Observational properties of TeV GRBs and physical implications

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Image Credit: Gabriel Pérez Díaz, IAC

Gamma-Ray Burst (GRB)

- **Biggest explosion in the universe** **(E_{iso} ~ $10^{48\text{-}54}$ erg)**
- Extragalactic object, isotropic distribution
- Two emission classes
  - prompt emission
    - mainly in MeV range, short-time variability
    - Long GRBs (T > ~2 sec), short GRBs (T < ~2 sec)
  - afterglow emission
    - multiwavelength from radio to GeV gamma ray, power-law decay
- Highly relativistic jet (Γ_{bulk} > 100)
  - Launching mechanism unknown (fireball model, B reconnection)
- Possible progenitors
  - Core-collapse supernova (for long GRBs)
  - Neutron star merger (for short GRBs)

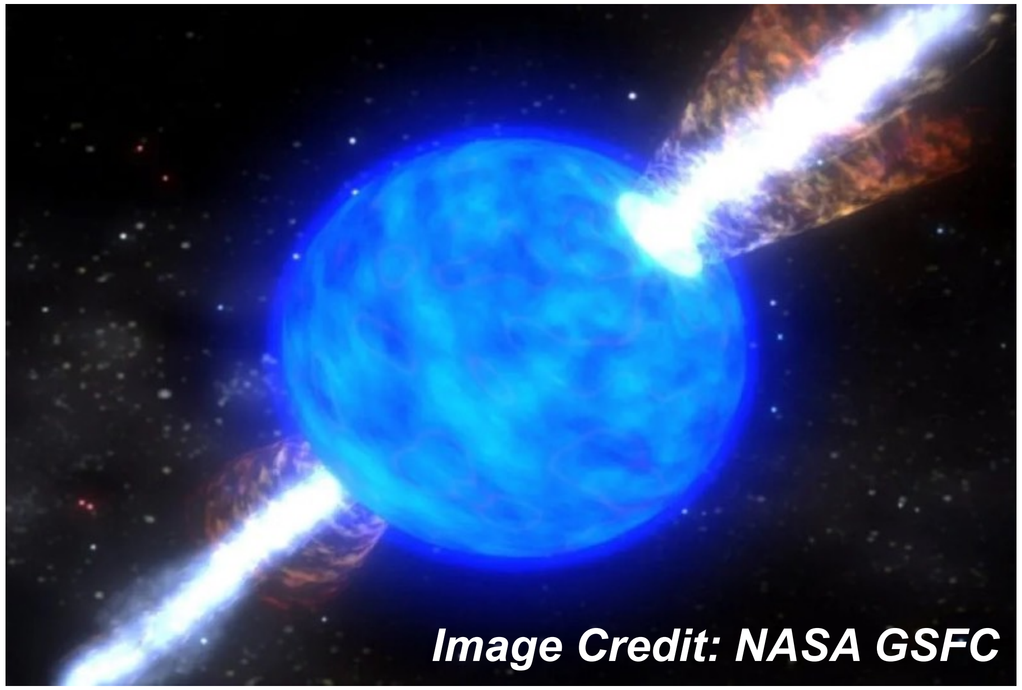


Image Credit: NASA GSFC

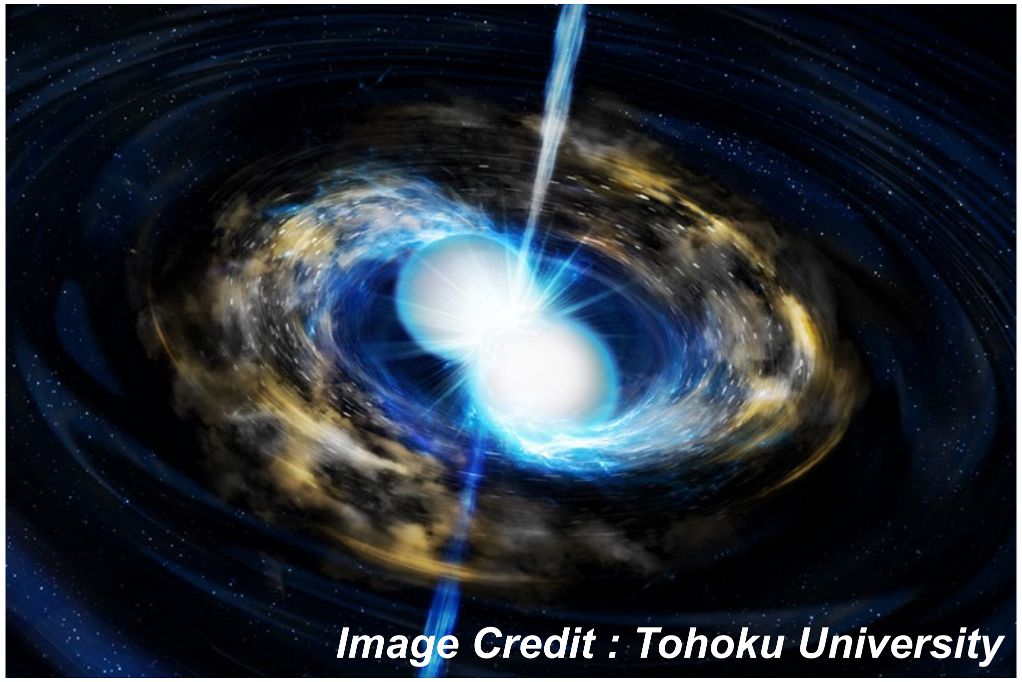
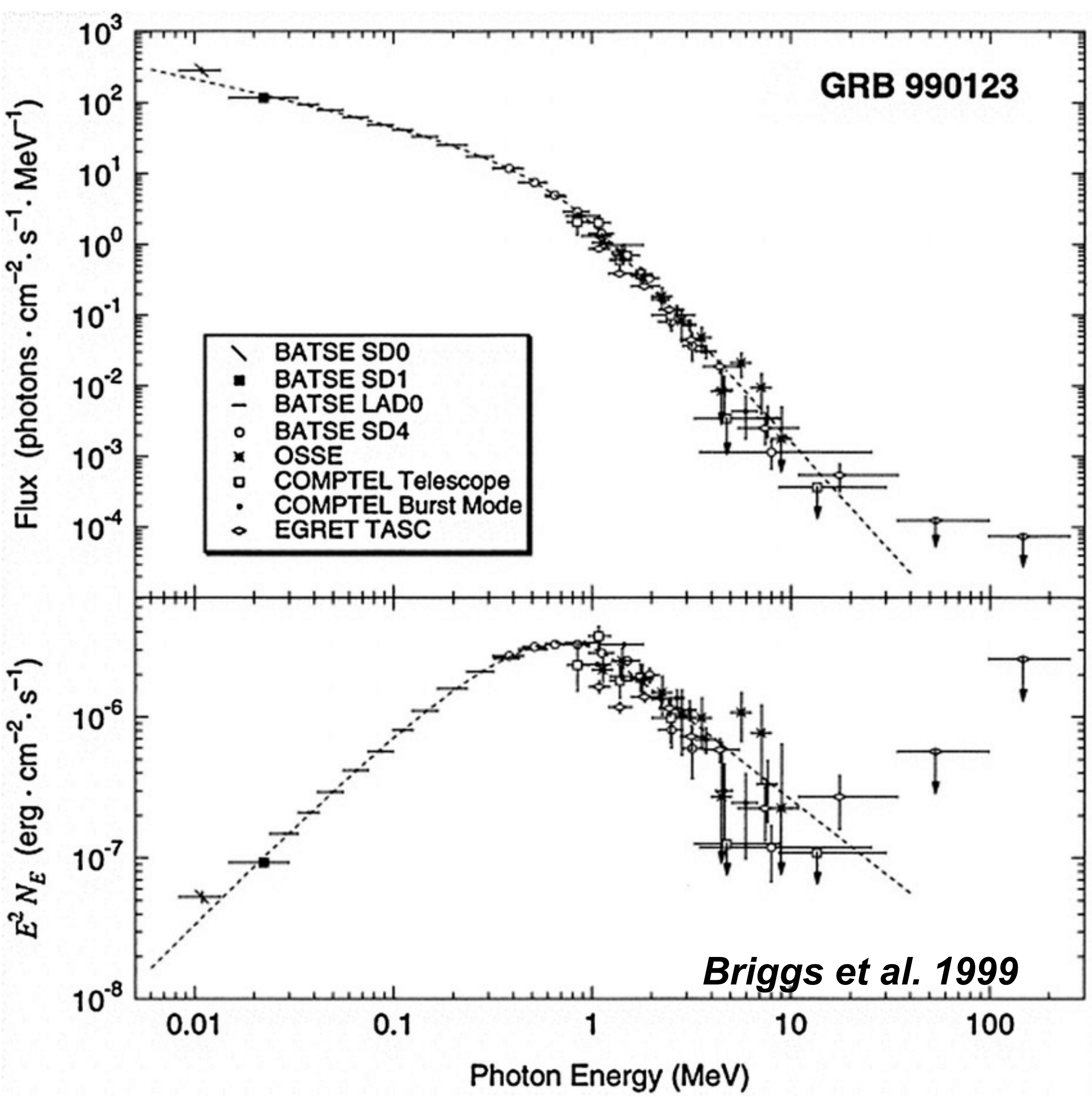


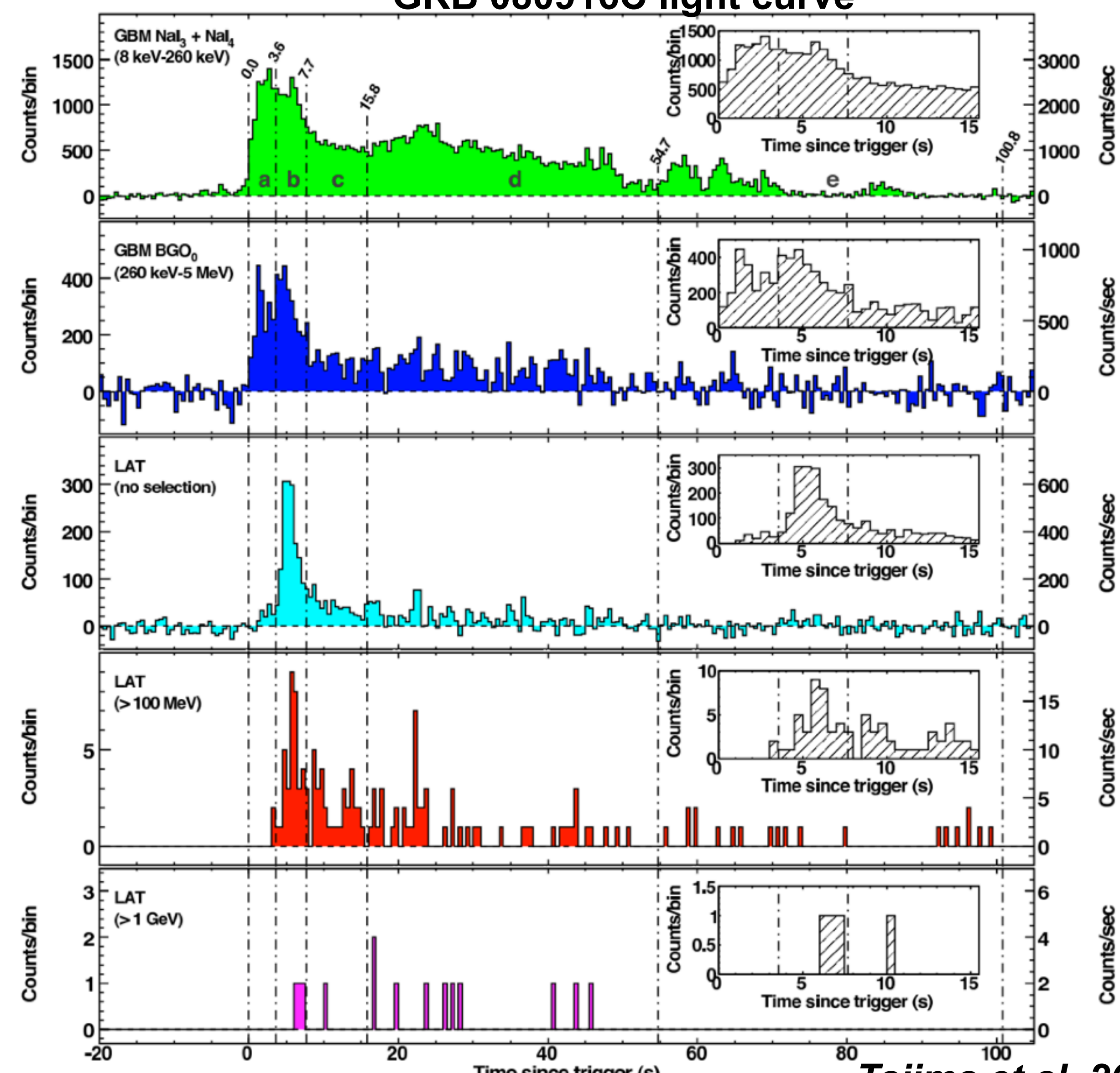
Image Credit : Tohoku University

Prompt emission

- Emission features (mechanism still unknown):
  - Broken power-law spectrum (Band Function) with peak energy (E_{peak}) 0.1-1 MeV
  - Time variability down to millisec -> emission region should have Γ>100 to be optically-thin
  - Empirical correlation between E_{peak} and E_{iso}/L_{iso} (Amati/Yonetoku relation)



