GRBs and their Afterglows at Very High Energies

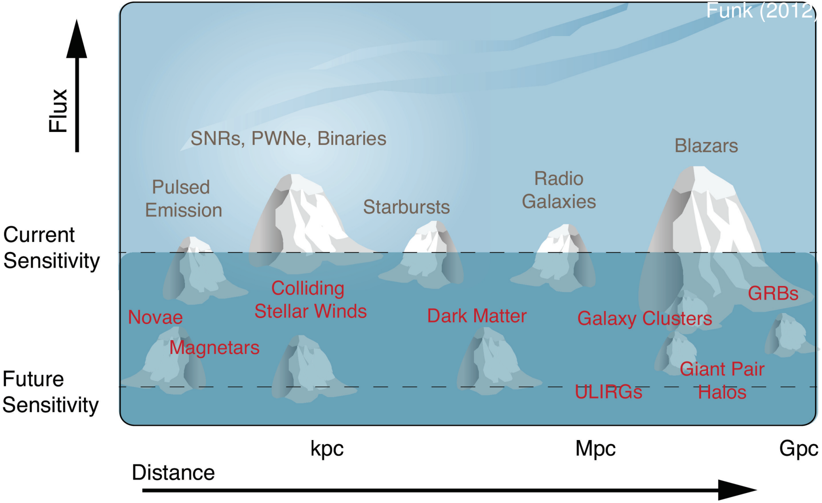
D. Khangulyan (Rikkyo University)

"7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy"

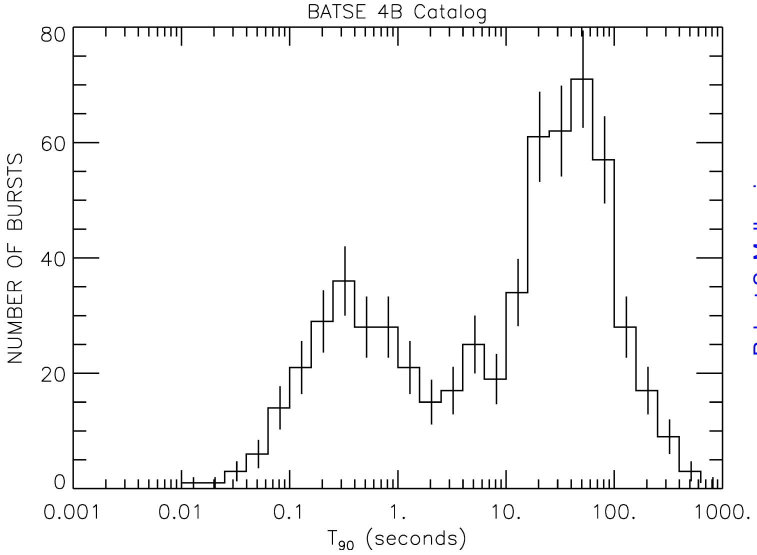
4th July 2022

OVERVIEW

Gamma-Ray Sources

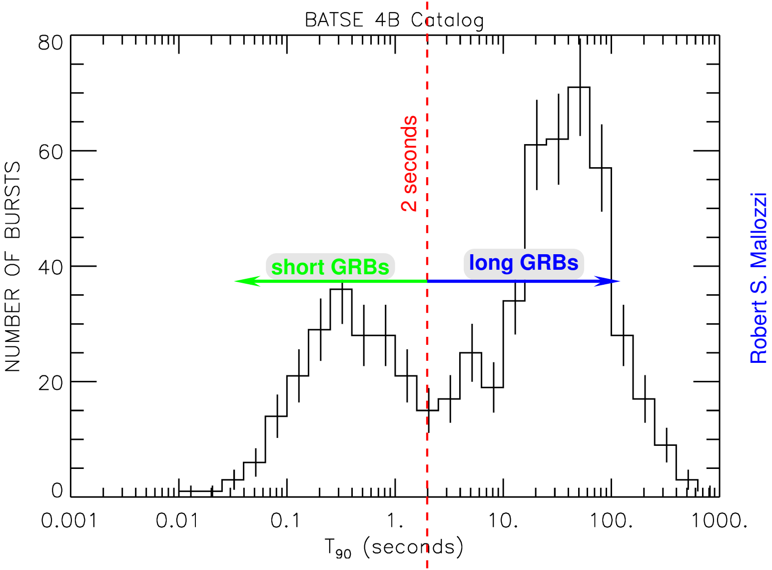


GRBs

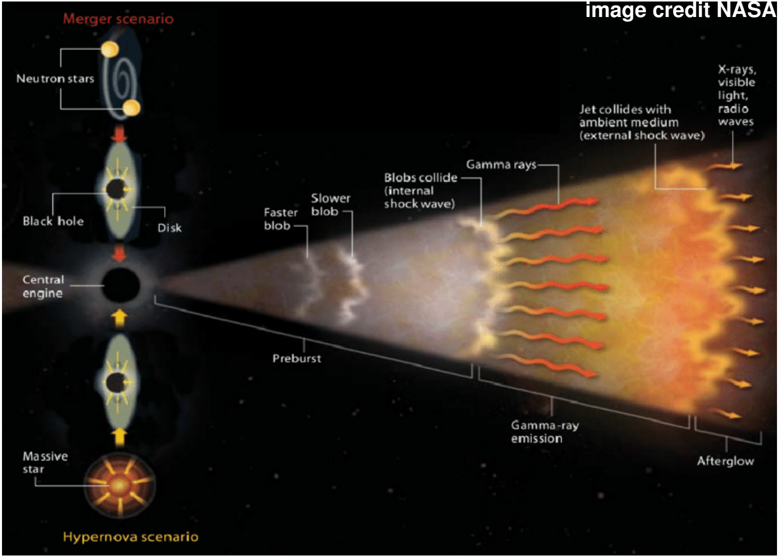


Robert S. Mallozzi

GRBs


BATSE 4B Catalog
80
60
40
20
0
NUMBER OF BURSTS
0.001
0.01
0.1
1.
10.
100.
1000.
T90 (seconds)
2 seconds
short GRBs
long GRBs
Robert S. Mallozzi

