A TeV afterglow from a narrow jet in the extremely bright GRB 221009A

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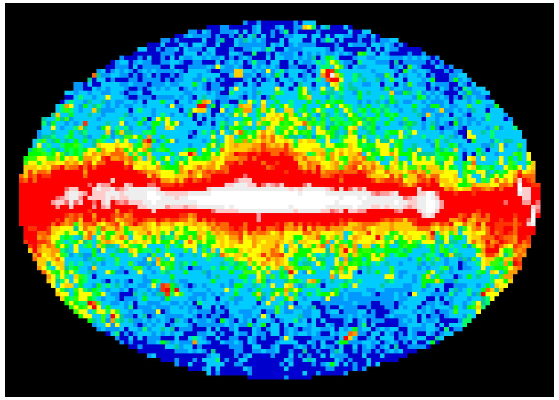
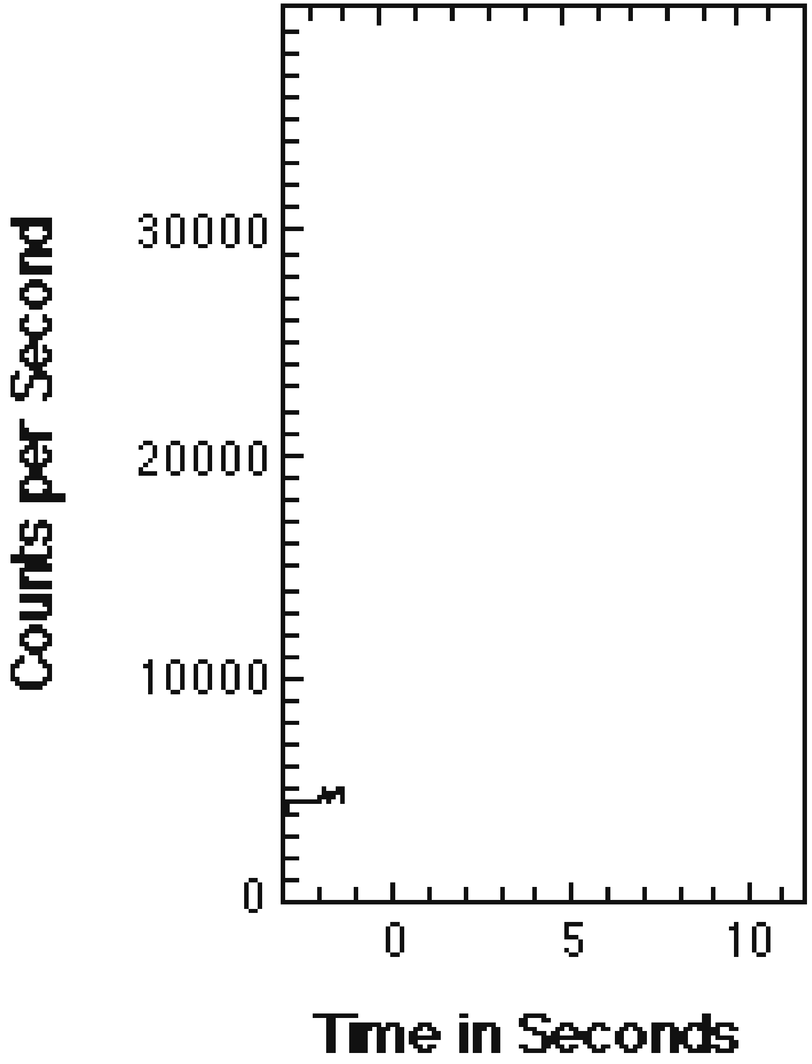
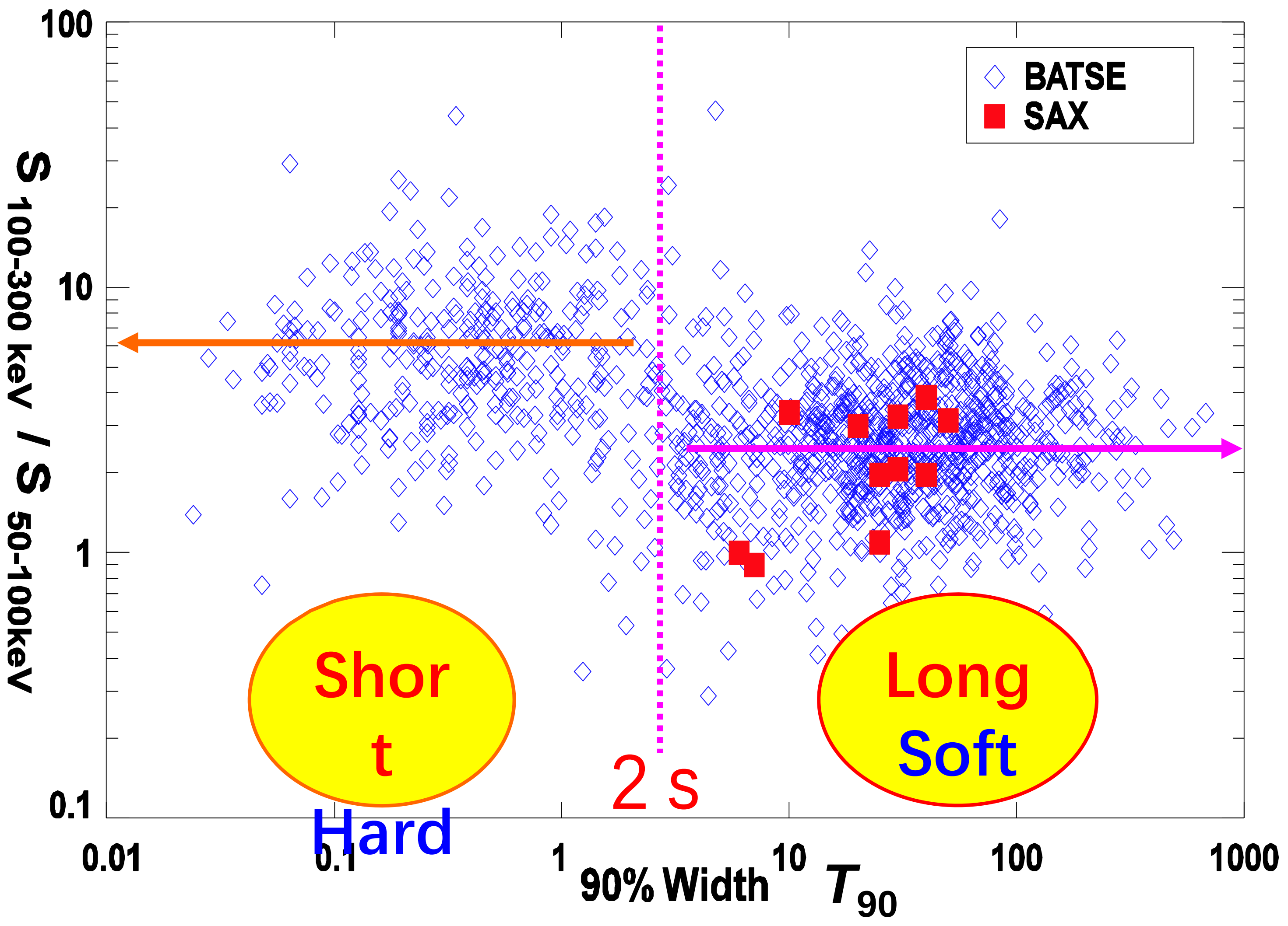
On behalf of LHAASO Collaboration

