Full lepto-hadronic treatment of GRBs in the internal shock scenario and application to Fermi-LAT detected events

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Gamma-Ray Bursts

Examples of observed light curves

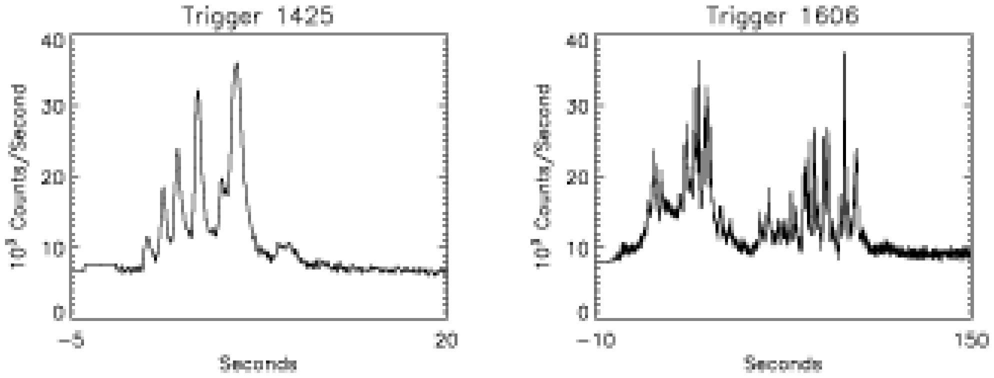


Image credit: J.T. Bonnell (NASA/GSFC)

Observational properties of GRBs

- Energetic outbursts of gamma-rays

  $E_{iso} \sim 10^{49} - 10^{55}$ erg

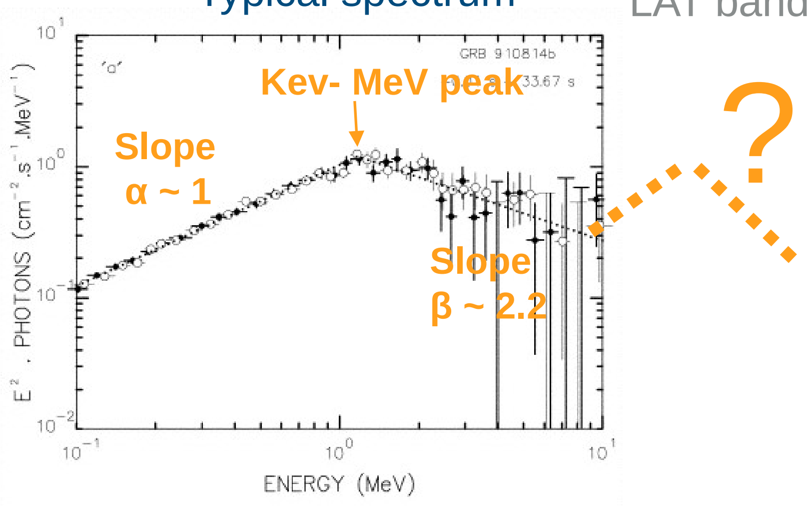
- Large variety of **light curves with fast time variability**
- **Similar spectra** (Band function)
- **Sample of Fermi-LAT detected bursts:**

  - populate higher end of E_{iso} distribution

  - additional SED component?

  -> signature of baryon-loaded jet or low magnetic fields?

Typical spectrum



Barat et al 2000, ApJ 538 : 152-164,

GRB internal shock model

Alternative scenarios: **Photospheric, magnetic reconnection**

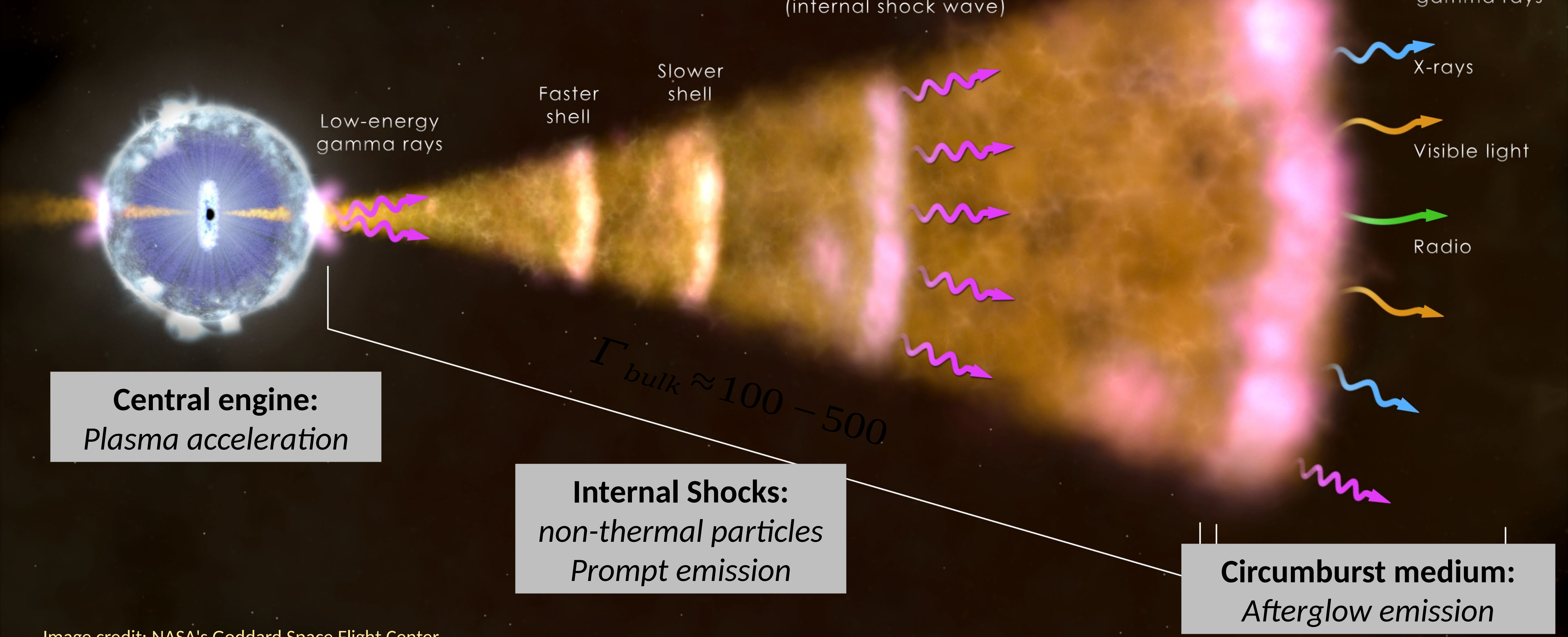
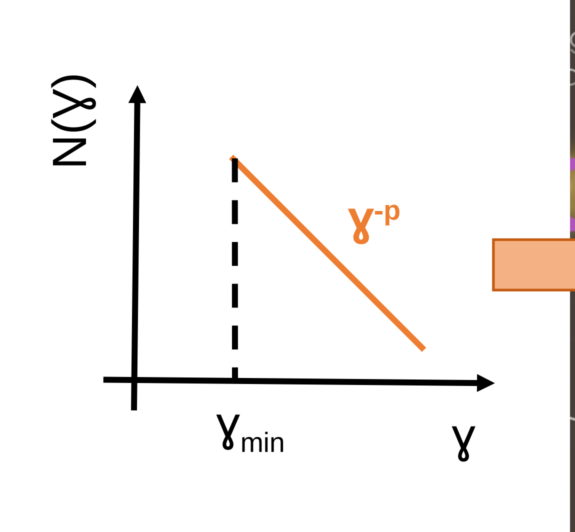
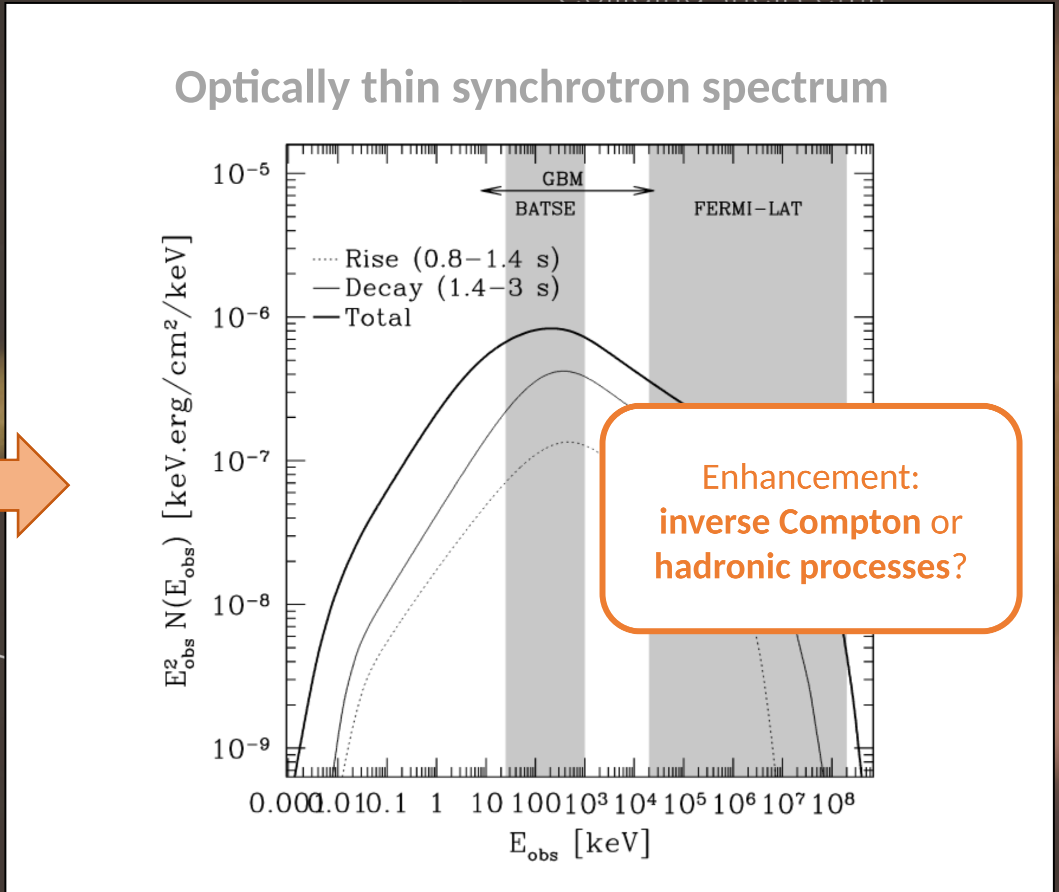


