Very-high-energy gamma-ray emission from gamma-ray bursts

Jan. 23rd, 2023 Science Meeting @ Ecogia

Satoshi Fukami

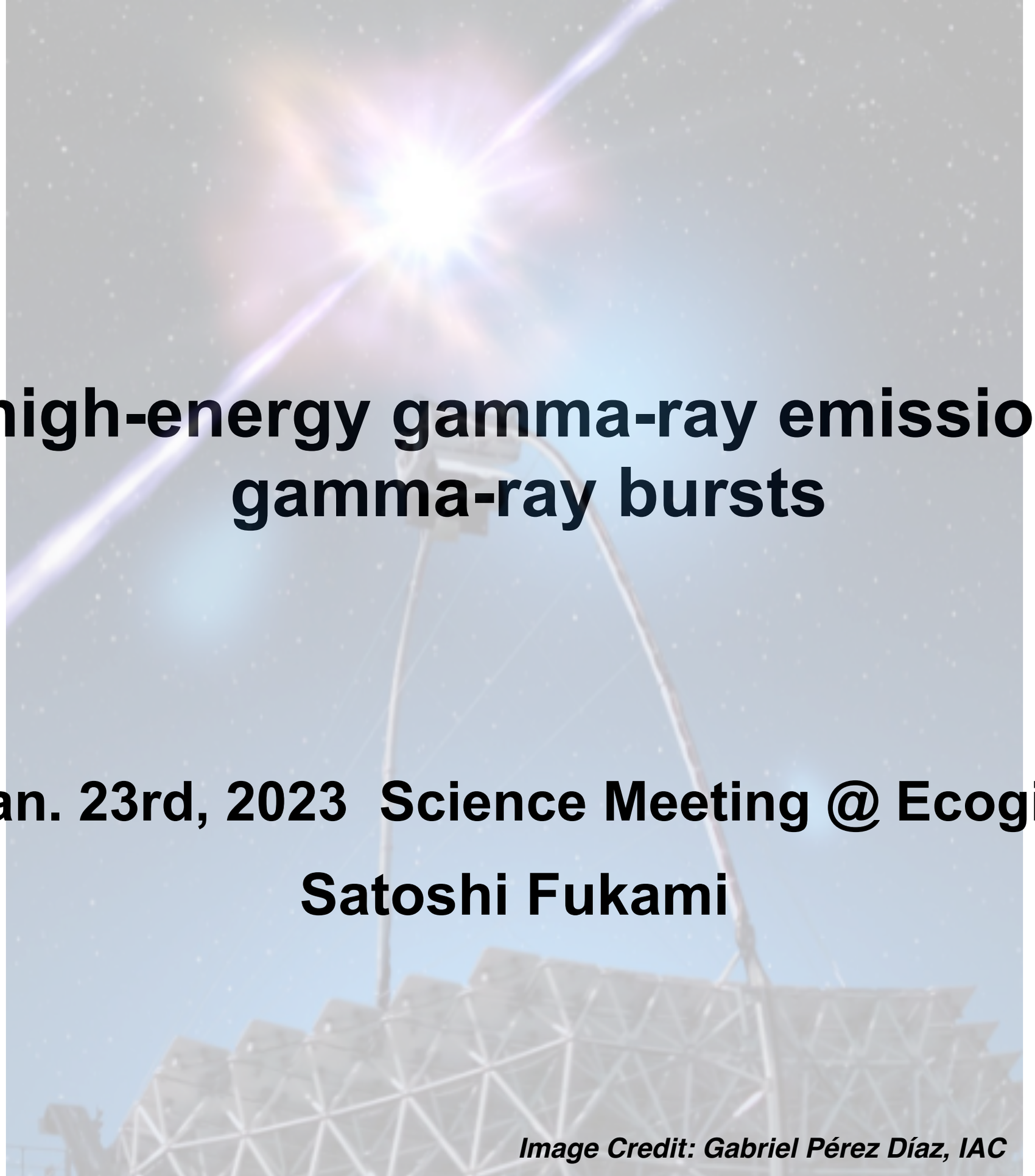
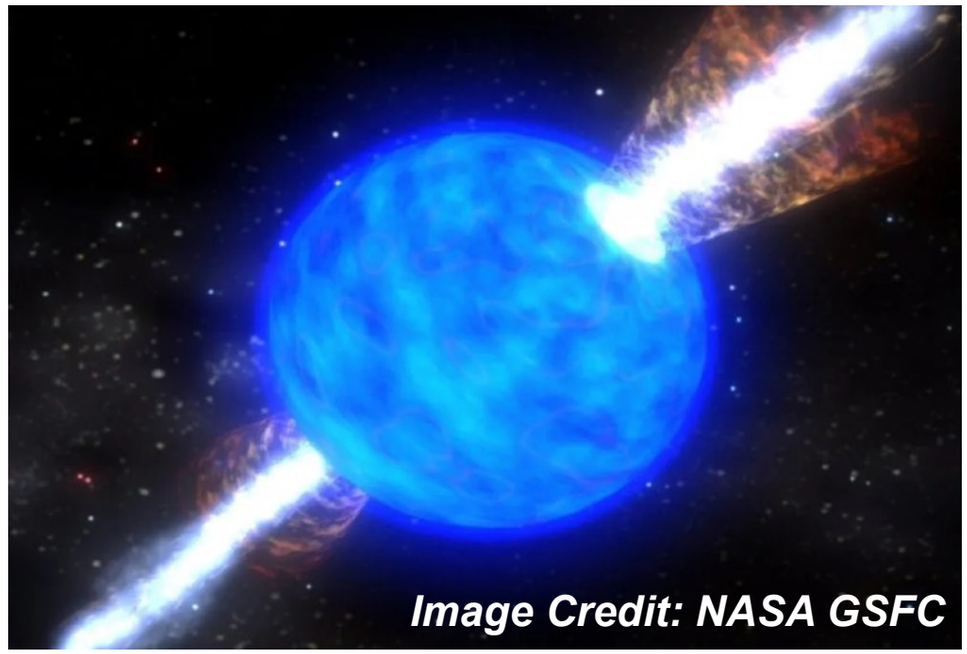
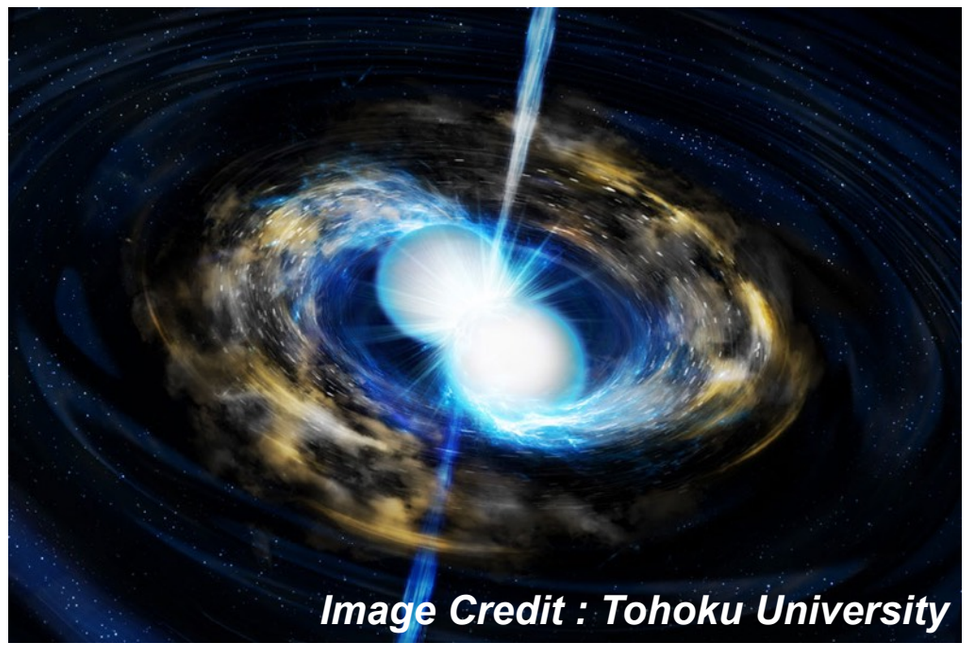


Image Credit: Gabriel Pérez Díaz, IAC

Gamma-Ray Burst (GRB)

- **Biggest explosion in the universe ($E_{iso} \sim 10^{48\text{-}54}$ 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)

