JC @ IAP

25/3/2021

Gill, Granot & Beniamini: GRB spectrum from gradual dissipation in a magnetized outflow (arXiv 2008.10729v2)

Magnetic jet: acceleration

The acceleration of a magnetic jet can proceed either by **dissipation of magnetic field** (if the magnetic field has the right geometry and scale), or by **adiabatic expansion** of the outflow.

- magnetization parameter:

$$\sigma = \frac{B^2}{4\pi(\rho' c^2 + p')\Gamma^2} = \frac{B'^2}{4\pi(\rho' c^2 + p')}$$

- conservation of energy flux:

$$R^2 \left[\pi \rho' c^2 \Gamma^2 v + B'^2 \Gamma^2 v/4\right] \theta_j(R)^2 = L$$

- conservation of mass flux:

$$\pi R^2 \theta_j(R)^2 \rho' \Gamma v = \dot{M}$$

$$\rightarrow \quad \boxed{\Gamma(1+\sigma) = L/\dot{M}c^2 = \Gamma_0(1+\sigma_0)}$$

Goldreich & Julian 1970
Granot 2011
Drenkhahn 2002

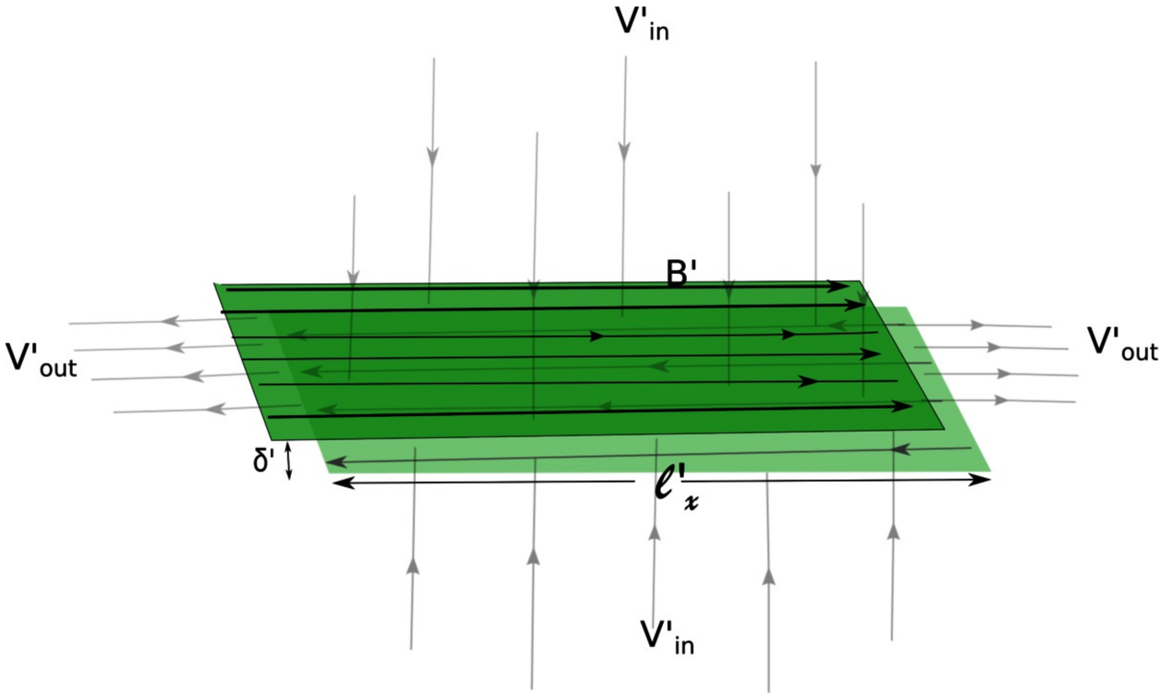
$$\Gamma \approx \sigma_0^{1/3}$$

Magnetic jet: energy dissipation

The rate of magnetic energy dissipation is governed by the reconnection rate between neighbouring regions of different field line direction.

The reconnection time scale = (variation length scale) / v_{in}
v_{in} = velocity at which field lines of different directions are brought togehter

Gill, Granot, Beniamini:
The rate of reconnection set by the inflow plasma velocity, $v_{in} = \epsilon \, v_A$
(a fraction ϵ ~ 0.1 of the Alfvén speed)



