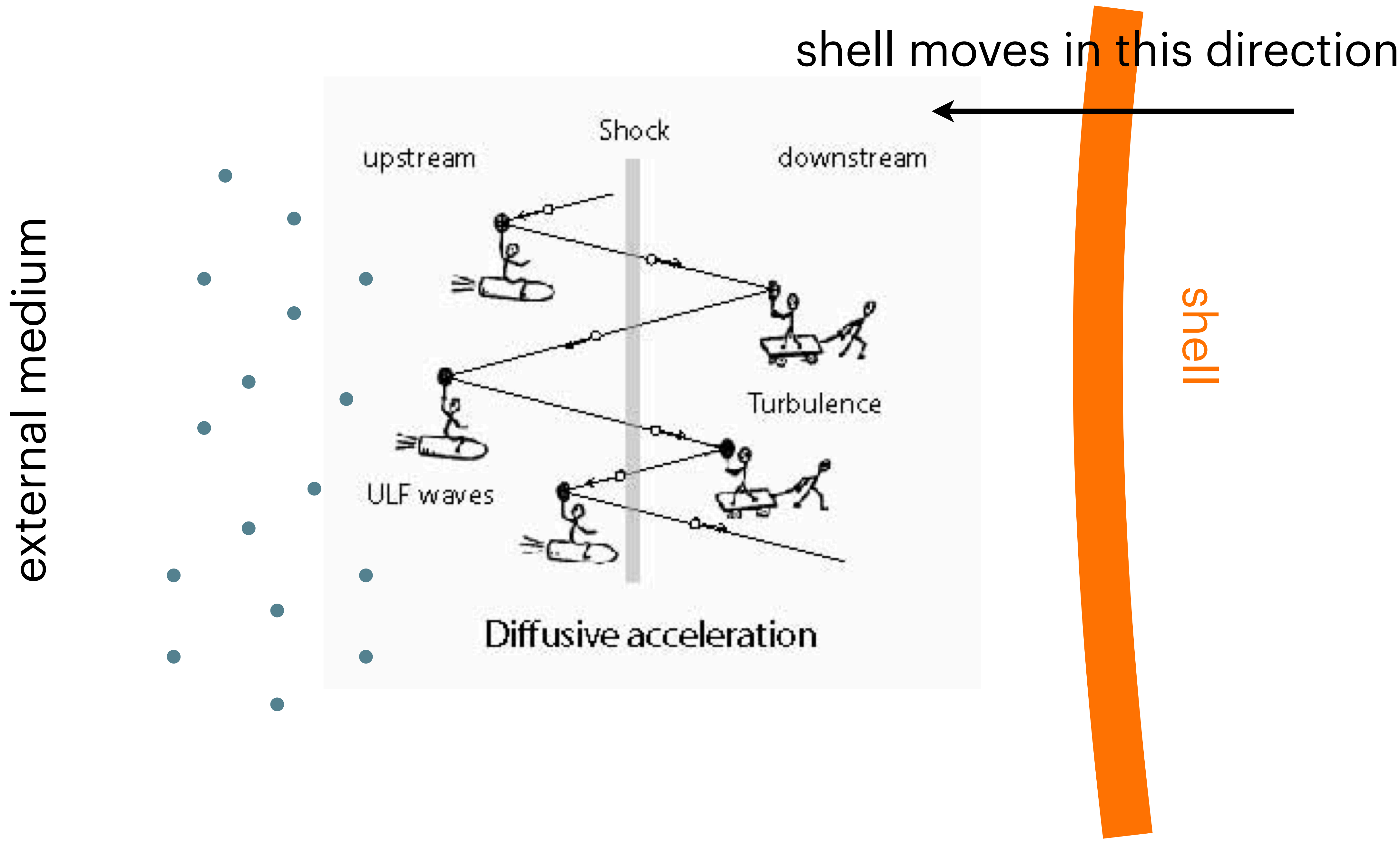
$$t_{obs} \simeq (1+z)\frac{r}{c\Gamma^2} \quad \rightarrow \quad \Gamma(t_{obs}) \propto r^{\frac{3-s}{8-2s}}$$