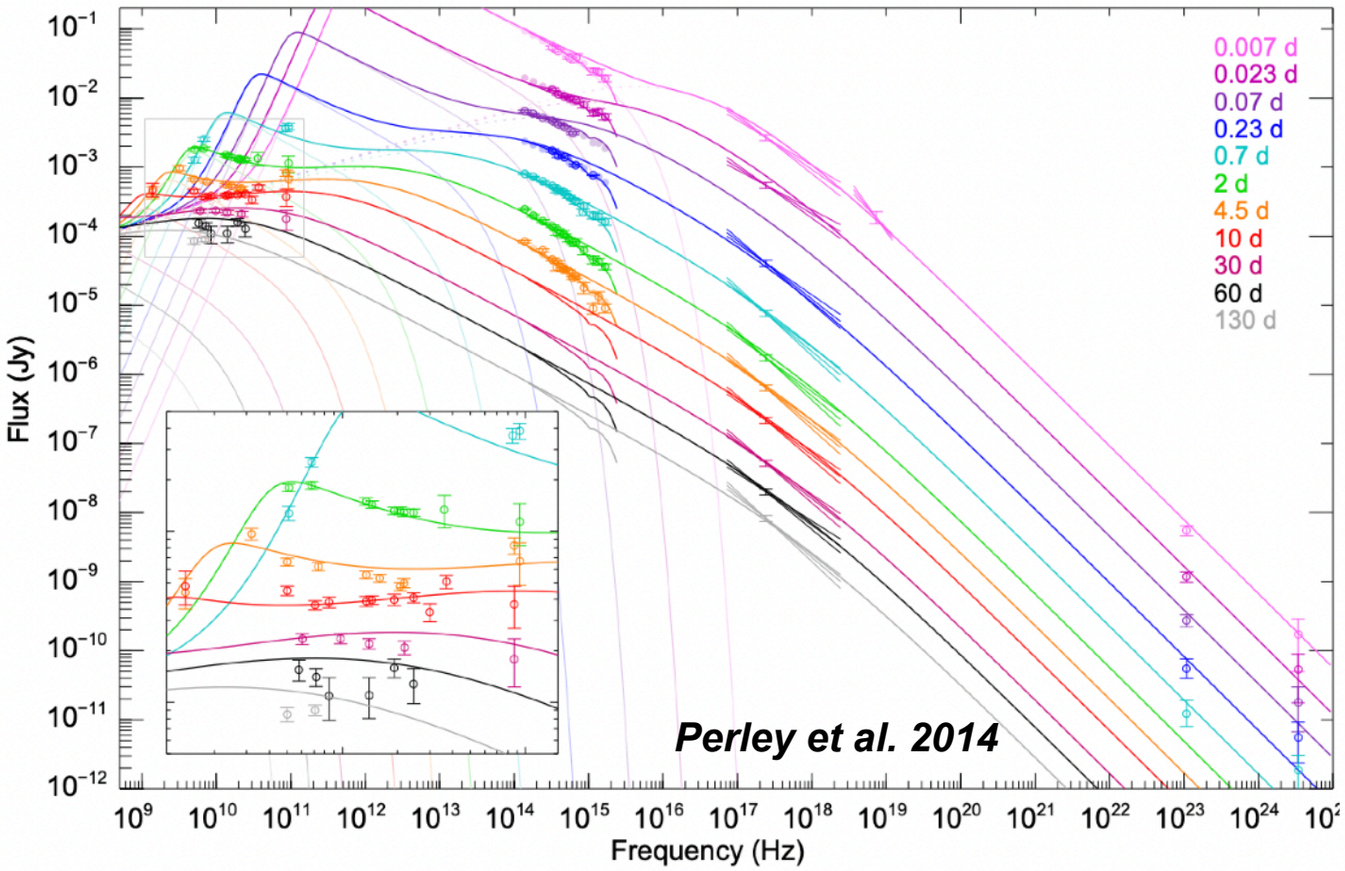




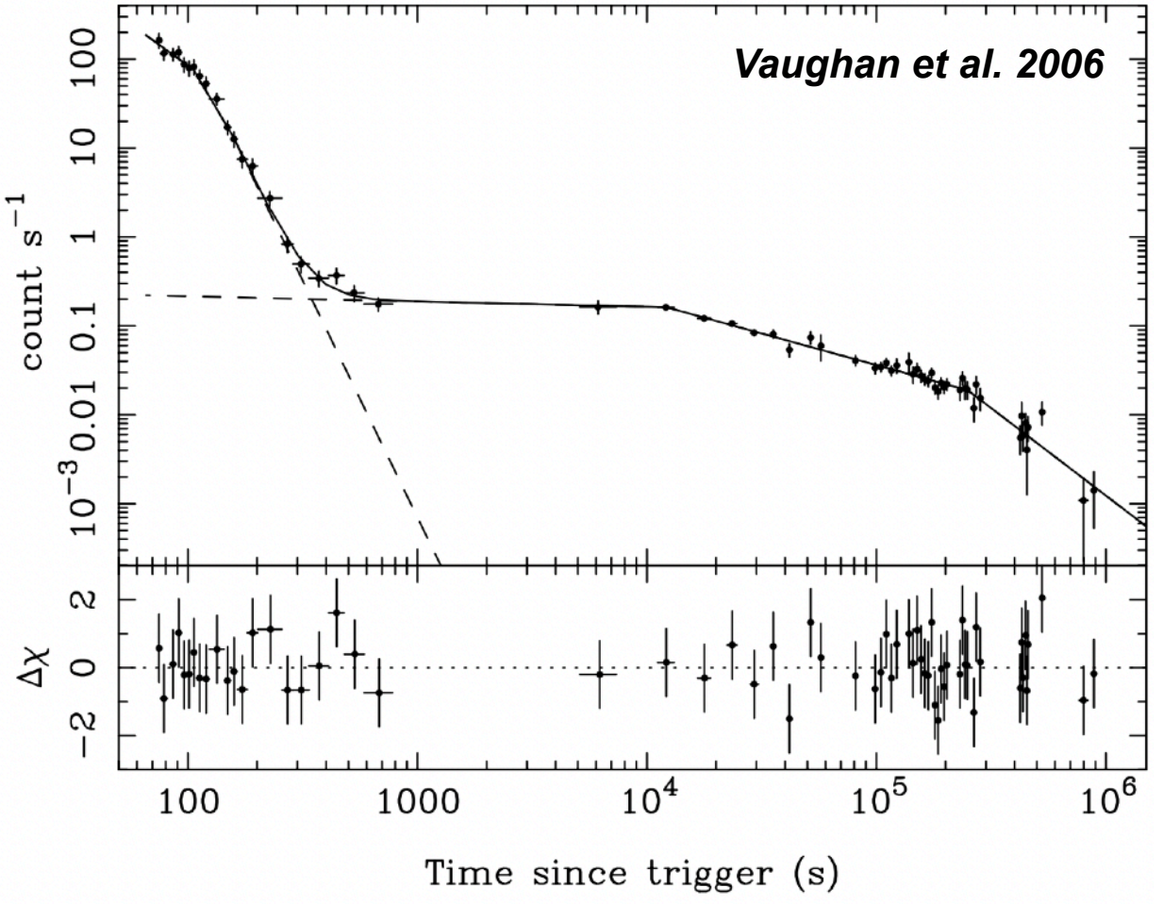
Afterglow emission

- 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



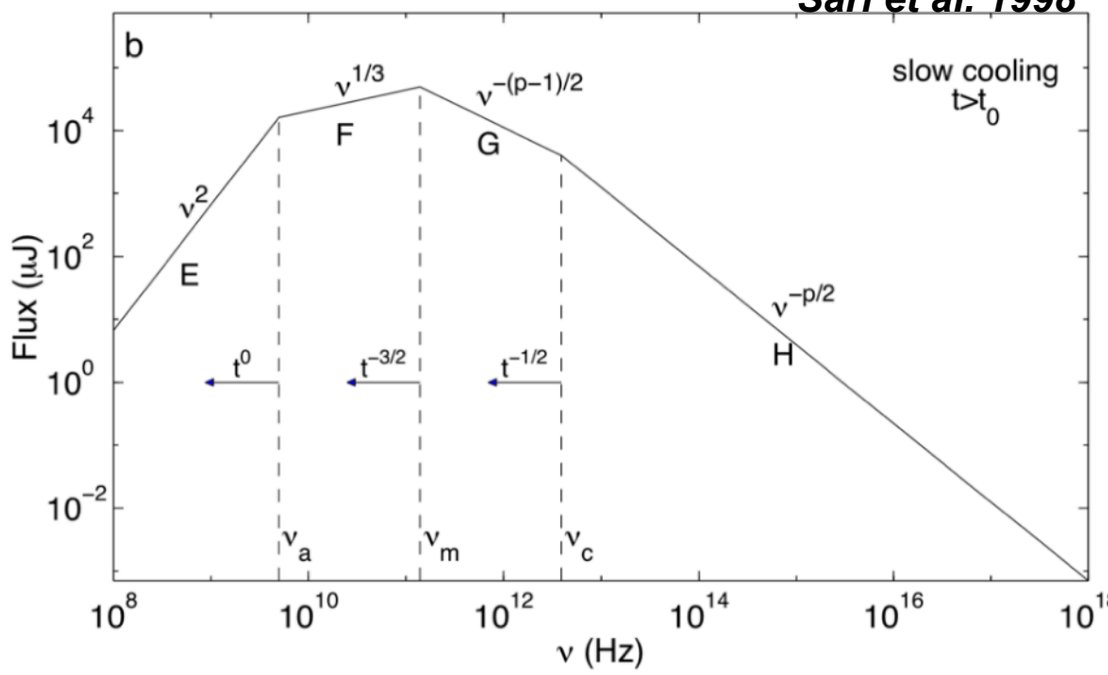
GRB 050315 X-ray light curve

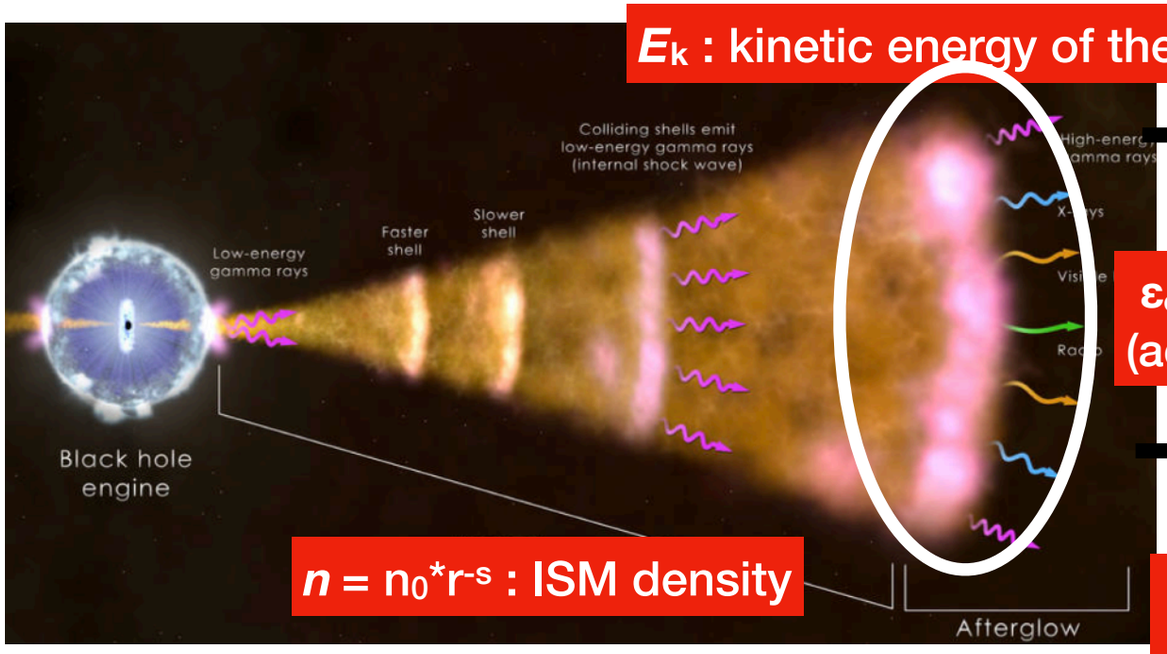


Afterglow emission

- 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

Sari et al. 1998





E_k : kinetic energy of the shell

$E_k \times (\chi_e) \times \varepsilon_e$

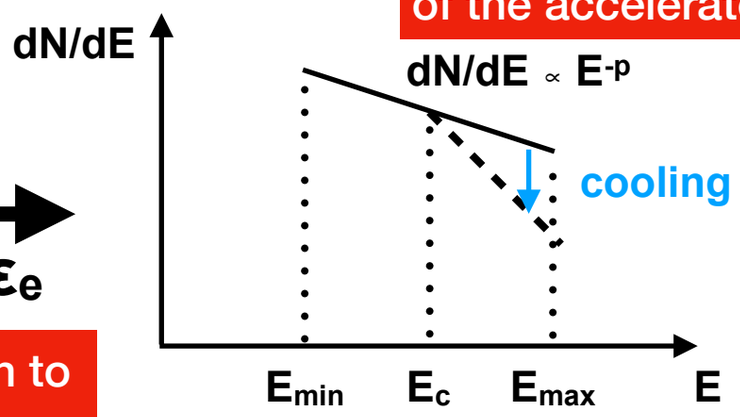
ε_e : energy fraction to (accelerated) electrons

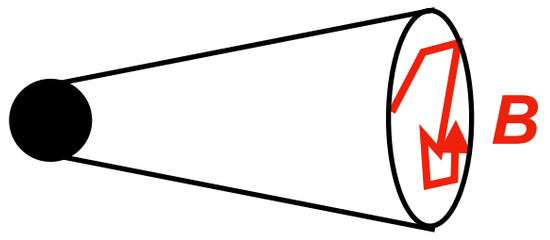
$E_k \times \varepsilon_B$

ε_B : energy fraction to magnetic field

$n = n_0 * r^{-s}$: ISM density

p : power-law index of the accelerated electrons





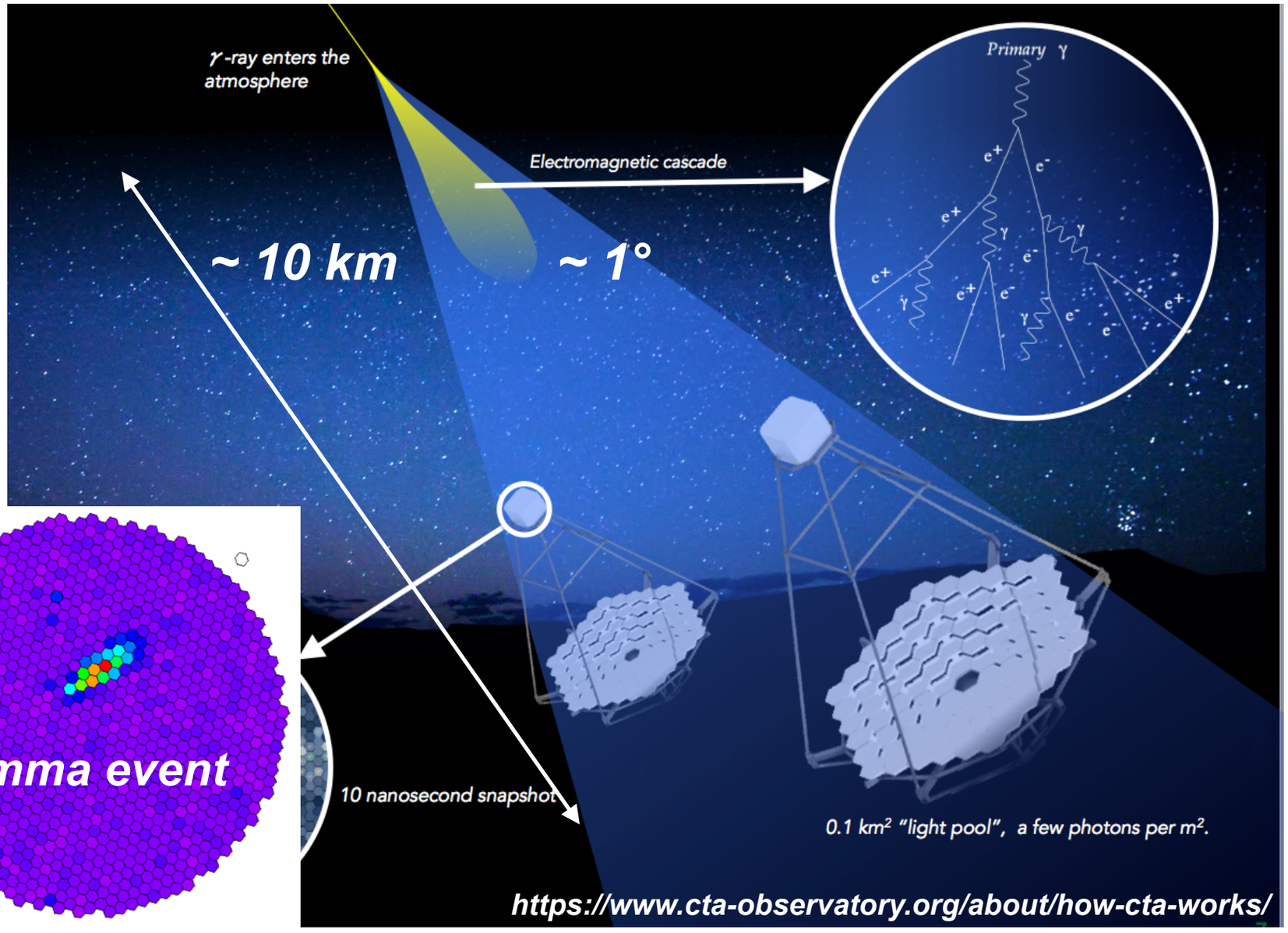
Ground-based gamma-ray telescope (Imaging Cherenkov)

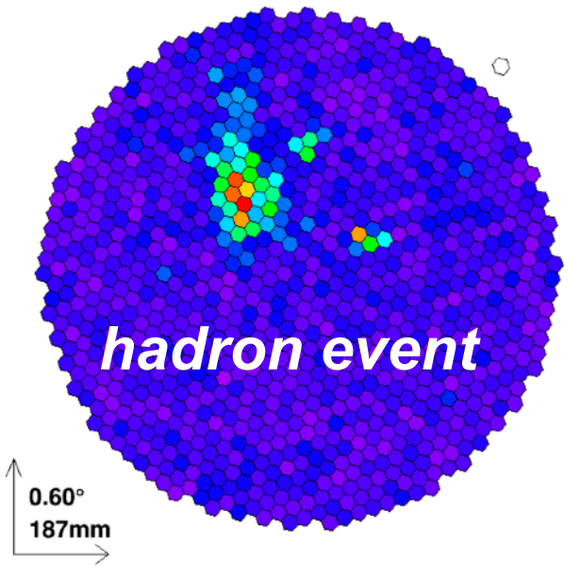
- Primary gamma rays create electromagnetic showers in the atmosphere.