Image credit: NASA's Goddard Space Flight Center

GRB internal shock model

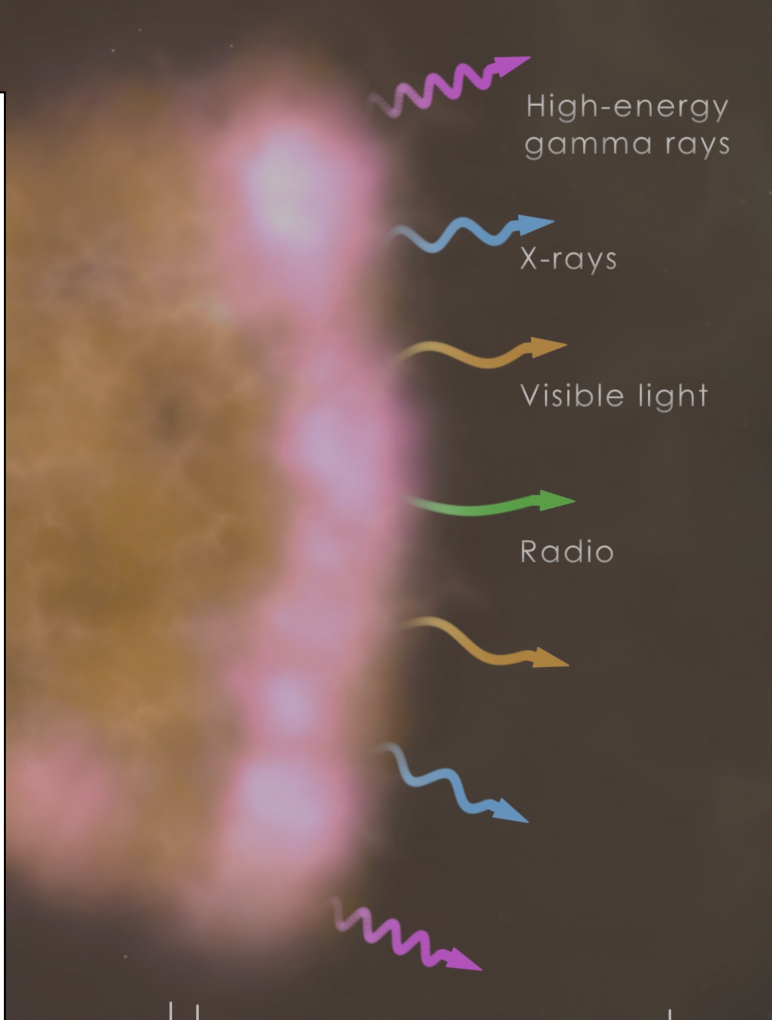


Plasma acceleration



Bosnjak et al, A&A 498 (2009)

Prompt emission



Circumburst medium:
Afterglow emission

Image credit: NASA's Goddard Space Flight Center

Model and Methods

1. Fireball evolution

Internal shock model (Daigne & Mochkovitch, MNRAS 296 (1998))

⟶ Evolution of plasma properties as a function of radius (resolved in 1000 collisions)

2. Single-collision radiation modeling

Power-law distribution of particles $n(\gamma) = n_0 \gamma^{-p}$ above γ_{min} γ_{max} by balancing losses and acceleration
Time-dependent radiation modeling with AM3 (Gao et al, ApJ 843 (2017)), accounting for all leptonic & hadronic processes and full treatment of secondary particles

⟶ Emitted spectrum for each single collision

3. Calculation of observed quantities

Sum over contributions of all single collisions + curvature of the emitting surface (Granot et al, ApJ 513 (1999))