Gamma-ray bursts are short-duration flashes of gamma-rays occurring at cosmological distances!

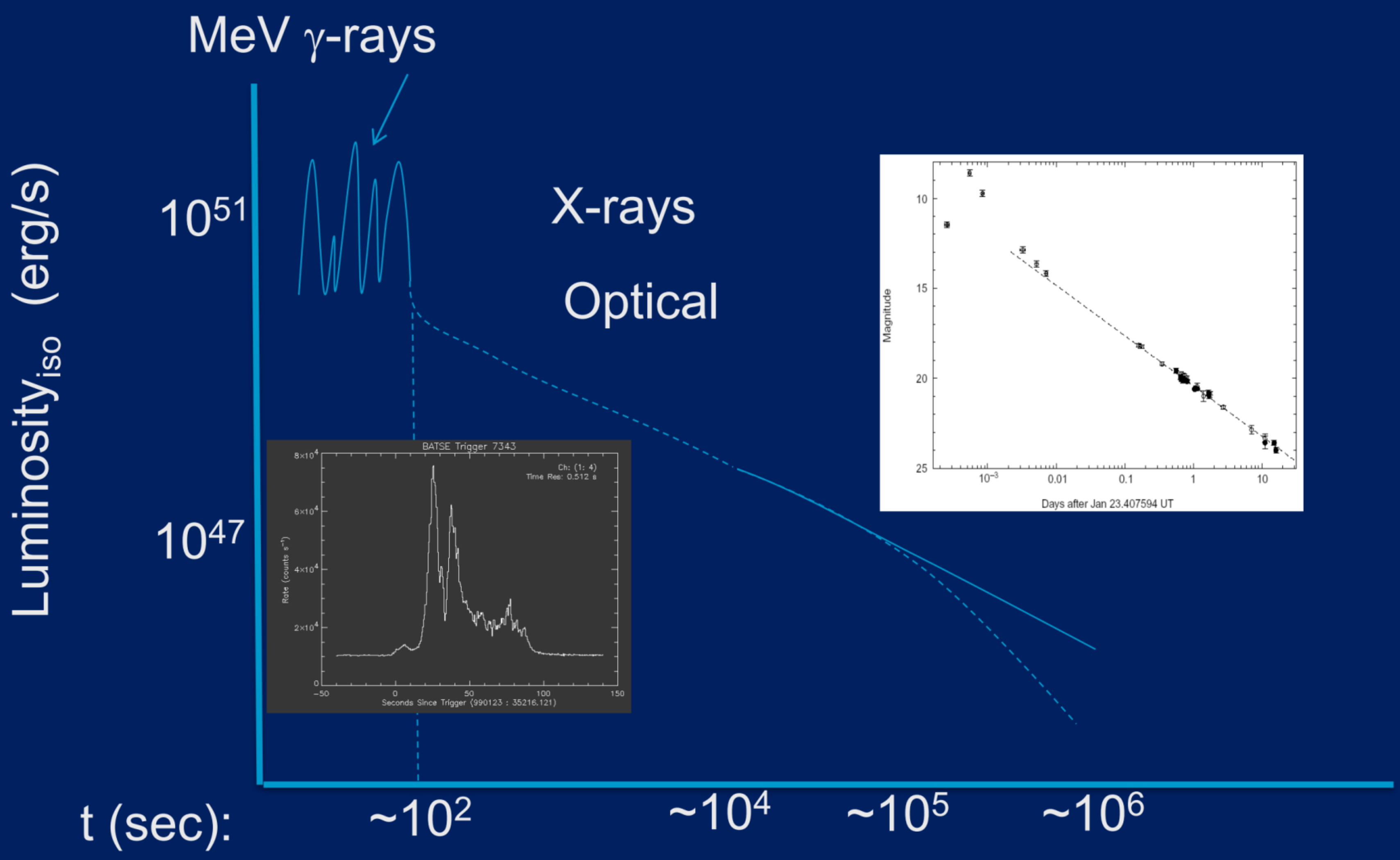