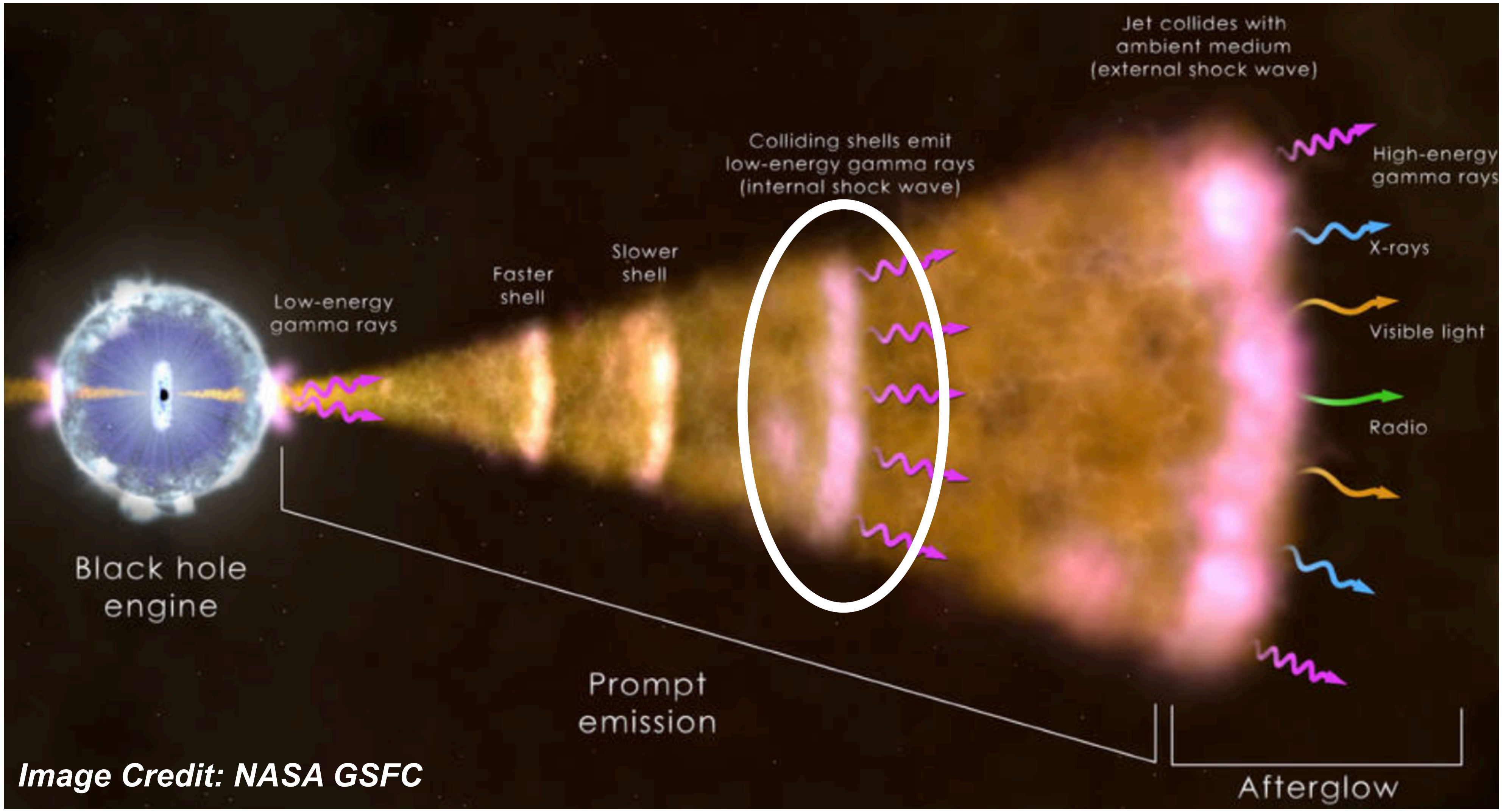
GRB 080916C light curve

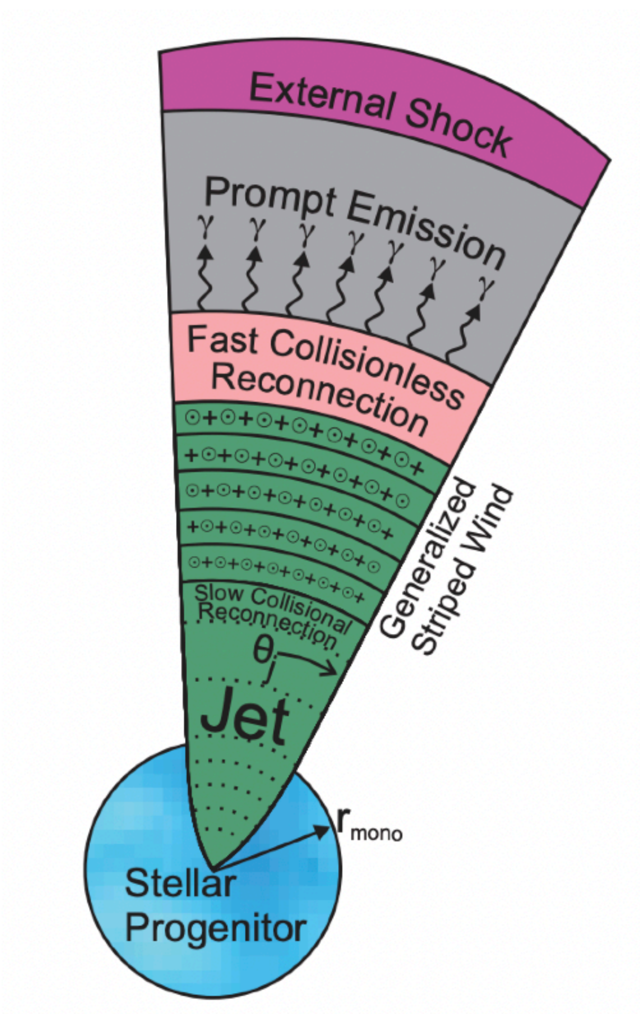


Tajima et al. 2009

Prompt emission

- Possible mechanisms
  - Synchrotron (inverse Compton) emission from internal shock
  - Thermal emission from expanding fireball (photosphere emission)
  - Magnetic reconnection in *B*-dominated jet



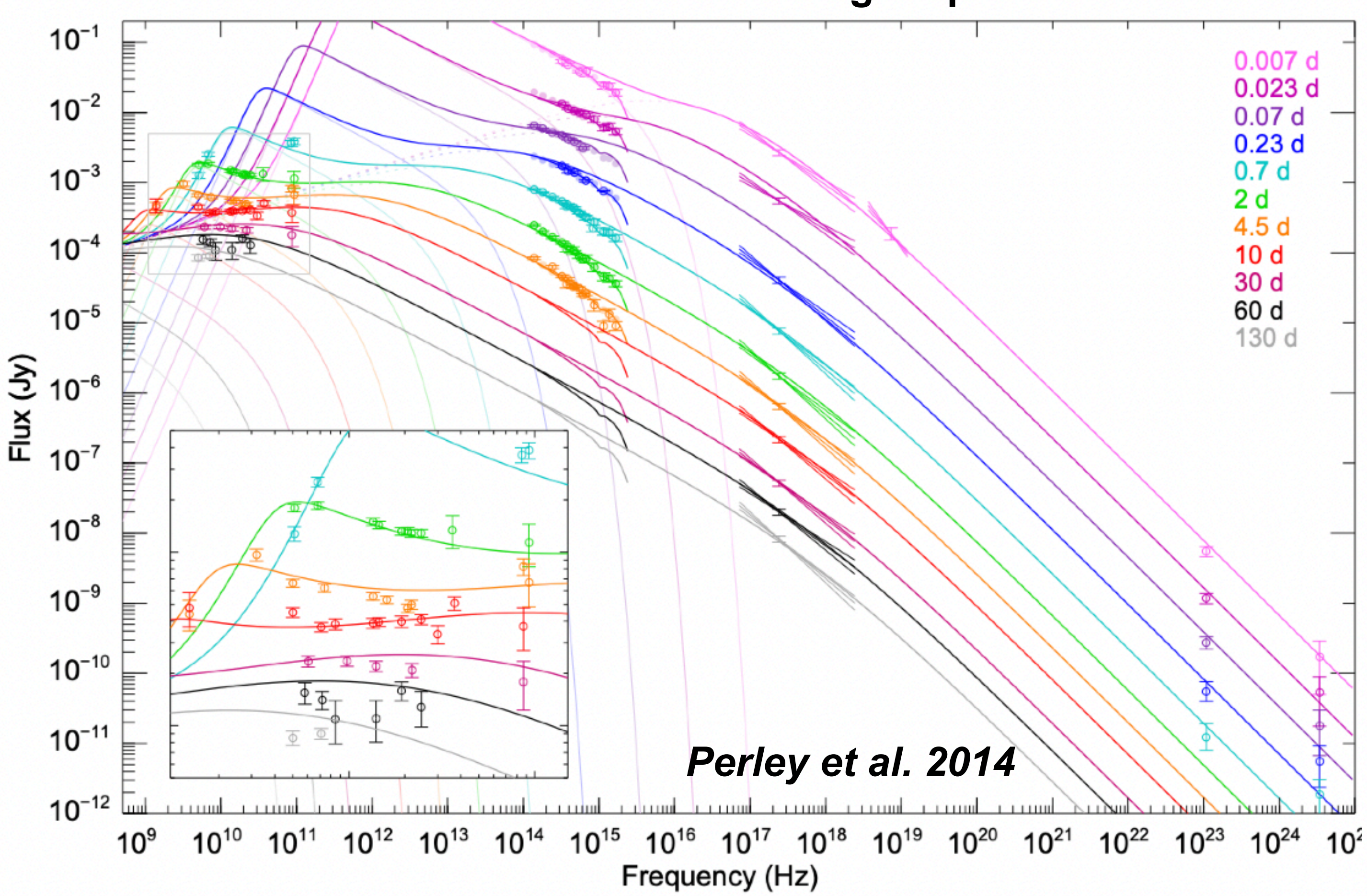


McKinney & Uzdensky 2012

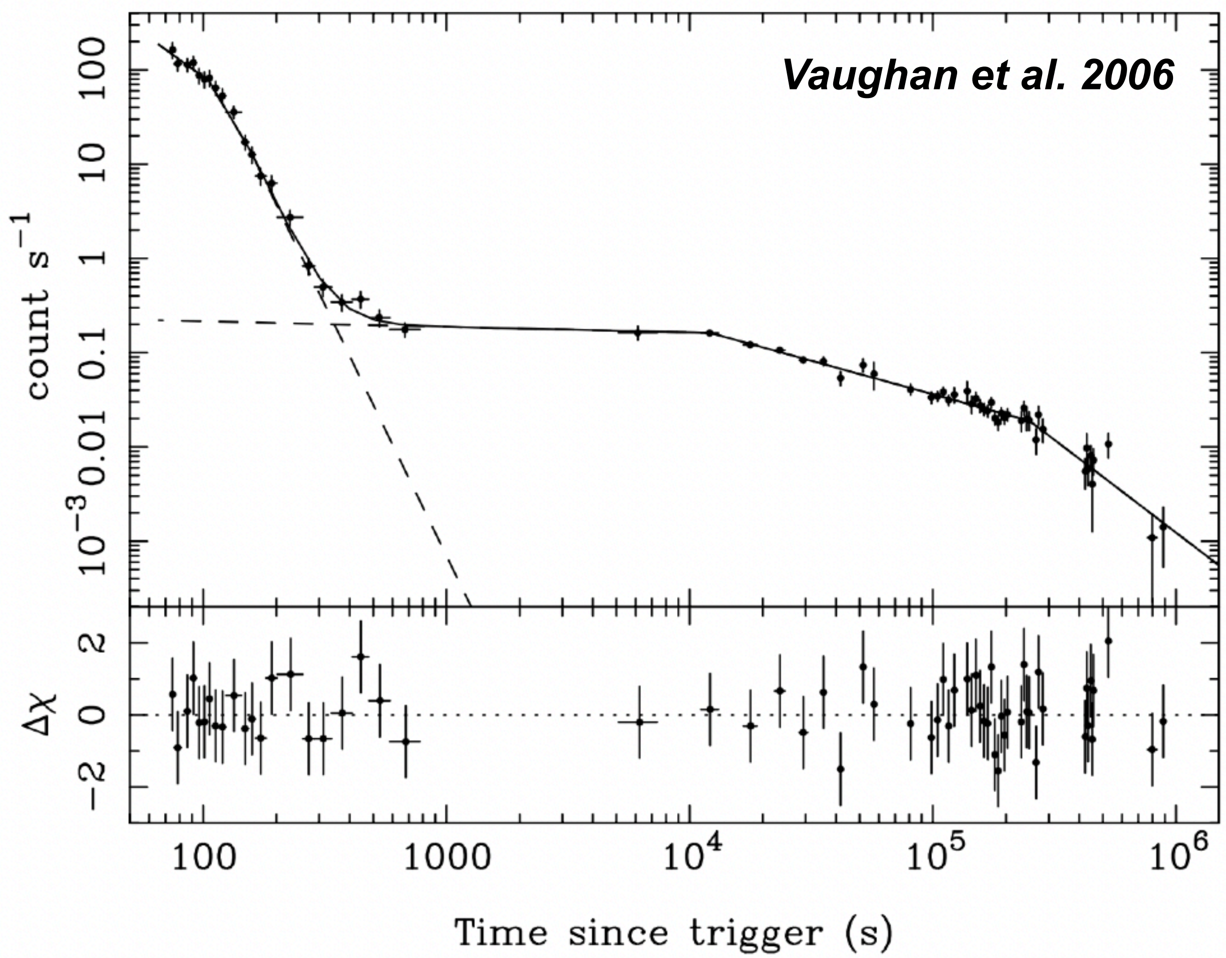
Afterglow emission

- Emission features:
  - Power-law spectrum with a few breaks at different energy bands
  - Power-law temporal decay with a few breaks (chromatic and achromatic)
  - Complicated temporal evolution / flares in early time in some GRBs