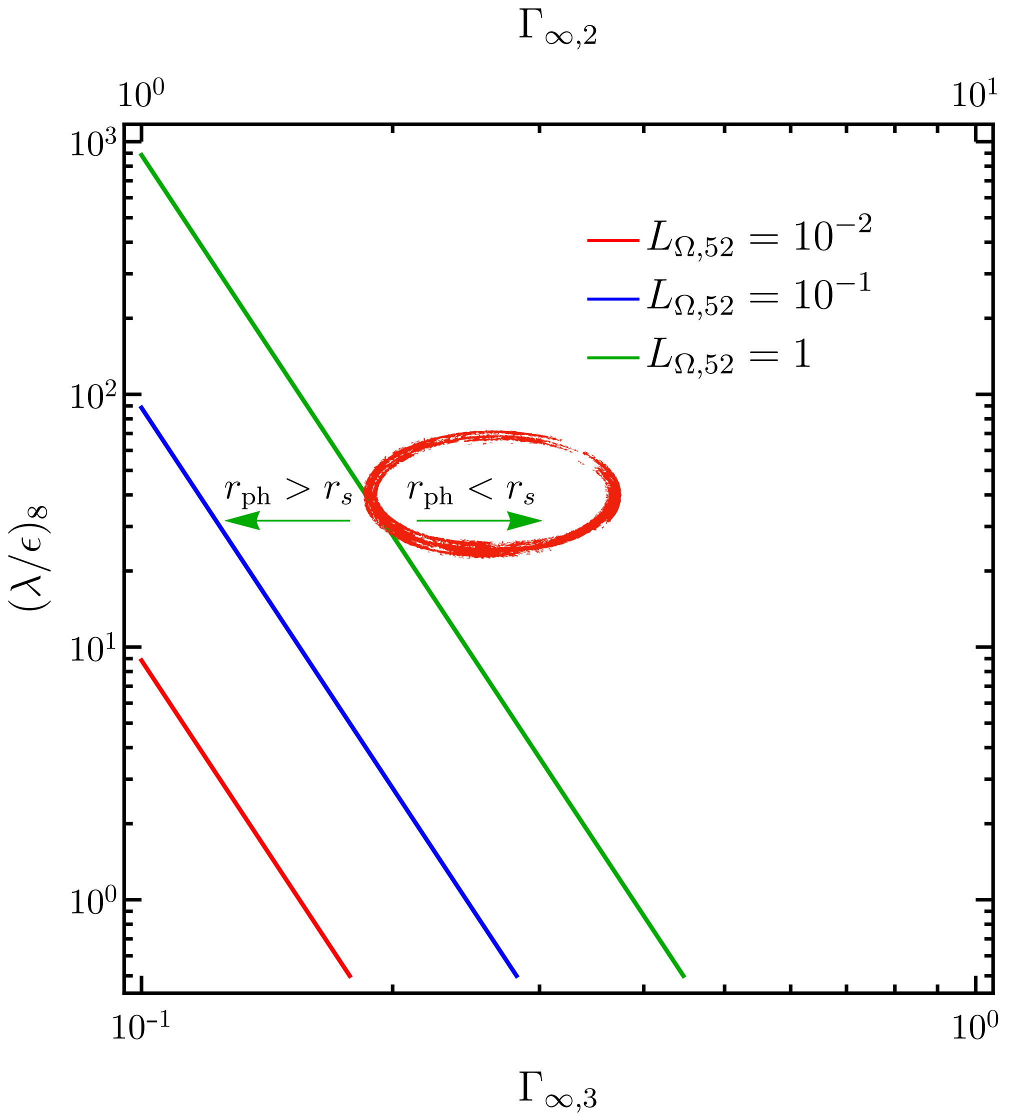
Kumar & Zhang 2015

Gill, Granot & Beniamini: GRB spectrum from gradual dissipation in a magnetized outflow

Flow dynamics

- steady Poynting flux dominated relativistic spherical flow, with a striped wind magnetic field structure
- characteristic length scale λ over which B field lines reverse polarity is set by the central engine's rotational angular frequency, $\lambda \sim \pi c/\Omega \sim 10^7$ cm

Magnetic energy is dissipated in the flow when field lines of opposite polarity are brought together and undergo reconnection.



$$\Gamma(r) = \Gamma_\infty \left(\frac{r}{r_s}\right)^{1/3}, \qquad r_A < r < r_s ,$$

$$\Gamma(r > r_s) \approx \Gamma_\infty \approx \Gamma_0\sigma_0 = \sigma_0$$

$$r_s = \frac{\Gamma_\infty^2 \lambda}{6\epsilon} = 1.7 \times 10^{13} \Gamma_{\infty,3}^2 \left(\frac{\lambda}{\epsilon}\right)_8 \text{ cm}$$

⇒ further dissipation can still occur due to internal shocks which become efficient when $\sigma < 1$

$$L_\Omega = L_{B,\Omega} + L_{k,\Omega} + L_{\gamma,\Omega}$$

Gill, Granot & Beniamini: GRB spectrum from gradual dissipation in a magnetized outflow

Energy dissipation and particle acceleration

- energy is dissipated gradually in the flow as magnetic field lines of opposite polarity come into contact and undergo magnetic reconnection

The rate of energy dissipation:

$$\frac{dL_{\mathrm{diss},\Omega}}{dr} = -\frac{dL_{B,\Omega}}{dr} = -\frac{d}{dr}\left[L_\Omega\left(1-\frac{\Gamma}{\Gamma_\infty}\right)\right] = \frac{1}{3}\frac{L_\Omega}{\Gamma_\infty}\frac{\Gamma}{r} \propto r^{-2/3}$$

$$L_{\mathrm{diss},\Omega}(<r) \propto r^{1/3} \text{ at } r_0 < r < r_s$$

Half of the dissipated energy goes directly into the flow's kinetic energy, while the other half goes towards particle acceleration. It is divided between electrons (ϵ_e $E_{\mathrm{diss}}/2$) and protons (($1 - \epsilon_e$) $E_{\mathrm{diss}}/2$), where most of the latter energy is also typically quickly converted into kinetic energy. Acceleration of electrons (Beniamini & Giannios 2017):

$$dn' \propto \gamma_e^{-p} d\gamma_e \qquad p = 4\sigma^{-0.3}$$

+ only a fraction $\zeta < 1$ of electrons is accelerated during magnetic reconnection, and the remaining fraction (1- ζ) forms a thermal distribution

Gill, Granot & Beniamini: GRB spectrum from gradual dissipation in a magnetized outflow

Numerical treatment

- one-zone kinetic code (Gill & Thompson 2014), lacking spatial and angular information of the flow and the radiation field. **The emission is approximated to arise from a blob of comoving causal size r/Γ, that is radially localized**

- Compton scattering, cyclo-synchrtoron emission and self-absorption, pair production and annihilation, Coulomb interaction among the pairs

- magnetic energy dissipation commences when the flow is highly optically thick τ =100. Wien-like spectrum:

$$\frac{dn'_\gamma}{d\ln E'} = \frac{U'_0}{6(k_B T_{\rm th})^4} E'^3 \exp\left(-\frac{E'}{k_B T'_{\rm th}}\right)$$