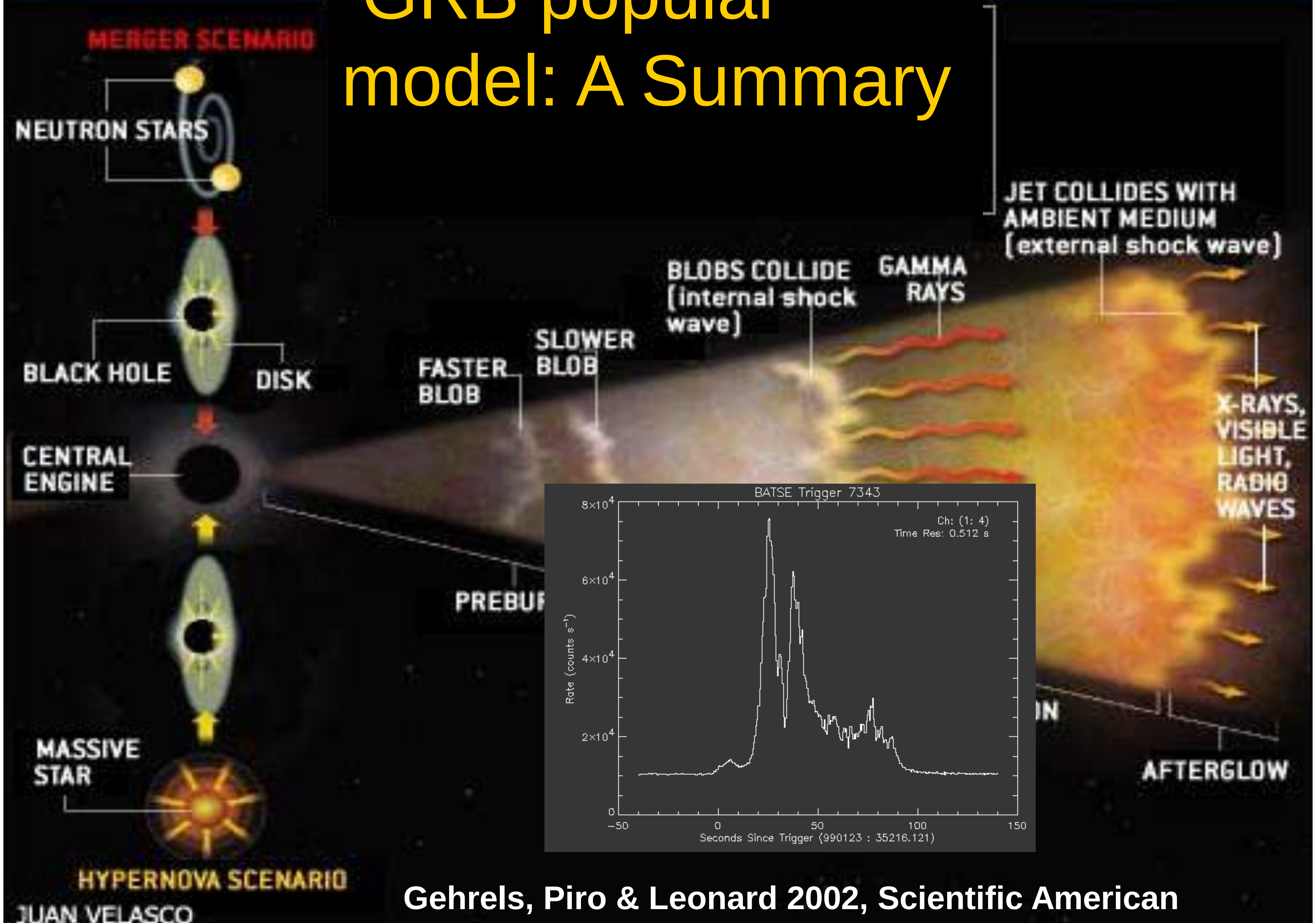
Bimodal distribution of durations



Typical GRB light curves

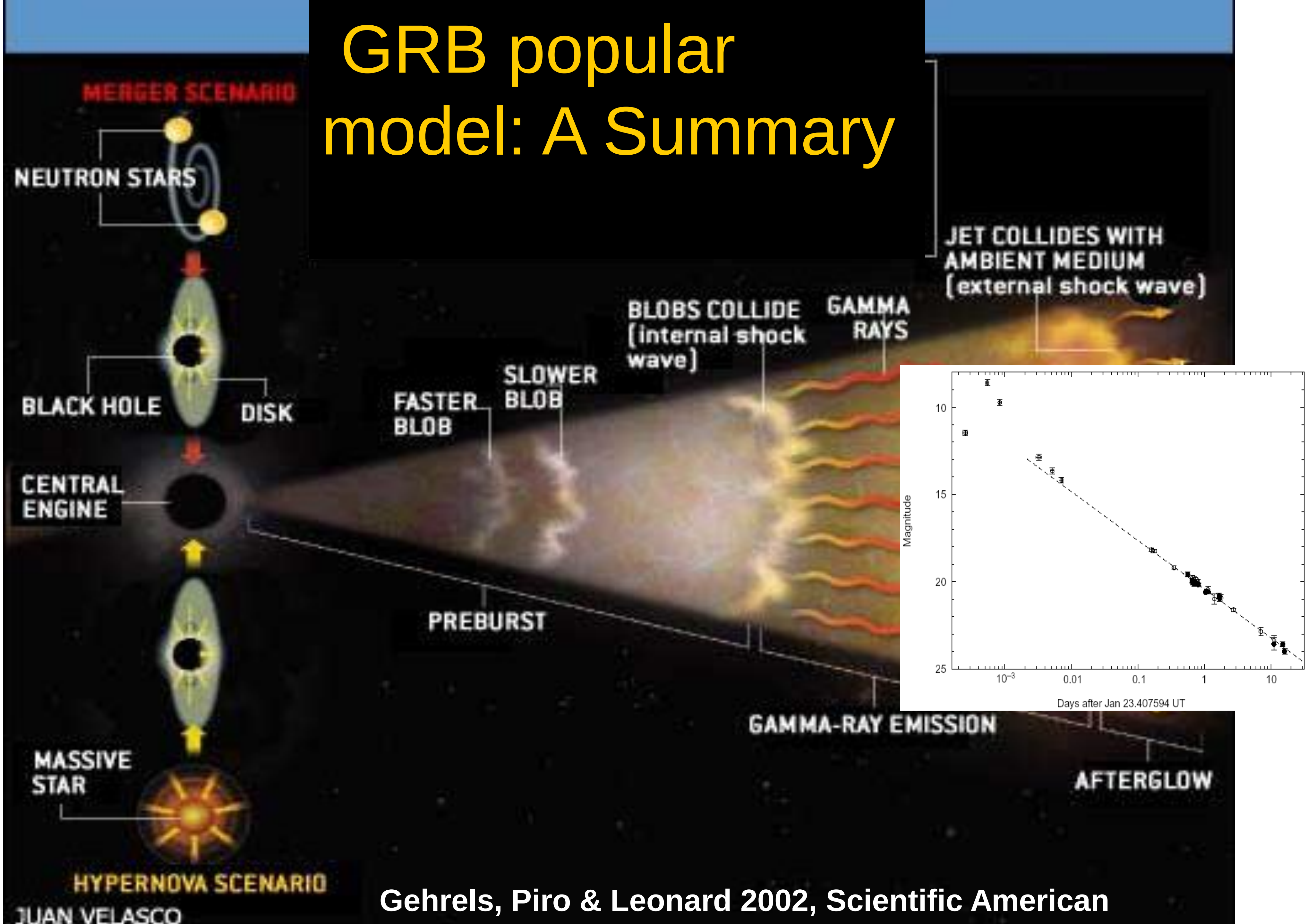