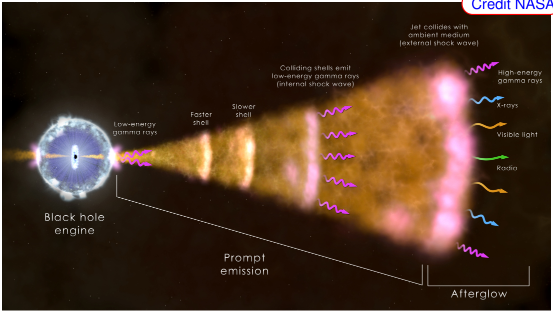
GRB Physical Scenarios for short and long GRBs



GRB Afterglow: physical scenario

- GRBs are most likely produced at collapse of massive stars/neutron star binaries
- Magnetic field accumulated at the BH horizon launches a B&Z jet
- Prompt emission: initial jet outburst, internal jet emission
- Afterglow: jet–circumburst medium interaction, last for weeks

Credit NASA



Self-similar solution for a relativistic blast wave (the relativistic version of the Sedov's solution for SNR, Blandford&McKee 1976):

$$E = \Gamma^2 M c^2, \ \text{assuming } \rho \propto r^{-s} \Rightarrow \Gamma \propto R^{(s-3)/2} \Rightarrow \Delta t \approx \int_0^R \frac{dr}{2c\Gamma(r)^2}$$

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Based on the explosion energy, E, and density of the circumburst medium, $\rho = \rho_0 (r/r_0)^{-s}$ we obtain

- Bulk Lorentz factor of the shell

$$\Gamma \approx 40 \left(\frac{E_{53}}{\rho_0 t_3^3}\right)^{1/8}\Bigg|_{s=0} \approx 20 \left(\frac{E_{53} v_8}{\dot{m}_{21} t_3}\right)^{1/4}\Bigg|_{s=2}$$

- Shell radius

$$R \approx 2 \cdot 10^{17}\,\mathrm{cm} \left(\frac{t_3 E_{53}}{\rho_0}\right)^{1/4}\Bigg|_{s=0}$$

$$3 \cdot 10^{16}\,\mathrm{cm} \left(\frac{t_3 E_{53} v_8}{\dot{m}_{21}}\right)^{1/2}\Bigg|_{s=2}$$

- Integernal energy of the plasma: $\varepsilon \approx \Gamma^2 \rho$

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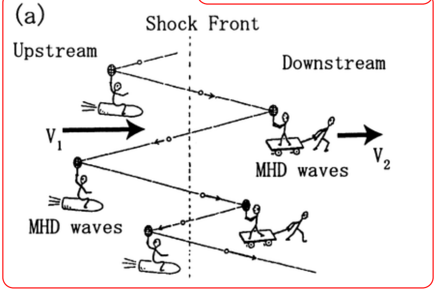
GRB is relativistic version of SN explosions

- Shock acceleration is a very important mechanism for production of cosmic rays
- It is fairly well understood in the non-relativistic regime, but **not in the relativistic one**
- GRB afterglows are produced by relativistic shocks in their simplest realization
- Detection of IC emission helps to constrain the downstream conditions and define energy of synchrotron emitting electrons
- Because of the synchrotron burn-off limit, emission detected in the VHE regime is expected to be **of IC origin**

credit M.Hoshino (after M.Schore)



Diffusive shock acceleration

- Power-law spectrum with $\frac{dN}{dE} \propto E^{-s}$ where $s = \frac{v_1/v_2+2}{v_1/v_2-1} \approx 2$
- Acceleration time $t_{\rm ACC} \approx \frac{2\pi r_{\rm G}}{c}\left(\frac{c}{v_1}\right)^2$

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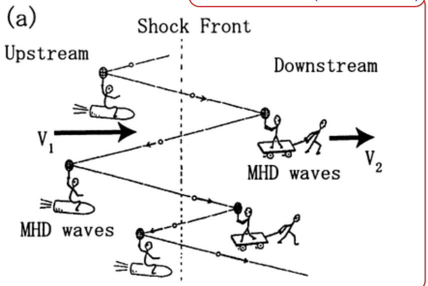

Relativistic shocks

- Particles can get a significant energy by shock crossing, but
- Particles **do not** have time to **isotropize** in the downstream

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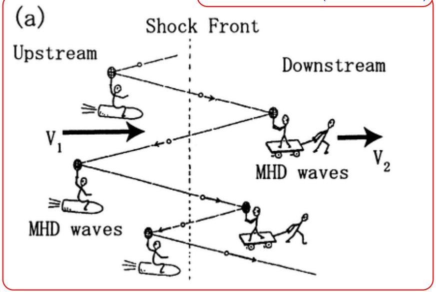

Relativistic shocks

- Forward shock propagates through ISM medium (or stellar wind)
- There is a self-similar hydrodynamic model (Blandford&McKee1976)

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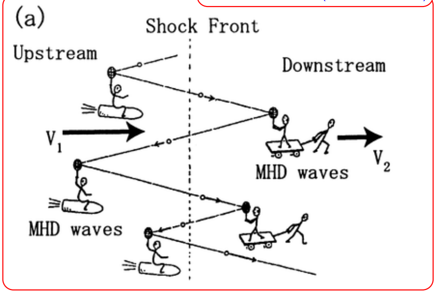

Leptonic source

- Interpretation of synchrotron emission is ambiguous because of "magnetic field" – "electron energy" degeneracy
- Detection of **IC** helps to resolve it

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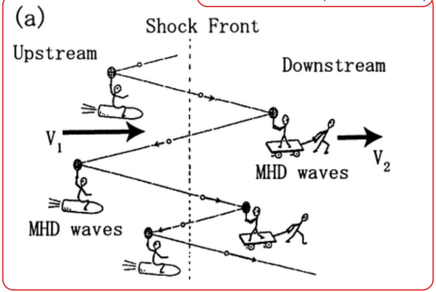


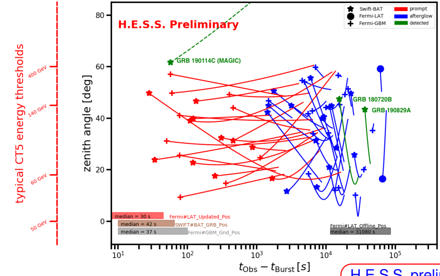
Synchrotron burn-off limit

- Synchrotron cooling time: $t_{\rm SYN} \approx 400 E_{\rm TeV}^{-1} B_{\rm B}^{-2}$ s
- Acceleration time: $t_{\rm ACC} \approx 0.1 \eta E_{\rm TeV} B_{\rm B}^{-1}$
- Max energy: $\hbar\omega < 200 \frac{\Gamma}{\eta}$ MeV

Hunt for GRBs in the VHE band

Why do we expect to see GRBs@VHE?