GRB 130427 multiwavelength spectrum

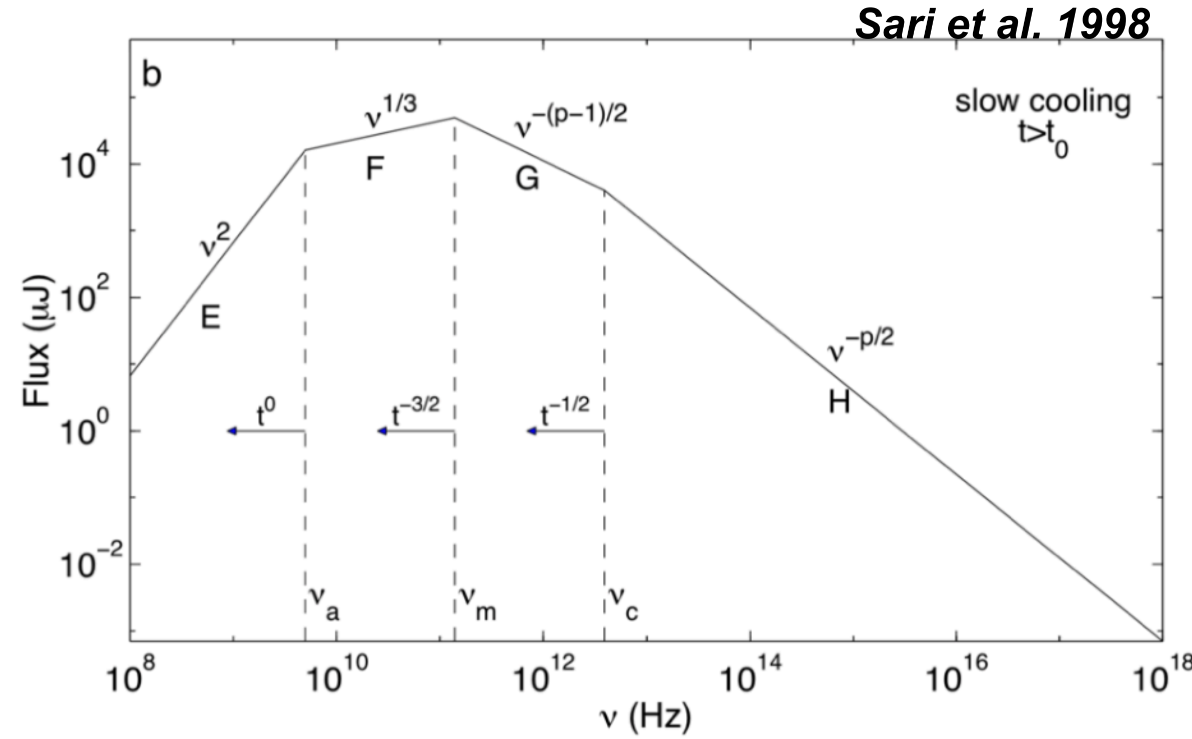


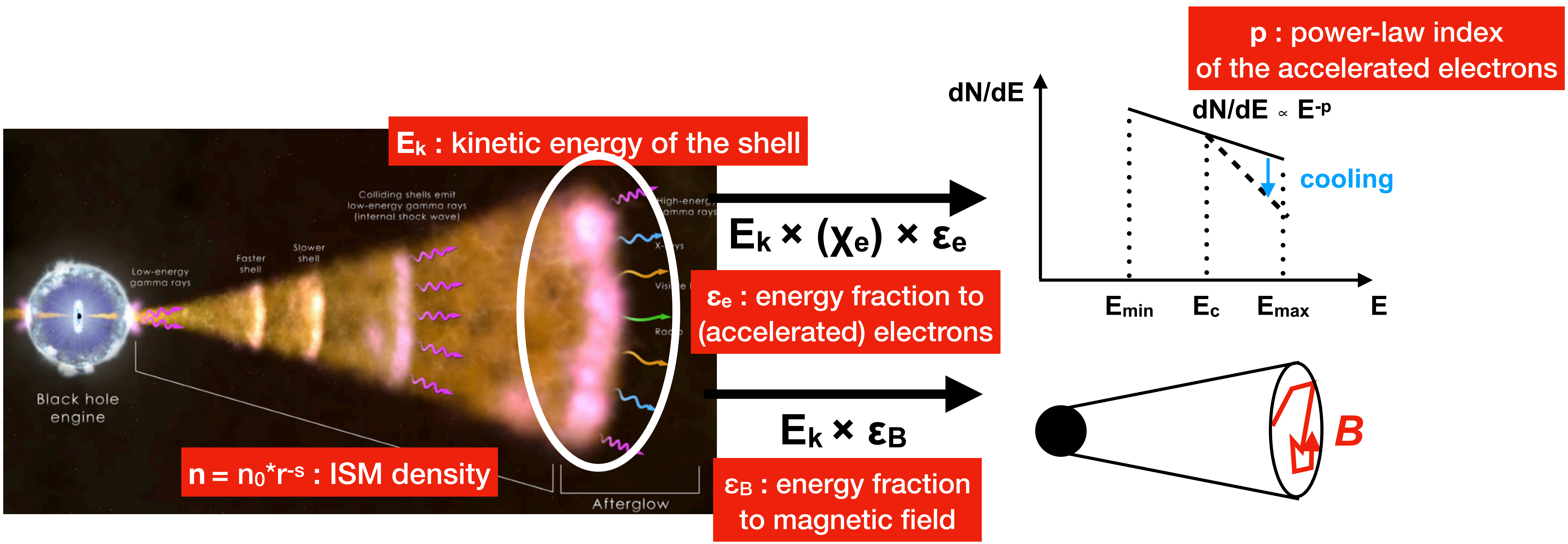
GRB 050315 X-ray light curve



Afterglow emission

- Standard emission mechanism is synchrotron from external shock
  - only ~5 free physical parameters in the model
- Explain late-time afterglow emission well for most of the GRBs

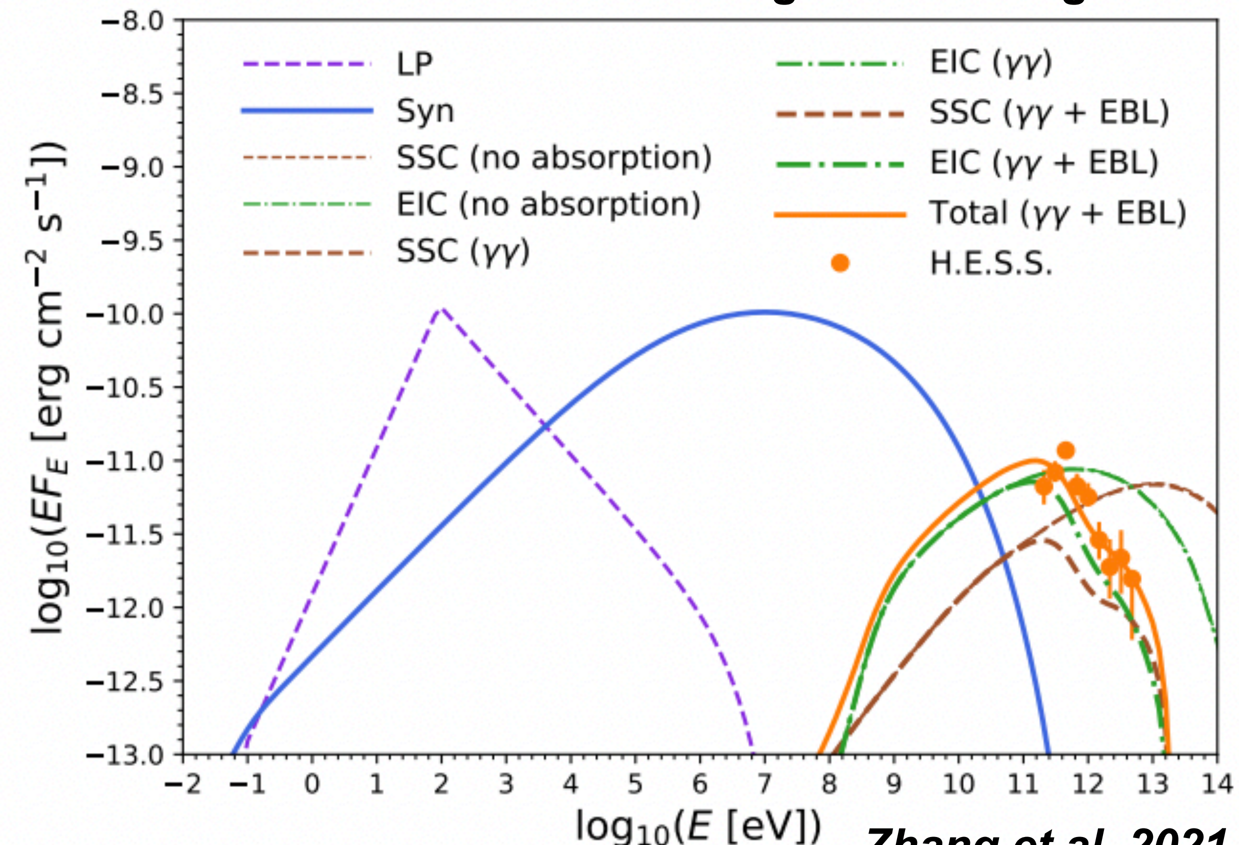




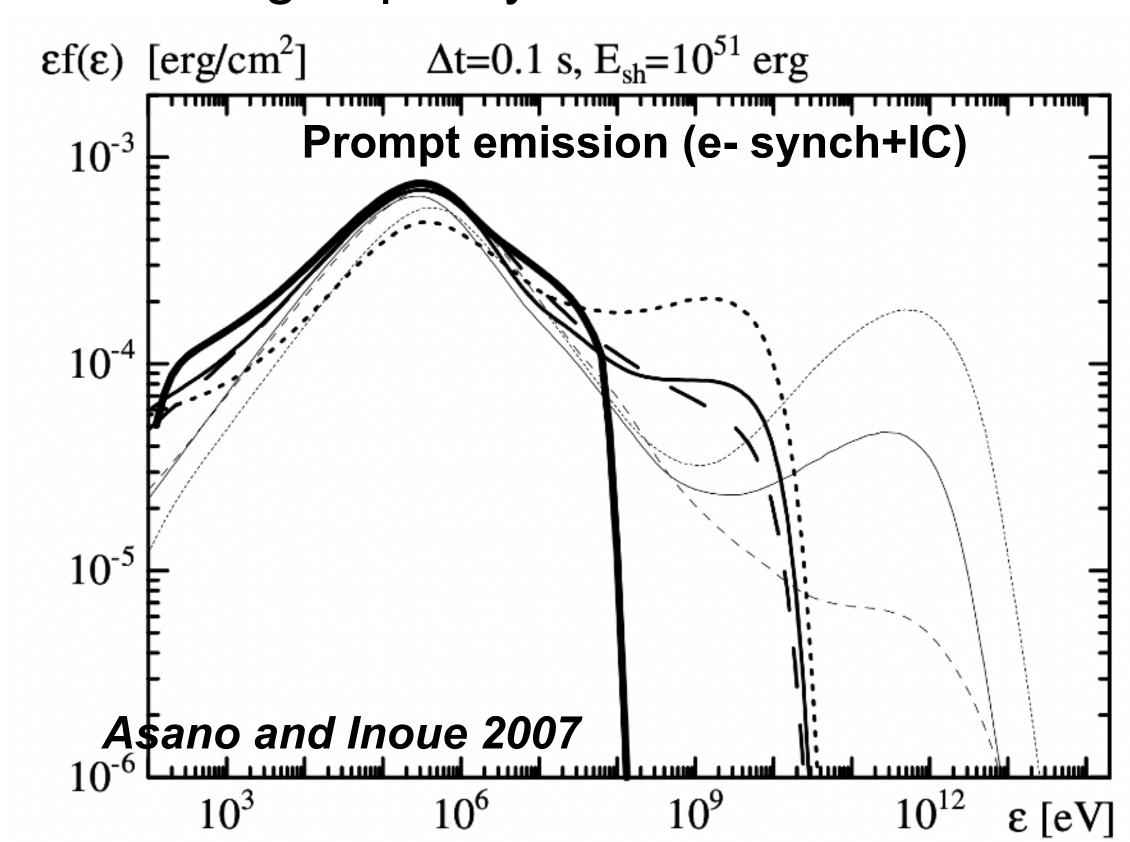
High-Energy gamma-ray emission from GRBs

- Leptonic model :
  - Synchrotron Self-Compton (SSC) emission naturally expected
  - External photon-field inverse Compton (EIC) might be also possible
- For prompt emission, GeV-TeV IC component might be suppressed due to Klein-Nishina effect/high opacity