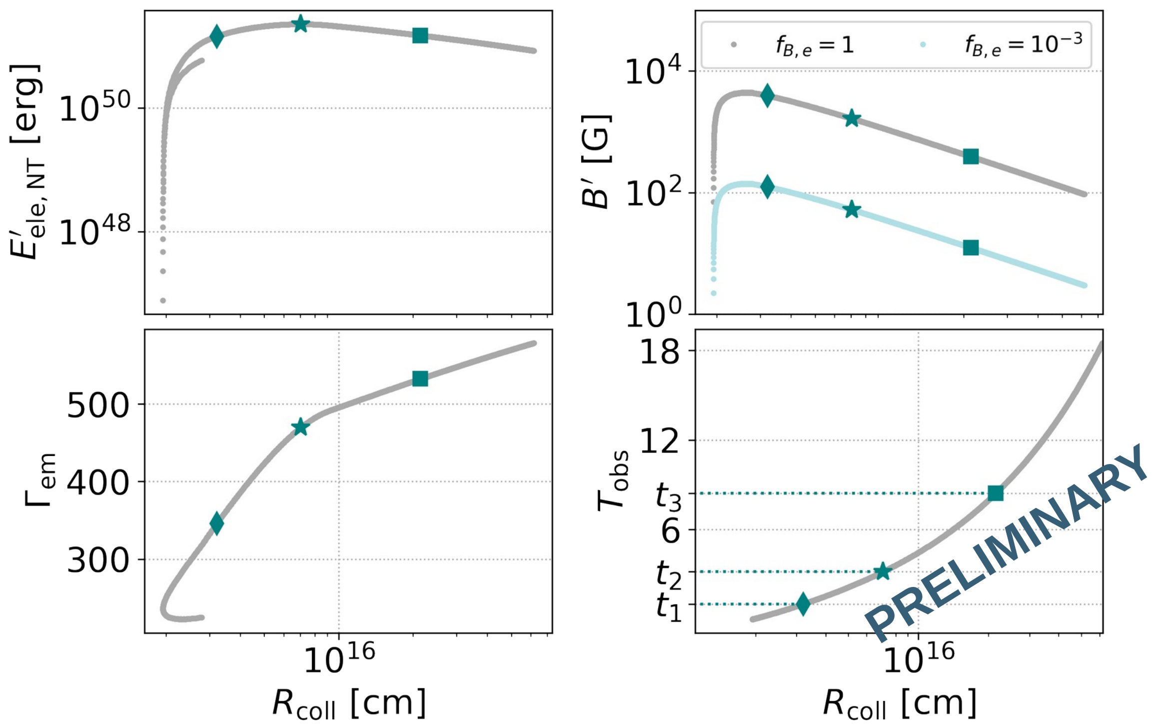
⟶ Observed SED, light curves

Introducing an educative example

Burst characteristics

- Redshift z = 2
- T_{90} = 15 s
- $E_{iso} = 10^{54}$ erg
- $E_{peak,obs}$ = 400 keV
- high-energy slope β = –2.25
- Simple, single-peaked smooth light curve

Fireball evolution of plasma parameters

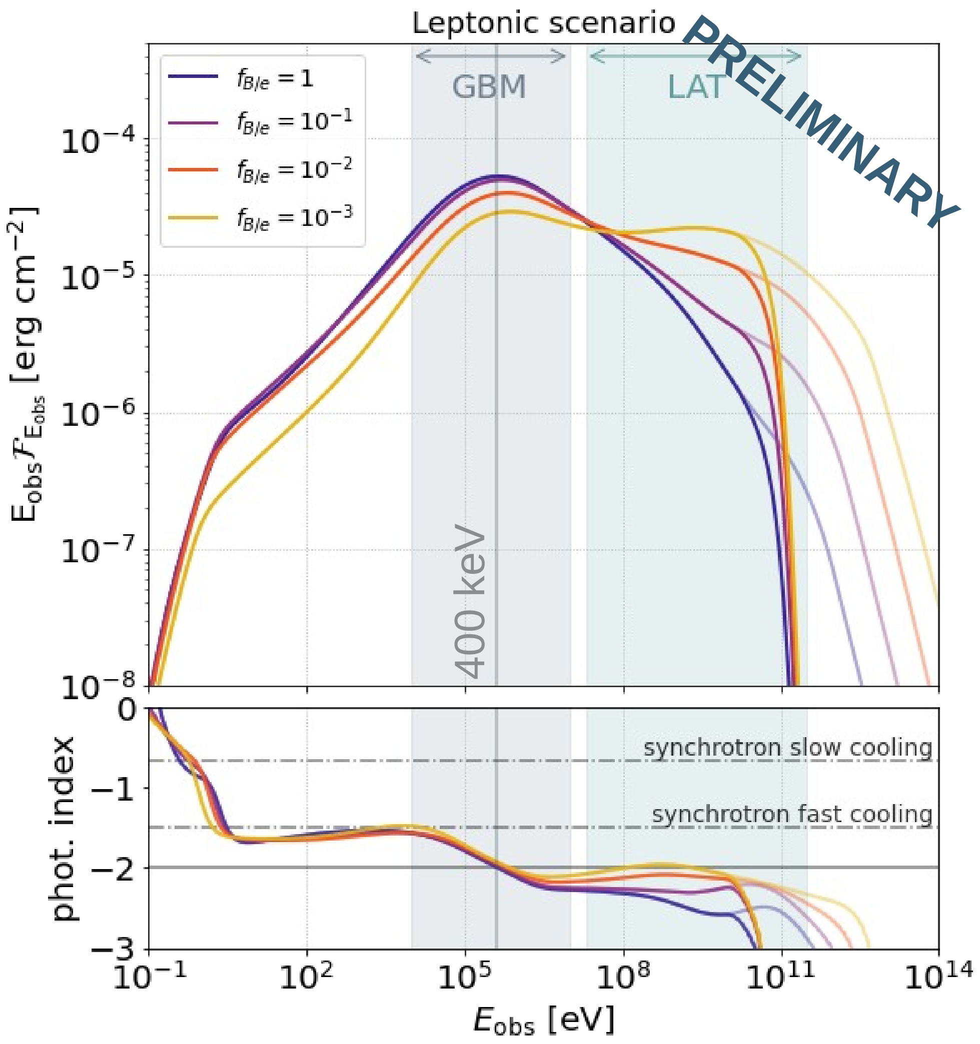


- Leptonic model for the sub-MeV peak -> normalization to energy in non-thermal electrons, adjust magnetic field and fraction of accelerated electrons ζ (that defines $\gamma_{e,min}$) to reproduce peak energy by synchrotron $E_{\mathrm{syn}} \propto \frac{1}{1+z}\Gamma_{\mathrm{em}}\gamma^2_{e,\mathrm{min}}B'$
- Study impact of magnetic field trough $\mathbf{f_{B/e} = \varepsilon_B / \varepsilon_e}$ $B' = \sqrt{8\pi f_B u'_{\mathrm{ele,NT}}}$
  and impact of non-thermal protons through baryonic loading $\mathbf{f_{p/e} = \varepsilon_p / \varepsilon_e}$

Educative example: Leptonic results

Can inverse Compton scatterings enhance the fluence in the Fermi-LAT band?