- Particles ($e^{\pm}$) which exceed the speed of light emit Cherenkov light. This bluish light is focused by reflectors into the focal plane camera.

- Energy, directions of primary gamma rays can be reconstructed by Cherenkov light images.

- Background events (like protons) can also be distinguished by the images.





MAGIC telescopes

MAGIC (Major Atmospheric Gamma Imaging Cherenkov telescope)

- **location** : La Palma, Canary Islands, Spain (28°N, 18°W)

- **systems** : 17-m parabolic primary mirror, photomultiplier focal plane × 2

- **performance** :

  - energy range : **50 GeV - 30 TeV**

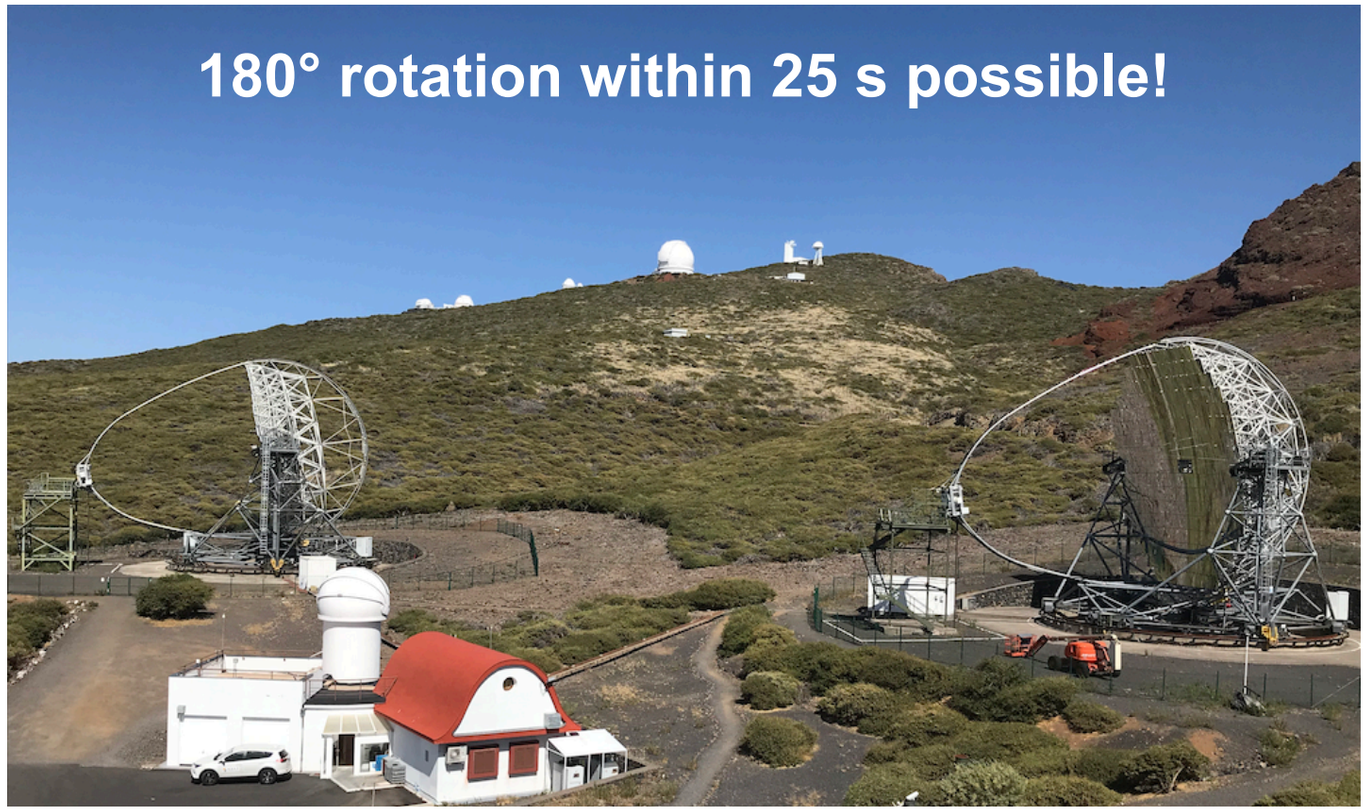
  - field of view : 3.5° (0.1° for 1 pixel)

- energy resolution :
  ~20% @100 GeV, 15% @1 TeV

- angular resolution :
  ~5 arcminutes @100 GeV,
  ~3 arcminutes @1 TeV

- effective area :
  ~10^4 m^2 @100 GeV, **~10^5 m^2** @1 TeV

- integral sensitivity :
  ~0.6% crab unit > 220 GeV



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)

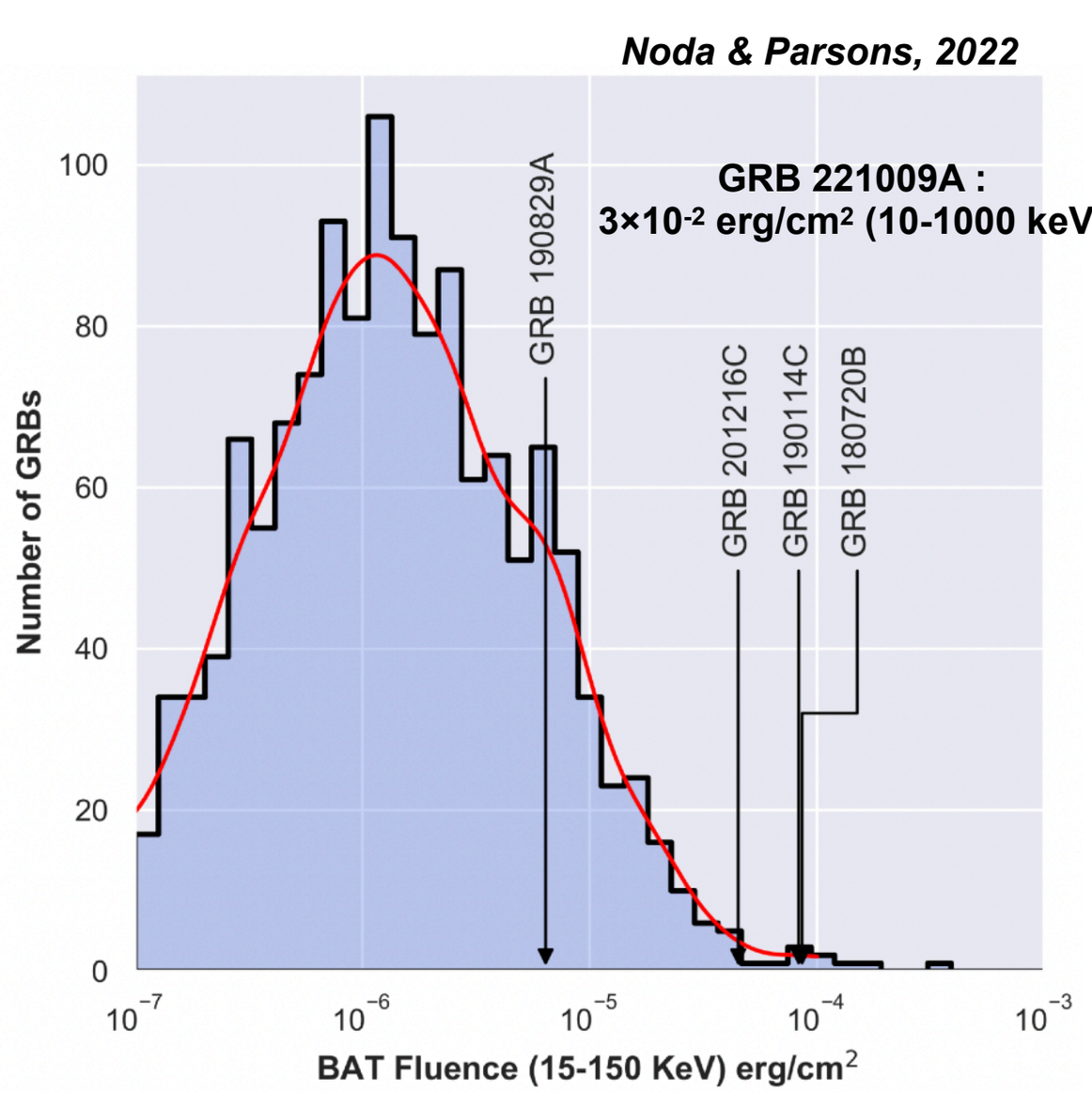
- Synchrotron Self-Compton (SSC) by relativistic electrons can explain the VHE emission for at least the first 2 GRBs.

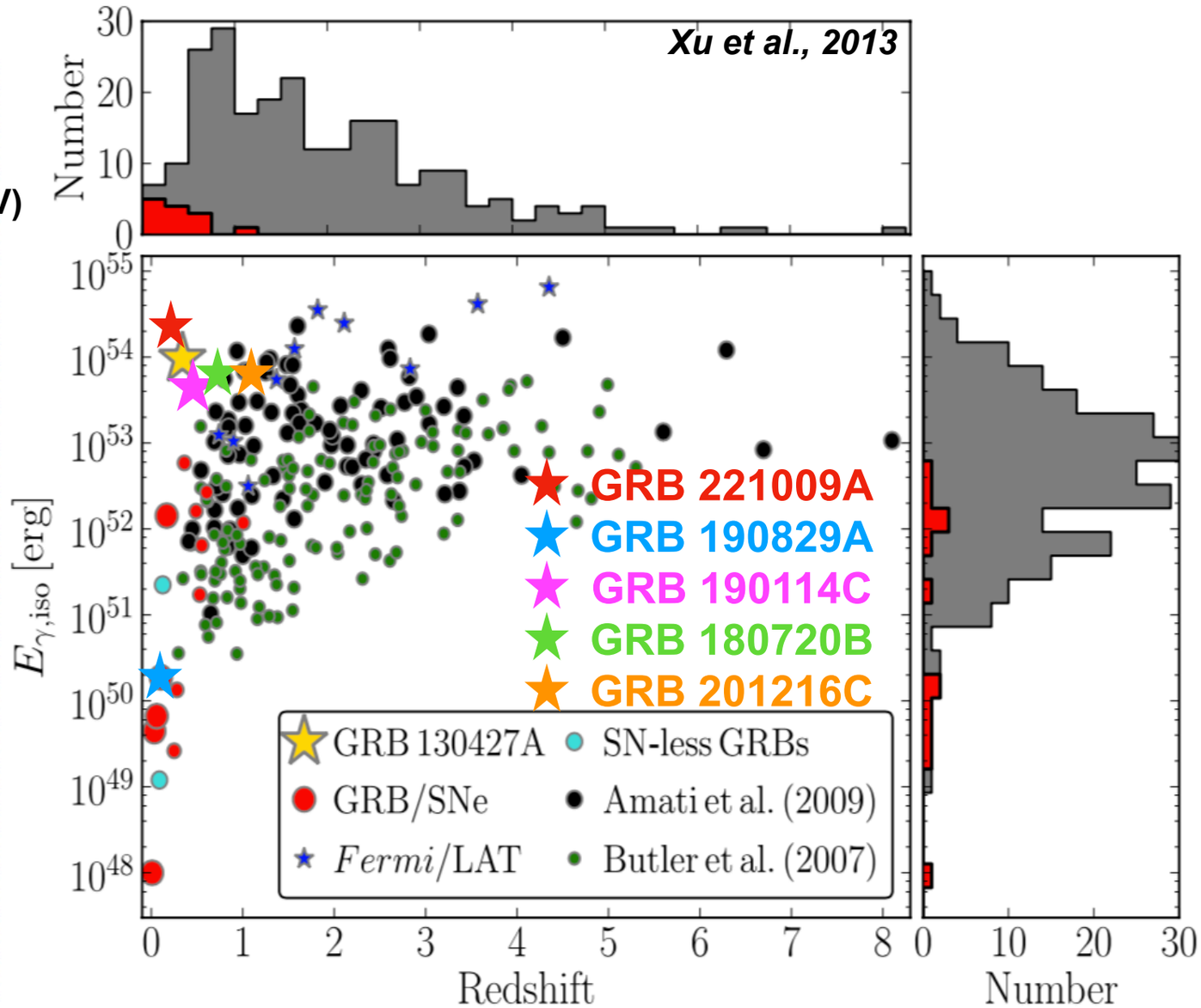
- All of them are detected during the afterglow phase except for LHASSO one
  - no published info on prompt or afterglow for the LHASSO one, only the detection within T_0+2000 s is announced (GCN circular 32677)