RELATIVISTIC SHOCKS



RELATIVISTIC SHOCKS

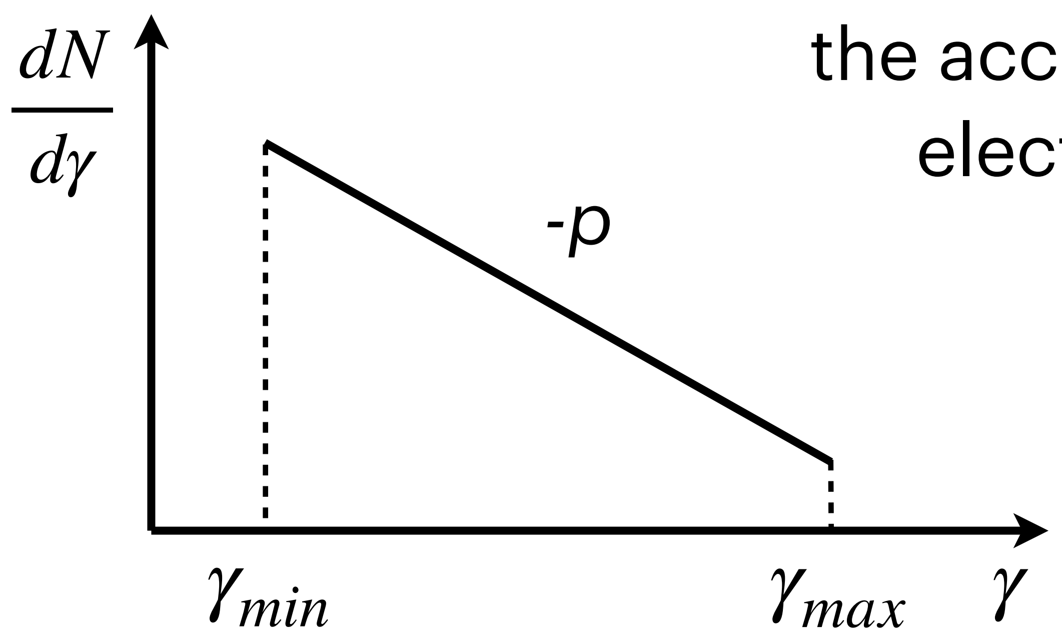
DIFFUSIVE SHOCK ACCELERATION (FERMI MECHANISM)



RELATIVISTIC SHOCKS

PARTICLE ACCELERATION

A fraction of the dissipated energy is used to accelerate particles through **collisionless** (no Coulomb collision) **shocks**. The output of this acceleration process is a power-law particle spectrum with index *p = 2.2 - 2.4*

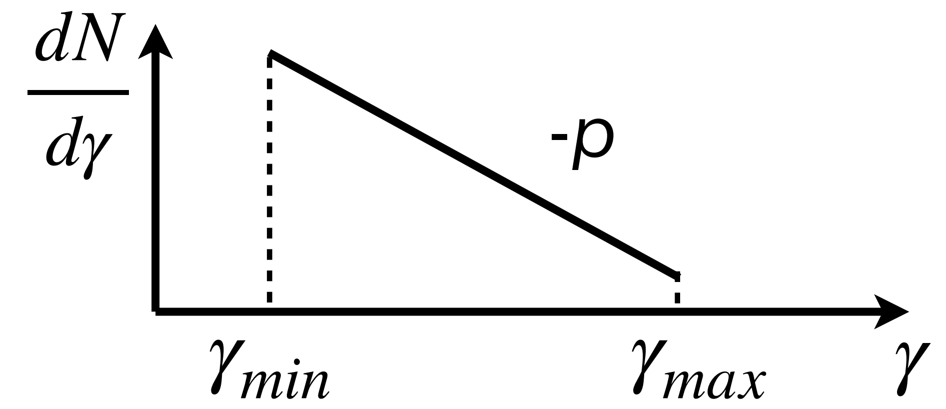


energy spectrum of the accelerated electrons

RELATIVISTIC SHOCKS

PARTICLE ACCELERATION

Derivation of the average and minimum Lorentz factor (<γ> and γ_{min}) of the electrons



- $N_e < \gamma > m_e c^2 = \epsilon_e N_p m_p c^2 (\Gamma - 1)$

$$\Rightarrow < \gamma > = \epsilon_e \frac{m_p}{m_e} (\Gamma - 1) \simeq 2 \times 10^4 \epsilon_{e,-1} \Gamma_2$$

- $< \gamma > = \dfrac{\int_{\gamma_{min}}^{\gamma_{max}} \frac{dN}{d\gamma} \gamma d\gamma}{\int_{\gamma_{min}}^{\gamma_{max}} \frac{dN}{d\gamma} d\gamma} = \dfrac{\int_{\gamma_{min}}^{\gamma_{max}} \gamma^{-p+1} d\gamma}{\int_{\gamma_{min}}^{\gamma_{max}} \gamma^{-p} d\gamma}$

for $\gamma_{max} >> \gamma_{min}$ and $p > 2$

$$\Rightarrow \quad \gamma_{min} = \epsilon_e \frac{m_p}{m_e} \frac{p-2}{p-1} (\Gamma - 1)$$