- Relativistic outflows
- Bright non-thermal sources
- A few GRBs per week



H.E.S.S. preliminary

Why did it take so long to detect GRBs in the VHE regime?

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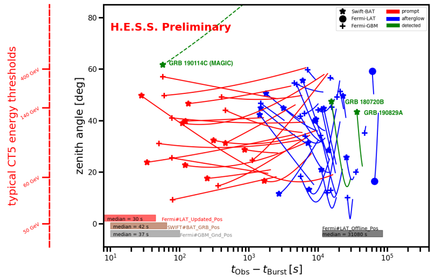

- Highly variable sources
- Bright synchrotron emission
  - IC can be suppressed
  - Internal absorption
- Cosmological distances, EBL attenuation ⇒

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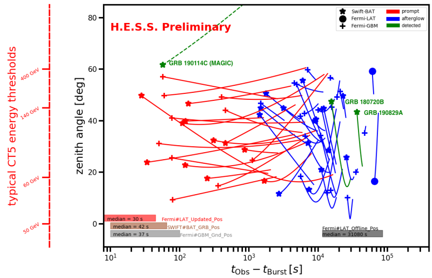

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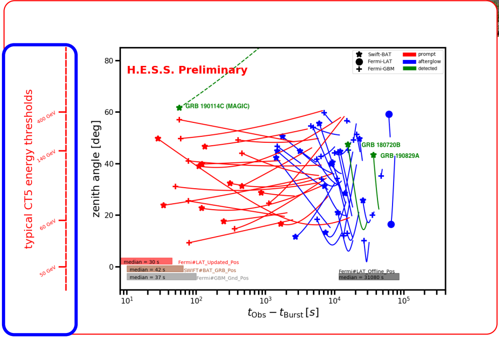

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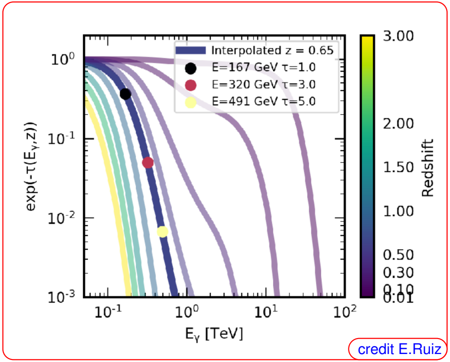
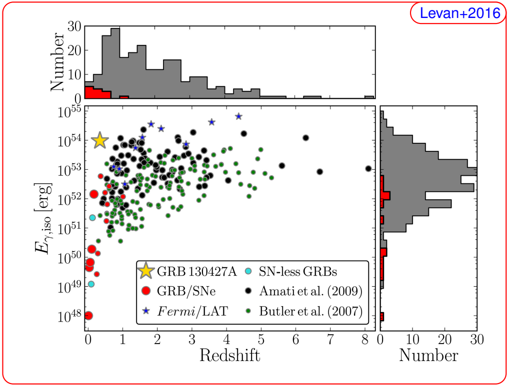
EBL attenuation

- GRBs are typically registered from $z_{\rm rs} > 1$
- The EBL attenuation for TeV γ rays from cosmological distances is severe





One of the key challenges

- Operating Cherenkov telescopes have a threshold at $\sim 100\,\mathrm{GeV}$
- $300\,\mathrm{GeV}$ γ rays traveling from $z_{\rm rs} = 0.5$ are attenuated by a factor of 10

EBL attenuation

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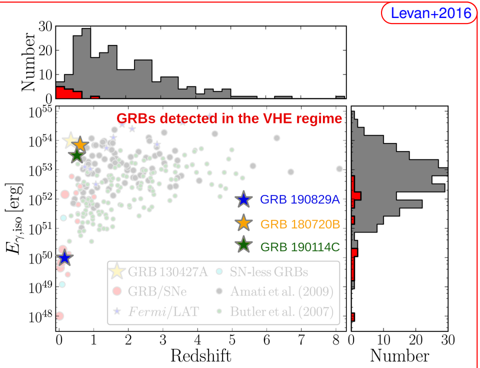

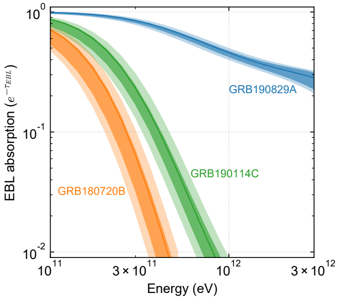

GRBs detected in the VHE regime:

- GRB 190829A: $z_{\rm rs} \approx 0.08$ and $L_{\rm iso} = 2 \times 10^{50}$ erg
- GRB 190114C: $z_{\rm rs} \approx 0.42$ and $L_{\rm iso} = 3 \times 10^{53}$ erg
- GRB 180720B: $z_{\rm rs} \approx 0.65$ and $L_{\rm iso} = 6 \times 10^{53}$ erg

EBL attenuation

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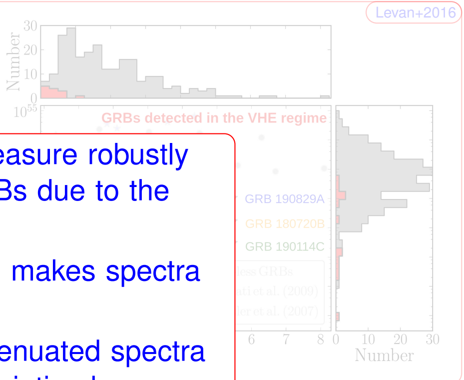
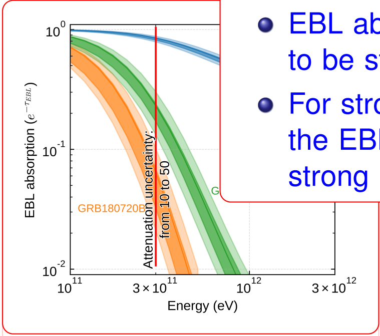
  γ rays from c…
  tances is sev…