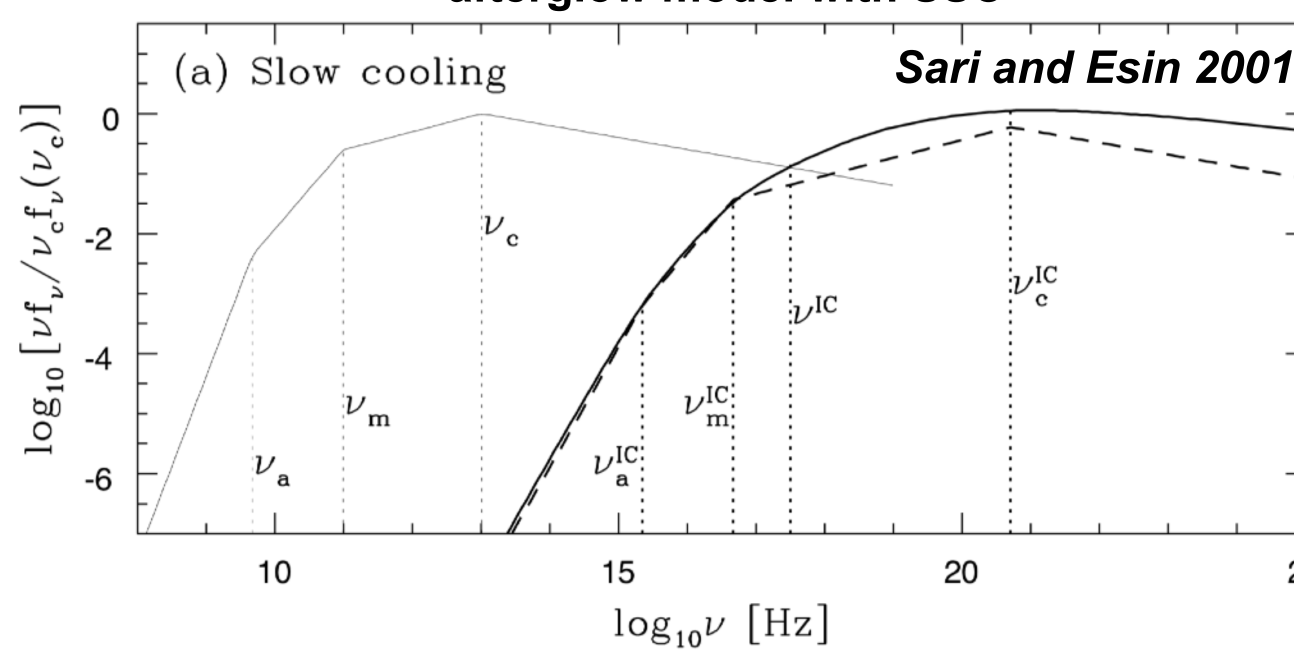
GRB 190829A afterglow modeling



Zhang et al. 2021



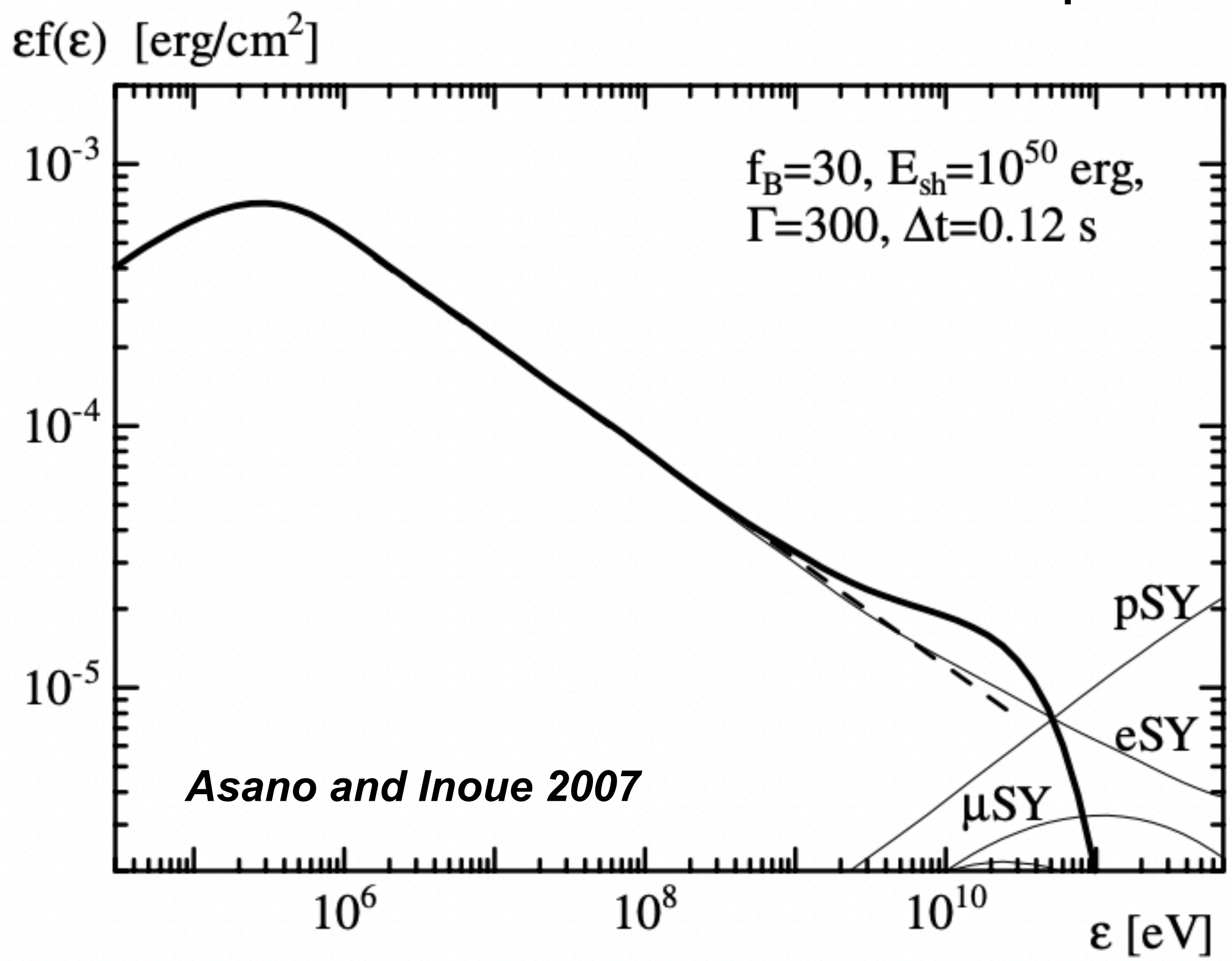
afterglow model with SSC



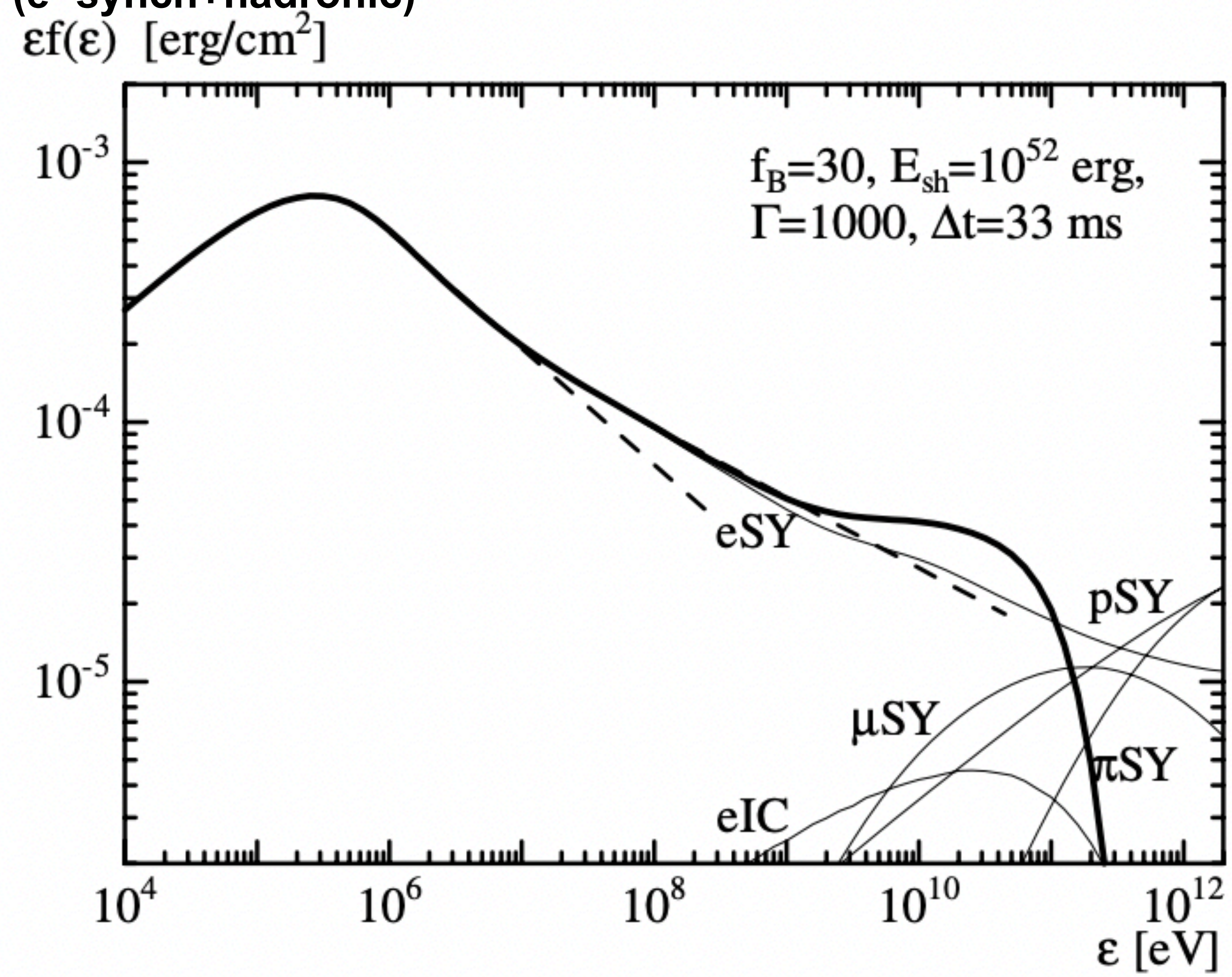
High-Energy gamma-ray emission from GRBs

- hadronic model : UHE cosmic rays
  - emission from photo-meson interaction secondaries
    - electromagnetic cascade
    - muon/pion synchrotron
  - UHE proton synchrotron

Prompt emission (e- synch+hadronic)



Asano and Inoue 2007



TeV gamma-ray observations of GRBs

- So far 5 GRBs have been detected at very high energy (**VHE, > 50 GeV**) gamma rays.

    - GRB 180720B (H.E.S.S.) : a long GRB (z 0.65, E_{iso} $6*10^{53}$ erg @ 50-300 keV)
    - **GRB 190114C** (MAGIC) : a long GRB (z 0.42, E_{iso} $3*10^{53}$ erg @ 1-10^4 keV)
    - **GRB 190829A** (H.E.S.S.) : a low-L long GRB (z 0.078, E_{iso} $2*10^{50}$ erg @ 10-1000 keV)
    - GRB 201216C (MAGIC) : a long GRB (z 1.1, E_{iso} $6*10^{53}$ erg @ 10-1000 keV)
    - **GRB 221009A (LHAASO)** : a long GRB (z 0.15, E_{iso} $2*10^{54}$ erg @ 10-1000 keV)

- Synchrotron Self-Compton (SSC) by relativistic electrons can explain the VHE emission for at least the first 2 GRBs.