$f_{B/e} = \varepsilon_B / \varepsilon_e$
fraction of energy supplying the magnetic field/ fraction of energy going into non-thermal electrons

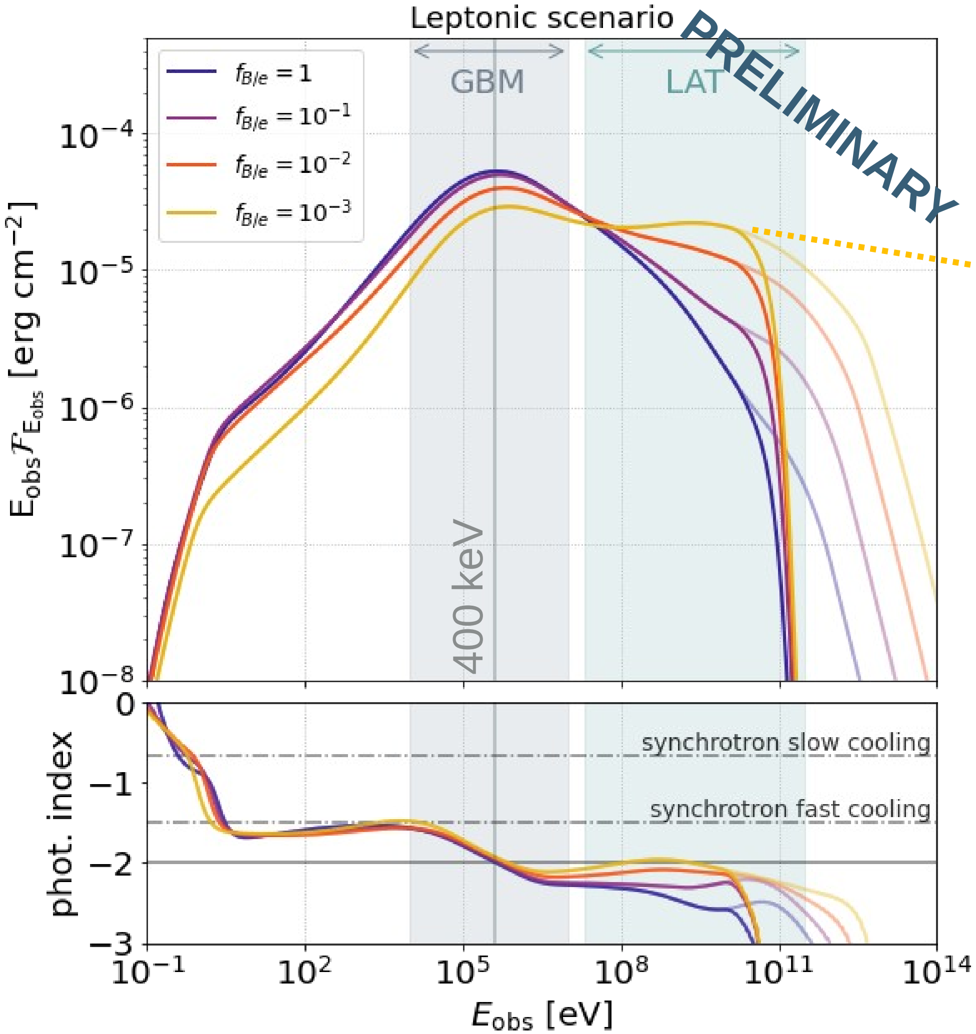


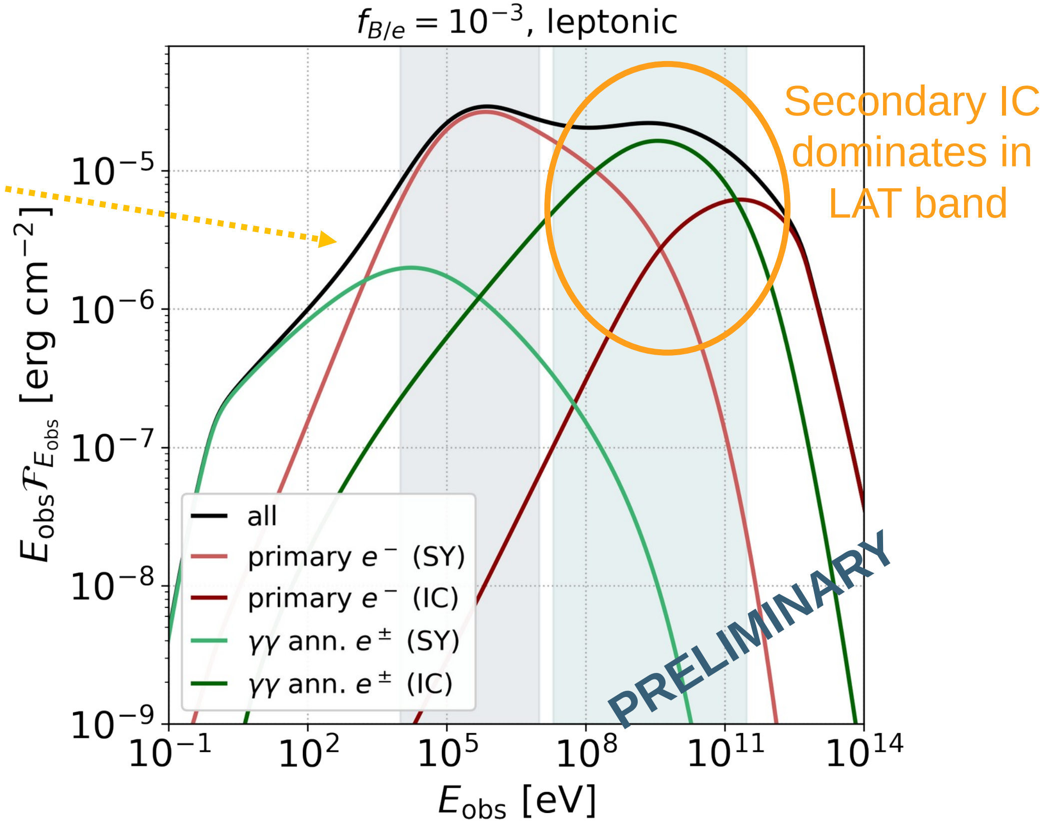
- **Impact of magnetic field**
  For low $f_{B/e}$: LAT fluence is enhanced while sub-MeV peak is reduced, scatterings in KN regime
  Note: Dependency on bulk Lorentz factor
  (-> comoving densities)
- **EBL absorption (z = 2)**
  suppresses anything beyond LAT band
- **Spectral slopes**
  - close to/ lower than synchrotron fast-cooling at low energies
  - flat spectra above peak for low $f_{B/e}$

Educative example: Leptonic results

Spectra de-composed by emission process

$f_{B/e} = \varepsilon_B / \varepsilon_e$
fraction of energy supplying the magnetic field/ fraction of energy going into non-thermal electrons