GRB popular model: A Summary



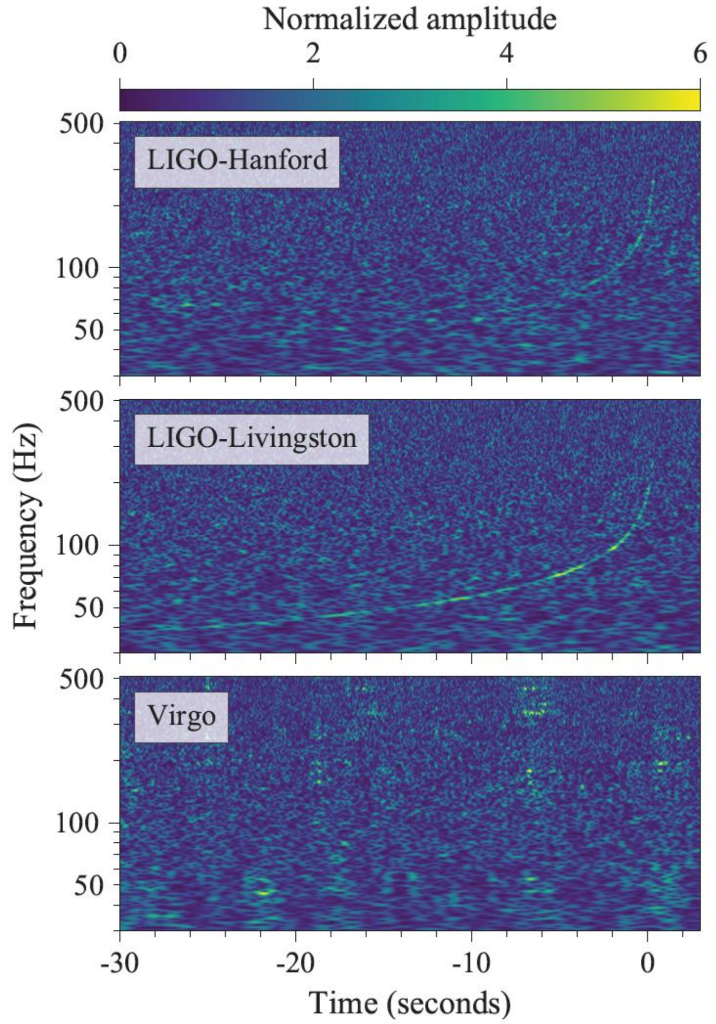
Gehrels, Piro & Leonard 2002, Scientific American