RELATIVISTIC SHOCKS

MAGNETIC FIELD AMPLIFICATION

Derivation of the magnetic field strength

- $$\epsilon_B\, n'\, m_p\, c^2\, (\Gamma - 1) = \frac{B'^2}{8\pi}$$

  $$n'_p = \frac{N_p}{V'} = \frac{N_p}{V/\Gamma} = n_p\,\Gamma$$

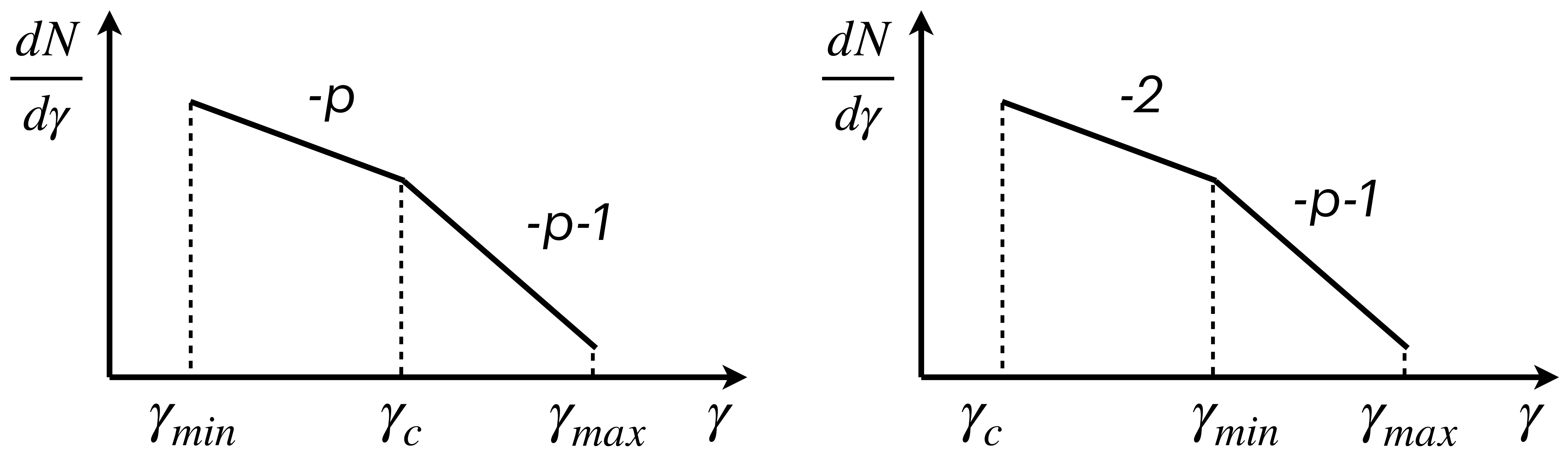
  factor 4 due to shock compression $\quad \Longrightarrow \quad n' = 4\,\Gamma\, n$

  $$\Longrightarrow \quad B' = \sqrt{32\pi\epsilon_B\, n\, m_p\, c^2}\;\Gamma$$

SYNCHROTRON EMISSION

Synchrotron cooling time $$t'_c(\gamma, B') = \frac{E(\gamma)}{P(\gamma, B')} = \frac{6\,\pi\, m_e\, c}{\sigma_T\, \gamma\, B'^2}$$

