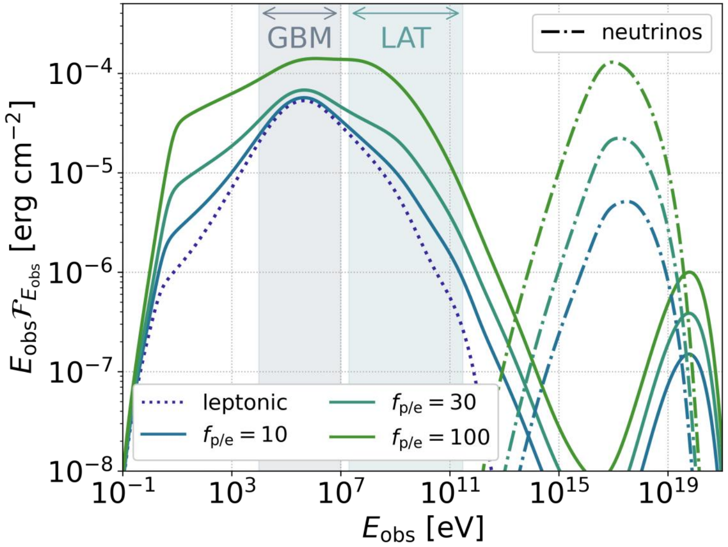
Multi-collision lepto-hadronic models for energetic GRBs

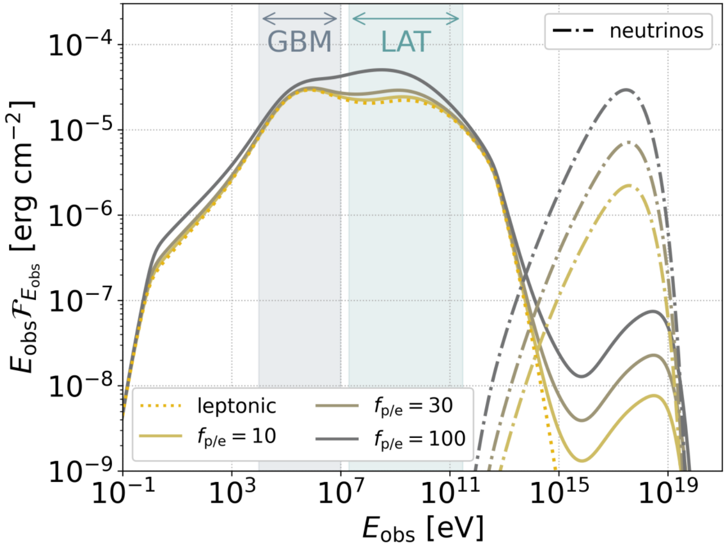
In a nutshell!

Synchrotron dominated scenario



- Hadronic scenarios: wing-like broadening of keV peak due to synchrotron emission of secondary lepton cascade
- Neutrino peak energies reduced due to intermediate pion and muon cooling

inverse Compton dominated scenario



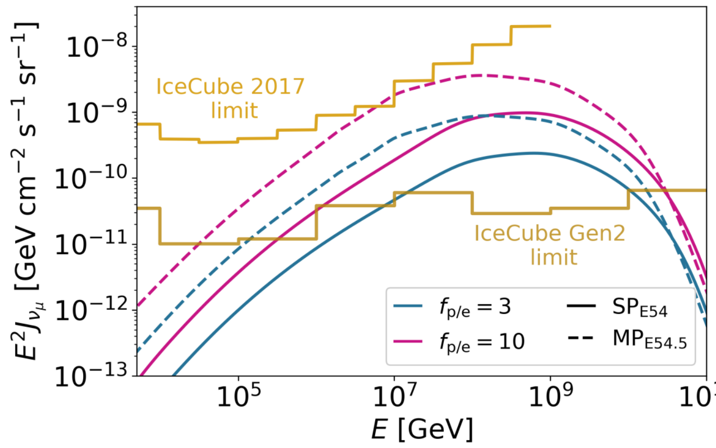
- Inverse Compton of secondary lepton cascade visible in LAT band
- Hadronic signatures: clearly visible only in VHE regime
- No effect of intermediate pion and muon cooling on neutrino energies

Similar results for complex (multi-pulse) and simple (single-pulse) burst. Density-related processes (photo-pion, photo-photon annihilation) depend on typical emission radius!