It is very hard to measure robustly VHE spectra of GRBs due to the EBL attenuation:

- EBL absorption makes spectra to be steep
- For strongly attenuated spectra the EBL uncertainties have a strong impact



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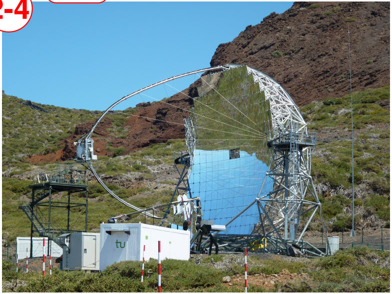
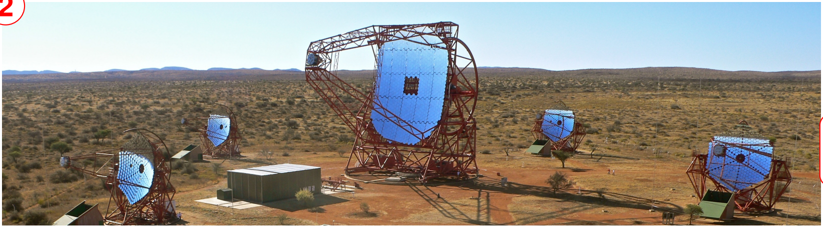
GRBs detected in the VHE regime (~ 0.1 TeV)

2-4 MAGIC



0 Veritas

2 H.E.S.S.



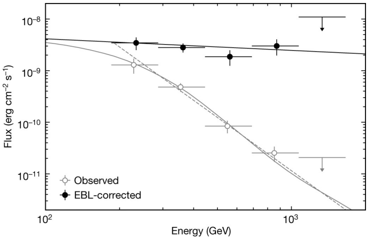
GRBs detected in the VHE regime ($\sim 0.1\,\mathrm{TeV}$)

- ? GRB160821B: 3σ detection of a nearby short GRB ($z = 0.162$) above $0.5\,\mathrm{TeV}$ 4h after the trigger (MAGIC Col, 2021)
- ✔ GRB180720B: 5σ detection of a long GRB from $z = 0.65$ above $0.1\,\mathrm{TeV}$ **10h** after the trigger (HESS Col, 2019)
- ✔ GRB190114C: $\sim 50\sigma$ detection of a long GRB from $z = 0.42$ above $0.2\,\mathrm{TeV}$ $\sim$min after the trigger (MAGIC Col, 2019)
- ✔ GRB190829A: 20σ detection of a long GRB from $z = 0.08$ at energies $0.18 - 3.3\,\mathrm{TeV}$ **4-50h** after the trigger (HESS Col, 2021)
- ? GRB201015A: $> 3\sigma$ detection of a long GRB at $z = 0.43$ (MAGIC Col, Atel)
- ✔ GRB201216C: $> 5\sigma$ detection of a long GRB at $z = 1.1$ (MAGIC Col, Atel)

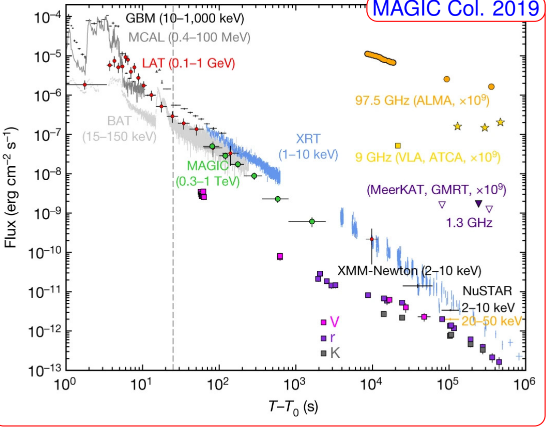
GRB190114C

GRB190114C

- ✔ 50σ detection
- ✔ $E_{\rm iso} = 3 \times 10^{53}\,{\rm erg}$
- ? $z = 0.42$
  or $D \approx 1\,{\rm Gpc}$
- ✔ $t_{\rm vhe} \sim {\rm min}$
  time decay measured
  in X-rays/VHE: $L \propto t^{-1.6}$



MAGIC Col. 2019



- The first GRB detection reported in the VHE regime
- Bright late prompt – early afterglow emission
- EBL absorption is very significant at $\sim 500\,{\rm GeV}$

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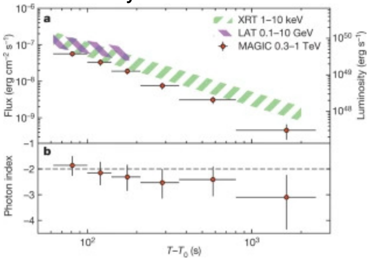
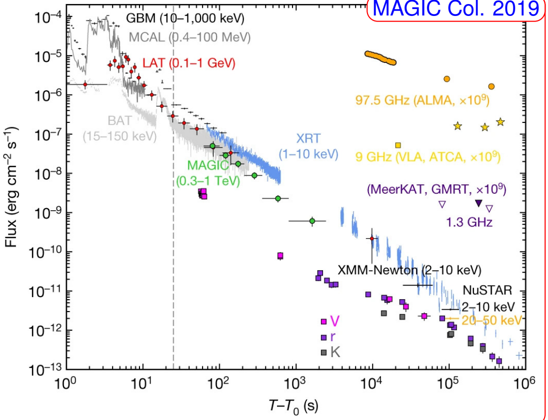