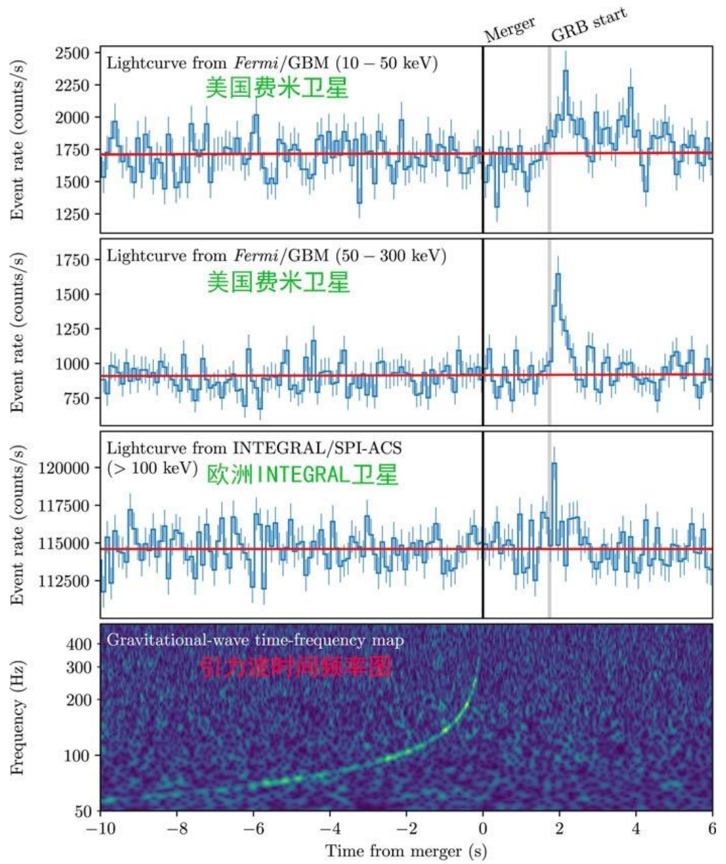
GRB popular model: A Summary



Gehrels, Piro & Leonard 2002, Scientific American

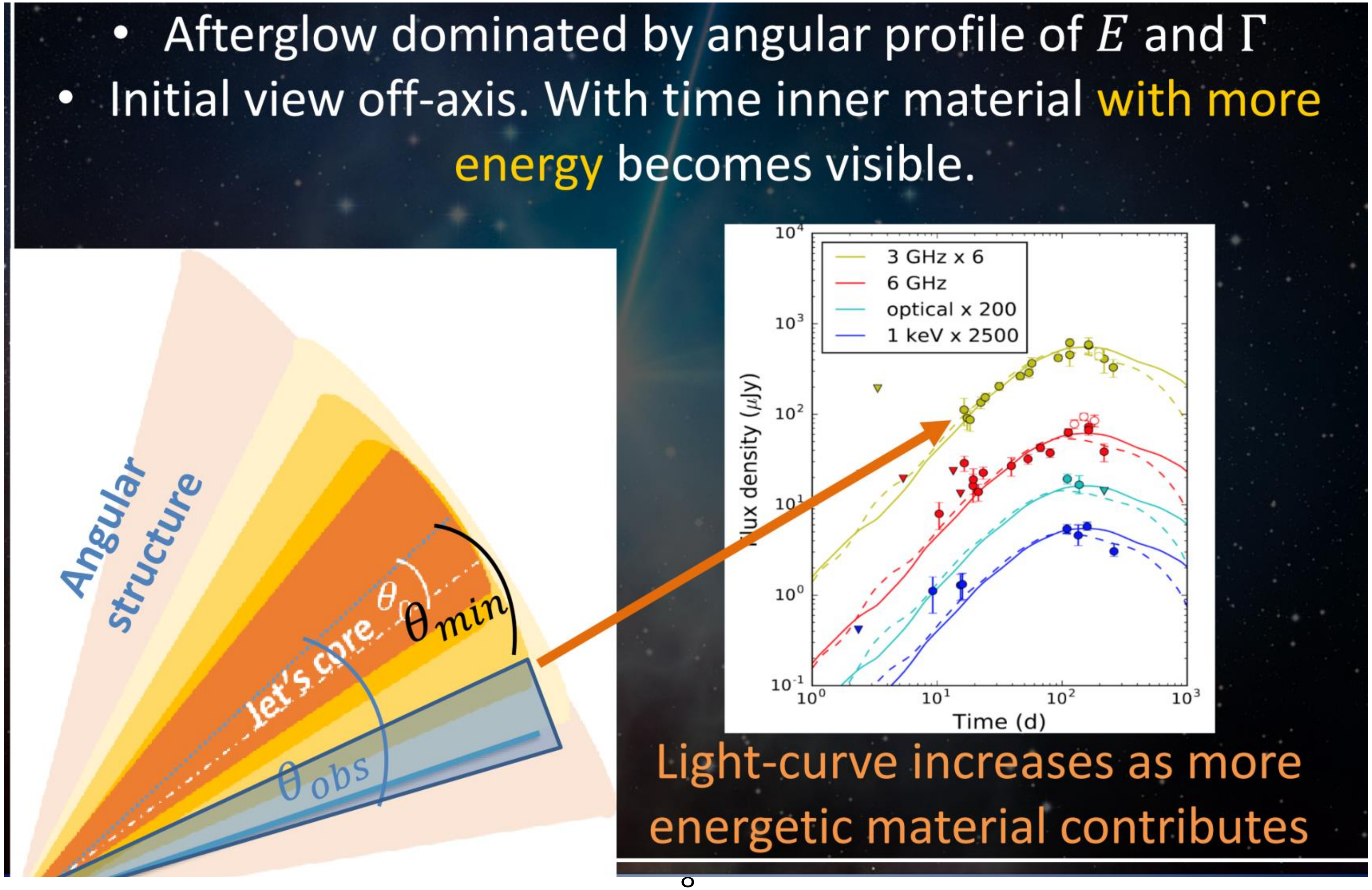
Gravitation wave detection from GW170817/GRB170817A