- power law electrons emit **synchrotron radiation** with characteristic energies (p = 4 when σ =1 at r = r_s):

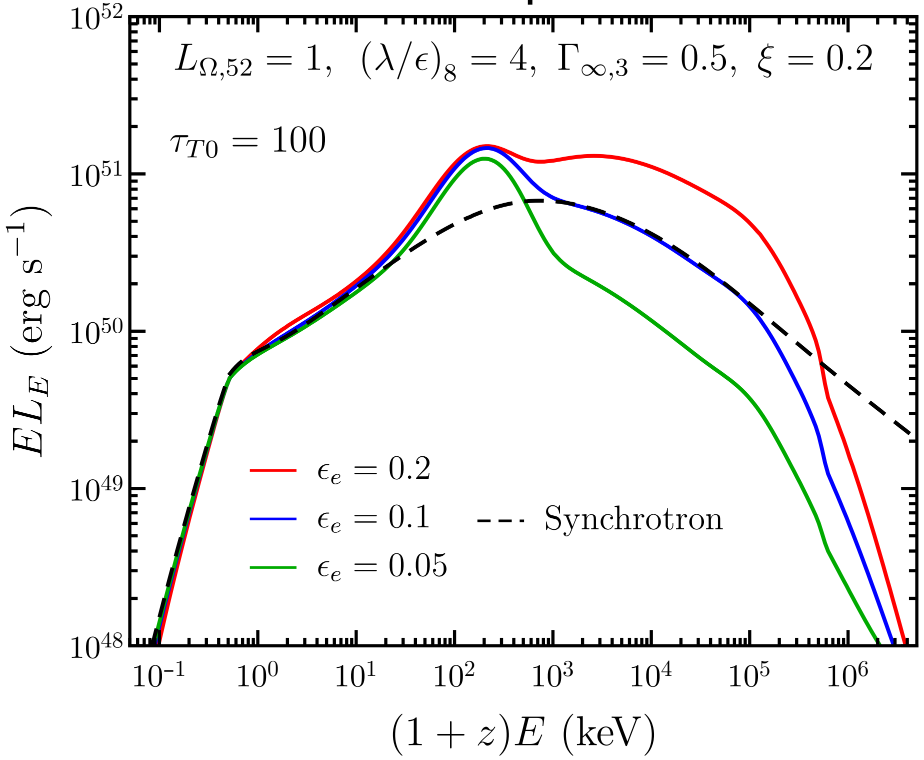
$$E_m = \frac{\Gamma}{1+z} h\nu'_m = \frac{\Gamma}{1+z}\gamma_m^2\left(\frac{\hbar e B'}{m_e c}\right) \approx \frac{530}{1+z}\left(\frac{\epsilon_e}{\xi}\right)^2 \frac{L_{\Omega,52}^{1/2}}{\Gamma_{\infty,3}^2\left(\frac{\lambda}{\epsilon}\right)_8} \,\mathrm{keV} \quad (p=4)$$

$$E_c = \frac{36\pi^2}{1+z}\frac{\hbar e m_e c^3}{\sigma_T^2}\frac{\Gamma^3}{B'^3 r^2} \approx \frac{2.6\times 10^{-9}}{1+z}\frac{\Gamma_{\infty,3}^2 r_{12}^3}{L_{\Omega,52}^{3/2}\left(\frac{\lambda}{\epsilon}\right)_8^2} \,\mathrm{keV}$$

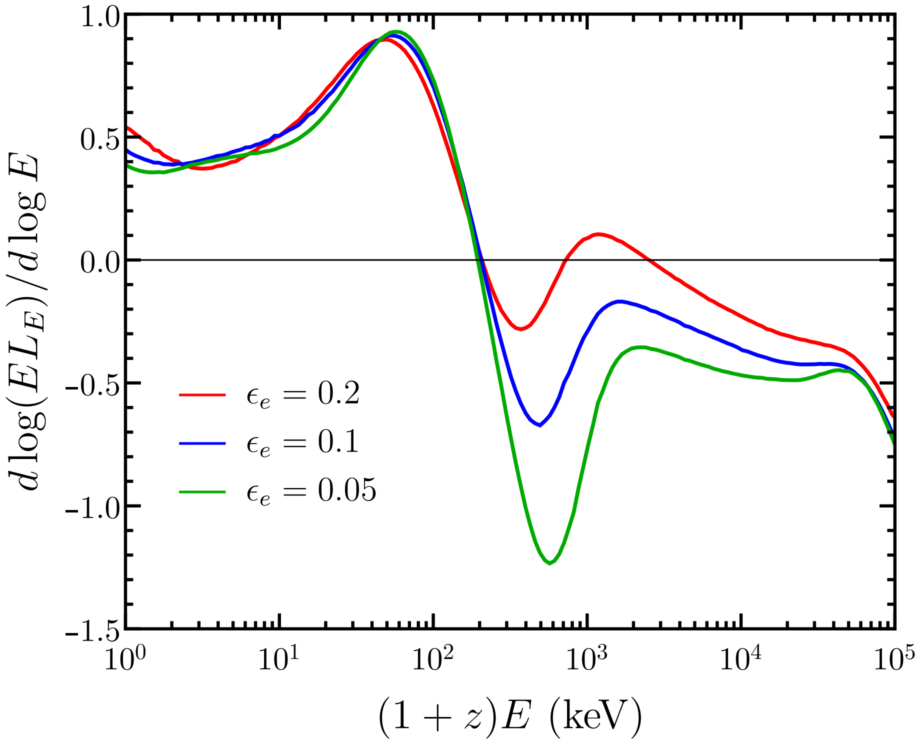
$$E_{\rm sa} \sim \frac{\Gamma}{1+z}\left(\frac{h^3}{8\pi m_p}\frac{\xi L_\Omega}{\Gamma_\infty}\frac{1}{r^2\Gamma}\right)^{1/3} \approx \frac{1.4}{1+z}\frac{\xi^{1/3} L_{\Omega,52}^{1/3}}{\Gamma_{\infty,3}^{1/9}\left(\frac{\lambda}{\epsilon}\right)_8^{2/9} r_{12}^{4/9}} \,\mathrm{keV}$$