MAGIC Col. 2019



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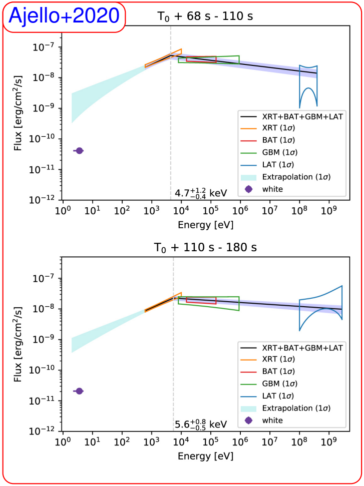
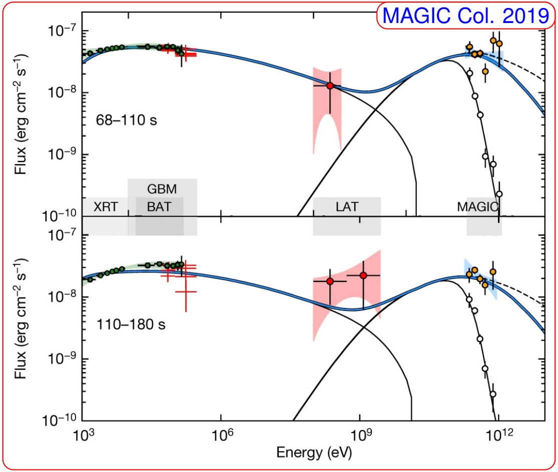
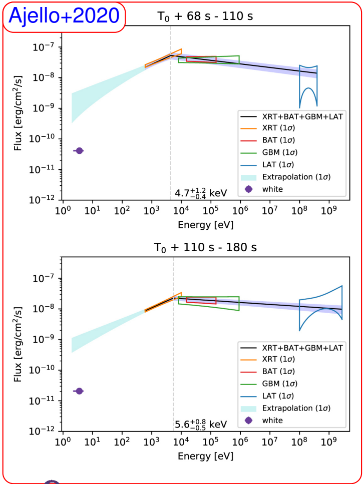


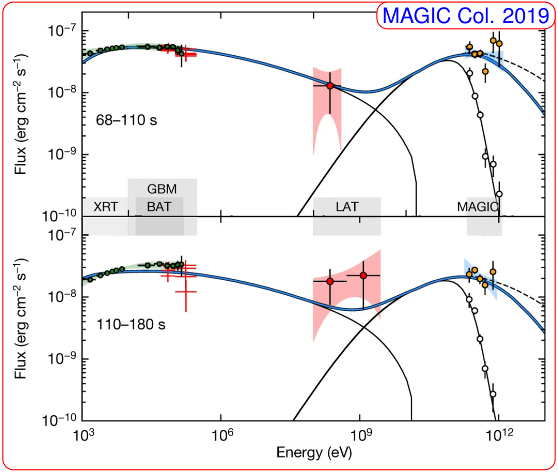
Ajello+2020
T0 + 68 s - 110 s
Flux [erg/cm2/s]
Energy [eV]
4.7+1.2−0.4 keV
XRT+BAT+GBM+LAT
XRT (1σ)
BAT (1σ)
GBM (1σ)
LAT (1σ)
Extrapolation (1σ)
white
T0 + 110 s - 180 s
5.6+0.8−0.5 keV



MAGIC Col. 2019
Flux (erg cm−2 s−1)
68–110 s
110–180 s
XRT
GBM
BAT
LAT
MAGIC
Energy (eV)

GRB190114C





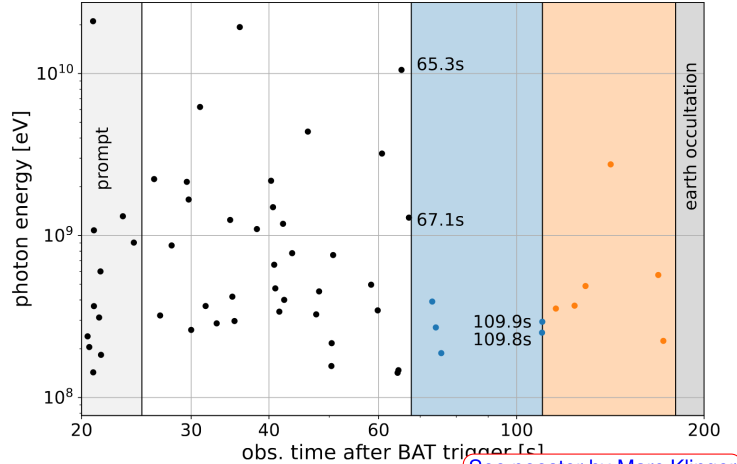
- ✔ We do detect photons with energy exceeding the synchrotron burn-off limit
- ✘ Maybe we see / don’t see a TeV component emerging above the emission in the Fermi/LAT band in the 2/3 min.

GRB190114C

Ajello+2020

MAGIC Col. 2019

Can one get a statistically sound conclusion?



See pooster by Marc Klinger

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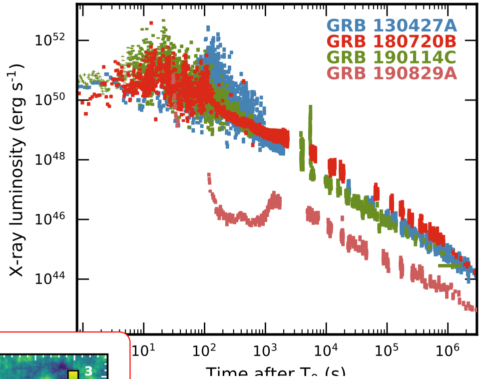
GRB 190114C: summary of the observational results

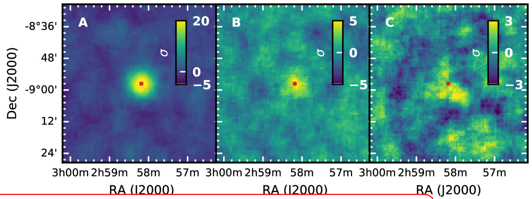
- Remarkably significant detection, $\sigma > \mathbf{50}$
  - this required an early start of observations, $t > \mathbf{68}\,\mathrm{s}$
- Simultaneous detection with Fermi/LAT
  - this required an early start of observations, $t > \mathbf{68}\,\mathrm{s}$
- VHE light-curve with 6 significant points, $\mathbf{68}\,\mathrm{s} < t \lesssim \mathbf{2 \cdot 10^3}\,\mathrm{s}$
  - this required an early start of observations, $t > \mathbf{68}\,\mathrm{s}$
- Intrinsic VHE spectum shows marginal softening
  - $\gamma_{\mathrm{VHE}}^{\mathrm{int}} = \mathbf{2.2^{+0.23}_{-0.25}}(\mathrm{statistical})^{+0.21}_{-0.26}(\mathrm{systematic})$
- VHE and X-ray fluxes have a similar (not identical) time evolution
  - $\alpha_{\mathrm{XRT}} = \mathbf{1.36^{+0.02}_{-0.02}}$ and $\alpha_{\mathrm{VHE}}^{\mathrm{int}} = \mathbf{1.51^{+0.04}_{-0.04}}$
- **Evidence (or at least hints) for a two-component SED**