Speciality of VHE GRBs

- fluence : one of the highest among LAT GRBs
- $E_{\gamma,iso}$: not a brightest one

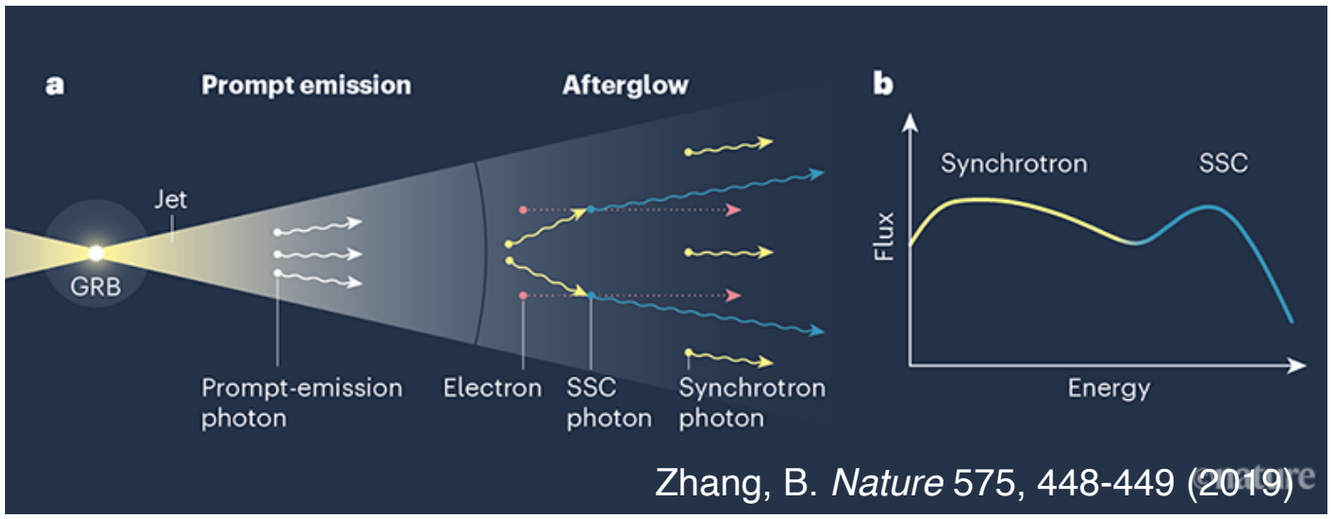
The GRBs are probably not peculiar.
TeV gamma rays may be detectable from more GRBs if nearby and/or bright





one-zone SSC model

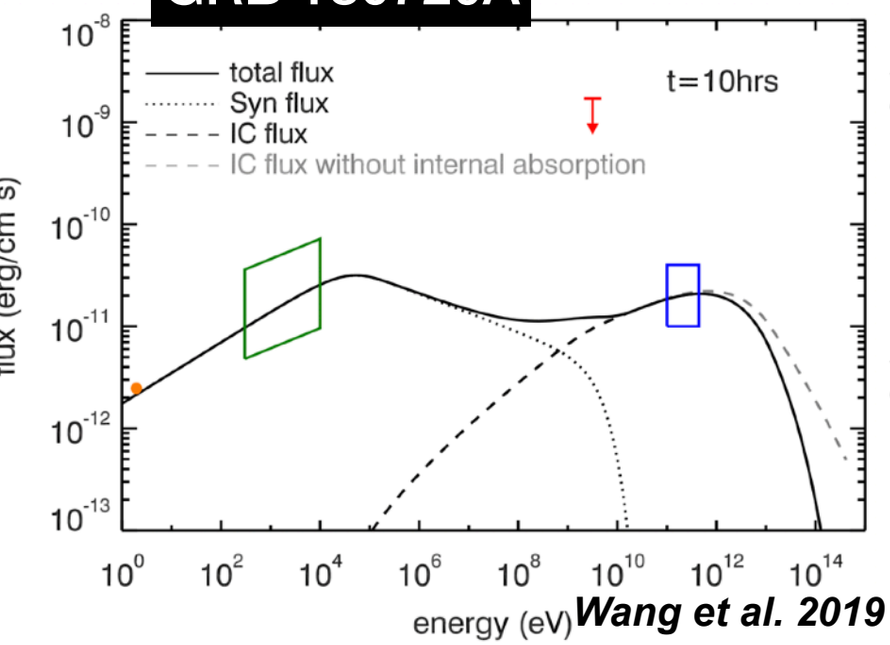
- one-zone SSC is consistent for most GRBs so far
  - physical parameters are very similar (ε_e, ε_B, n, p)



Zhang, B. *Nature* 575, 448-449 (2019)

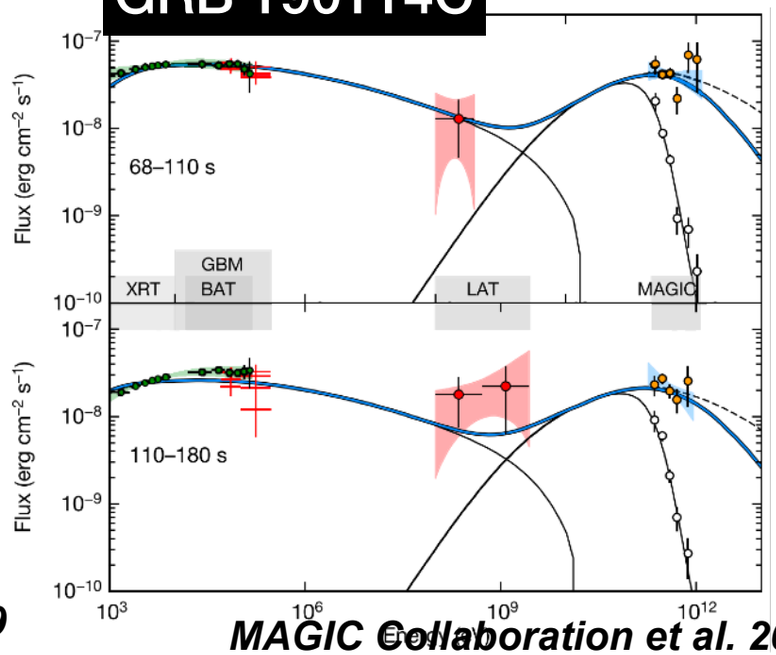
	E_k [erg]	p	ε_e	ε_B	n [/cm^3]
GRB 180720A	10^{54}	2.4	0.1	10^{-4}	0.1
GRB 190114C	8×10^{53}	2.6	0.07	8×10^{-5}	0.5