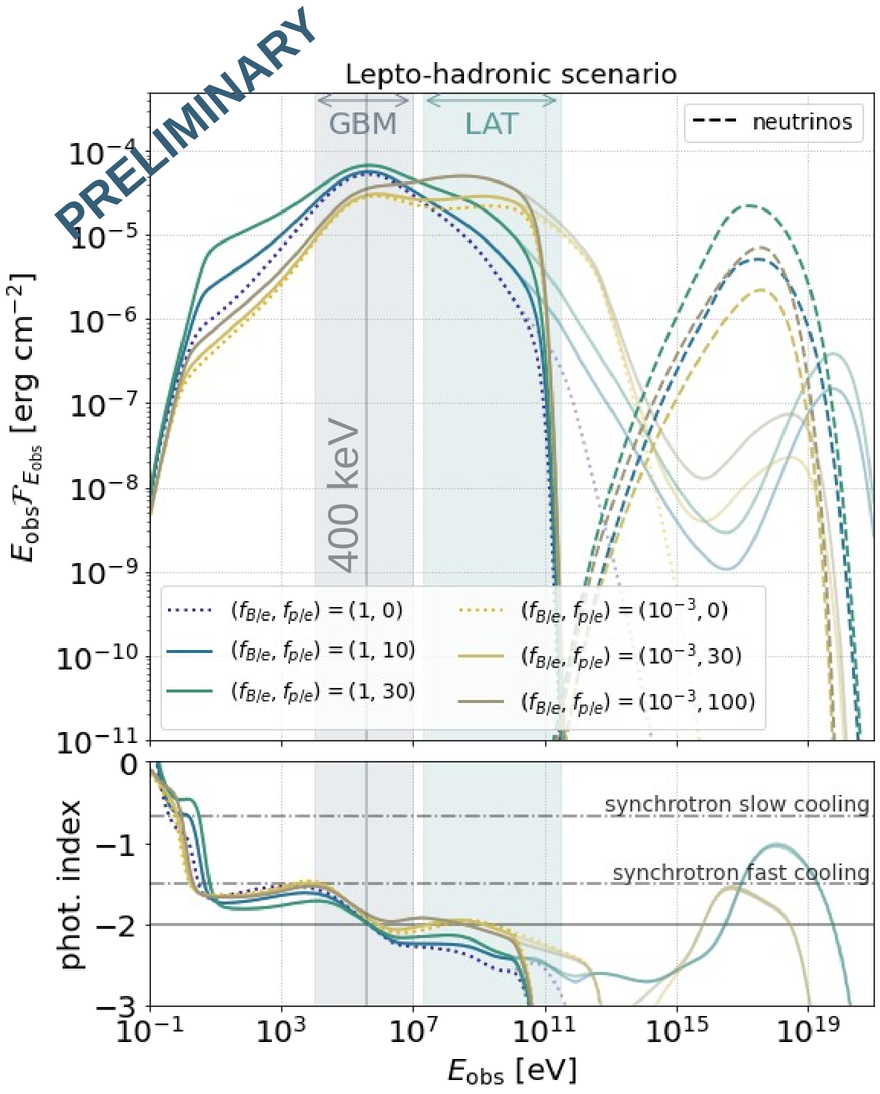




Educative example: Lepto-hadronic results

Can hadronic signatures enhance the fluence in the Fermi-LAT band?

$f_{p/e} = \varepsilon_p / \varepsilon_e$
baryonic loading
fraction of energy going into non-thermal protons vs non-thermal electrons