Gill, Granot & Beniamini: GRB spectrum from gradual dissipation in a magnetized outflow

rest frame spectrum



spectral slopes



- - - - - - - power-law electrons (without $\gamma\gamma$ annihilation)

- photon index:

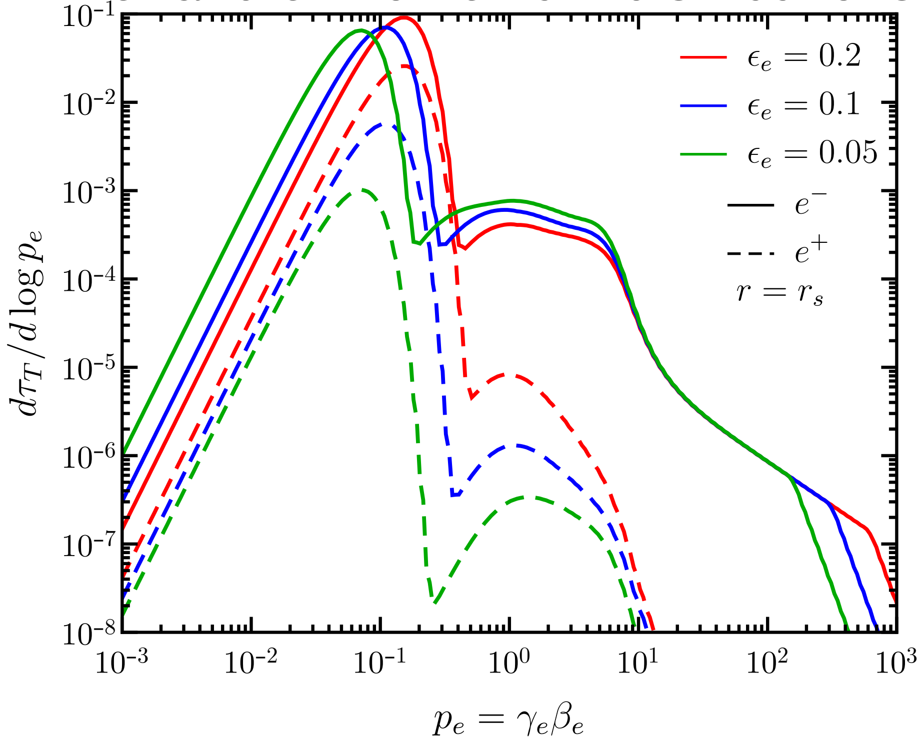
$$\alpha = -2 + d\log(EL_E)/d\log E$$

- $\zeta = 0.2$

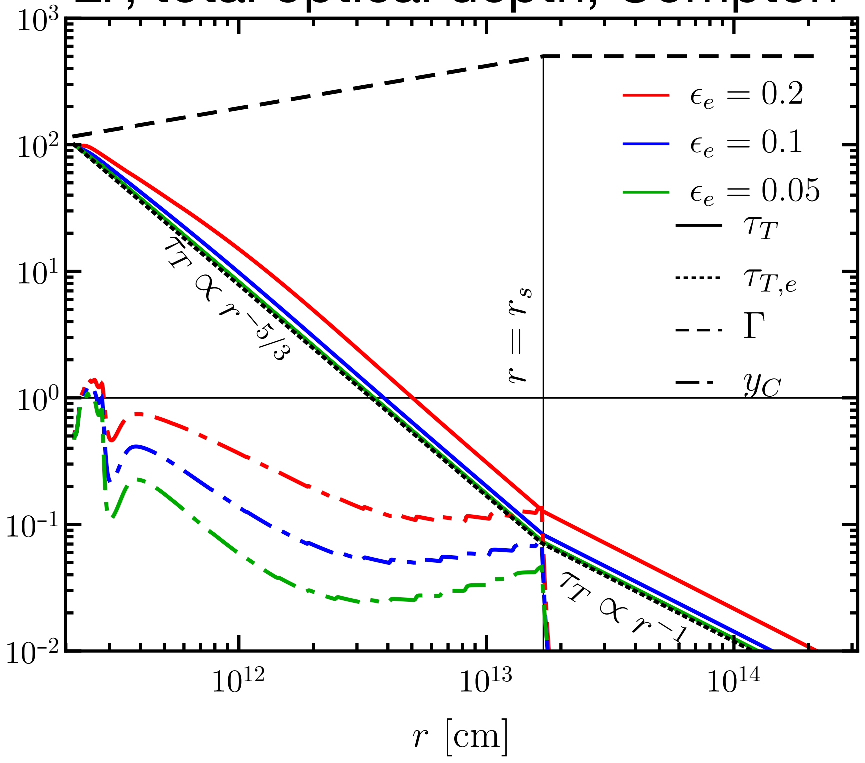
- for all cases, Compton-y remains smaller than unity:

$$y_C = (4/3)(\langle\gamma_e^2\rangle - 1)\tau_T$$

e$^+$ and e$^-$ momentum distributions



LF, total optical depth, Compton Y



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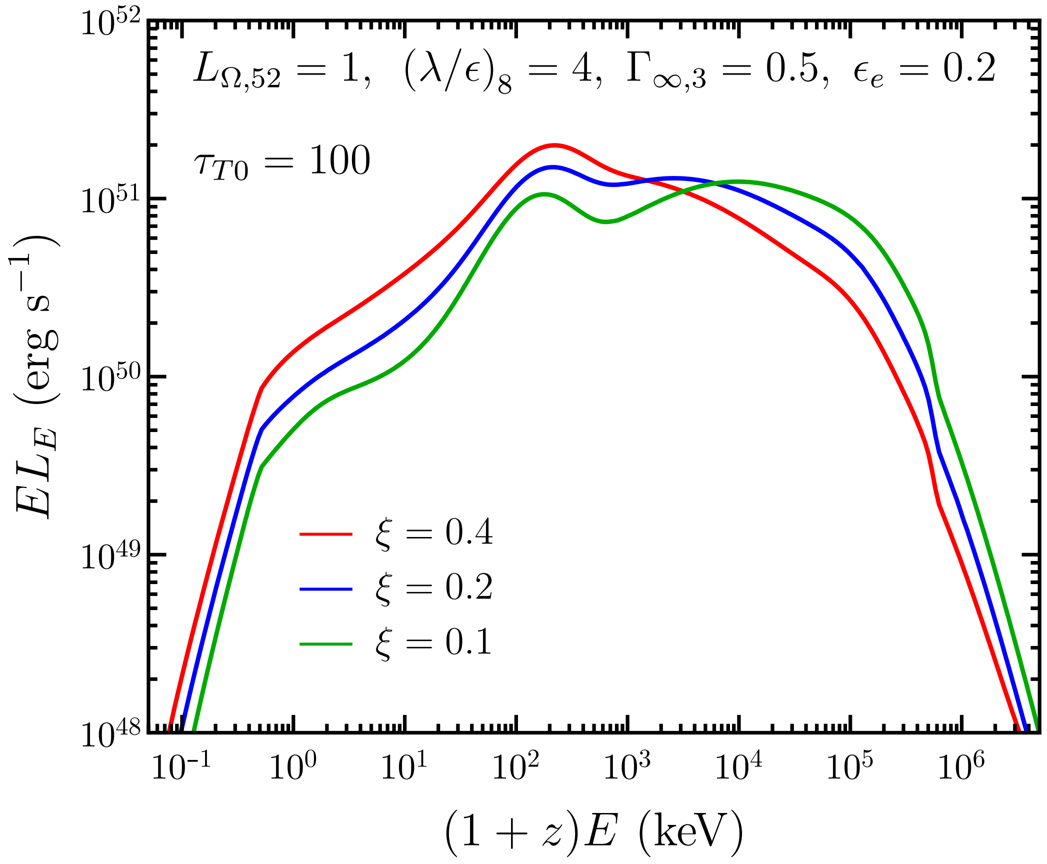
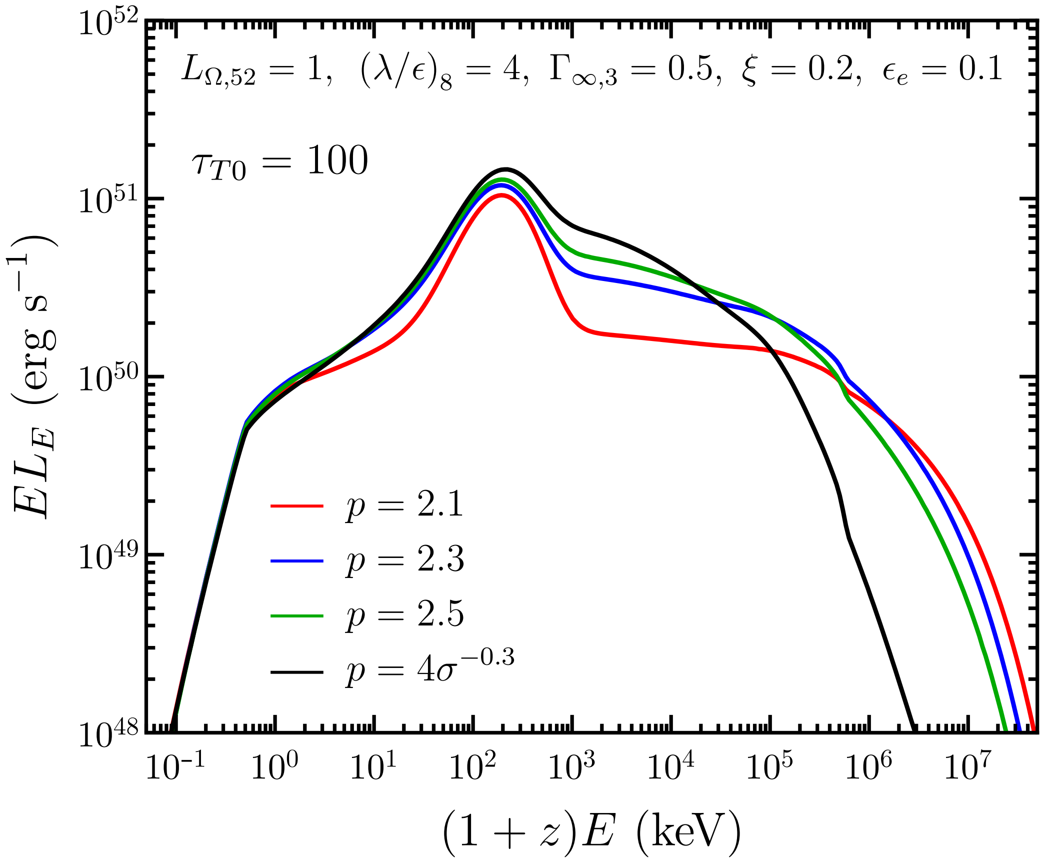