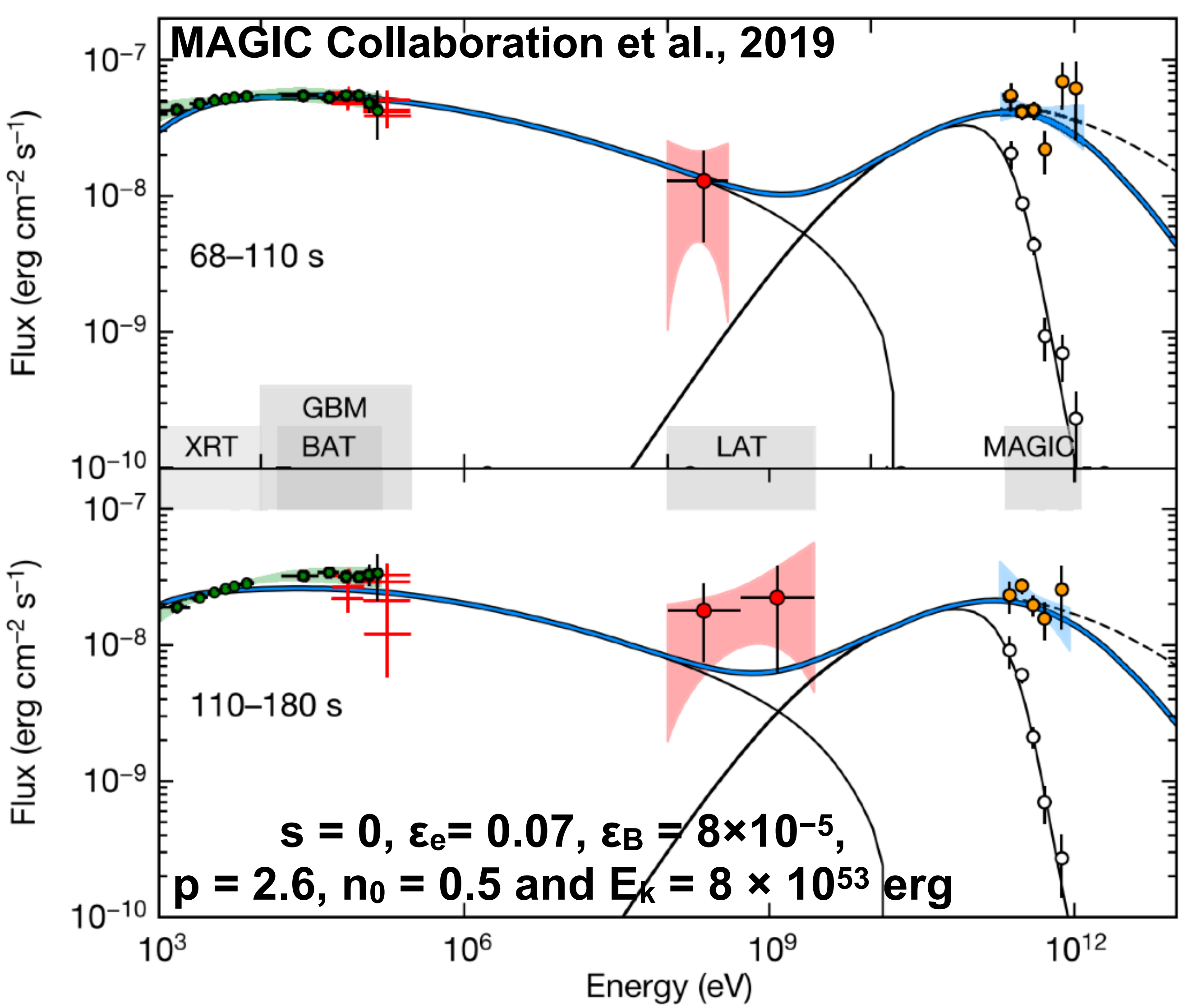
    - two-bump spectral feature in afterglow, E_{iso}-E_{peak} correlation -> analogy with AGNs (see Andrea's talk)

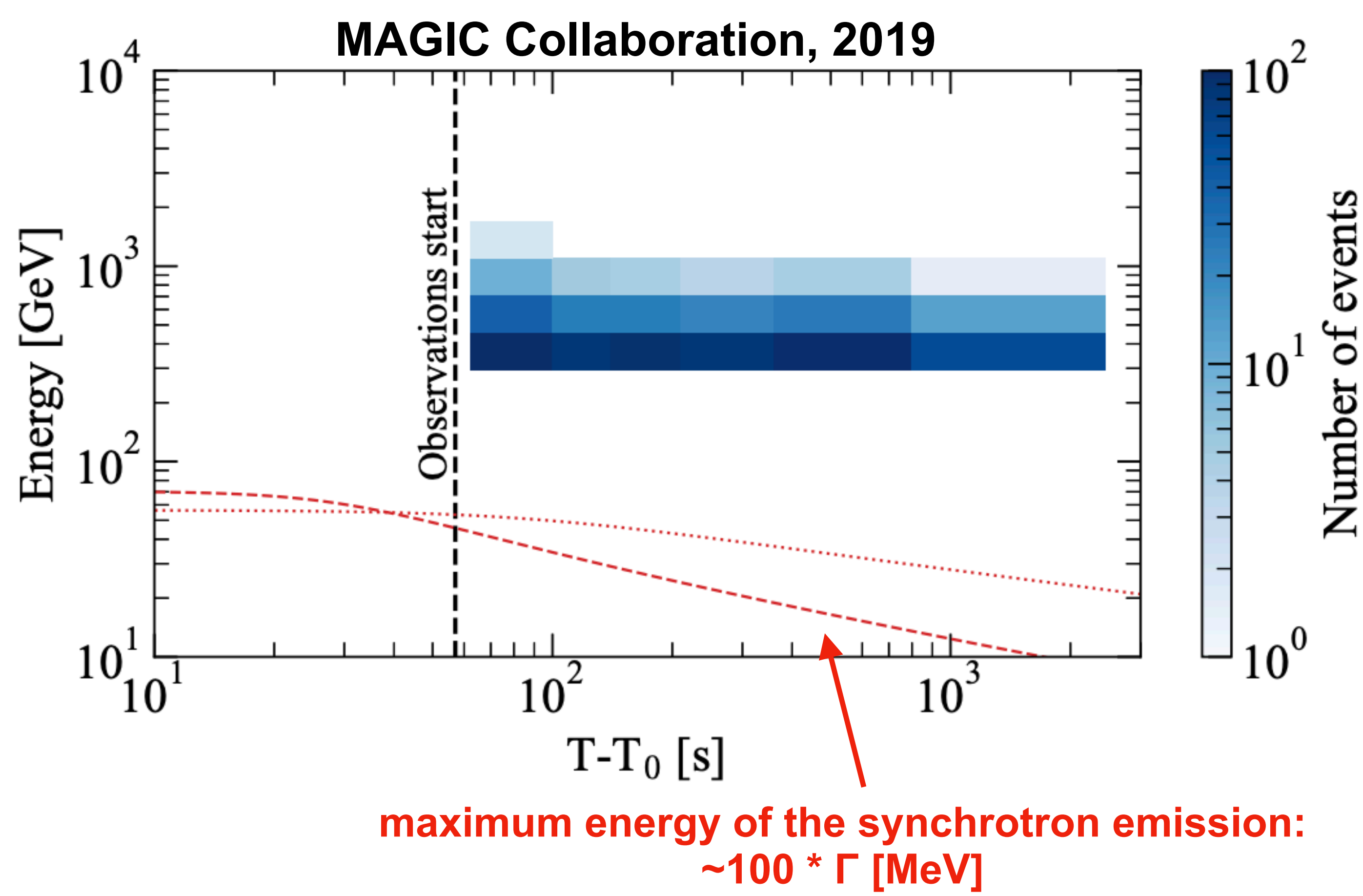
- All of them are detected during the afterglow phase except for LHASSO one

    - no published info on prompt or afterglow for the LHASSO one, only the detection within T_0+2000 s is announced (GCN circular 32677)

GRB 190114C

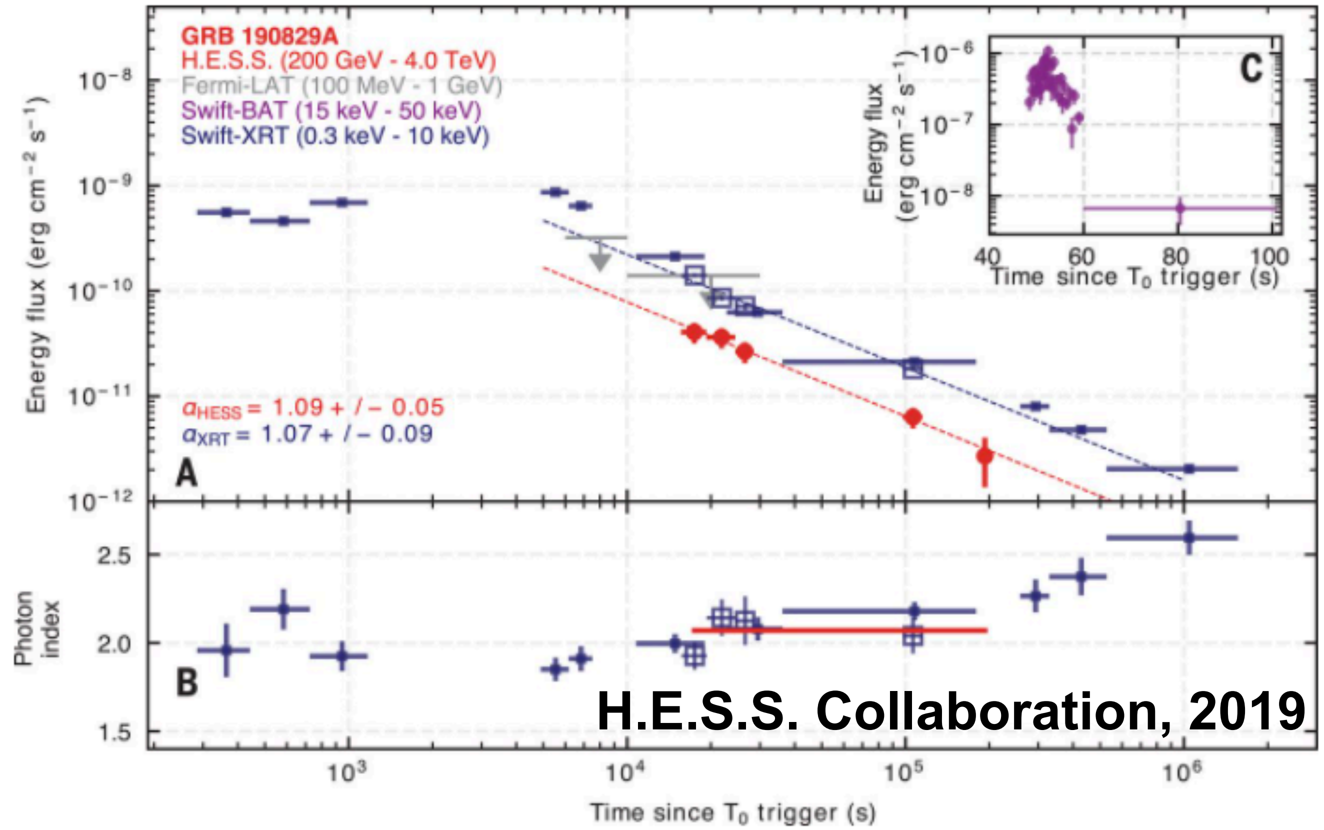
- bright long GRB (z 0.42)
- 50 sigma for the first 20 min
- evidence of a different component from synchrotron emission (above burn-off limit)
- detailed modeling of X-ray to VHE γ-ray consistent with the synchrotron + inverse Compton (synchrotron-self Compton)