$$\gamma_c = \frac{6\,\pi\, m_e\, c}{\sigma_T\, t'\, B'^2}$$



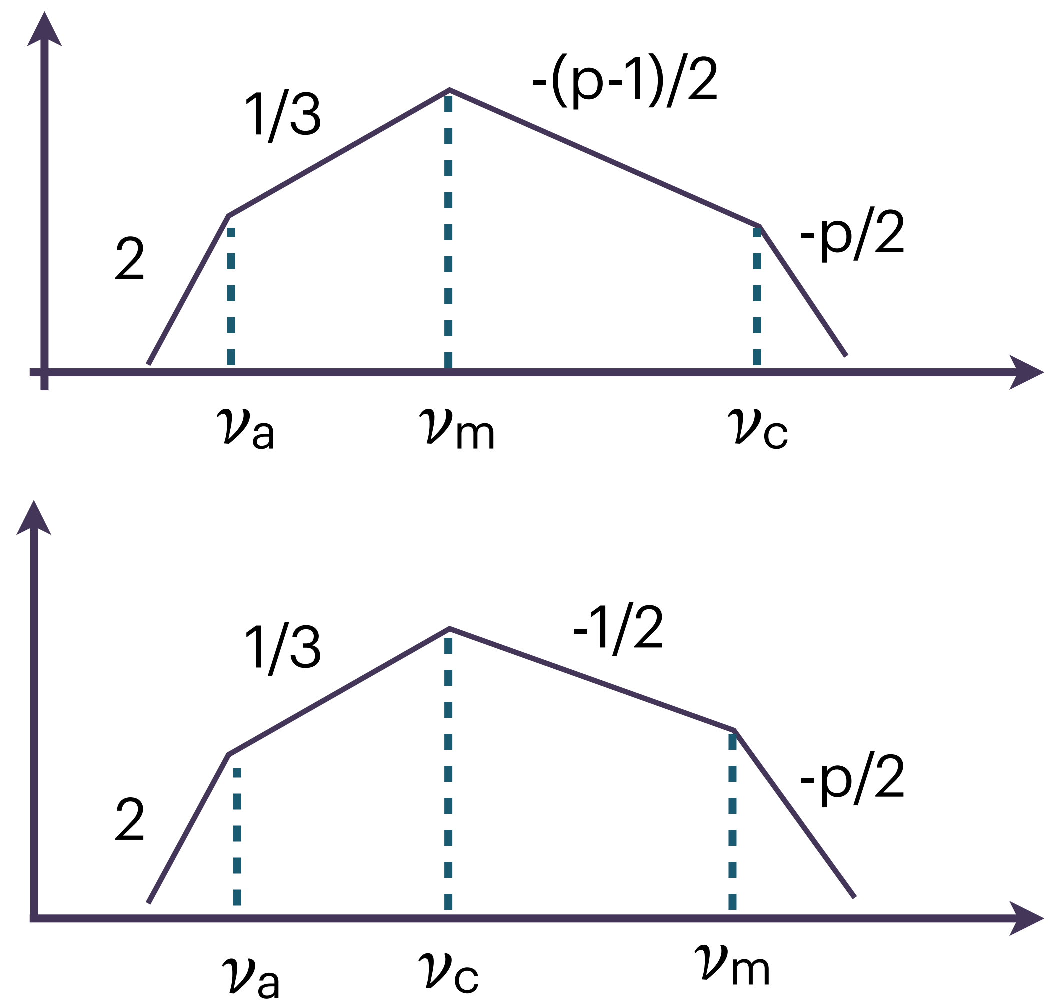
SYNCHROTRON SPECTRUM

SPECTRUM FROM A POPULATION OF ELECTRONS

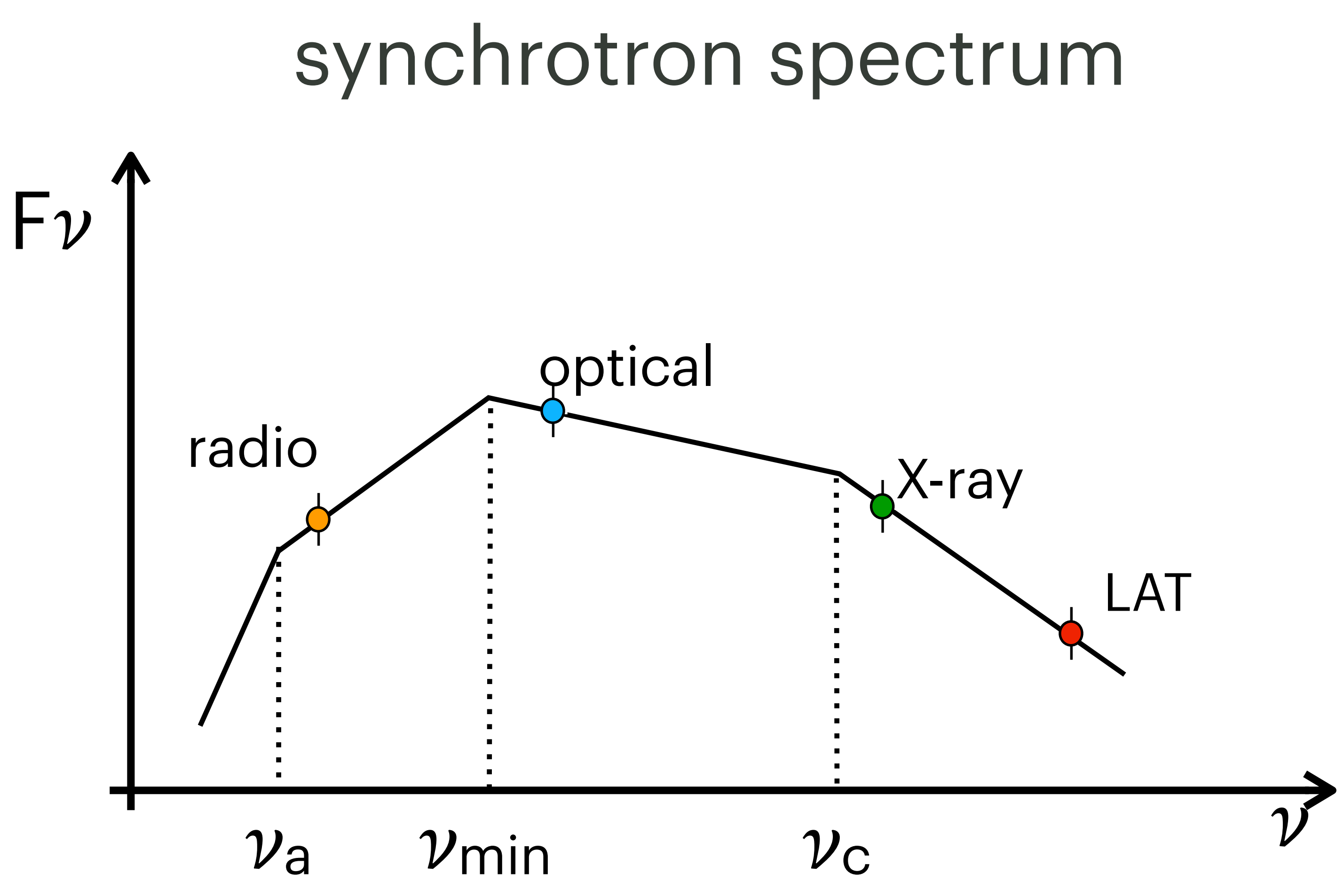
$$\nu_{syn} = \gamma^2 \frac{q_e B}{2\pi m_e c} \Gamma$$