Multi-messenger implications

- EBL absorption: VHE emission not observable -> multi-wavelength and neutrino signatures!
- From UHECR energy budget: For subpopulation of energetic bursts require $f_{p/e}$~3-10 to power UHECR flux
- Basic consistency with diffuse neutrino fluxes and SED

Diffuse neutrino fluxes



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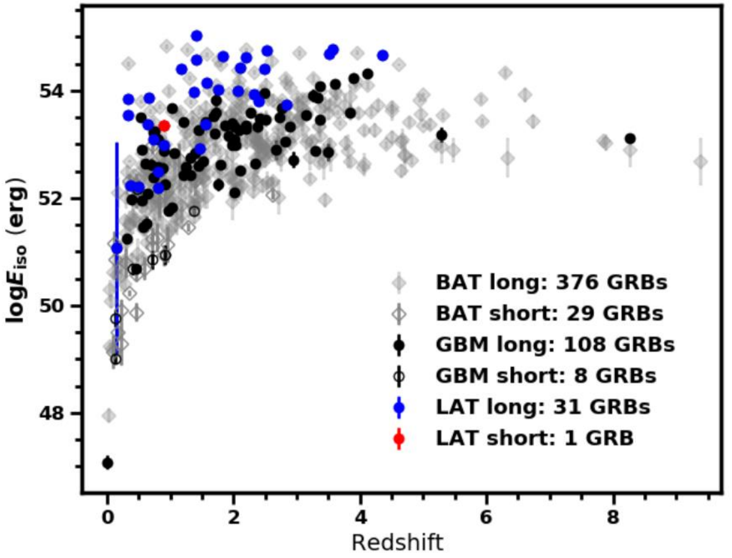
Motivation & Methods

Motivation and research questions

- GRBs detected in high energies by Fermi-LAT are among the most energetic events of the population



2nd Fermi-LAT GRB catalogue
Axelsson et al 2019

- *What are hadronic signatures in synchrotron and inverse Compton dominated scenarios in energetic bursts?*
- *Which are the implications for multi-messenger astrophysics and in connection to UHECR energy budget requirements?*

Methods

- Multi-collision internal shock model (Daigne & Mochkovitch 1998) for the GRB prompt phase
  --> Different emission zones along the astrophysical jet
- Time-dependent lepto-hadronic radiation modelling with AM3 (Gao et al 2016)
  --> coupled PDEs of leptons, hadrons, photons and neutrinos
  --> maximal electron and proton energies determined self-consistently
- Systematic study of different baryonic loadings $f_{p/e}$ (~energy transferred to non-thermal protons)
- Two prototypes:
  (1) simple, single peaked with E_{iso} 10^{54} erg -> SP_{E54}
  (2) multi-peaked with E_{iso} $10^{54.5}$ erg -> $MP_{E54.5}$
  Note: both have large emission radii!

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Multi-collision lepto-hadronic models for energetic GRBs