GRB 190829A

- Very close: $z = 0.0785^{+0.0005}_{-0.0005}$
- Detected by GBM and BAT
- Prompt luminosity $\sim 10^{50}\,\mathrm{erg}$ per decade in the X-ray band
- Afterglow luminosity $5\times10^{50}\,\mathrm{erg}$

Hinton (Taup2019)





detected with H.E.S.S. for **3 nights (H.E.S.S. Collaboration 2021)**

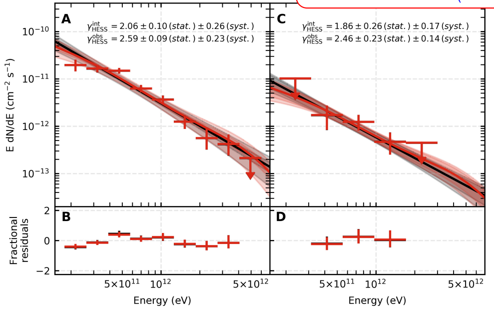
- $T_0+4.3\mathrm{h}$: $\mathbf{21.7\sigma}$
- $T_0+27.2\mathrm{h}$: 5.5σ
- $\boldsymbol{T_0+51.2\mathrm{h}}$: 2.4σ

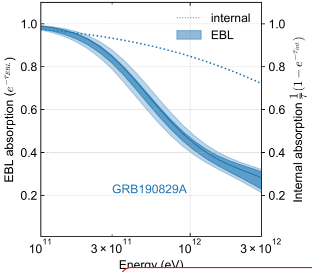
GRB 190829A: VHE spectrum

- Almost model independent of EBL absorption
- Weak internal absorption
- Fit the intrinsic spectrum

$$\frac{dN}{dE} \propto E^{-\gamma_{\rm VHE}^{\rm int}} e^{-\tau_{\rm EBL}} \propto E^{-\gamma_{\rm VHE}^{\rm obs}}$$

H.E.S.S. Collaboration (2021)





H.E.S.S. Collaboration (2021)

Observed spectrum

- night 1: $\gamma_{\rm VHE}^{\rm obs} = 2.59^{+0.09}_{-0.09}$
- night 2: $\gamma_{\rm VHE}^{\rm obs} = 2.46^{+0.23}_{-0.23}$

Intrinsic spectrum

- night 1: $\gamma_{\rm VHE}^{\rm int} = 2.06^{+0.1}_{-0.1}$
- night 2: $\gamma_{\rm VHE}^{\rm int} = 1.86^{+0.26}_{-0.26}$
- all: $\gamma_{\rm VHE}^{\rm int} = 2.07^{+0.09}_{-0.09}$

GRB 190829A: light-curve

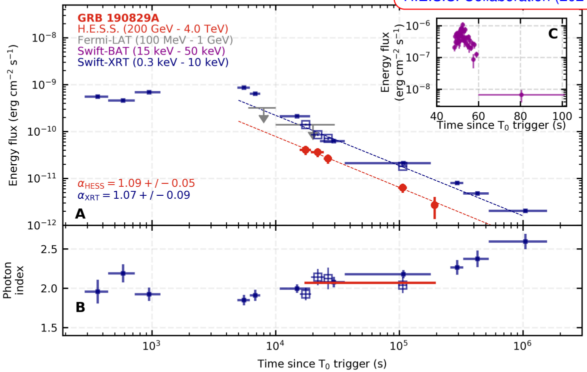
- from 4h to 56h
- 5 data points
- can be directly compared to the X-ray light-curve
- Fit the flux with a power-law decay

$$F_{\rm VHE} \propto t^{-\alpha_{\rm VHE}}$$

$$F_{\rm XRT} \propto t^{-\alpha_{\rm XRT}}$$

- Remarkably consistent slopes ⇒

H.E.S.S. Collaboration (2021)



X-ray decay

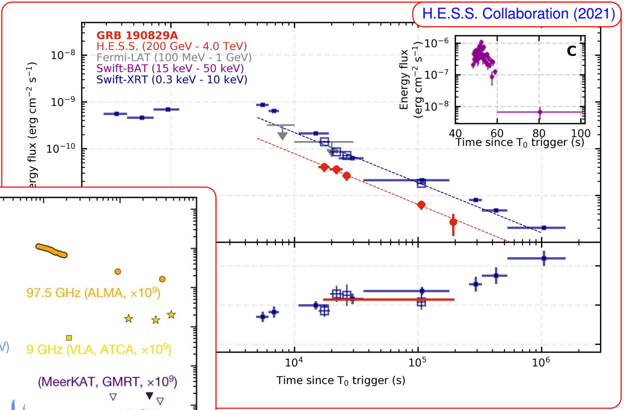
$$\alpha_{\rm XRT} = 1.07^{+0.09}_{-0.09}$$

H.E.S.S. decay

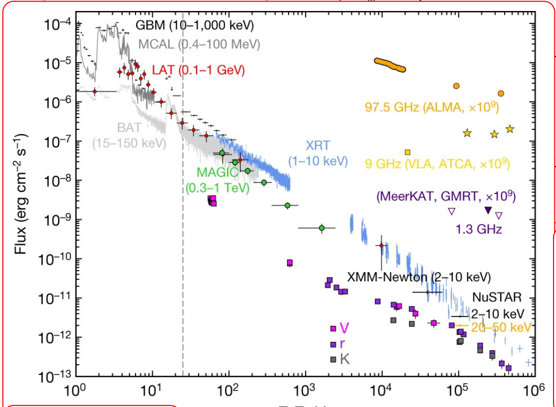
$$\alpha_{\rm VHE} = 1.09^{+0.05}_{-0.05}$$

GRB 190829A: light-curve

- from 4h to 56h
- 5 data points
- can be directly compared to the X-ray



H.E.S.S. Collaboration (2021)