$$t < t_{\rm cool} \quad \Rightarrow \quad F(\nu) \propto \begin{cases} \nu^2 & \nu < \nu_{\rm a} \\ \nu^{1/3} & \nu_{\rm a} \le \nu < \nu_m \\ \nu^{-\frac{p-1}{2}} & \nu_m \le \nu < \nu_{\rm cool} \\ \nu^{-\frac{p}{2}} & \nu \ge \nu_{\rm cool} \end{cases}$$

$$t > t_{\rm cool} \quad \Rightarrow \quad F(\nu) \propto \begin{cases} \nu^2 & \nu < \nu_{\rm a} \\ \nu^{1/3} & \nu_{\rm a} \le \nu < \nu_{\rm cool} \\ \nu^{-\frac{1}{2}} & \nu_{\rm cool} \le \nu < \nu_m \\ \nu^{-\frac{p}{2}} & \nu \ge \nu_m \end{cases}$$

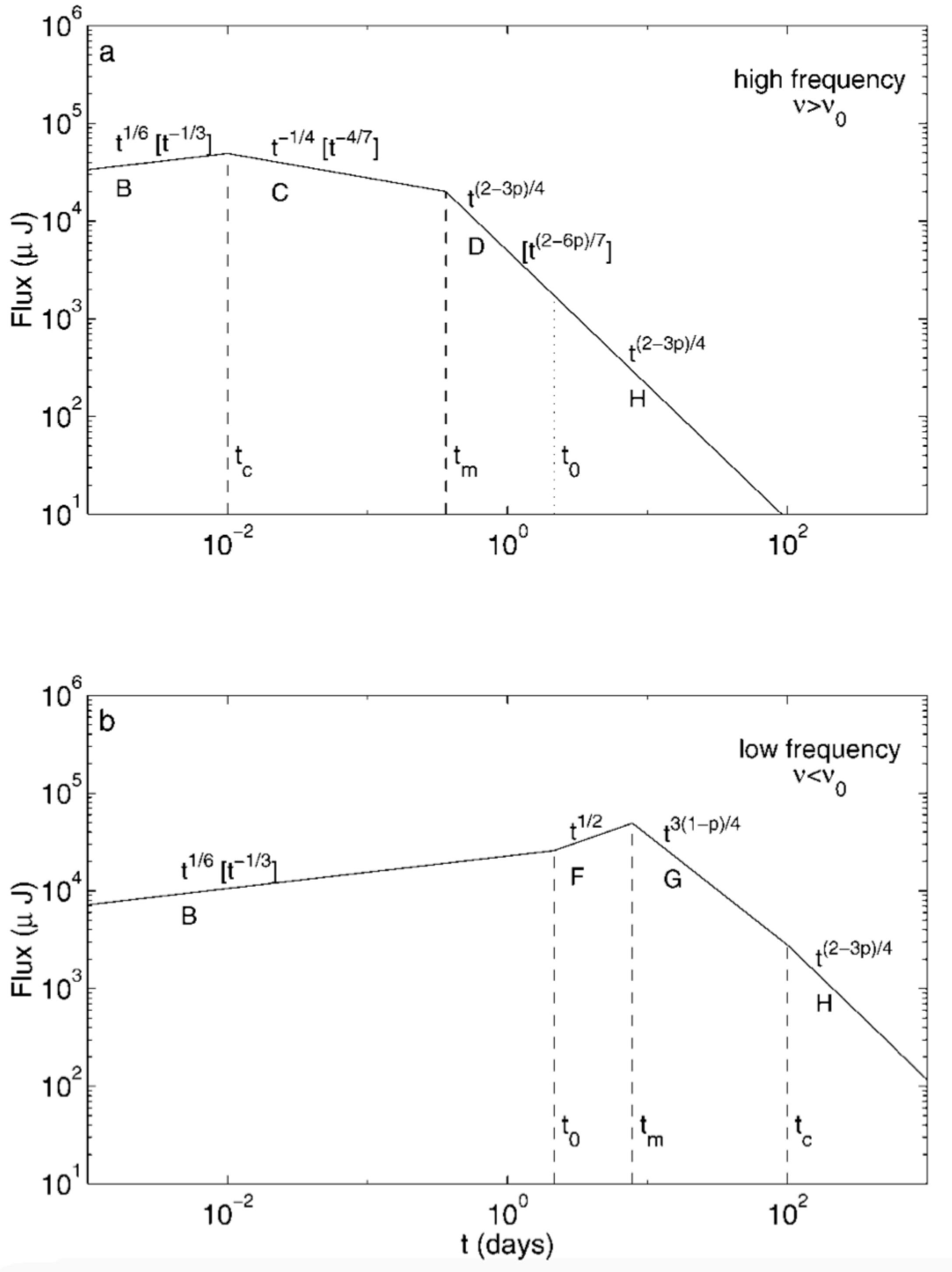


SYNCHROTRON SPECTRUM



SYNCHROTRON LIGHTCURVES

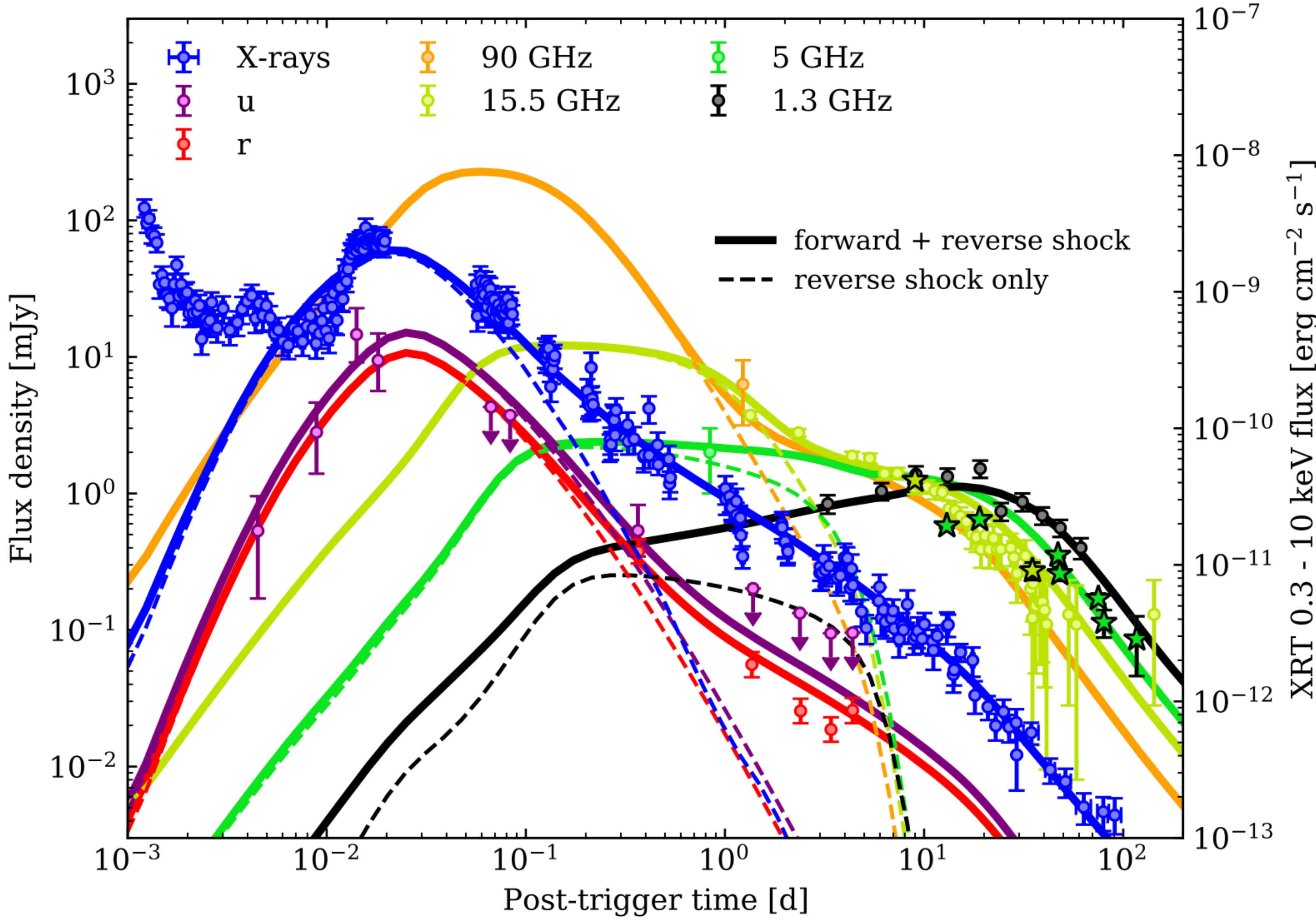
EXAMPLES OF EXPECTED AFTERGLOW LIGHTCURVES