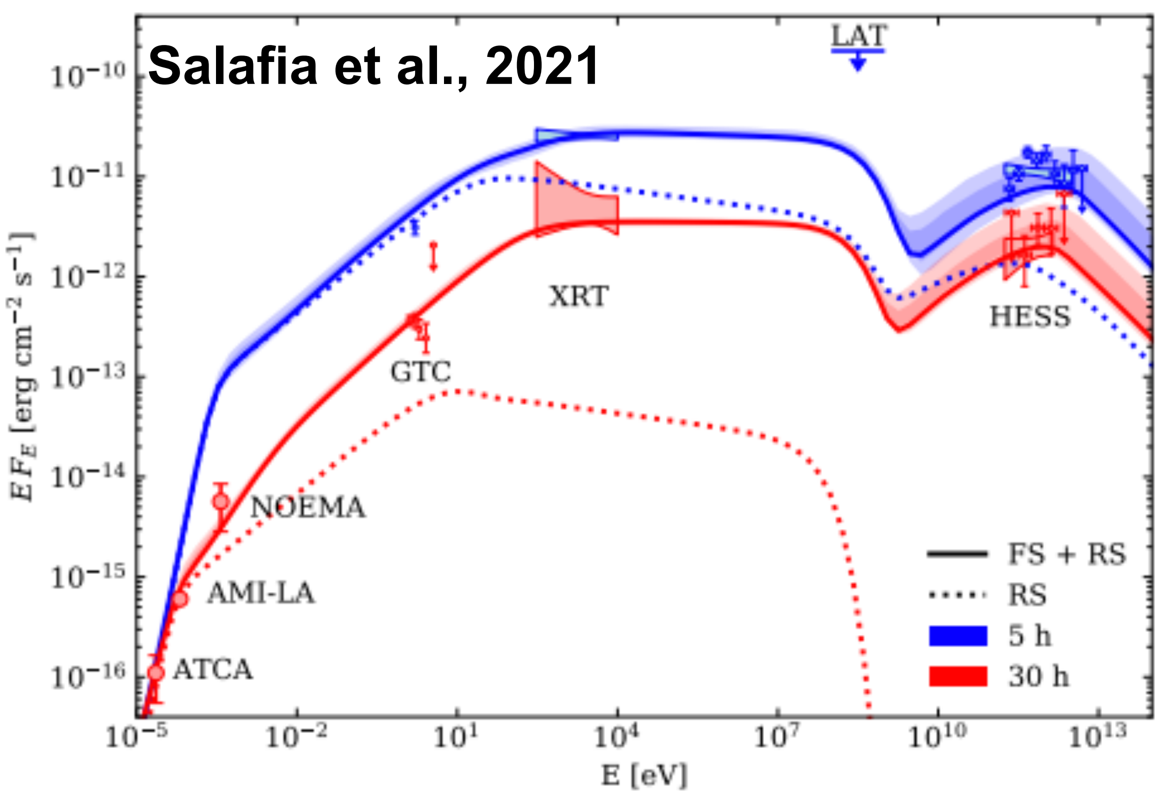




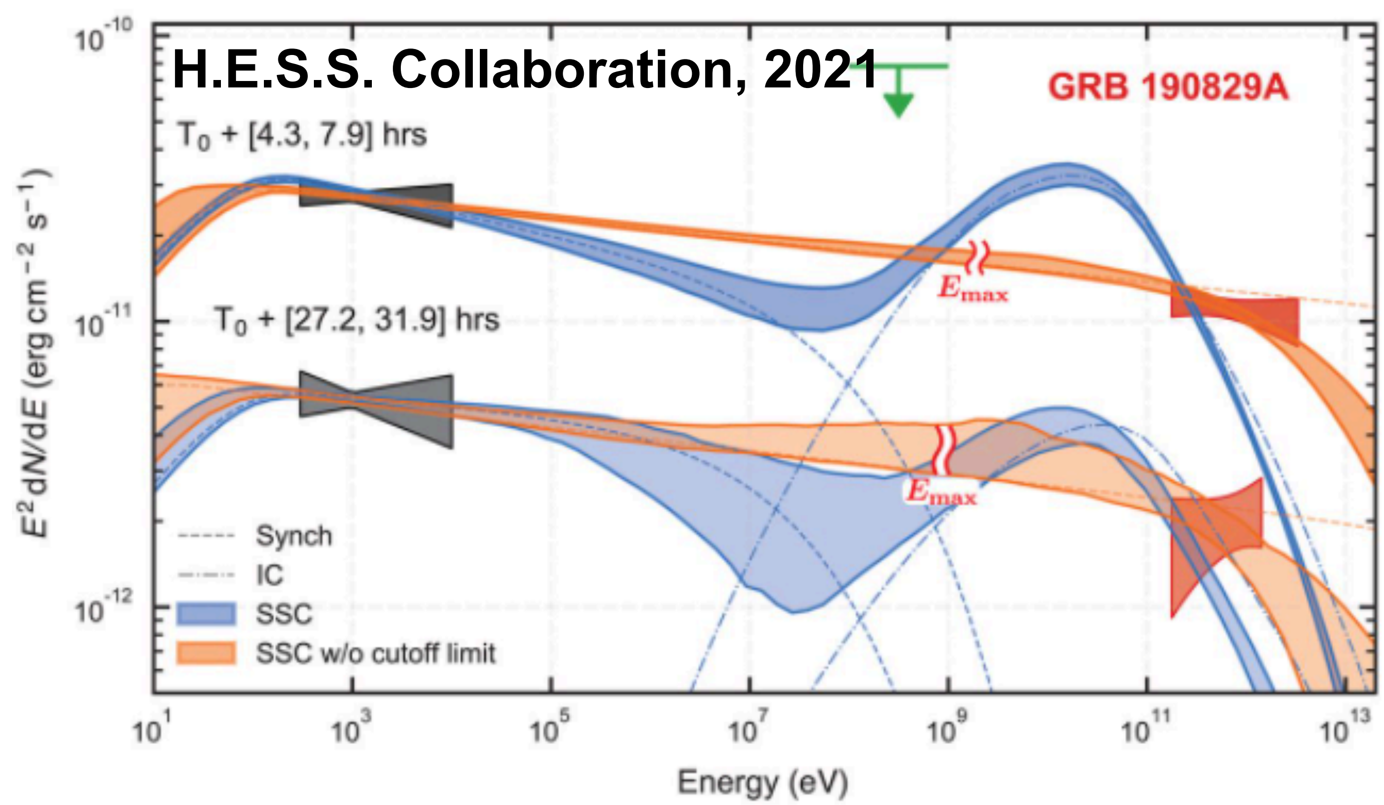
GRB 190829A

- low-L (E_{iso}: 10^{50} erg), nearby (z 0.078)
- significant excess even after 2 days
- emission mechanism is still under debate (both synchrotron alone and syncrotron + IC exist)





$s = 0$, $\varepsilon_e = 0.03$, $\varepsilon_B = 5\times10^{-5}$, $p = 2.0$:
simiar to the ones of GRB 190114C



GRB 221009A

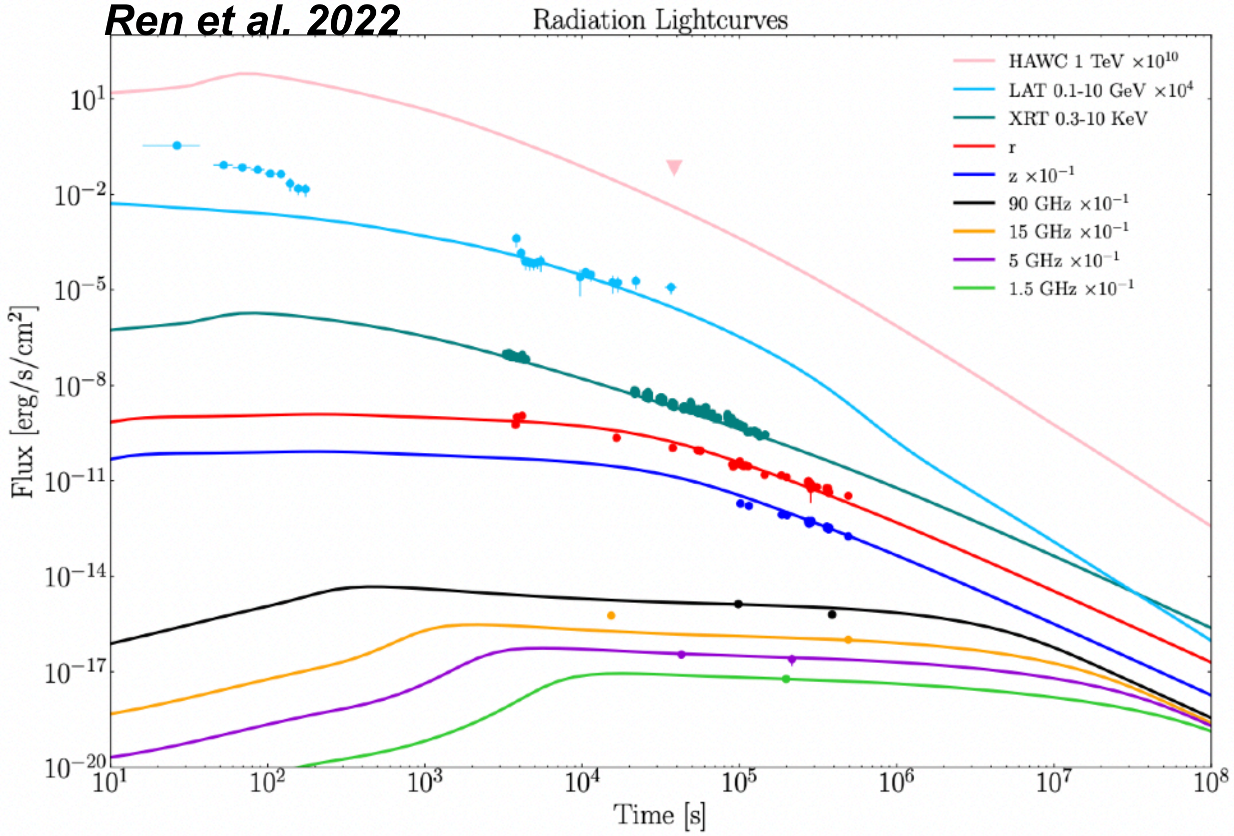
- Brightest of All Time (BOAT)
  - Emission modelling is far from concluded (LHAASO result not yet published)
  - Prompt emission might be detected
  - Late-time afterglow might be explained as the standard sync+SSC

See Volodymyr's talk

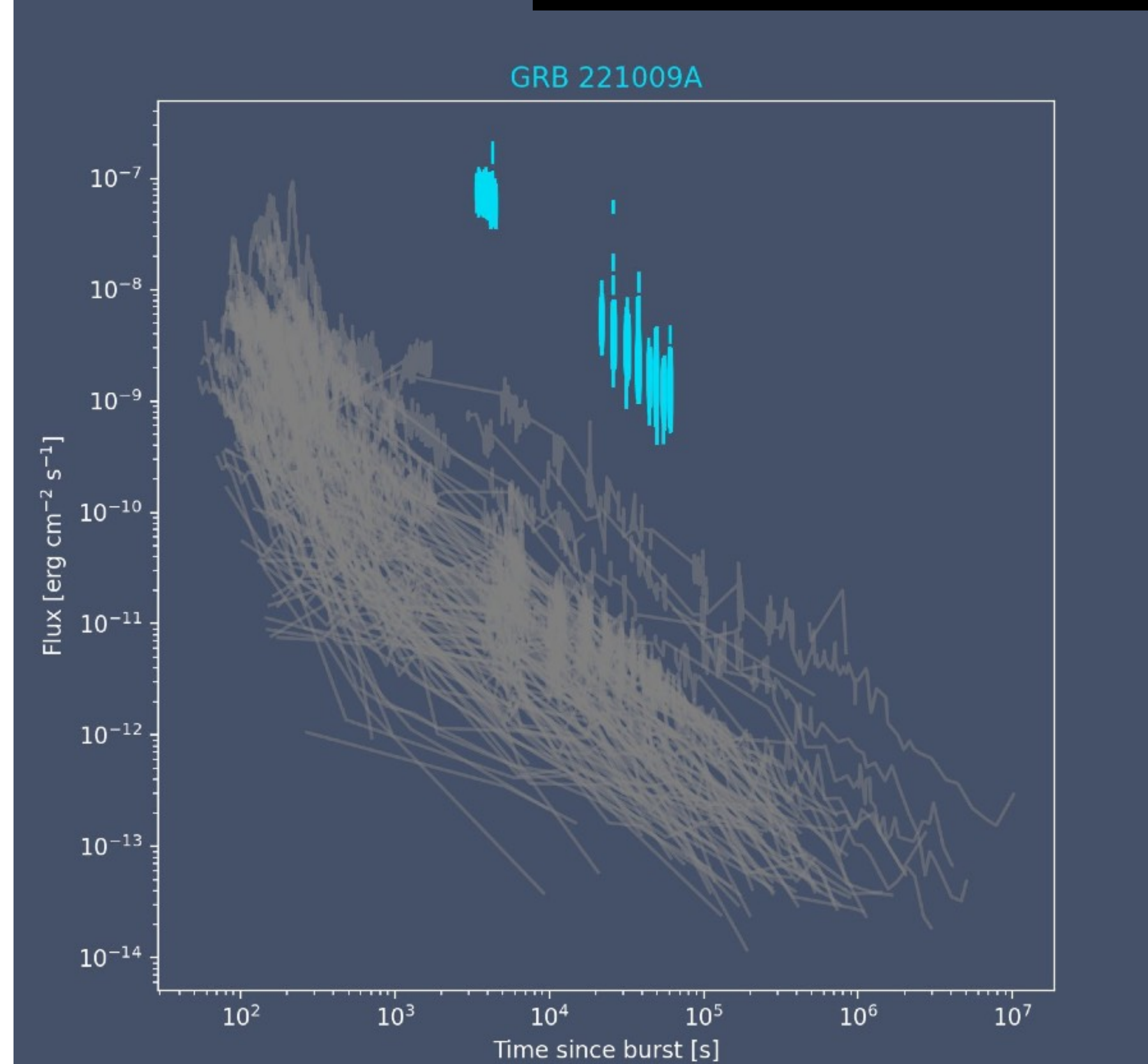
Table 1. Multiband Fitting Results with the Forward Shock Model

GRB	$\log_{10}E_{k,iso}$ (erg)	$\log_{10}\Gamma_0$	p	$\log_{10}\epsilon_e$	$\log_{10}\epsilon_B$	$\log_{10}\theta_j$	$\log_{10}A_*$
221009A	$54.83^{+0.10}_{-0.08}$	$2.28^{+0.02}_{-0.03}$	$2.60^{+0.03}_{-0.02}$	-0.69 ± 0.02	$-2.73^{+0.07}_{-0.10}$	$-1.61^{+0.06}_{-0.06}$	$-1.91^{+0.01}_{-0.01}$

Ren et al. 2022



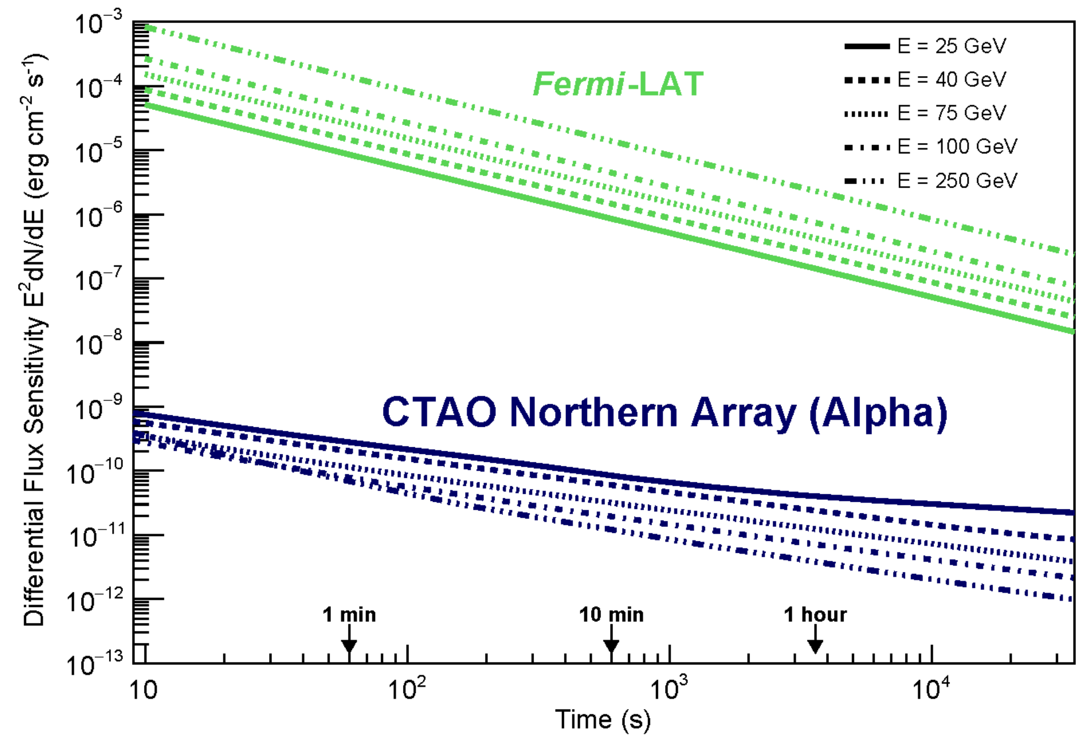
Swift-XRT light curve (since Fermi-GBM trigger time)