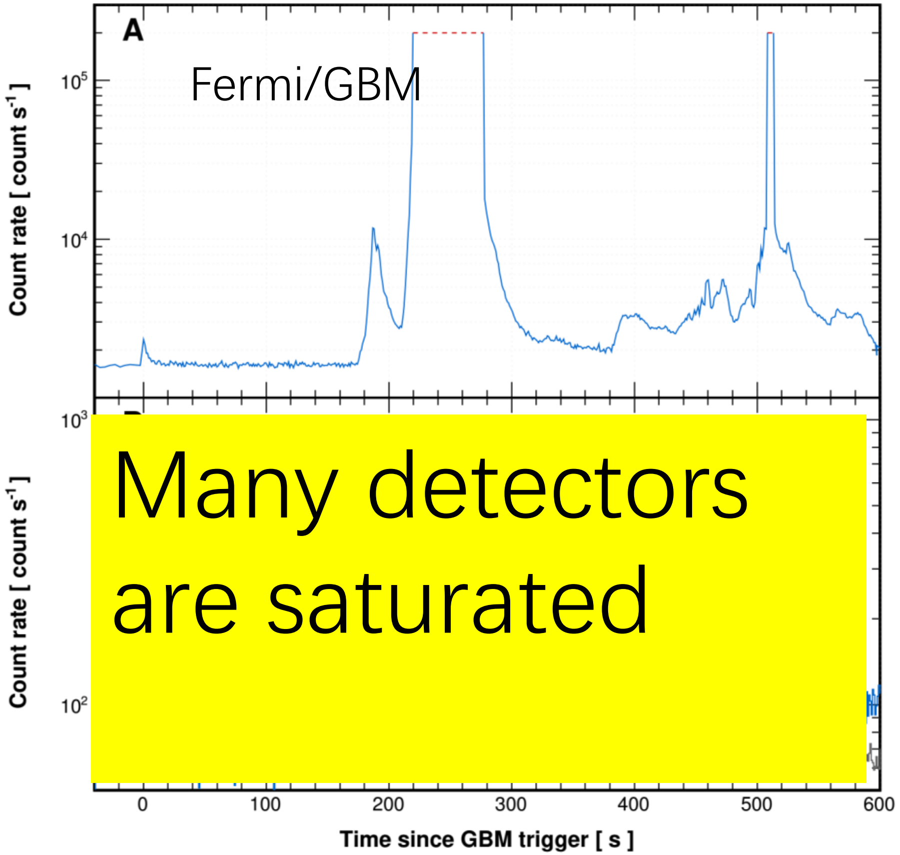
A short GRB

Multiwavelength observations of GRB 170817A



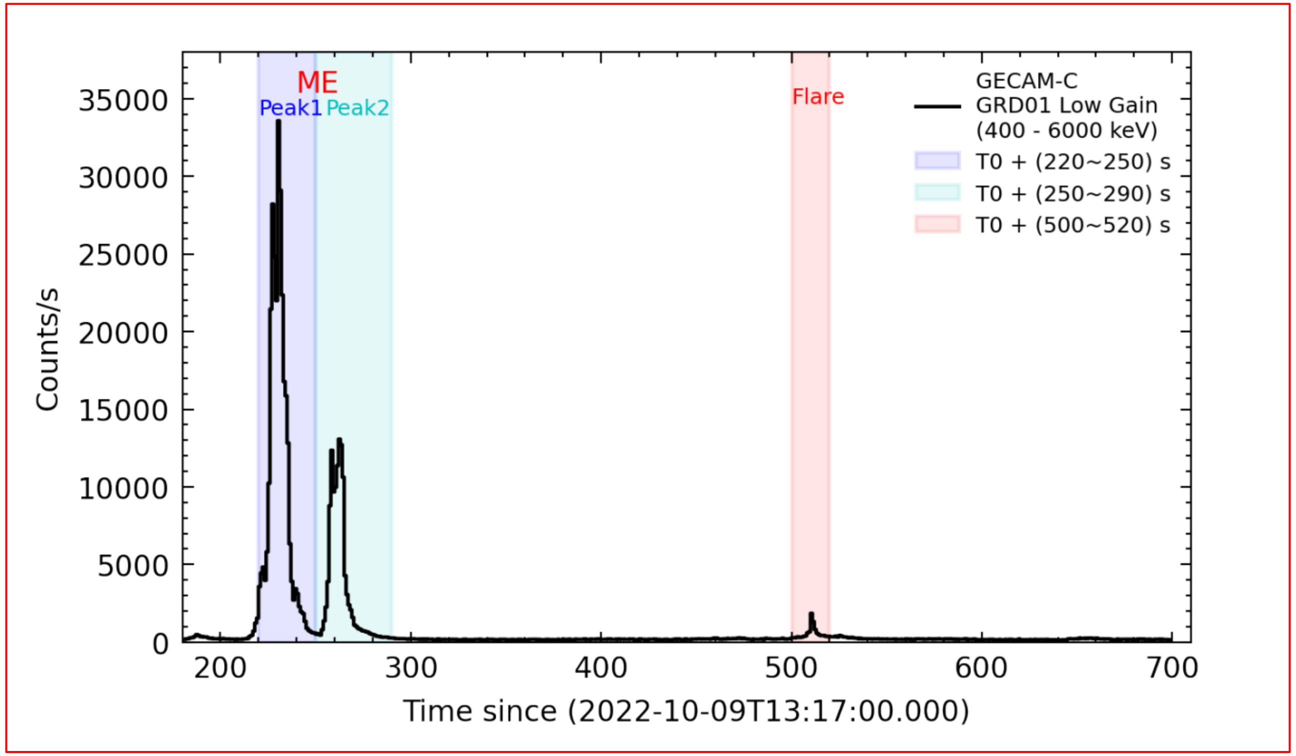
GRB 221009A: brightest-of-all-time (BOAT) GRB