Sari, Piran Narayan, 1998

MODELING OF AFTERGLOW LIGHTCURVES

EXAMPLE OF MODELING OF MULTI-WAVELENGTH AFTERGLOW LIGHTCURVES

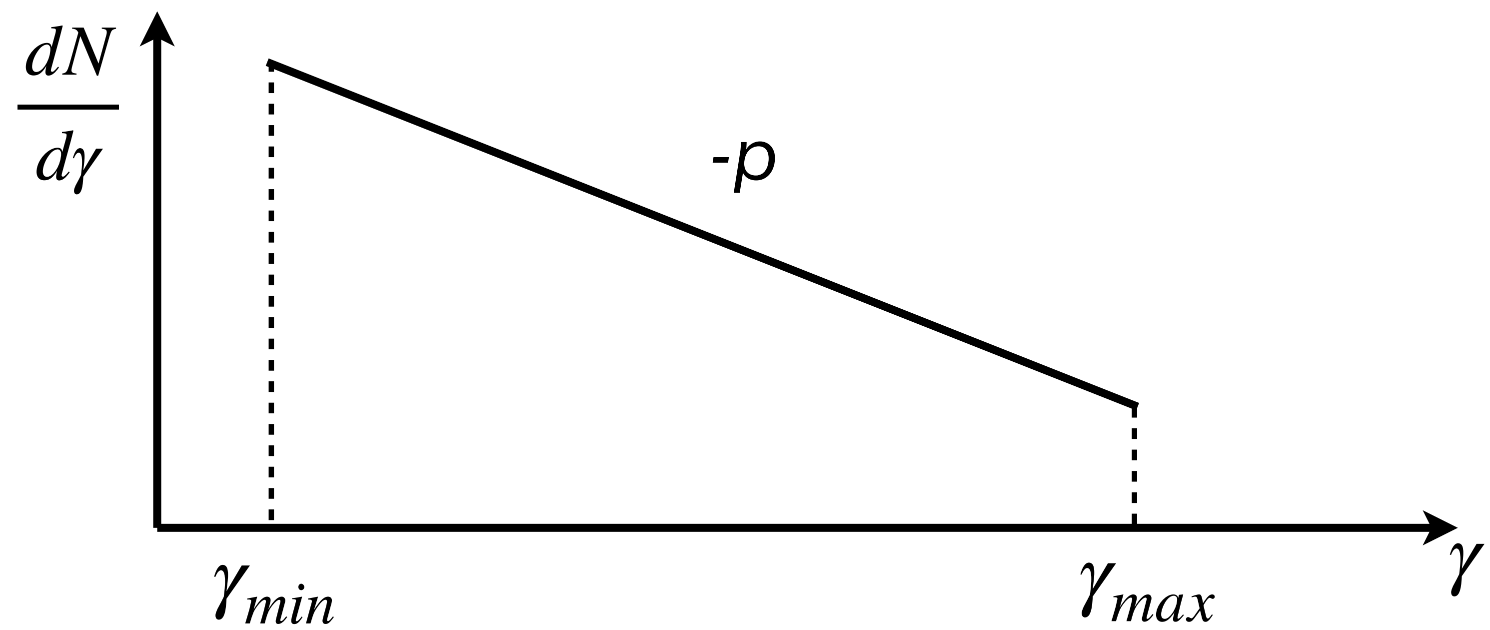


Salafia + 2022

GRBS AT GEV ENERGIES

The Maximal Synchrotron Frequency

electron spectrum after acceleration



$\Downarrow$ $\Downarrow$

$$\nu'_{min} = \gamma^2_{min} \frac{e\,B'}{2\pi\, m_e\, c} \qquad \nu'_{max} = \gamma^2_{max} \frac{e\,B'}{2\pi\, m_e\, c}$$

maximal energy of accelerated electrons implies
maximal energy of synchrotron photons