observed steady-state spectrum for different ζ



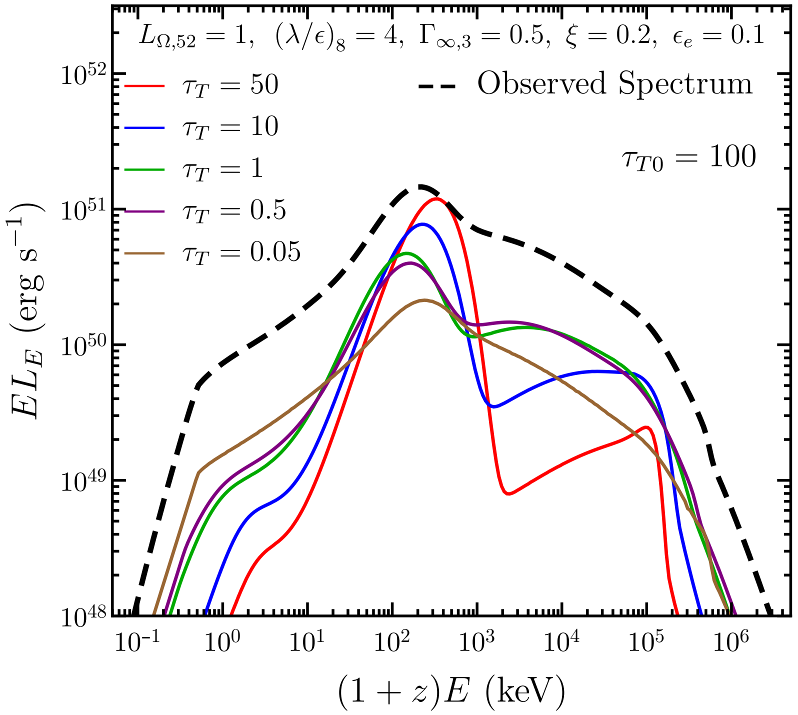
observed steady-state spectrum for different p

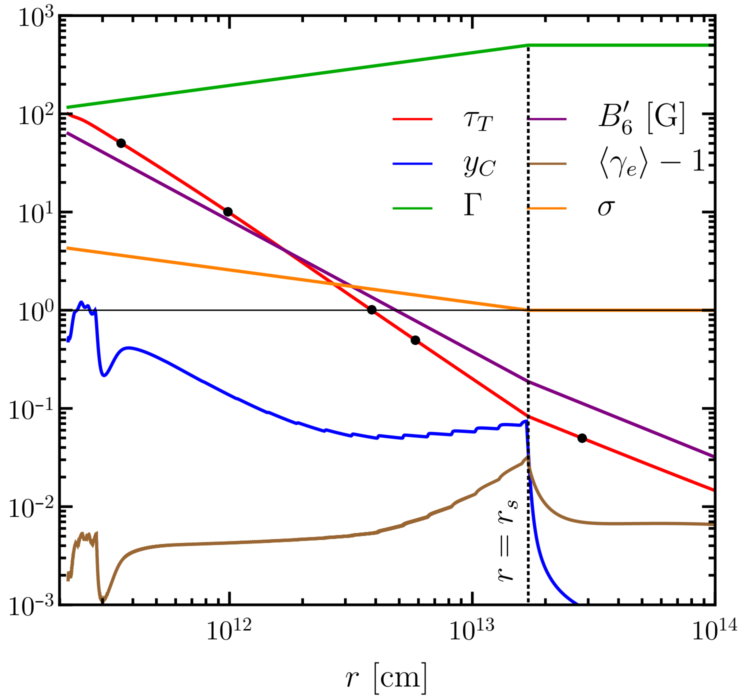
$E > E_m$ $L_E \propto E^{-p/2}$

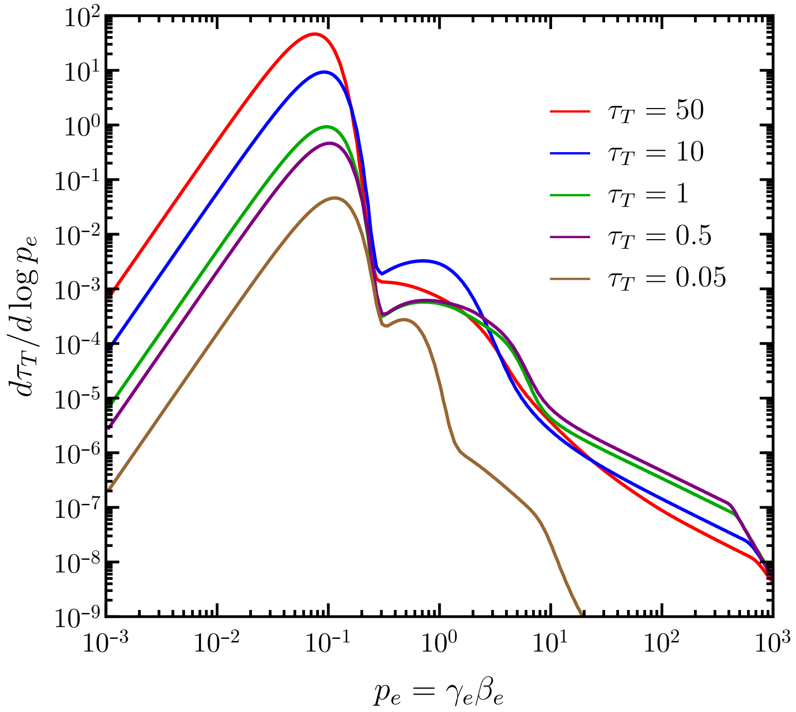
Note: Sironi & Spitkovsky 2014 find that p ≳ 1.5 for $\sigma \lesssim 50$, which means that the synchrotron spectrum can become even harder than shown in the figure if σ is larger in the emission region