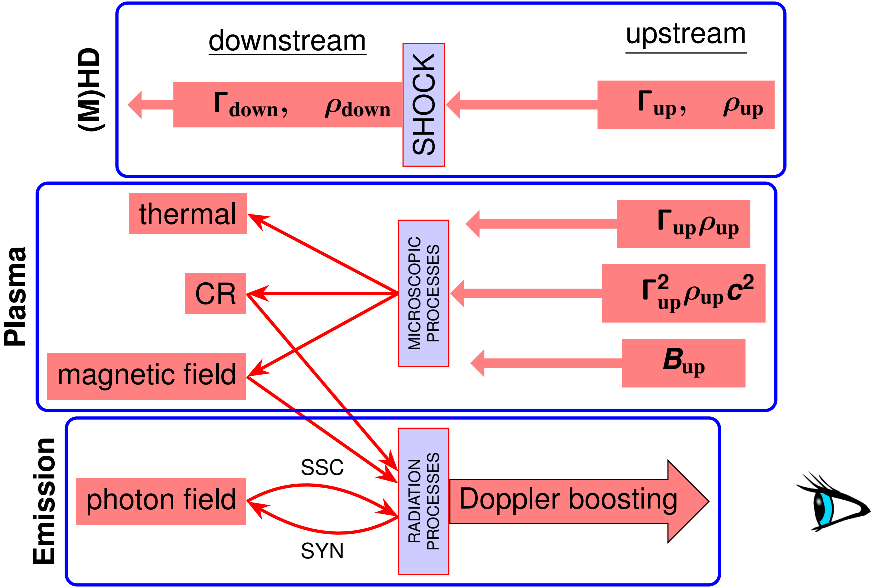
MAGIC Col. 2019

- ✔ For two GRBs with VHE light-curves we see decays identical to the X-ray band
- ✔ Slopes are quite different **1.1** vs **1.5**

GRB 190829A: summary of the observational results

- Remarkably broad spectrum measurement, between **180 GeV** and **3.3 TeV**
  - this required a close GRB, with $z_{\rm rs} < 0.1$
- Spectrum measurement close independent on EBL model
  - this required a close GRB, with $z_{\rm rs} < 0.1$
- Multi-day VHE light-curve, between **4 h** and **56 h**
  - this required a close GRB of that power
- Intrinsic VHE spectral slope matches the slope of the X-ray spectrum
  - $\gamma_{\rm XRT} = \mathbf{2.03^{+0.06}_{-0.06}}$ and $\gamma_{\rm VHE}^{\rm int} = \mathbf{2.06^{+0.1}_{-0.1}}$ (both for 1$^{\rm st}$ night)
- VHE and X-ray fluxes have a similar time evolution
  - $\alpha_{\rm XRT} = \mathbf{1.07^{+0.09}_{-0.09}}$ and $\alpha_{\rm VHE}^{\rm int} = \mathbf{1.09^{+0.05}_{-0.05}}$
- **Extrapolation of the X-ray spectrum to the VHE domain matches the slope and flux level measured with H.E.S.S.**

Afterglow emission: simple radiative model



Computing One-Zone SED

- Three ingridients are needed to calculated radiation
  1. Non-thermal particles
  2. Target fields (magneic + photons)
  3. Bulk Lorentz factor
  4. Attenuation
- Simple SSC model
  1. **Non-thermal particles: assumed**
  2. Target fields (magneic: assumed + photons: syn. photons)
  3. Bulk Lorentz factor: assumed or simple hydro (important for LC)
  4. Attenuation: syn. photons

Computing One-Zone SED

- Three ingridients are needed to calculated radiation
  1. Non-thermal particles
  2. Target fields (magneic + photons)
  3. Bulk Lorentz factor
  4. Attenuation
- SSC model
  1. Non-thermal particles: injection spectrum is assumed, particles are computed accounting for syn., IC, ad. losses
  2. Target fields (magneic: assumed + photons: syn. radiation)
  3. Bulk Lorentz factor: assumed or simple hydro (important for LC)
  4. Attenuation: syn. photons

Computing One-Zone SED

- Thr
  1.
  2.
  3.
  4.
- SS(
  1. rticles
  2. on)
  3. for LC)
  4.

it may seem that the differences between these two approaches are minor as

$$\frac{dN}{d\gamma} = \frac{1}{|\dot\gamma|}\int\limits_{\gamma}^{\infty} q(\gamma')d\gamma'$$

and

$$q(\gamma') = -\frac{d}{d\gamma}\left[\frac{dN}{d\gamma}|\dot\gamma|\right]$$

so by "simple SSC modelling" one determines the injection spectrum. However, one needs to remember that injection is strictly positive, $q > 0$. Also the injection spectrum may depends on M(HD) **and non-thermal particles** (e.g., Derishev&Piran 2019, more on that in the next talk(?))

Internal $\gamma - \gamma$ absorption and the Klein-Nishina effect

GRBs produced a lot of high-energy photons, these photons make an important target for the IC emission and may provide target for VHE gamma rays. There are important consequences:

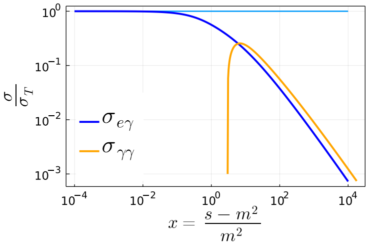
- The Klein-Nishina cutoff
- Internal $\gamma - \gamma$ attenuation

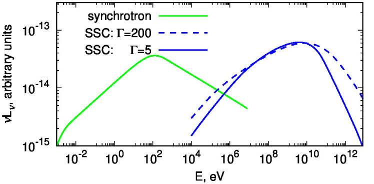
These effects are important if

$$1 < \frac{\hbar\omega_{\rm syn}E}{\Gamma^2 m_e^2 c^4} \approx \frac{4\times10^3}{\Gamma^2}\omega_{\rm syn,keV}E_{\rm TeV}$$

Internal $\gamma - \gamma$ optical depth

$$\tau \approx \frac{\sigma_{\gamma\gamma}L_{\rm X}}{10\varepsilon_{\rm X}cR\Gamma^2} \propto E^{-1/2}$$