GRBS AT GEV ENERGIES

THE MAXIMAL SYNCHROTRON FREQUENCY

Maximal electron energy γ_{max} is reached when acceleration time is equal to cooling time: $t'_{acc}(\gamma) = t'_{syn}(\gamma)$

$$t'_{acc} \simeq \frac{r_L}{c} \simeq \frac{E'}{eB'c} = \frac{\gamma m_e c^2}{eB'c}$$

$$t'_{syn} = \frac{6\pi m_e c}{\sigma_T B'^2 \gamma}$$

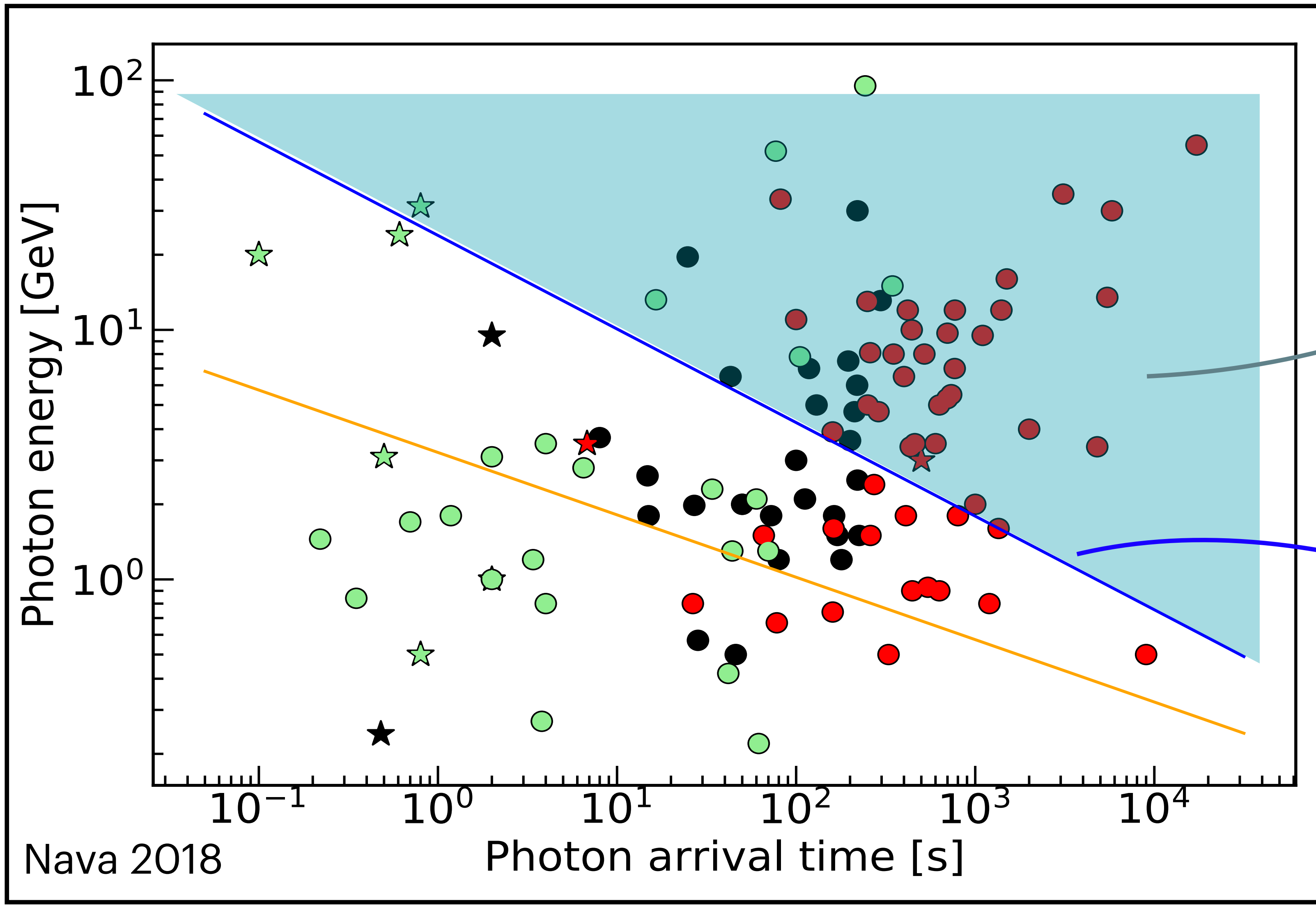
$$\Rightarrow \quad \gamma_{max}^2 = \frac{6\pi e}{\sigma_T B'}$$

$$\boxed{E_{max} = h\nu_{max} = h\nu'_{max} 2\Gamma = \gamma_{max}^2 \frac{eB'h}{2\pi m_e c} 2\Gamma = \frac{9 m_e c^2 h}{4\pi e^2}\Gamma \simeq 150\, MeV \times \Gamma}$$

GRBS AT GEV ENERGIES

PROBLEM WITH THE INTERPRETATION

Many photons detected from GRBs have energies exceeding the maximal synchrotron energy



all these photons can not have synchrotron origin! ...inverse Compton?

synchrotron limit: maximum energy for photons produced by synchrotron radiation

GRBS AT TEV ENERGIES???

PRESENCE OF SYNCHROTRON SELF COMPTON?