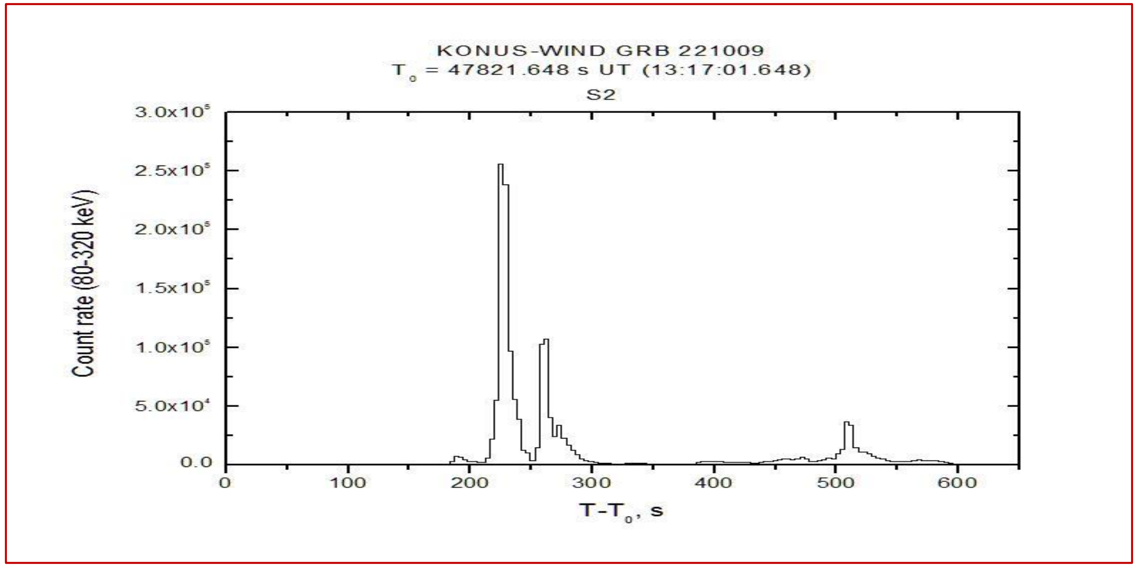
- Triggered on a weak precursor
- Fluence: >5e-2 erg/cm^2， deriving an enormous energy $E_{\gamma,iso}$~**10^{55}** erg
- brightest-of-all-time (BOAT GRB)