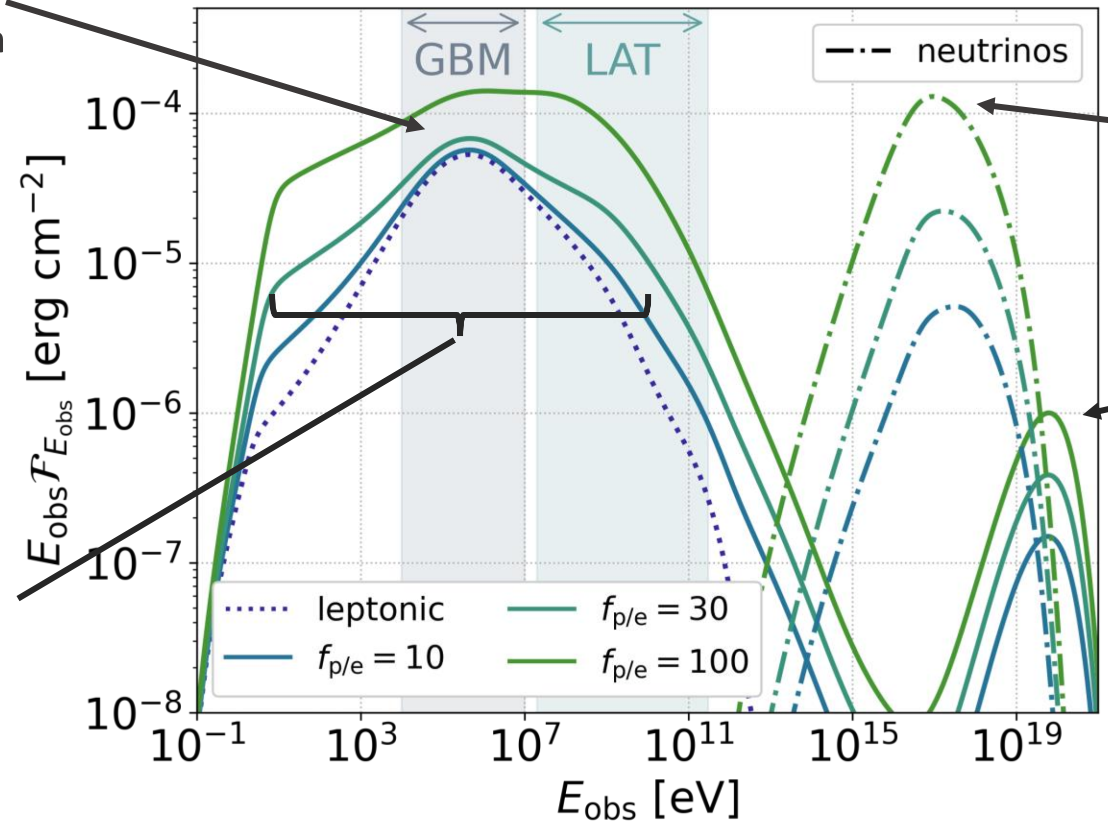
Results: SYN-dominated

$f_{p/e} = \varepsilon_p/\varepsilon_e$
'baryonic loading'

Typical keV peak: generated by synchrotron emission of primary electrons

Synchrotron of secondary lepton pairs: additional flat component, intensity scales with $f_{p/e}$--> wing-like broadening of peak

Spectrum in observers frame
synchrotron-dominated, simple single-pulse burst



Typical neutrino energy lower than neutral pion decay peak due to cooling of intermediate muons and pions

Neutral pion decay peak: not observable due to EBL absorption

- Results similar for more complex burst.
- Density-related processes (photo-pion, photo-photon annihilation) depend on typical emission radius
  --> defined by Lorentz factor of outflow, duration/ time variability of burst

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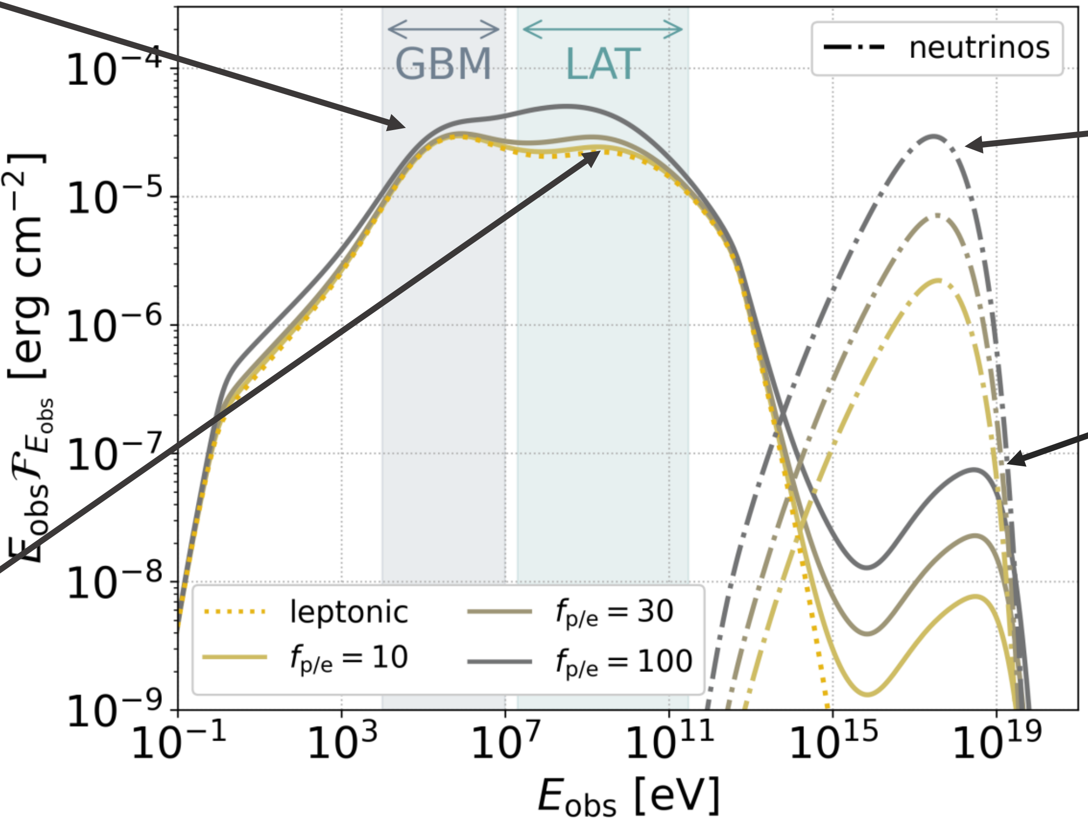
Multi-collision lepto-hadronic models for energetic GRBs