Gill, Granot & Beniamini: GRB spectrum from gradual dissipation in a magnetized outflow

- radial evolution of the spectrum, the corresponding particle distribution, and flow parameters in case $\epsilon_e = 0.1$







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- alternative heating of particles: magnetic energy dissipation in the flow, e. g. due to MHD instabilities, leads to **distributed heating of all electrons**

$$\frac{dU'_{\rm diss}}{dt'} = \frac{1}{3}\frac{L_\Omega}{\Gamma_\infty r^3} \qquad\qquad dU'_e/dt' = (\epsilon_e/2)dU'_{\rm diss}/dt'$$

- **the continuous heating and simultaneous cooling of particles drives their energy distribution to peak at a critical temperature at which point heating is balanced by cooling**

$$k_B T'_{e,\rm crit} = 138\frac{\epsilon_e \Gamma_{\infty,3}^{5/3} r_{12}^{5/3}}{L_{\Omega,52}\left(\frac{\lambda}{\epsilon}\right)_8^{2/3}}\ \mathrm{keV} \approx 132\frac{\epsilon_e}{\tau_{T,e}}\ \mathrm{keV}$$

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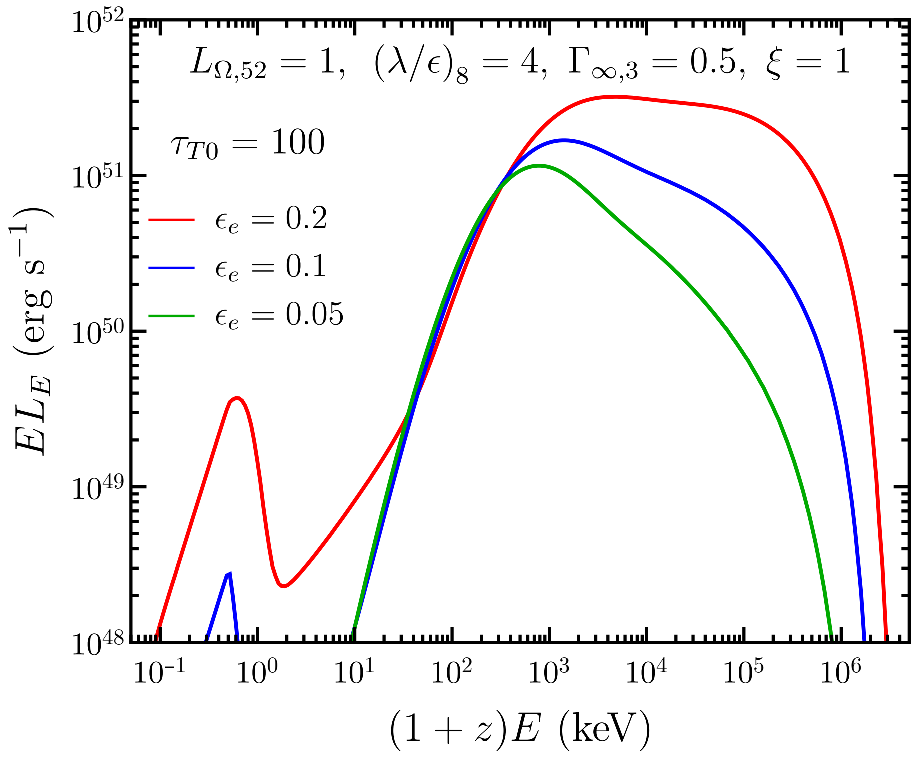
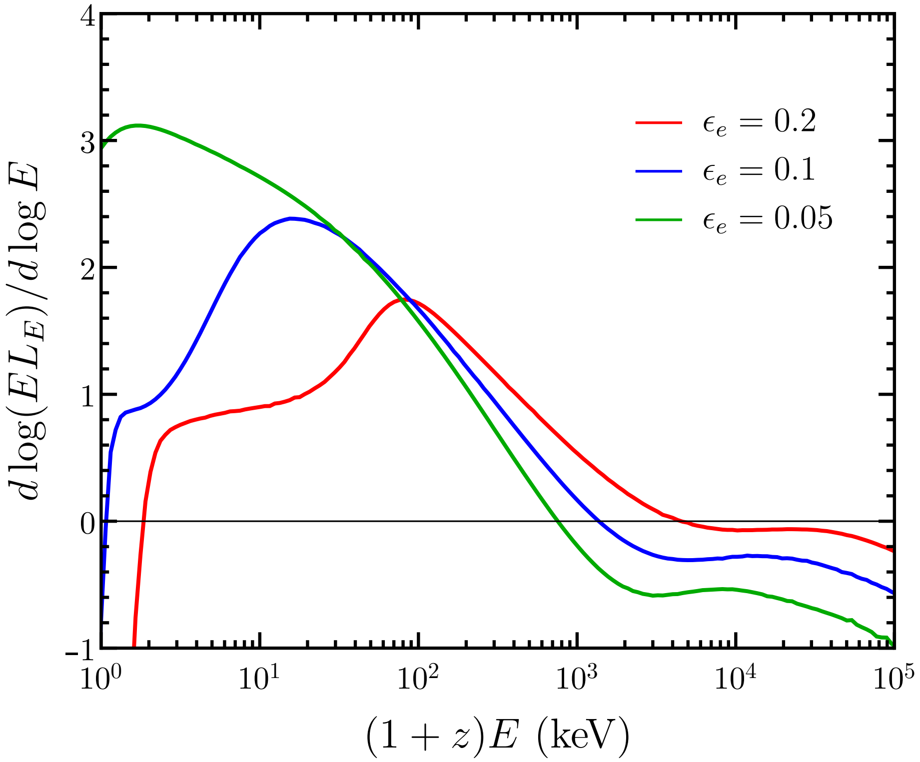
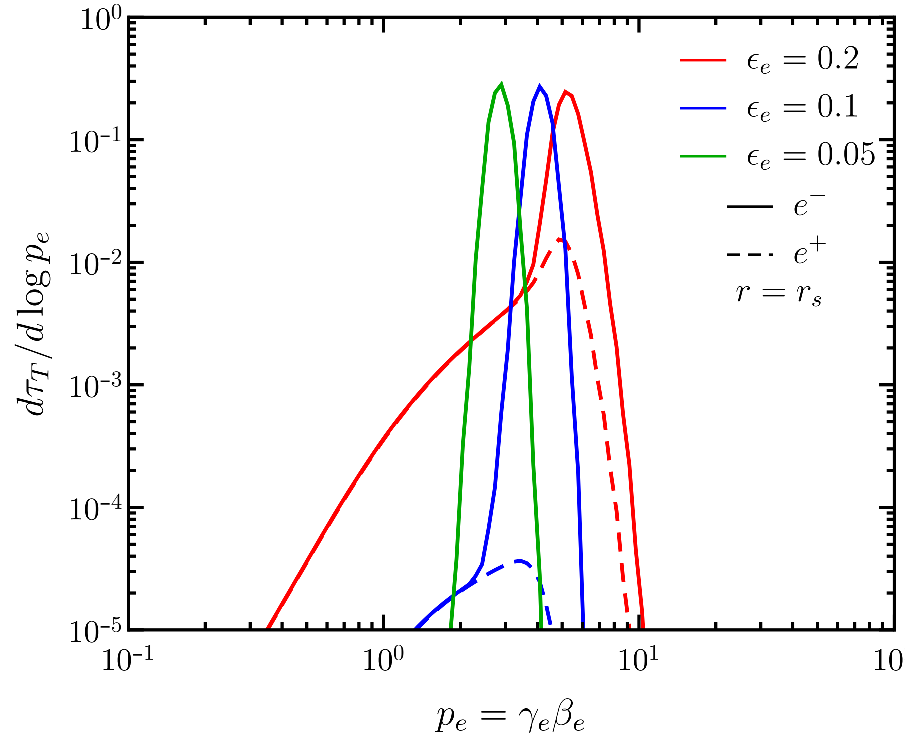
observed steady-state spectrum