GRB 180720A



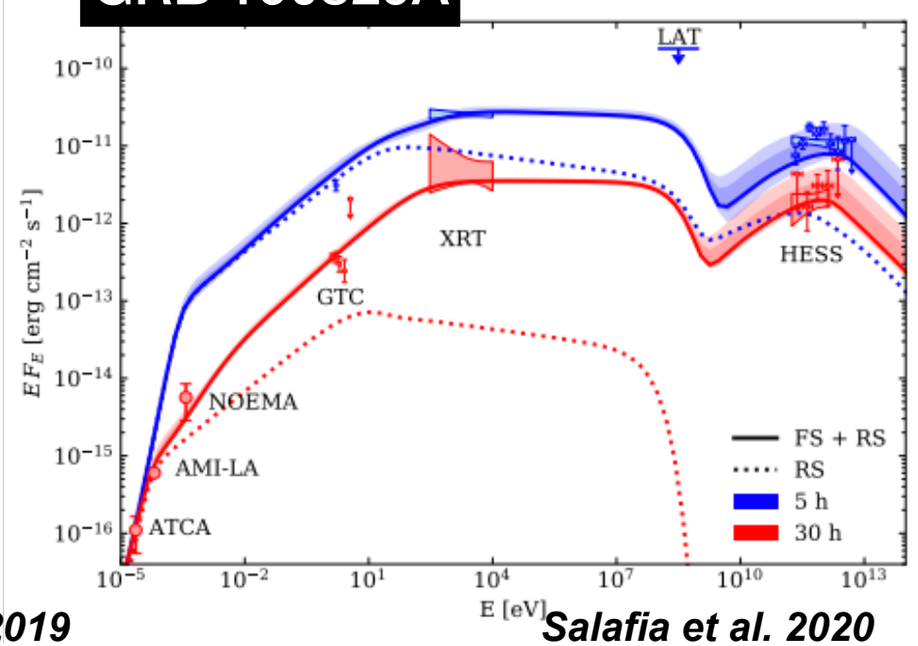
Wang et al. 2019

GRB 190114C



MAGIC Collaboration et al. 2019

GRB 190829A



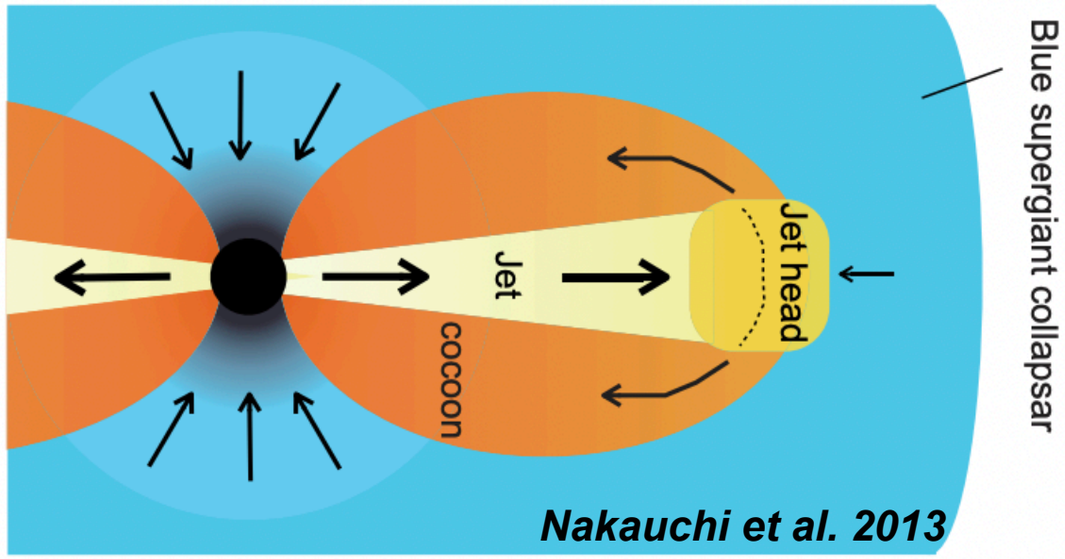
Salafia et al. 2020

other models

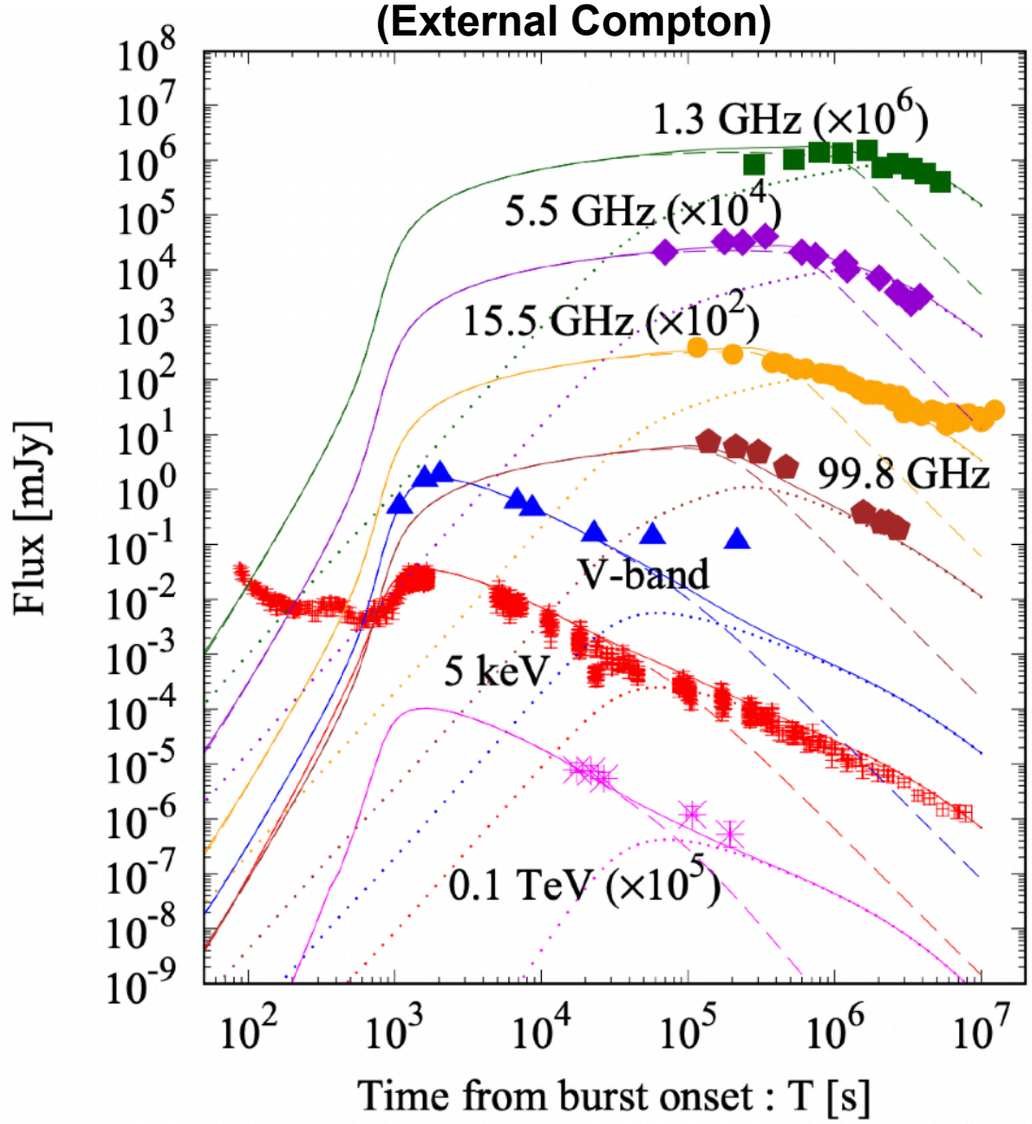
- two-zone synchrotron + SSC

- external inverse-Compton instead of SSC

- hadronic models (photo-hadronic, photo-meson)



GRB 190829A afterglow model
(External Compton)



GRB 190829A afterglow model
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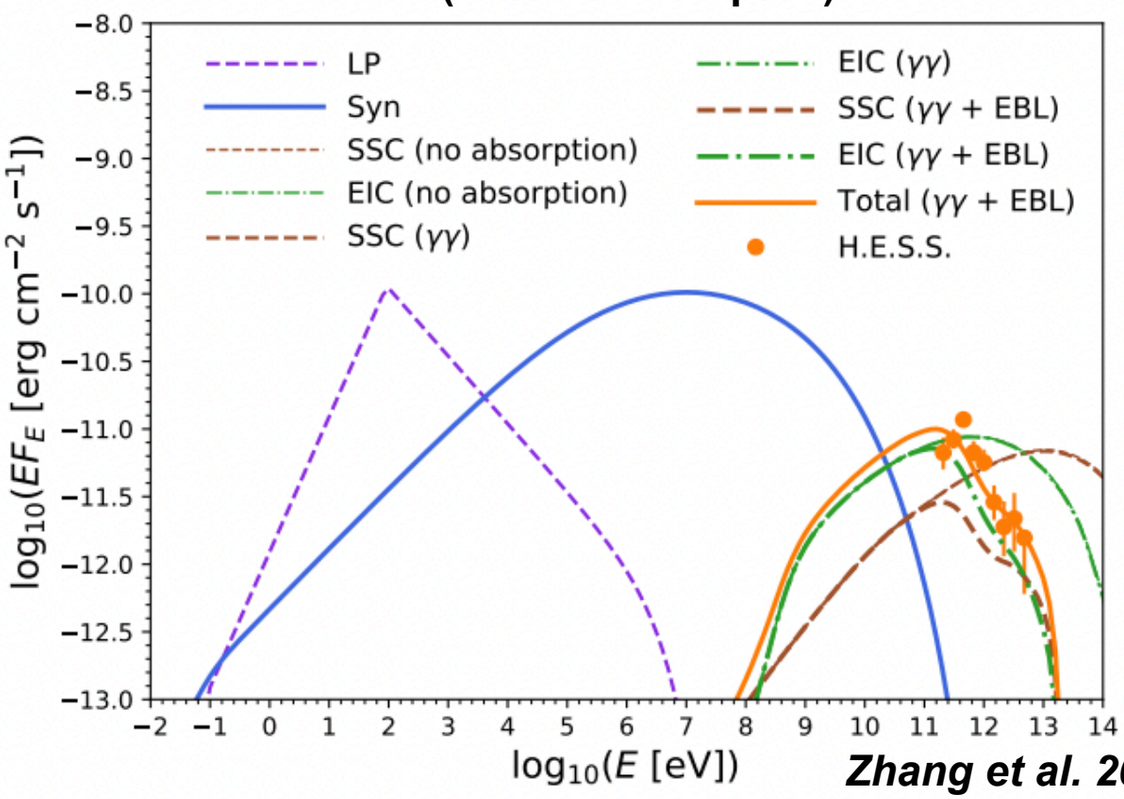
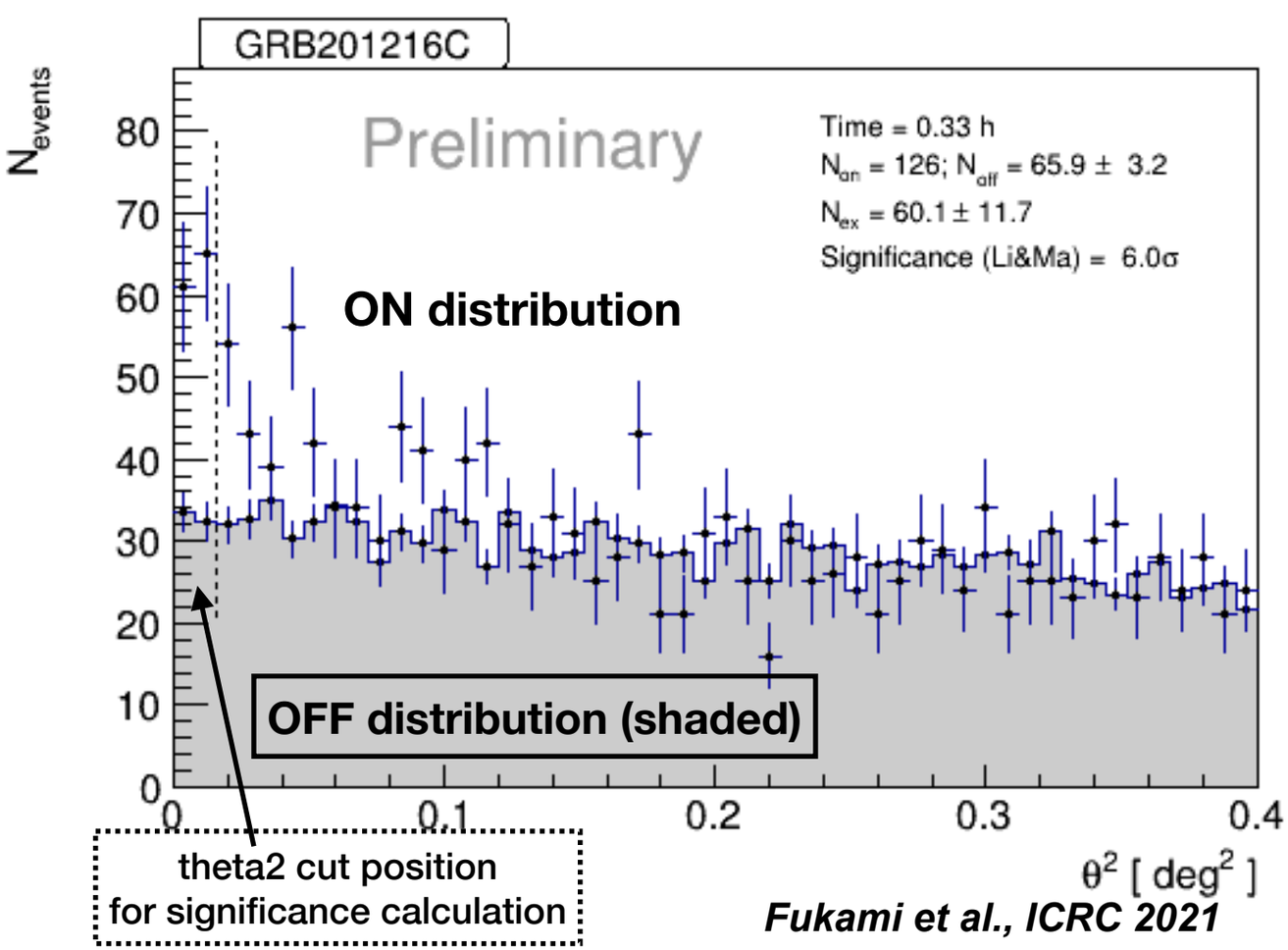


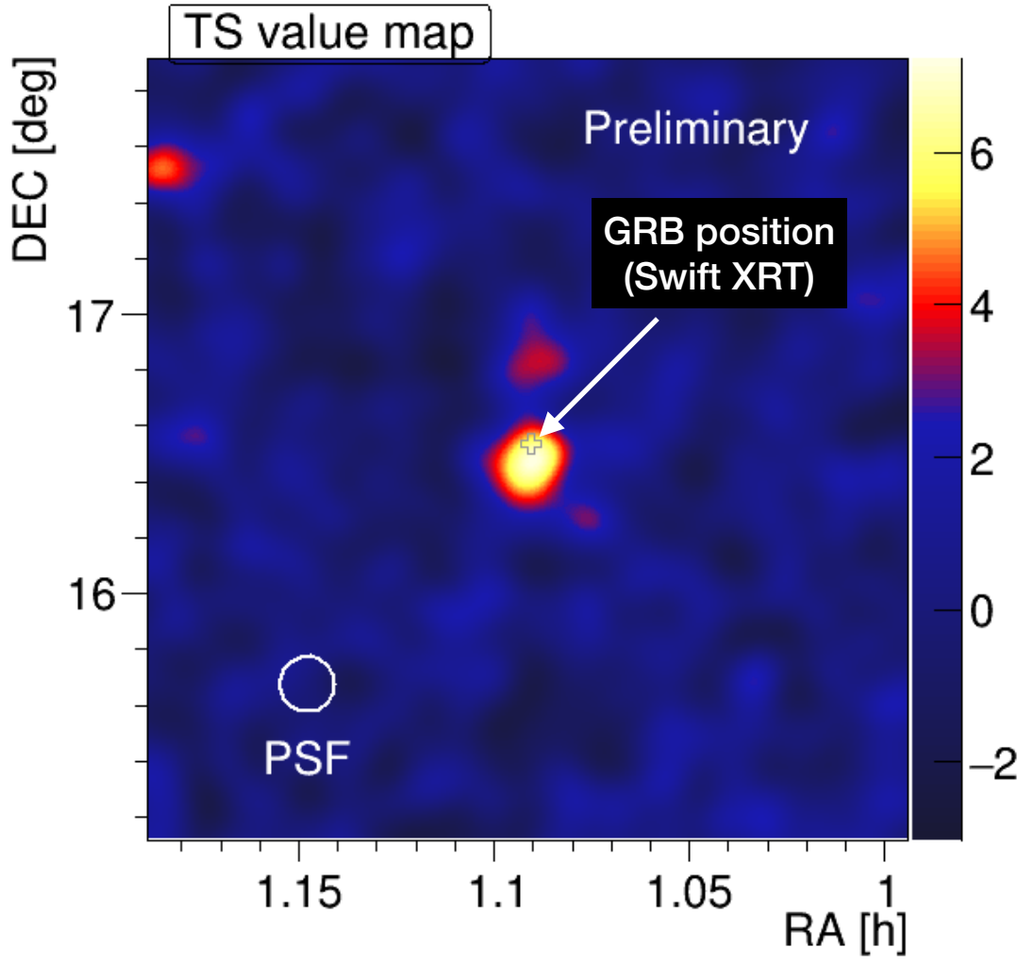
Zhang et al. 2021

GRB 201216C

- long GRB (**GBM T_{90} ~30 s, prompt phase finished <~25s**)
  - a relatively nearby GRB (**z ~ 1.1**) - relatively high energy (**$E_{\gamma,iso}$ ~ 5×10^{53} erg**)
- MAGIC observation started **56 s** after the satellite trigger time (T_0)
- first 20-min theta2 plot (squared angular distances to the GRB position for ON/OFF regions) :
  - **6 sigma significance** around the GRB position for the first 20 min with optimized cuts