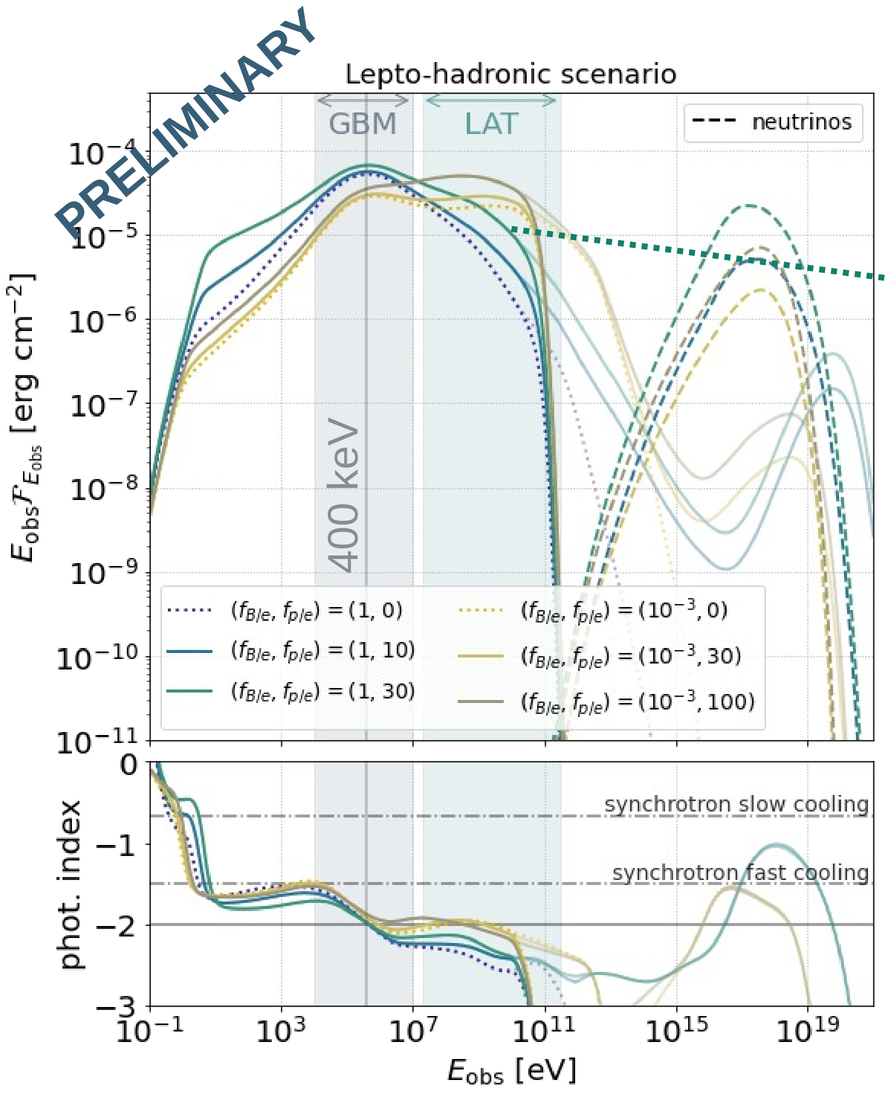


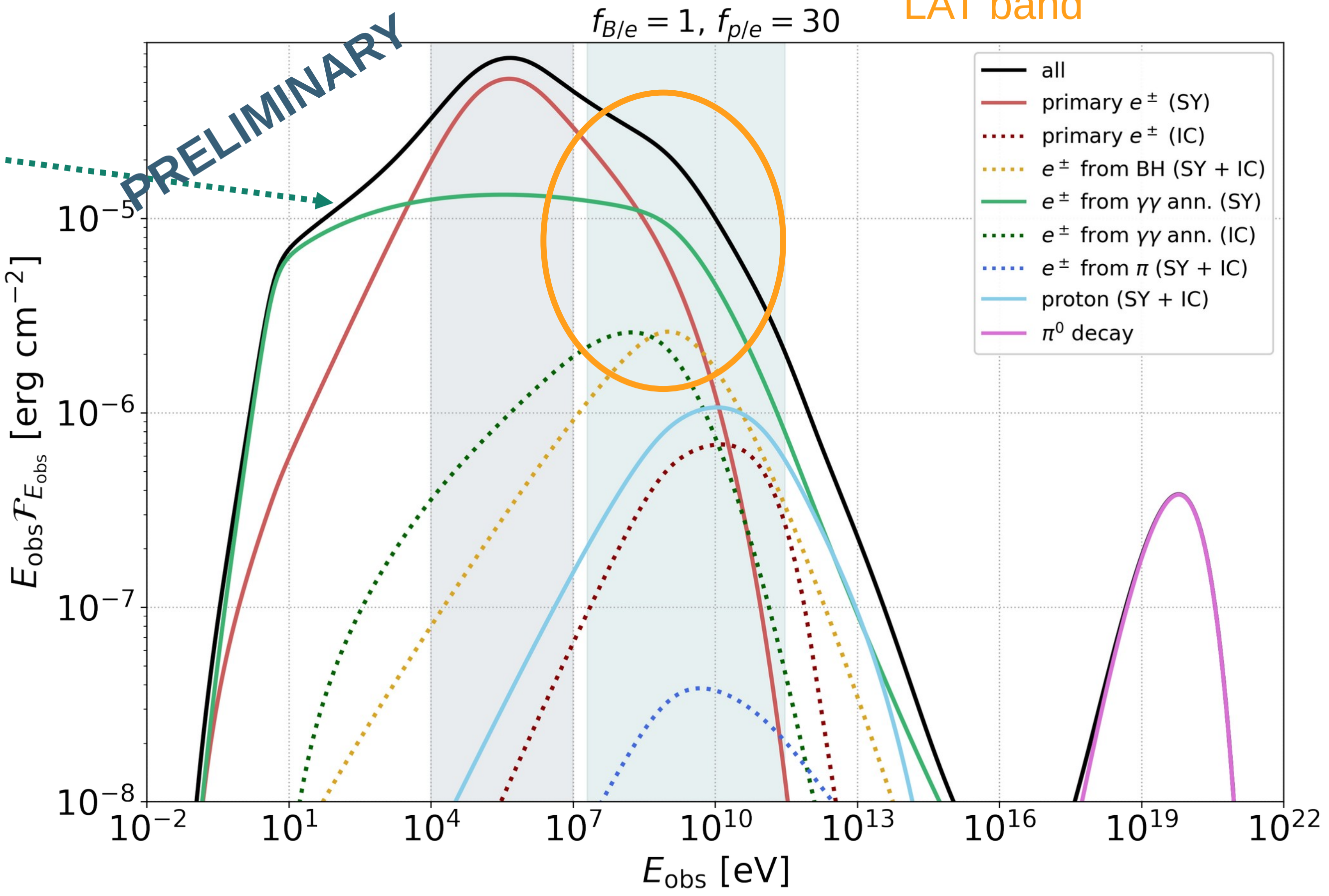
Impact of baryonic loading:

- **Large magnetic fields ($f_{B/e}$ = 1)**
  1. Wing-like broadening of sub-MeV peak
     see also Asano et al ApJ 299 (2008), Asano & Meszaros ApJ 757 (2012) , Petropoulou MNRAS 442 (2014), Wang et al ApJ 857 (2018)
  2. Intermediate pion and muon cooling shift the neutrino peak to lower energies wrt VHE peak from π^0 decays
- **Low magnetic fields ($f_{B/e}$ = 10^{-3})**
  1. Enhancement above the sub-MeV peak
  2. Lower π^0 -decay and neutrino peak energies due to lower maximum energies of protons (calculated balancing losses and acceleration $t'_{acc} = R'_L / c$)