Internal $\gamma - \gamma$ absorption and the Klein-Nishina effect

GRBs produced a lot of high-energy photons, these photons make an important target for the IC emission and may provide target f… important c…

- The Kl…
- Interna…

These effec…

$$1 < \frac{\hbar\omega \ldots}{\Gamma^2 \ldots}$$

Internal $\gamma - \gamma$ optical depth

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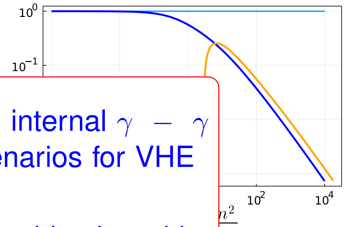
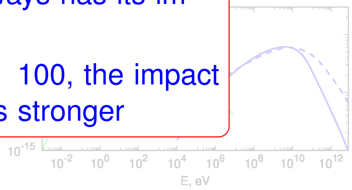


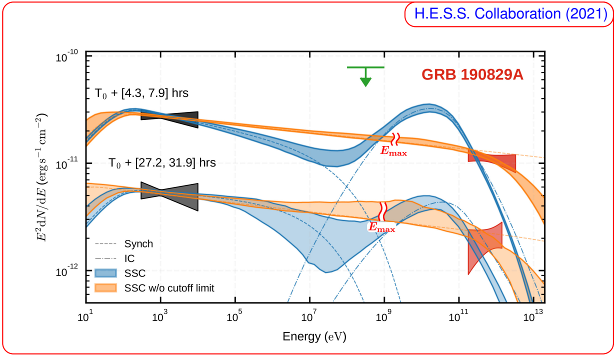


- The Klein-Nishina cutoff and internal $\gamma - \gamma$ need to be accounted in scenarios for VHE emission
- Internal $\gamma - \gamma$ can be considerably altered by a change in the model parameters
- The Klein-Nishina cutoff always has its imprint on the VHE spectrum
- At late epochs, when $\Gamma \ll 100$, the impact of the Klein-Nishina cutoff is stronger

GRB 190829A: MWL modelling

Five dimensional MCMC fitting of the X-ray and TeV spectra

- magnetization, η_B
- energy in electrons, η_e
- cooling break, E_{br}
- cutoff energy, E_{cut}
- powerlaw slope, β_2



Electron spectrum

$$f(E') = \exp\left(-\frac{E'}{E_{cut}}\right)\begin{cases} AE'^{-(\beta_2-1)} & : E' < E_{br} \\ AE_{e,br}E'^{-\beta_2} & : E' > E_{br}\end{cases}$$

$E_{cut} < E_{syn}^{MAX}$

$E_{cut} > E_{syn}^{MAX}$

Can we exclude SSC scenario?

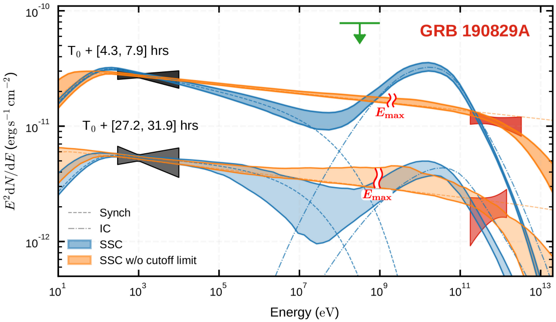
Our numerical analysis is limited to a

- One-zone model
- Power-law distribution of electrons
- Five-dimensional parameter space

Our analytic analysis takes some “must-have” elements

- One-zone model
- X-ray to VHE flux ratio
- X-ray spectral index
- VHE spectral index

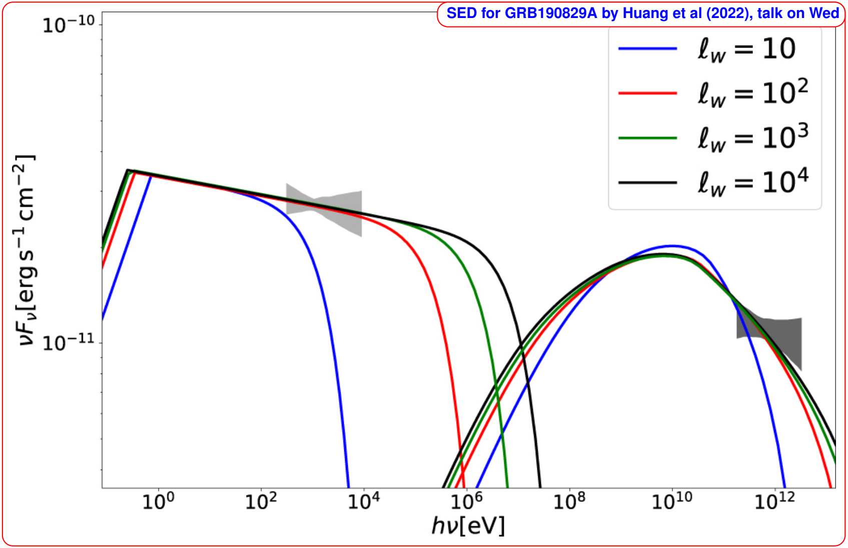
H.E.S.S. Collaboration (2021)



Under our assumptions we obtained that

- SSC can be responsible only under extreme assumptions for the magnetic field strength (e.g., very weak) and low radiation efficiency
- Alternatively we can fit the data if adopt a much larger bulk Lorentz factor

Can we exclude SSC scenario?



Summary I

- GRB afterglow are essential for studying relativistic shocks, including two processes with extremely broad implications: **magnetic field amplification** and **acceleration** of high-energy particles
- While there are little doubles that bright X-ray – soft-gamma-ray emission is synchrotron radiation of accelerated electrons, this component alone does not allow determining the particle energy
- Detection of the IC component is a key element for resolving magnetic field – particle energy degeneracy of the X-ray component
- Conventionally, synchrotron emission cannot extend beyond $\hbar\omega_{\rm MAX} = \mathbf{20(\Gamma/100)\,GeV}$, thus VHE band is the critical window for constraining the parameters of the downstream
    - defining the magnetic field amplification
    - constraining particle acceleration, in particular, the maximum energy
- Detection of GRB190114C (MAGIC) and GRB190829A (H.E.S.S.) provides a unique chance for understanding the properties of relativistic shocks