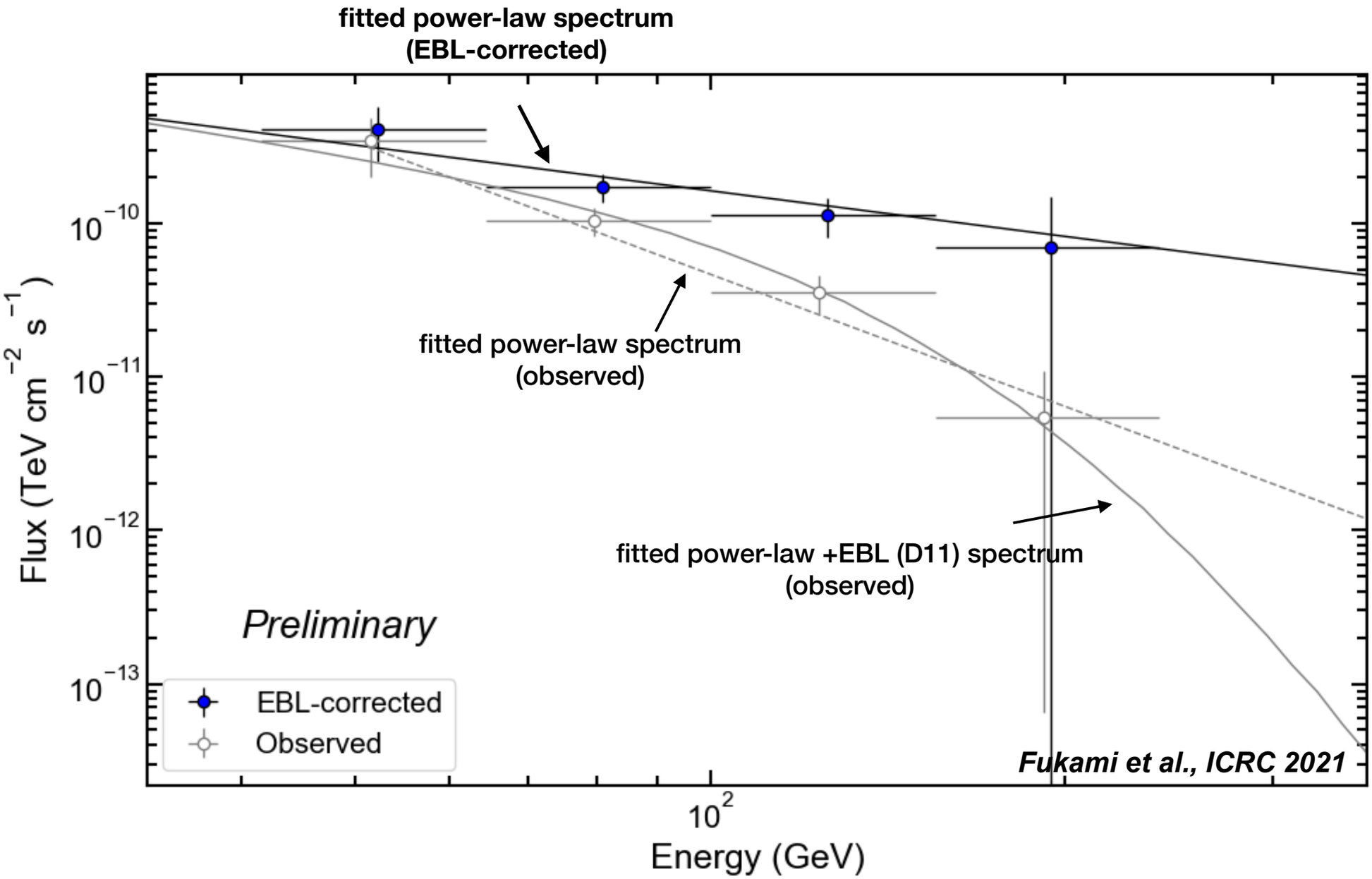
Fukami et al., ICRC 2021



GRB 201216C

- observed spectrum shows a steep slope due to strong attenuation by EBL at z~1.1

- EBL-corrected spectrum by Dominguez 2011 shows a much flatter shape



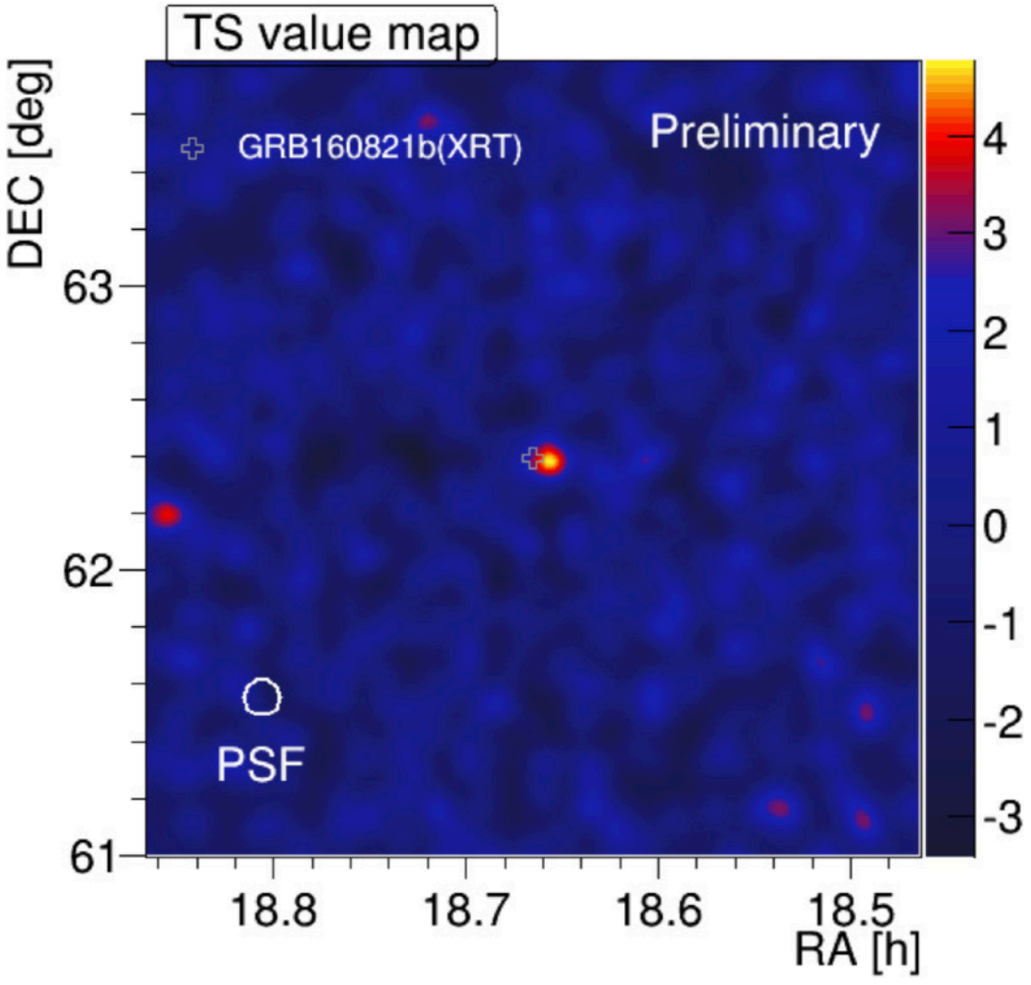
Short GRB 160821B (3 sigma hint)

- short GRB (**GBM T_{90} ~0.5 s, prompt phase finished <~25s**)

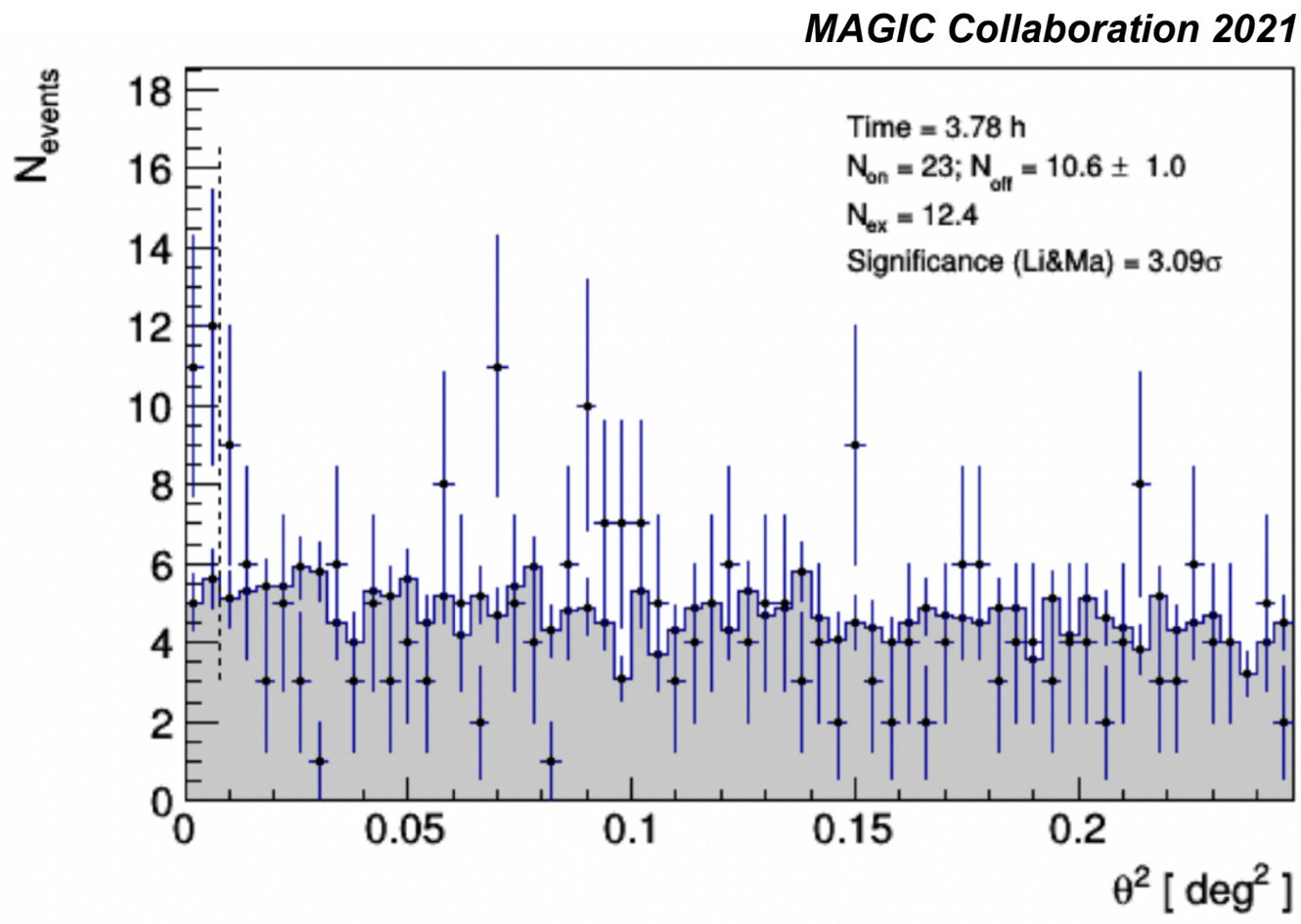
  - a nearby GRB (**z ~ 0.16**)

  - low luminosity (**$E_{\gamma,iso}$ ~ 1.3×10^{49} erg**)

- MAGIC observation started **24 s** after the satellite trigger time (T_0)