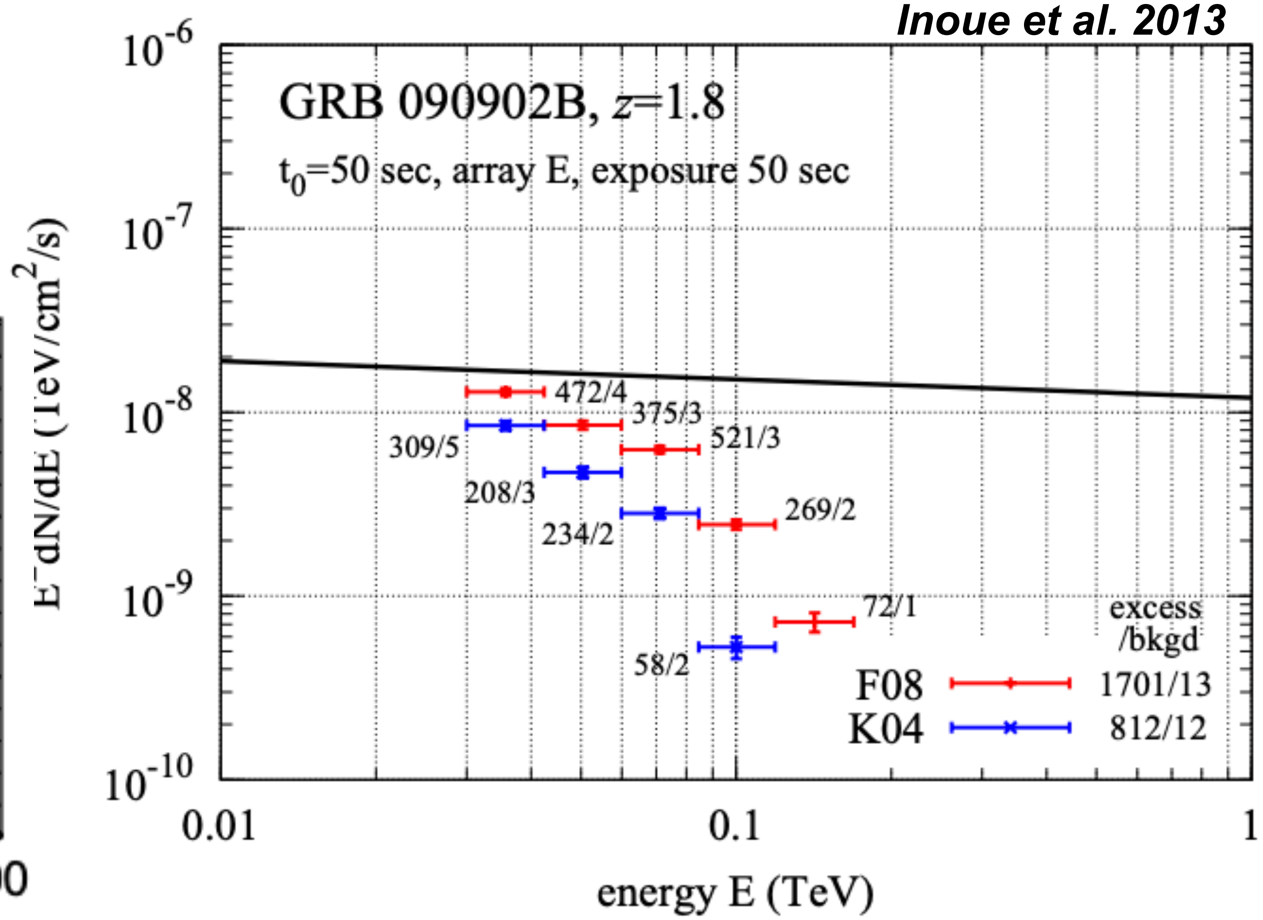
https://astro-colibri.com/

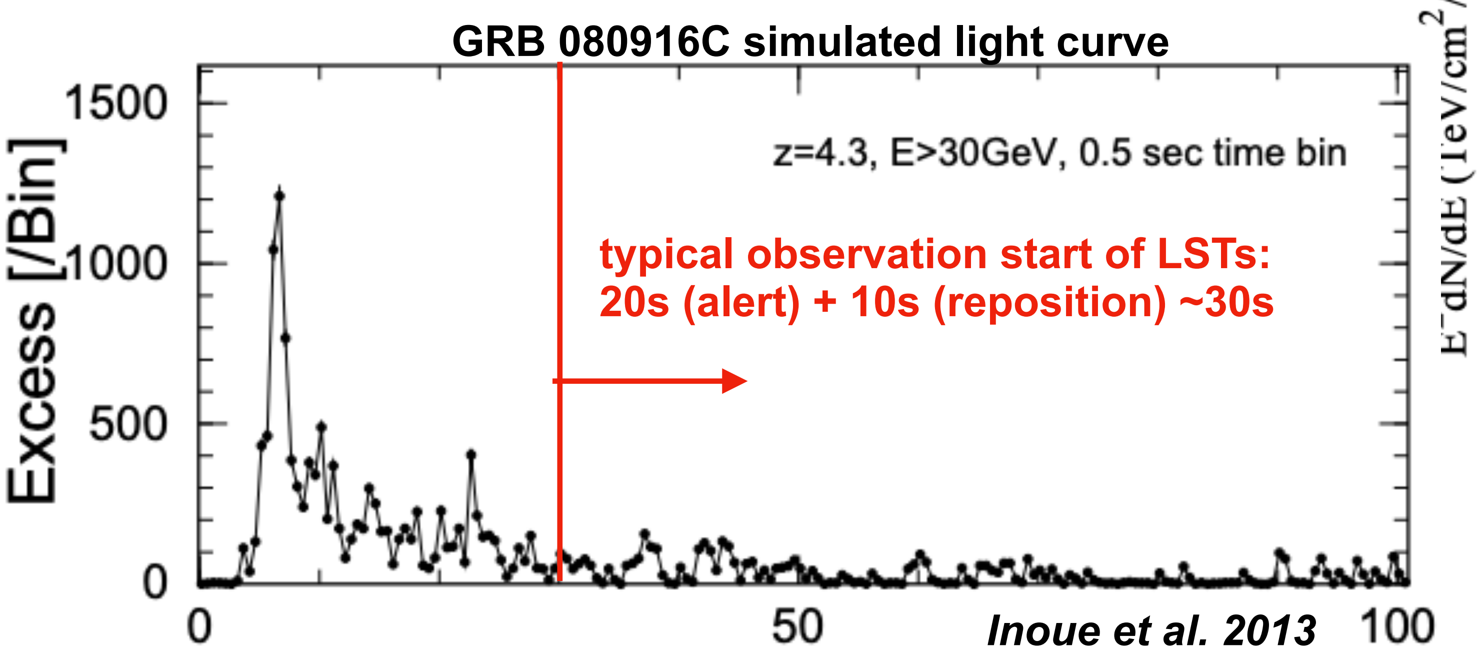
Prospects with CTA: performance

- highest sensitivity ever in TeV range
  - increase statistics
  - high spectral/temporal resolution
- sensitive for spectrum in 20-100 GeV (LSTs)
  - high-redshift GRB detections (z>~2) due to low attenuation by EBL
  - much better sensitivity than Fermi-LAT for short time observations
  - fast repositioning of LSTs (within 20 sec)



Inoue et al. 2013

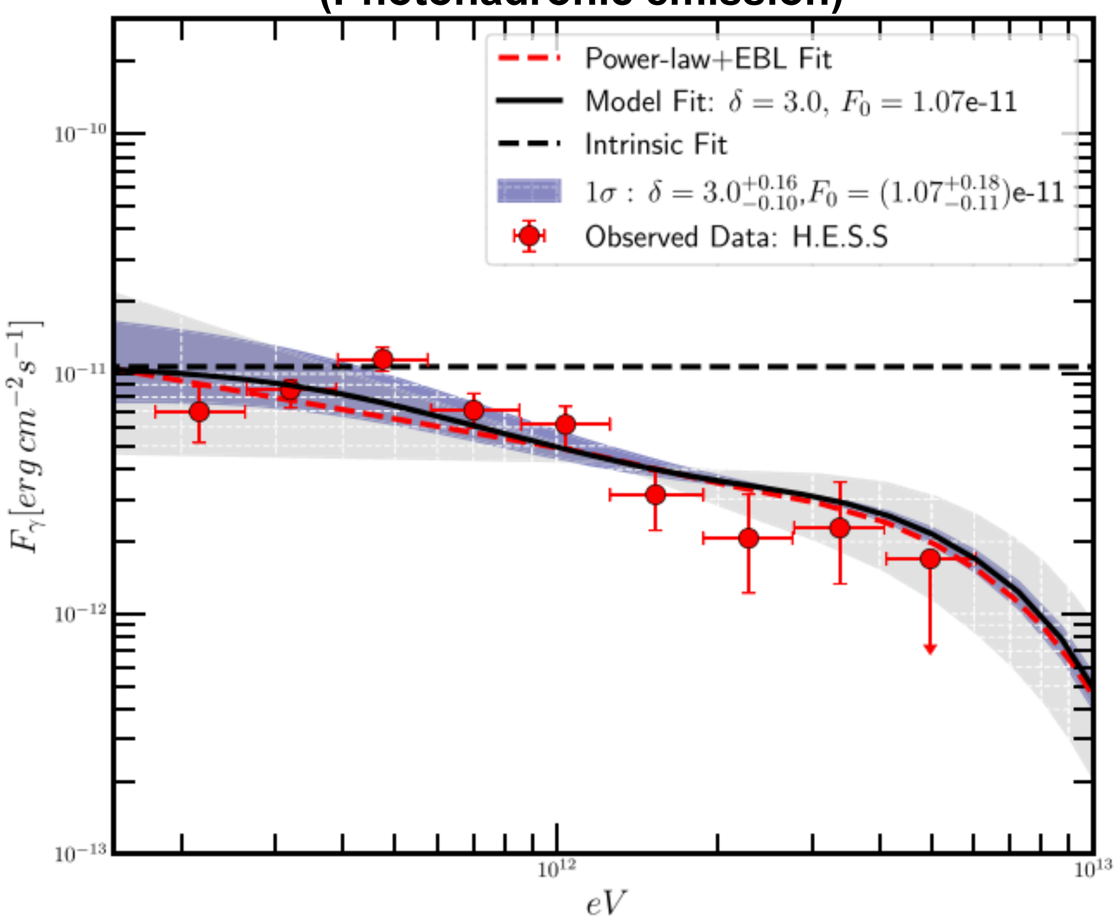




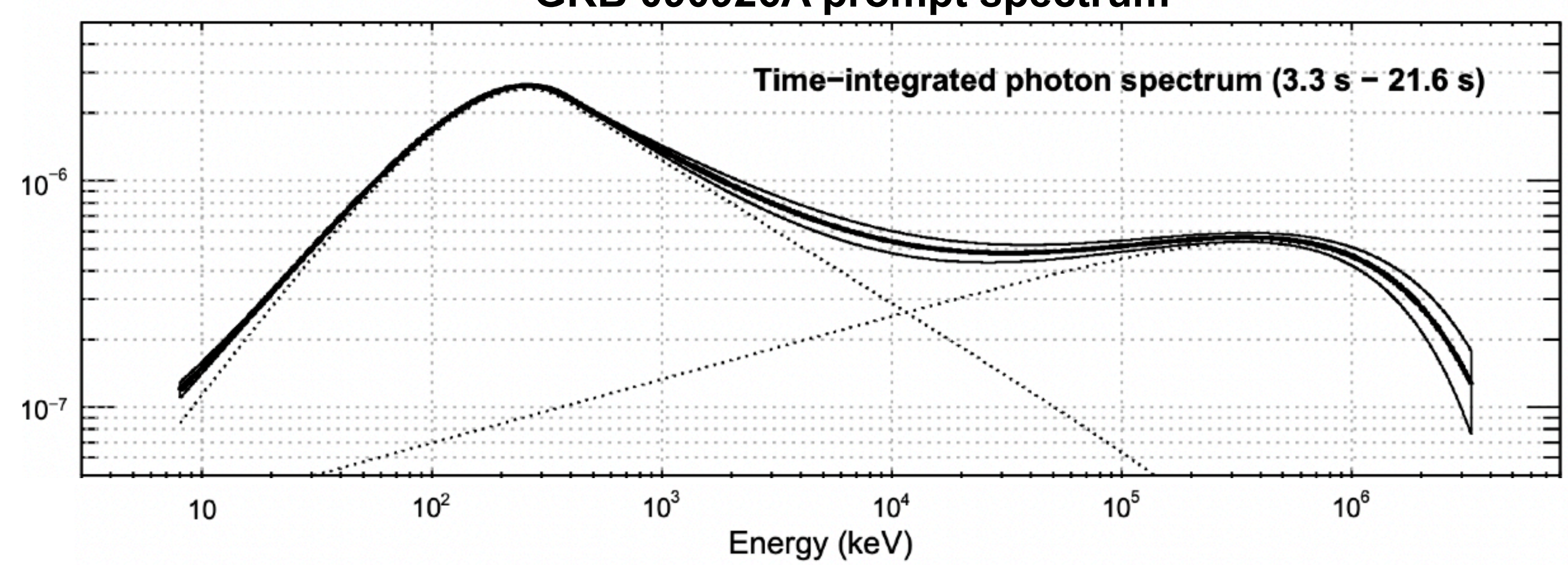
Prospects with CTA: emission mechanism

- constrain emission models/parameters
  - TeV prompt emission -> (second) discovery, SSC or hadronic models
  - TeV afterglow emission -> SSC validation, any sign of hadronic models
- cutoff search in sub-TeV range
  - direct indication of bulk Lorentz factor (*Ackermann et al. 2011*)