Educative example: Lepto-hadronic results

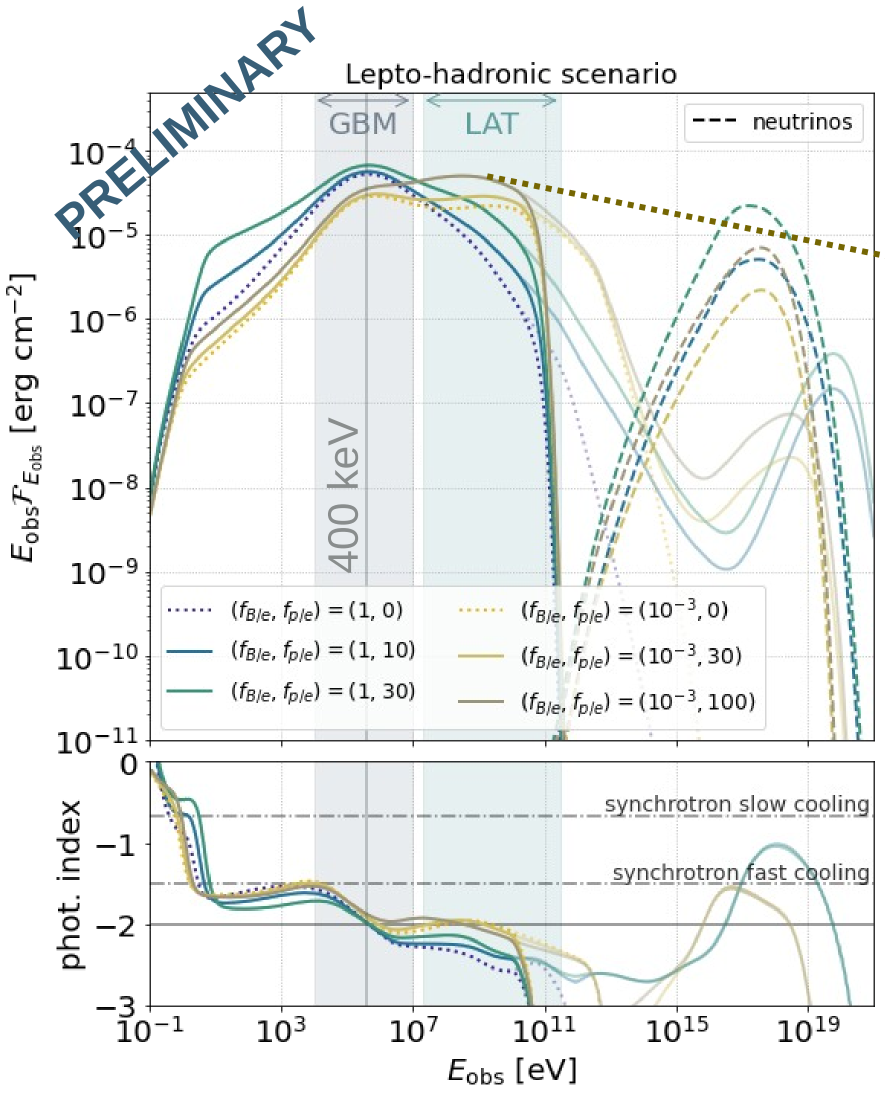
Spectra de-composed by emission process



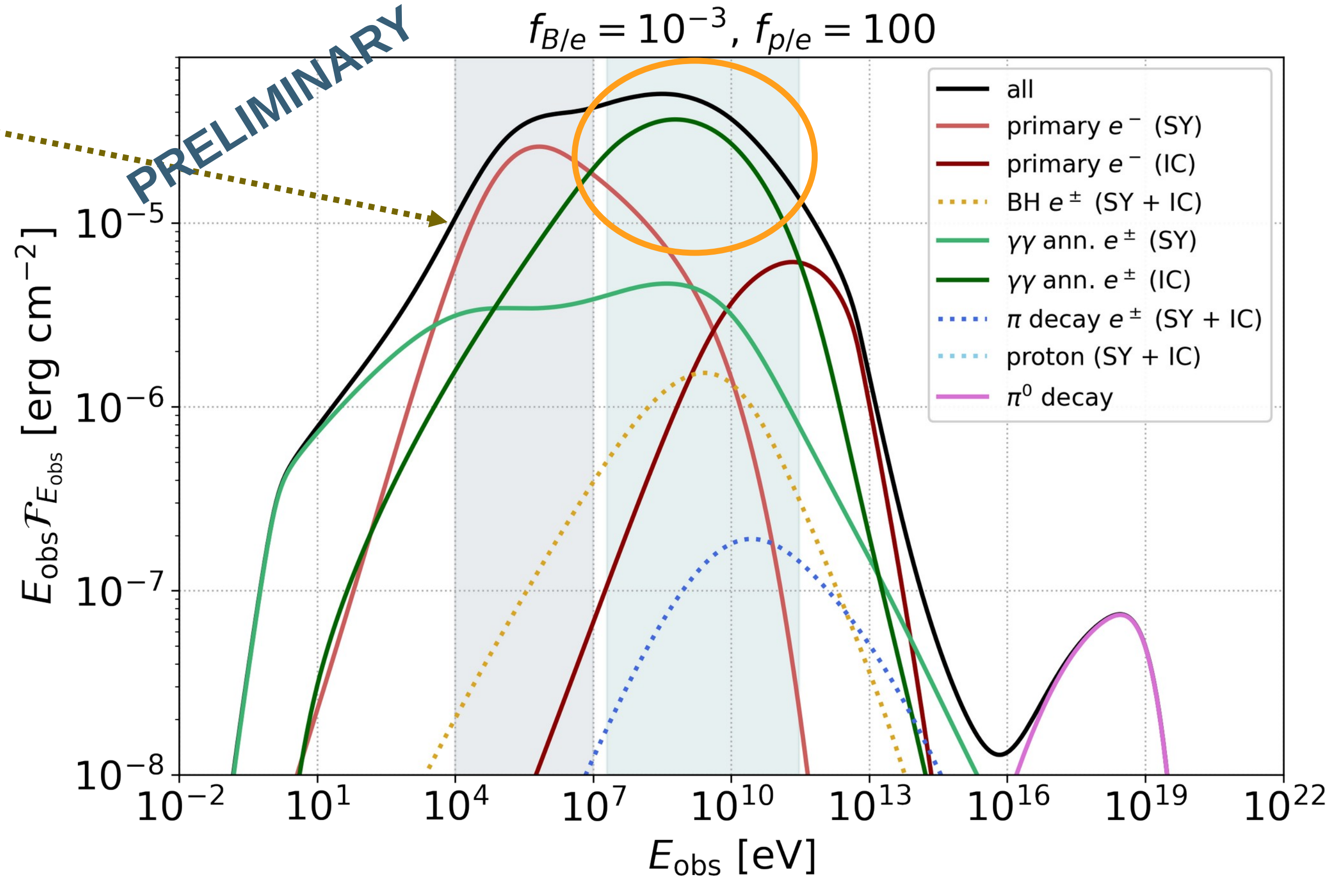


Educative example: Lepto-hadronic results

Spectra de-composed by emission process



Secondary IC dominates in LAT band



Application to a Fermi-LAT detected burst: GRB 170214A

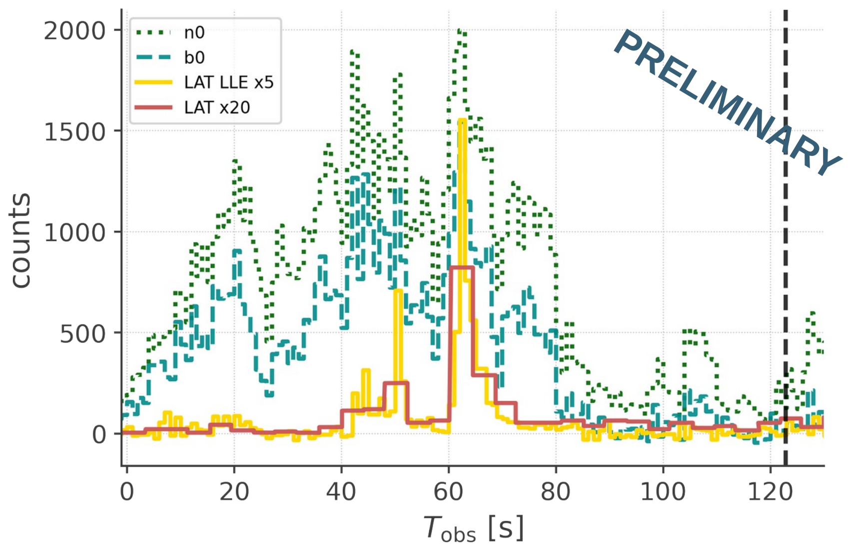
Are the same trends reproduced for a 'realistic' GRB?

- Bright burst, delayed onset of LAT
- Light curve variability of LAT tracks the GBM one -> Internal dissipation origin suggested Tang et al ApJ 844 (2017)

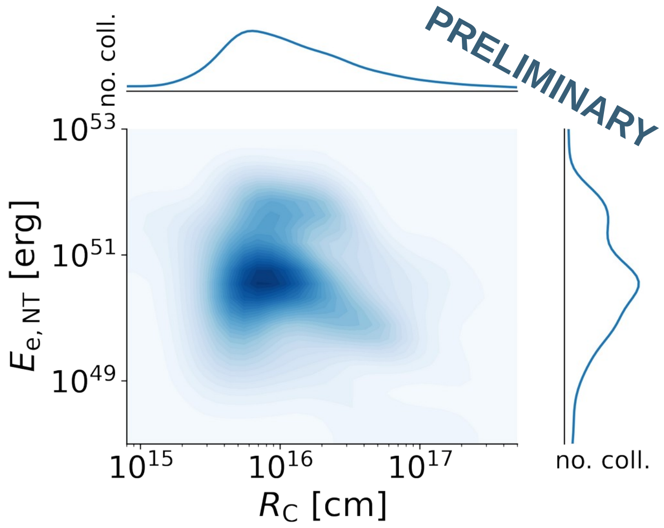
Burst characteristics

- Redshift z = 2.53
- T_{90} = 122 s
- E_{iso} = 2.9 10^{54} erg
- $E_{peak, obs}$ = 481 keV
- low-energy slope
  α = –0.98
  high-energy slope
  β = –2.51