MAGIC Collaboration 2021

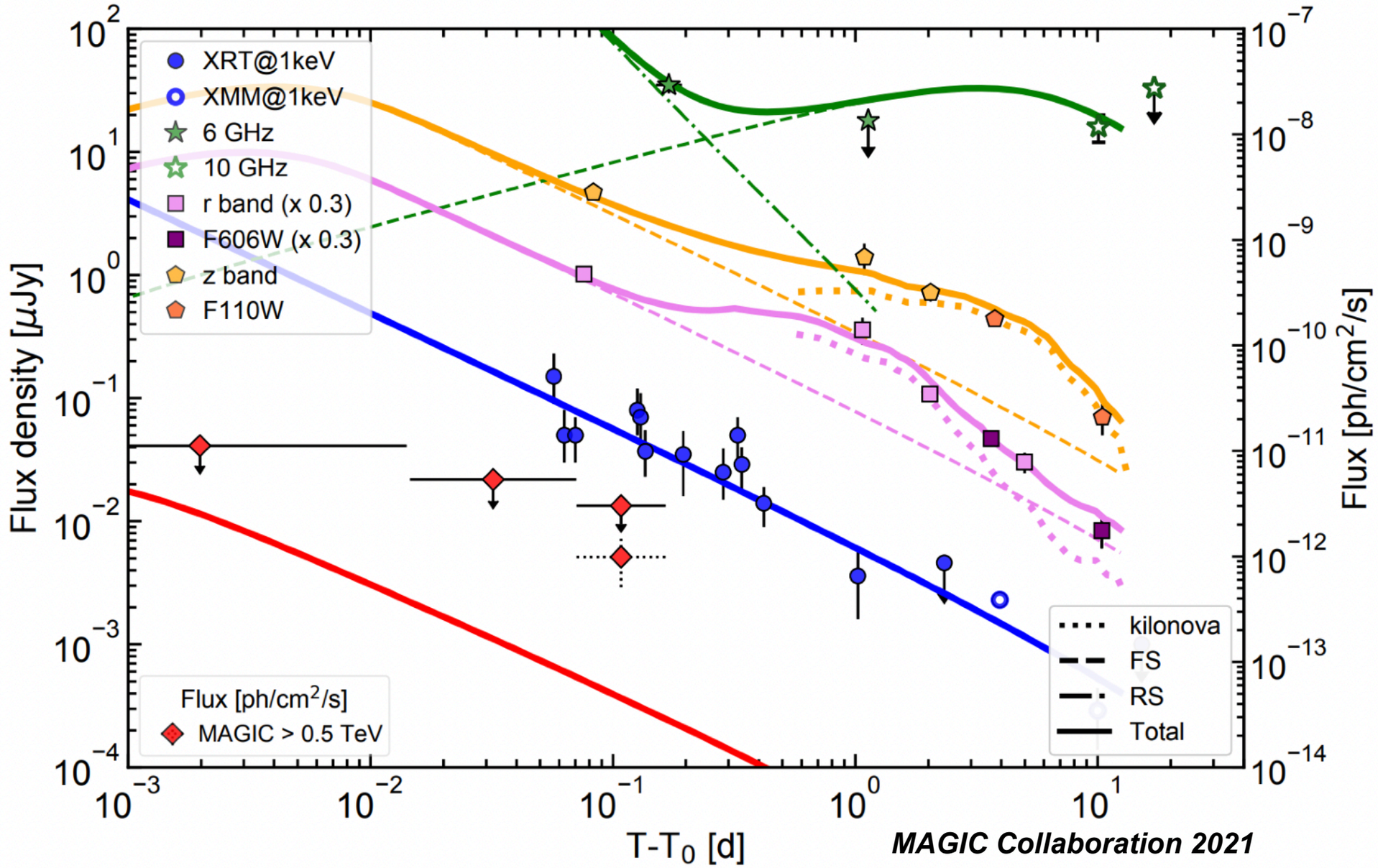


Short GRB 160821B (3 sigma hint)

- radio to X-ray : one-zone synchrotron + kilonova (optical-IR) radiation at day-scale

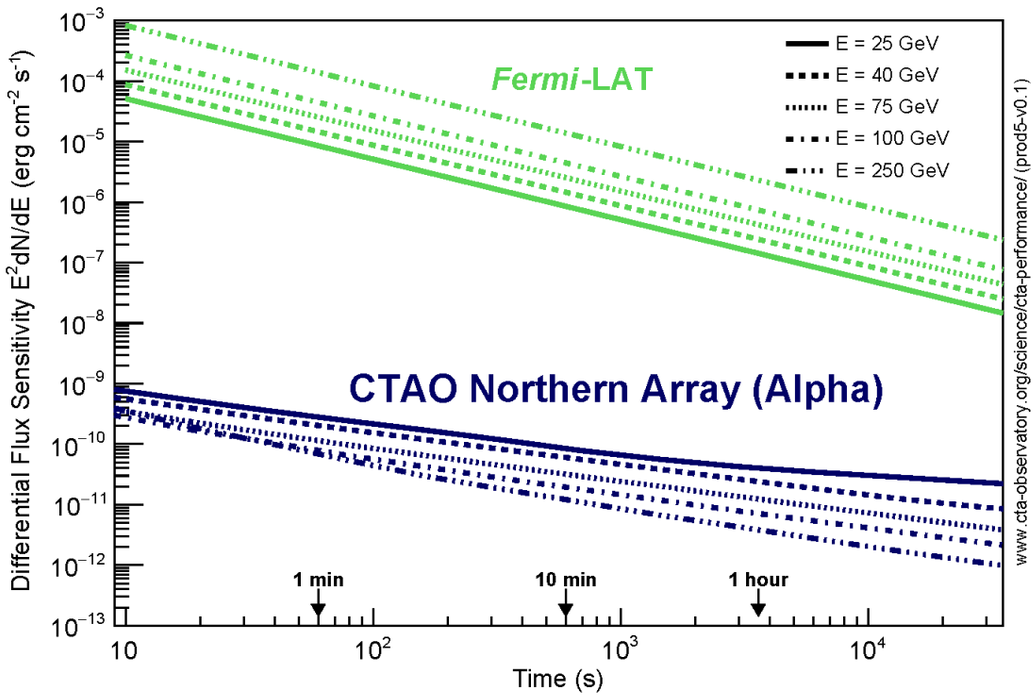
- TeV emission could not be explained by the model

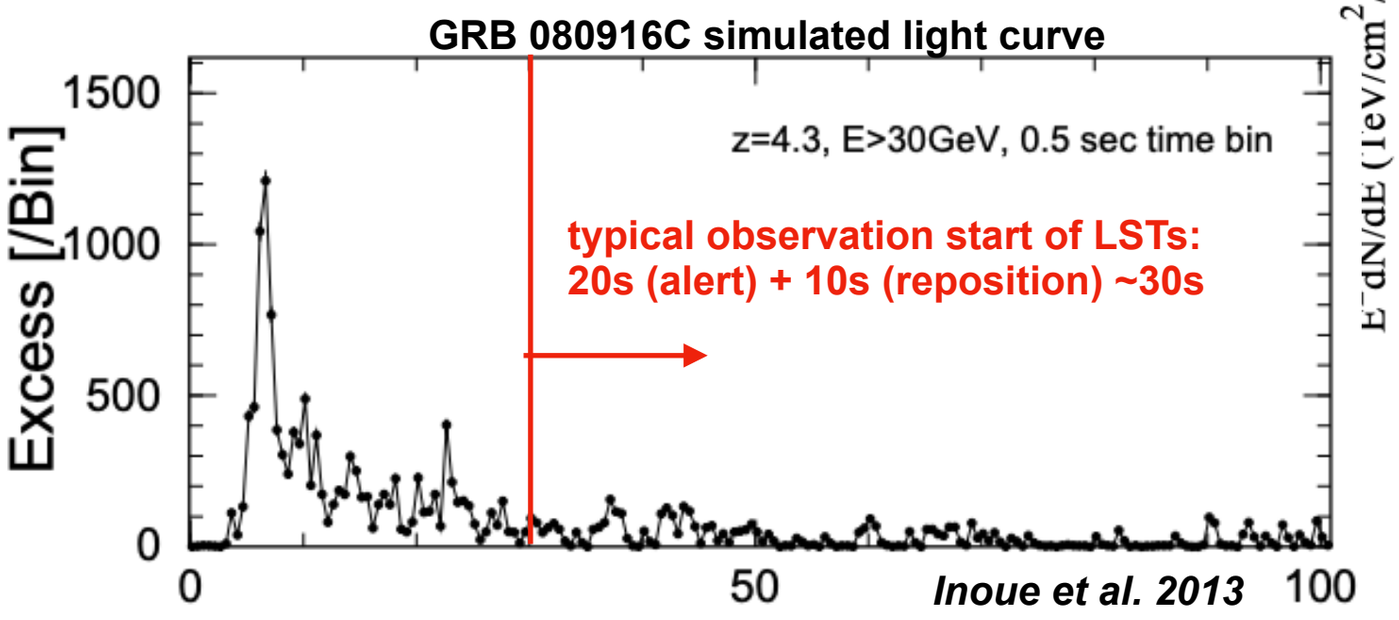
  - SSC and proton synchrotron are rejected

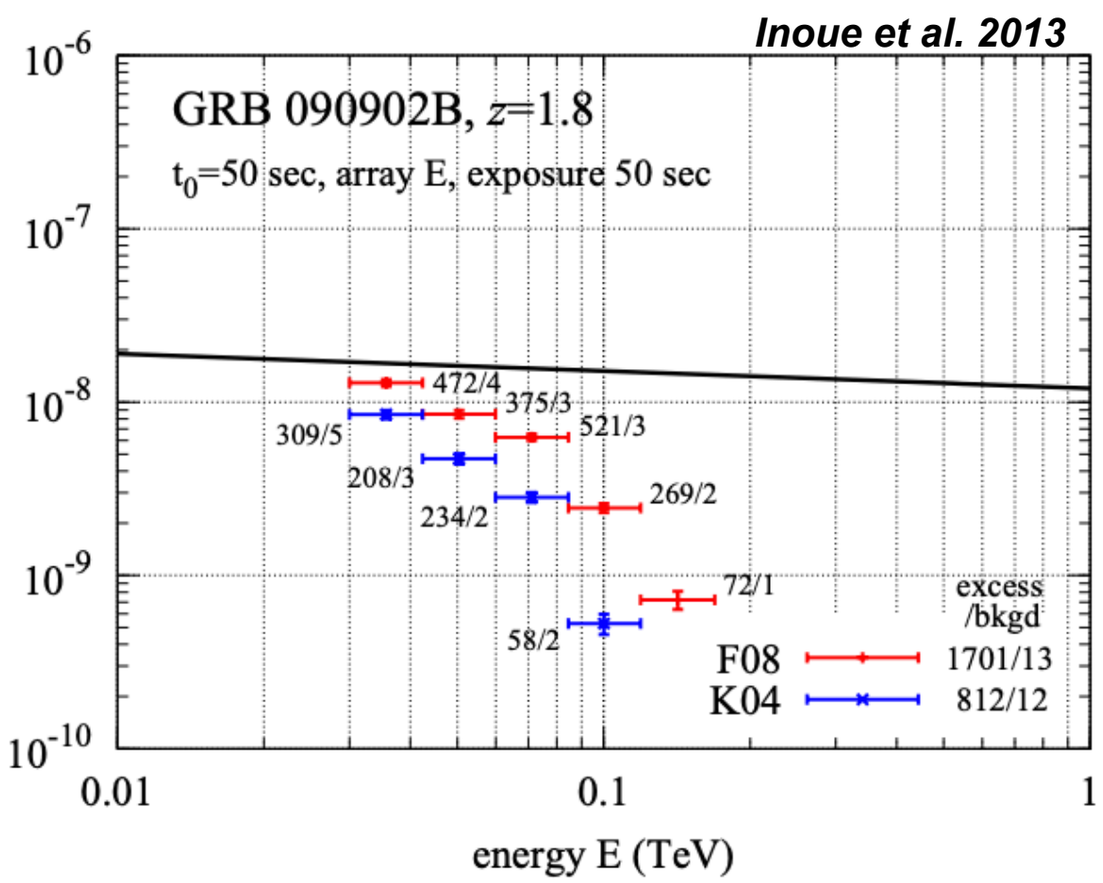


Prospects with CTA: performance

- 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)