GRB 190829A afterglow model (Photohadronic emission)



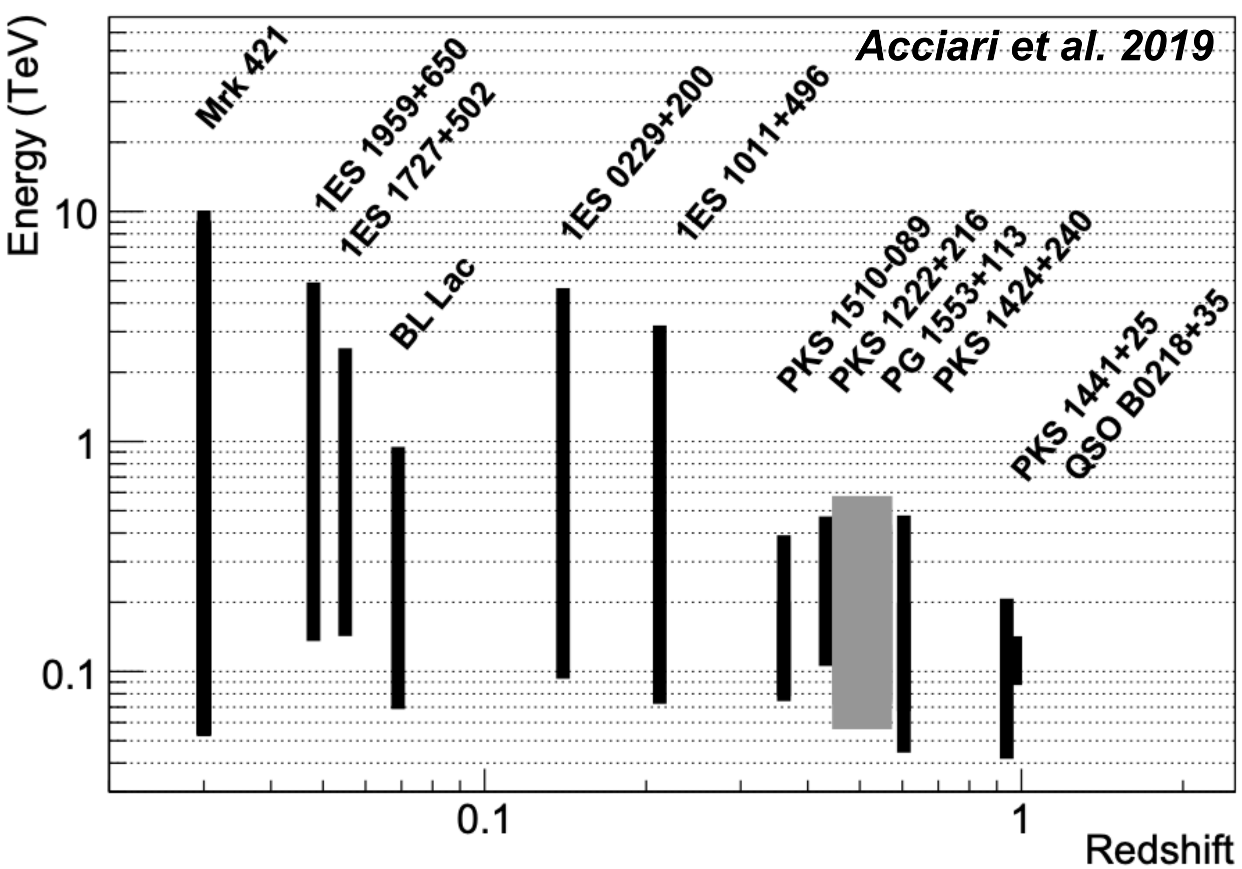
GRB 090926A prompt spectrum

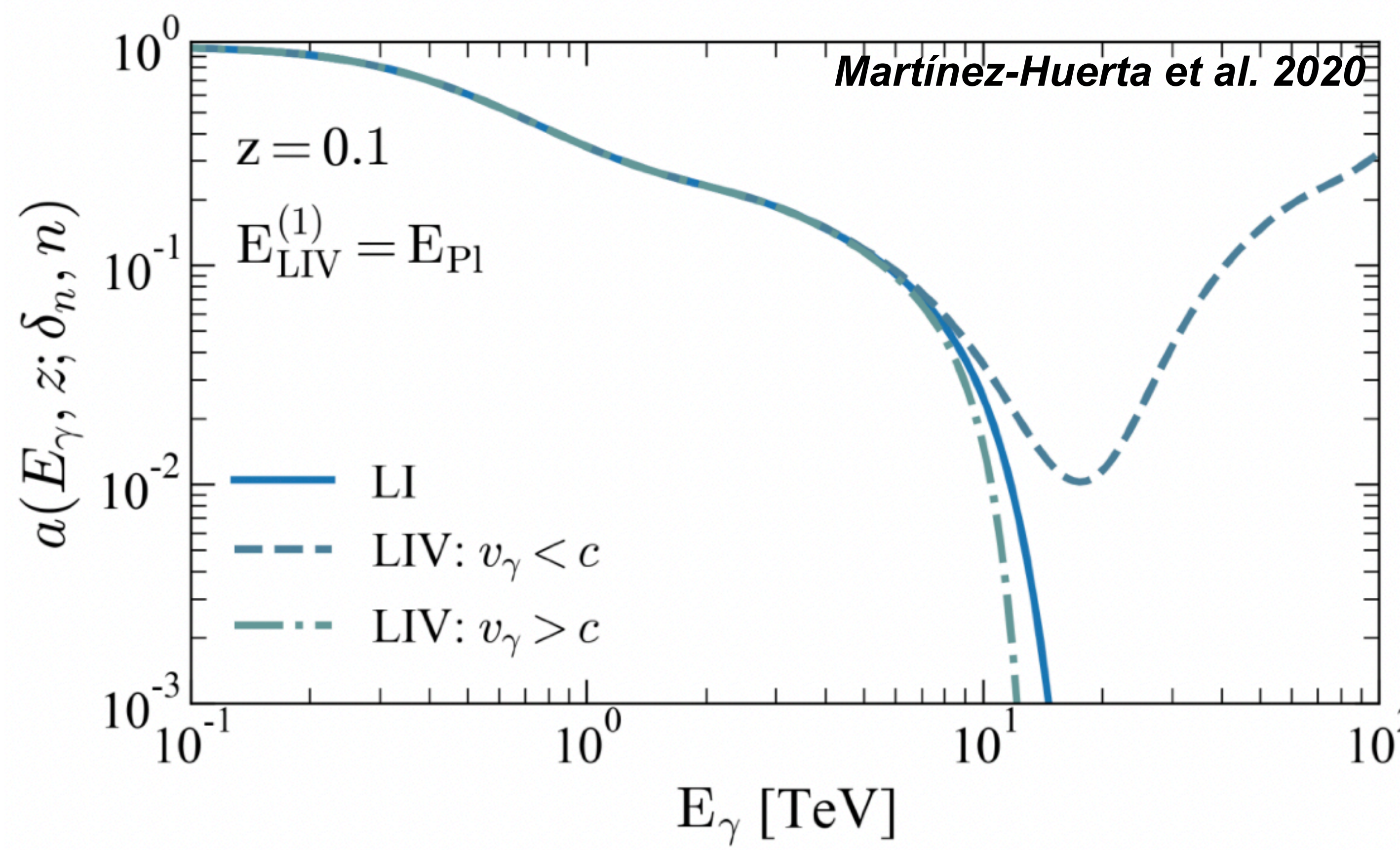


Ackermann et al. 2011

Prospects with CTA: EBL and more

- EBL measurement by GRB observations
  - probe the cosmological history back to z>2
    (c.f. all the current TeV objects have z<1)
- LIV (Lorentz invariance violation) tests
  - temporal delay, spectral modulation search
- IGMF (intergalactic magnetic field)





Summary

- GRBs have many aspects unknown, such as emission mechanism/jet launching mechanism.

- There are some leptonic/hadronic models to explain the VHE emission, which are not narrowed down yet.

- Thanks to the recent observations of the ground-based gamma ray telescopes like H.E.S.S., MAGIC and LHAASO, VHE emissions from 5 (long) GRBs have been detected so far. The VHE emission seems consistent with SSC for at least some of the GRBs.

- GRB observations with CTA can not only constrain the emission models but also be used for probing EBL or LIV.

Backup

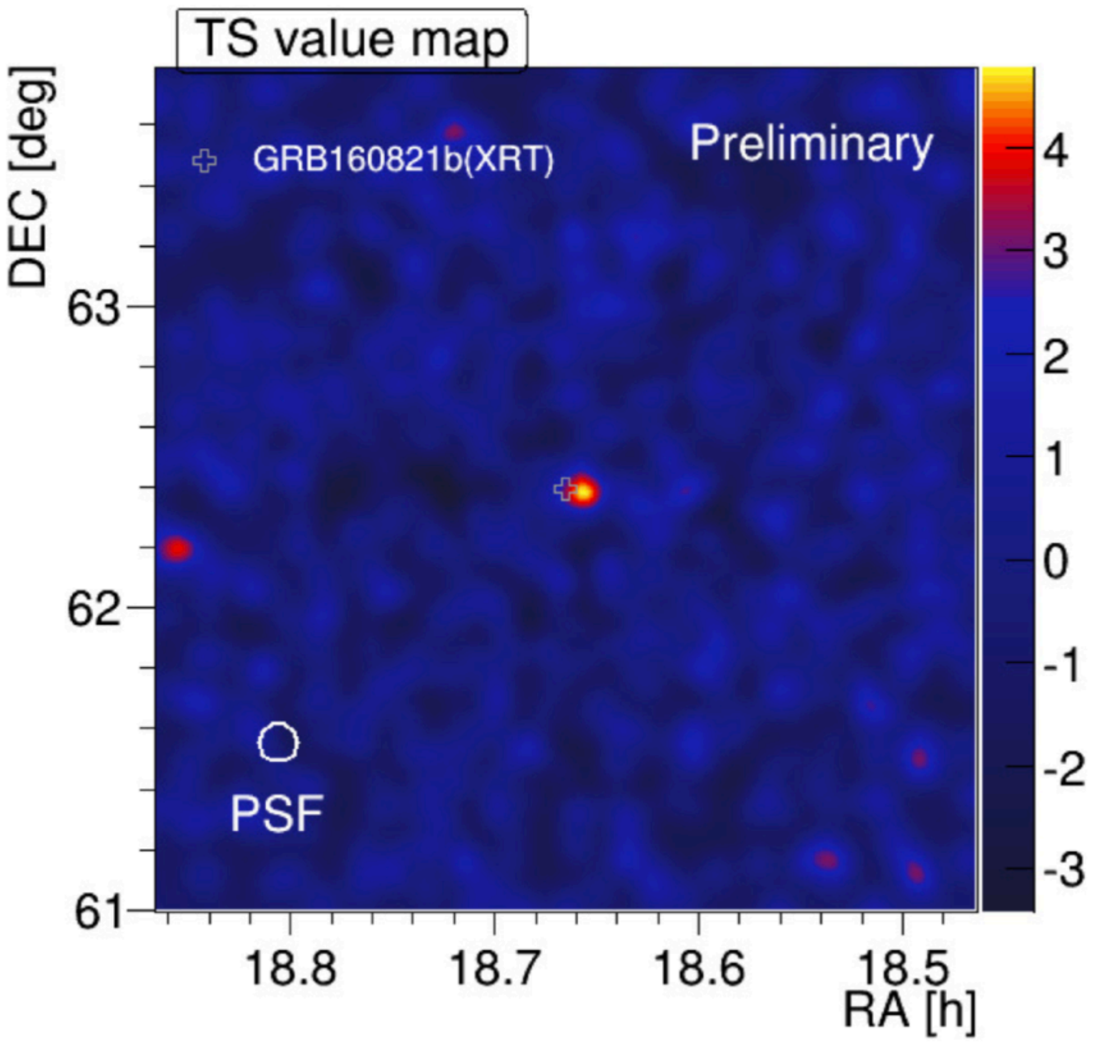
GRB 160821B (not detected but hint)

About GRB :

- short GRB (0.5 s)
- nearby GRB (**z 0.16**)
- bright prompt emission (**$E_{\gamma,iso}$ ~ 1.3×10^{49} erg**)

➔ **hint for signal (3σ at GRB, 4σ at hotspot)**

- TeV emission could not be explained by the standard model



MAGIC Collaboration 2021