Observed light curve



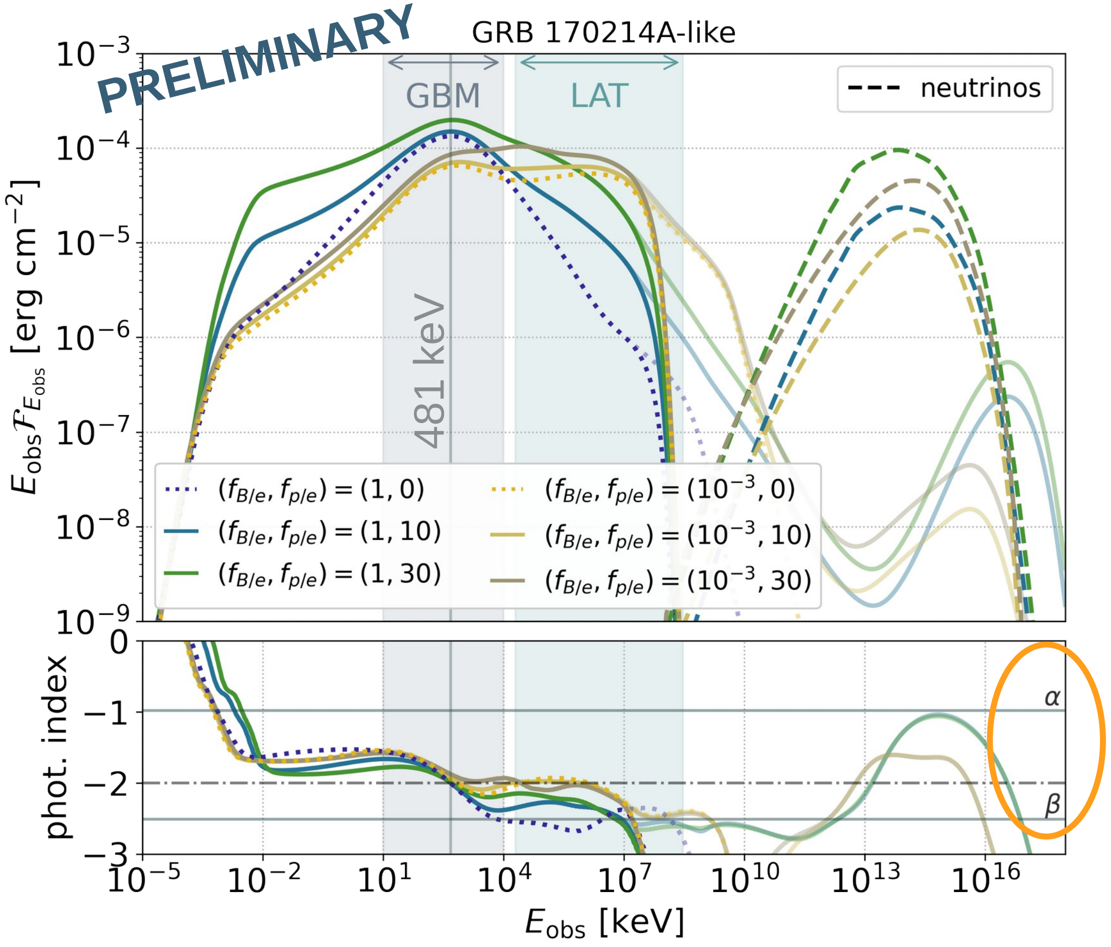
Simulated distribution of collisions



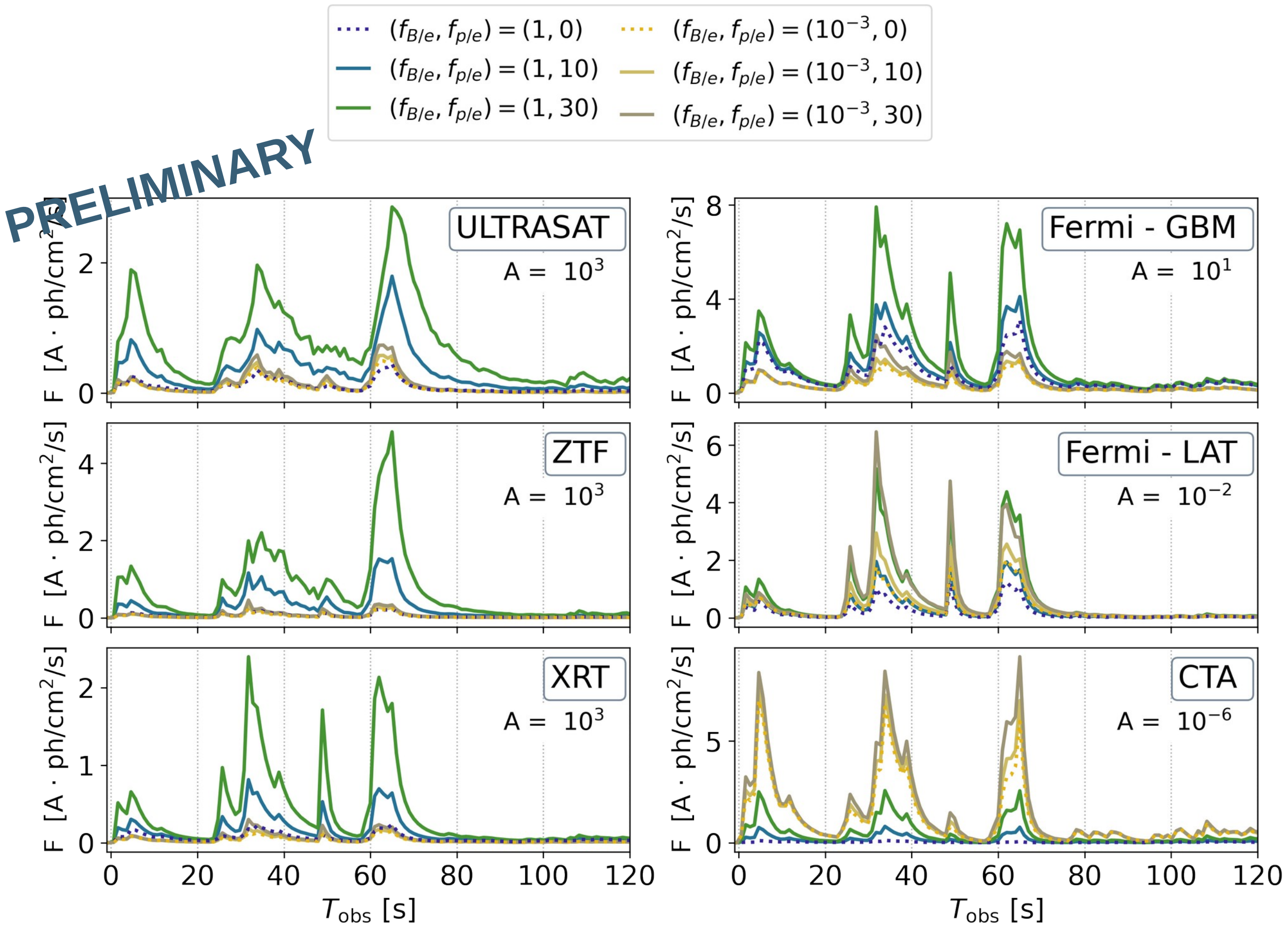
Application to a Fermi-LAT detected burst: GRB 170214A

Are the same trends reproduced for a 'realistic' GRB?

Spectrum



Light curve



Summary and conclusions

Multi-zone internal shock model capturing the evolution of plasma properties as a function of radius

Educative example: high isotropic energy, simple single-peaked light curve

- Low magnetic fields/low $f_{B/e}$: secondary emission IC dominates in LAT band
- Lepto-hadronic with high magnetic fields/high $f_{B/e}$: wing-like broadening by flat secondary SY + effects of pion/muon cooling on neutrino peak energies
- In all scenarios: Secondary emission dominates in LAT band -> need self-consistent, complete treatment

-> Constrains on microphysics parameters (ε_p, ε_B , ε_e , ζ) ?
-> Density-dependent processes: Strong impact of jet Lorentz factor

Fermi-LAT detected burst: **GRB 170214A**

- same behavior as for educative example for varying $f_{B/e}$ and $f_{p/e}$
- Variability of LAT and low energies similar to GBM
- Narrowest spectra for synchrotron-dominated scenario. Still too broad for observations!