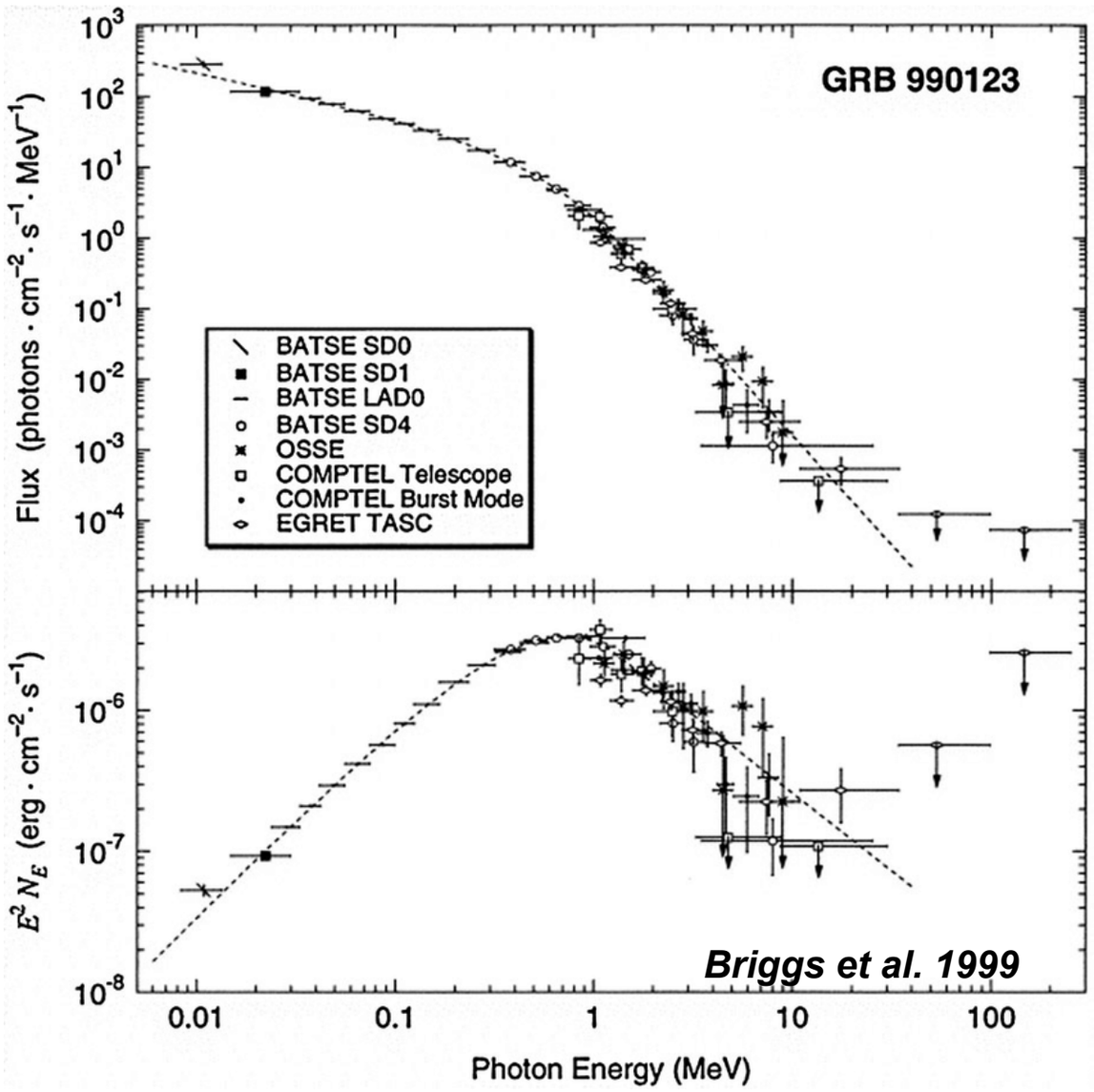
Summary

- Recently gamma-ray bursts started to be detected in the VHE gamma ray energy range. This emission is expected to provide additional information on unknown aspects on GRBs.
- So far VHE emission mechanisms are not yet well constrained. SSC is natural but there are other possibilities.
- GRB 201216C is the most distant VHE source at *z* 1.1. The emission feature is similar with the other VHE detected GRBs.
- GRB 160821B is a nearby short GRB showing a hint in the VHE energy range. The VHE emission could not be explained by the one-zone SSC or hadronic models.
- LST can extend the detectable distance and increase the statistics of VHE GRBs.

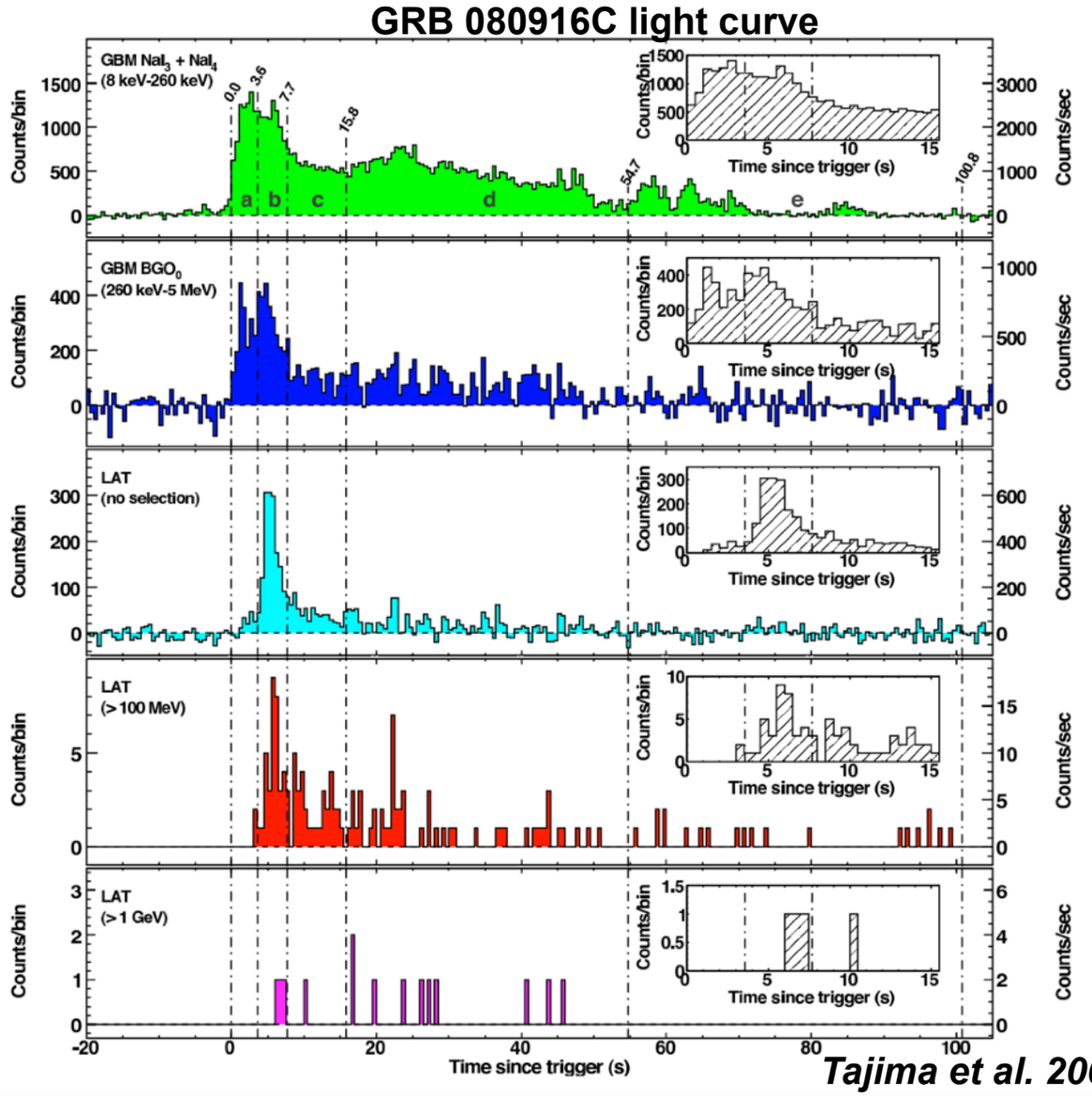
Backup

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



Briggs et al. 1999



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

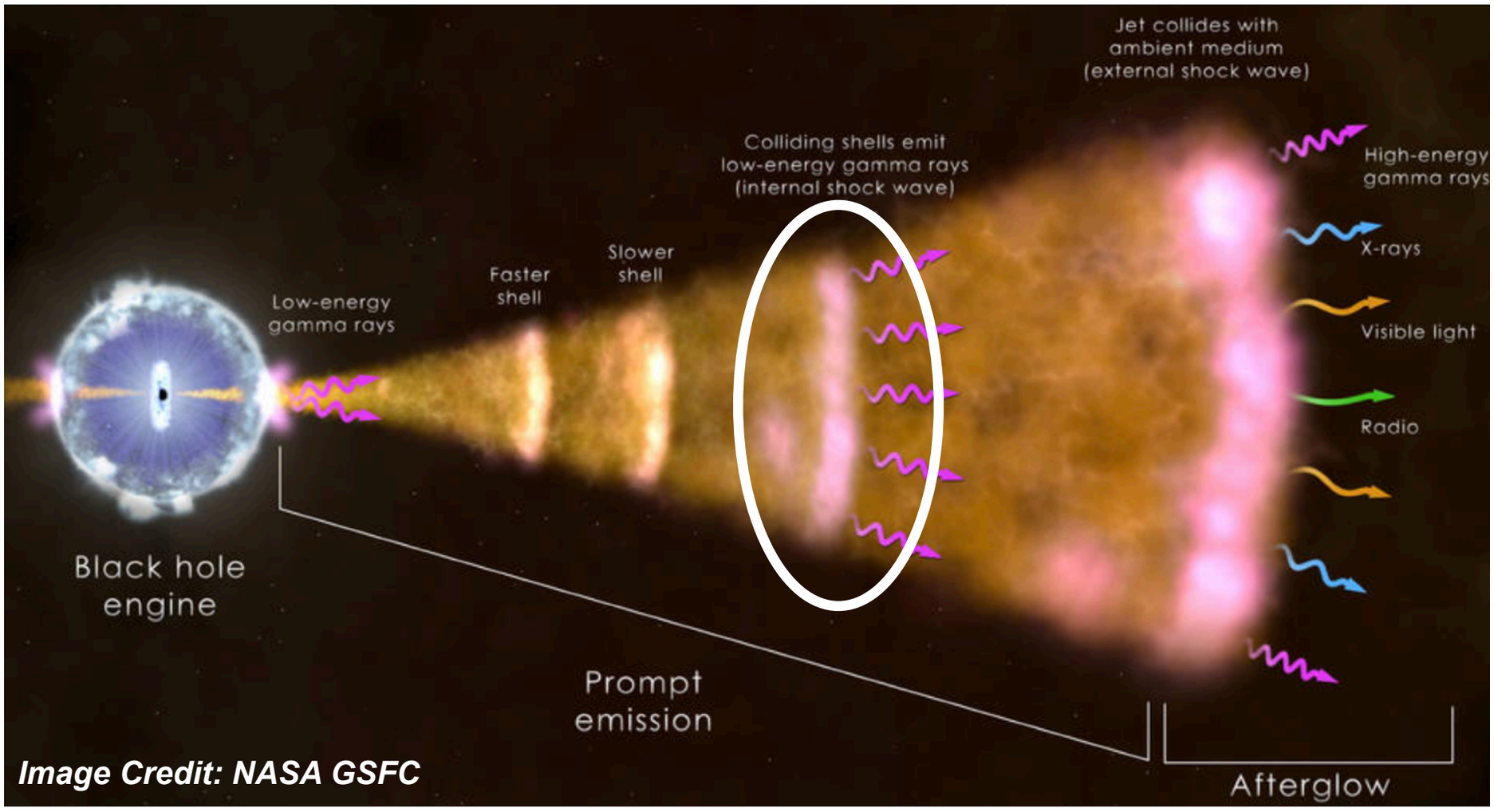
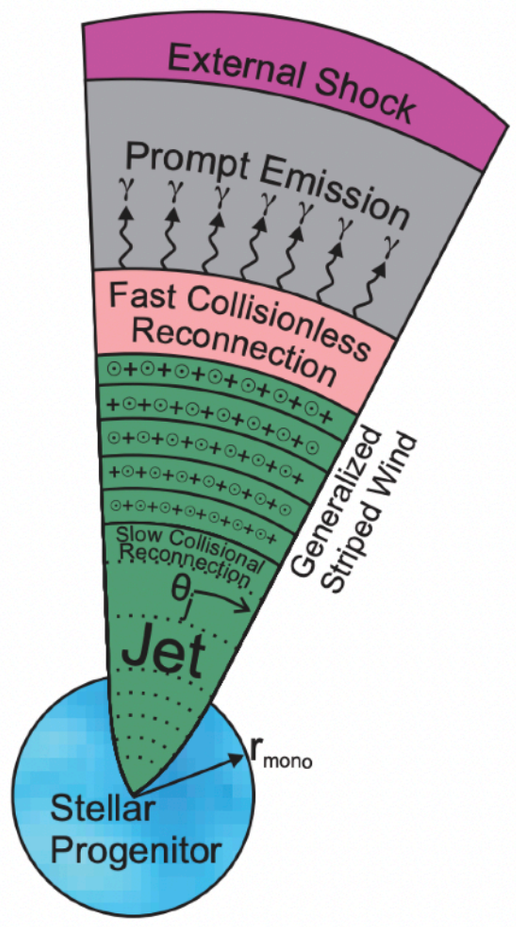


Image Credit: NASA GSFC



McKinney & Uzdensky 2012