Results: IC-dominated

$f_{p/e} = \varepsilon_p/\varepsilon_e$
'baryonic loading'

Spectrum in observers frame
synchrotron-dominated, simple single-pulse burst



Typical keV peak: generated by synchrotron emission of primary electrons

inverse Compton of secondary particle cascade enhances HE fluence --> dependence on baryonic loading weaker than in SYN-dominated scenario

no effect of intermediate pion and muon cooling on neutrino peak energy

Neutral pion decay peak energy lower, because maximal energy of primary protons lower

- Results similar for more complex burst.
- Density-related processes (photo-pion, photo-photon annihilation) depend on typical emission radius --> defined by Lorentz factor of outflow, duration/ time variability of burst

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Results: multi-messenger

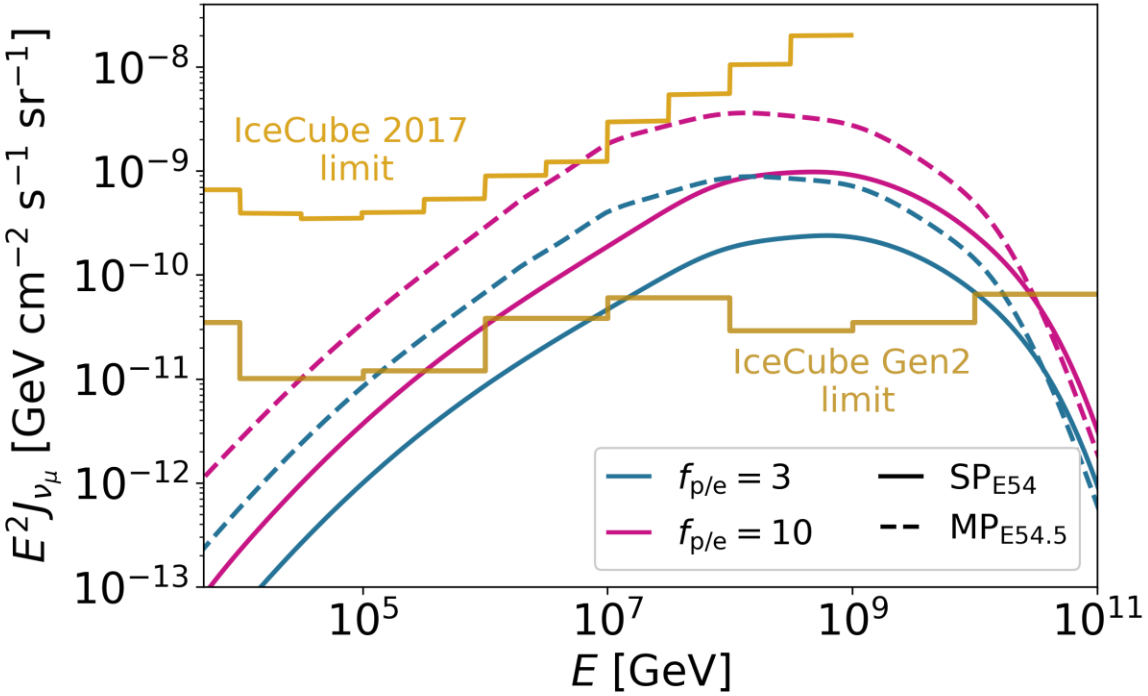
Multi-messenger hadronic signatures in light of EBL absorption:

1. *Multi-wavelength:*
   Eg. in SYN-dominated case low (optical) and high energy-fluences are enhanced for $f_{p/e} > 3$
2. *Neutrinos:*
   - point source predictions: for $f_{p/e}$ =10 number of expected neutrinos in IceCube < 3 10^{-3} (3 10^{-2}) for SP_{E54} ($MP_{E54.5}$)
   - diffuse fluxes: $f_{p/e}$~3-10 compatible with current IceCube limits
3. *Cosmic rays:*
   Required baryonic loading to power UHECR flux:

$$f_{\rm p/e} \simeq 10 \cdot \frac{E_{\gamma,\rm iso}}{10^{54}\,\rm erg} \cdot \frac{\dot\varepsilon_{\rm UHECR}}{10^{44}\,\rm erg\,Mpc^{-3}\,yr} \cdot \frac{0.1\,\rm Gpc^{-3}\,yr}{\dot n_0} \, .$$

--> $f_{p/e}$ ~ 3-10 for the local GRB rate n_0 of energetic bursts

Diffuse neutrino fluxes



Diffuse fluxes calculated with 148 (93) observable GRBs for SP_{E54} ($MP_{E54.5}$)

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