spectral slopes



e⁺ and e⁻ momentum distributions



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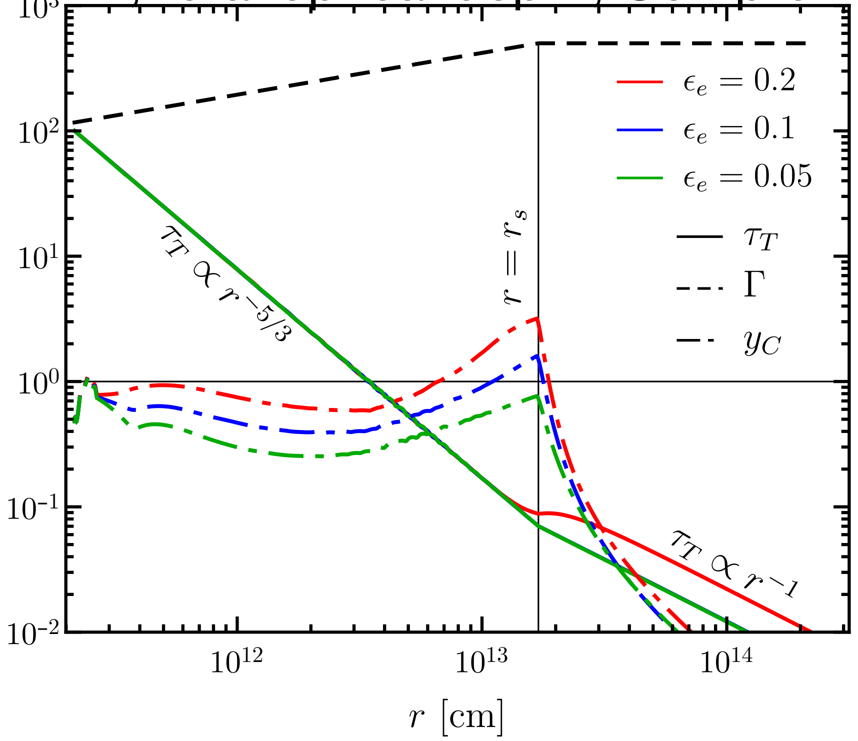

Gill, Granot & Beniamini: GRB spectrum from gradual dissipation in a magnetized outflow

- the two particle heating scenarios lead to different spectra and corresponding particle distributions

- in both cases, the spectrum exhibitis two main components: a thermal component peaking at 0.2-1 MeV and a non-thermal component extending to high energies from the thermal peak . The origin of the non-thermal component is different in the two scenarios

- when **power-law electrons are injected into the dissipation region,** the non-thermal component arises due to the fast-cooling synchrotron emission. It dominates the spectrum below the thermal peak < 50 keV, and above the thermal peak 1 MeV < E < 100 MeV. **The low energy photon index: $-1.6 < \alpha < -1.2$**

- when **the dissipated energy is distributed among all the electrons** (and the produced $e^{\pm}$ pairs are subdominant), the non-thermal spectrum above the thermal peak arises due to Comptonization of the softer thermal peak photons. This also leads to softening of the spectrum below the thermal peak as Compton-Y parameter grows above unity when the flow becomes optically thin. **The low energy photon index $\alpha > -1$**