Fermi

GECAM/Konus-Wind Observations of GRB 221009A





GRB 221009A: A very rate event

1. arXiv:2302.03642 [pdf, other] astro-ph.HE

GRB 221009A: Discovery of an Exceptionally Rare Nearby and Energetic Gamma-Ray Burst

Authors: Maia A. Williams, Jamie A. Kennea, S. Dichiara, Kohei Kobayashi, Wataru B. Iwakiri, Andrew P. Beardmore, P. A. Evans, Sebastian Heinz, Amy Lien, S. R. Oates, Hitoshi Negoro, S. Bradley Cenko, Douglas J. K. Buisson, Dieter H. ... sham, B.

... s not shown)

... 1009A, as

> Even more remarkable, we can use these results to derive the rate of GRB 221009A-like GRBs within the volume out to $z = 0.151$ ($1.1\,\mathrm{Gpc}^{-3}$). **This implies we would need to wait over $\approx 10^3$ years to detect another GRB 221009A-like event within this volume.** The combination of the large energy release and the small distance make GRB 221009A truly a once in a lifetime phenomenon.

Fluence: $>5 \times 10^{-2}$ erg/cm^2

R_GRB$\leq 6.1 \times 10^{-4}$ Gpc^{-3} yr^{-1}

R<10^-3 yr

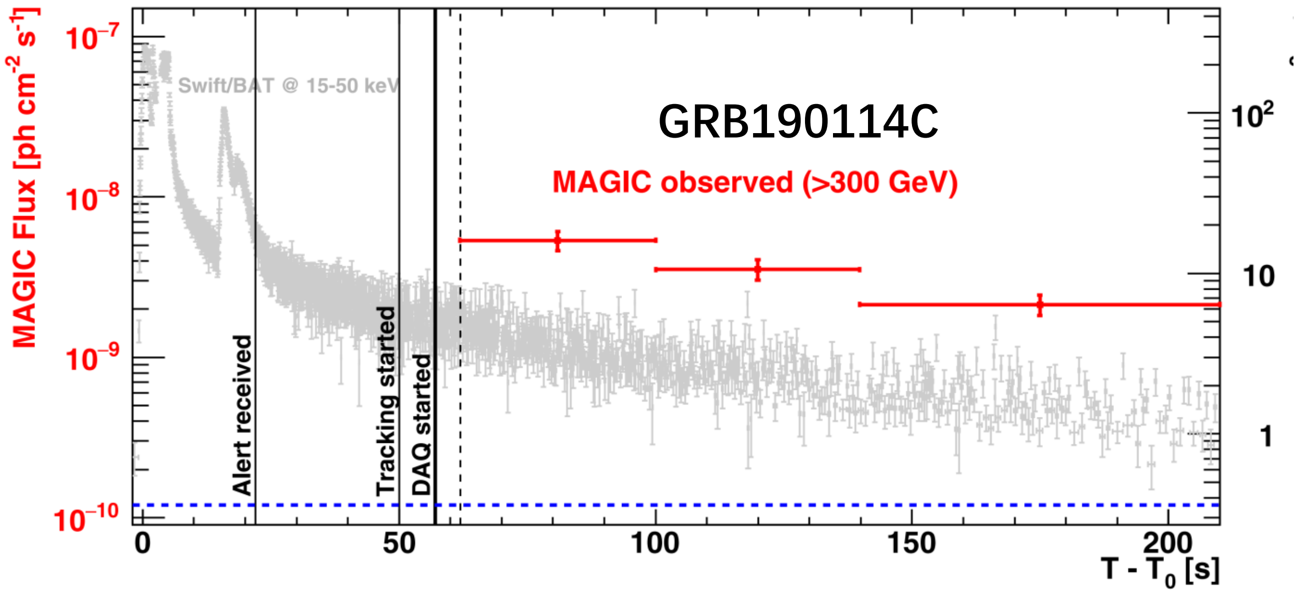
z=0.151 volume ~ 1 Gpc^3

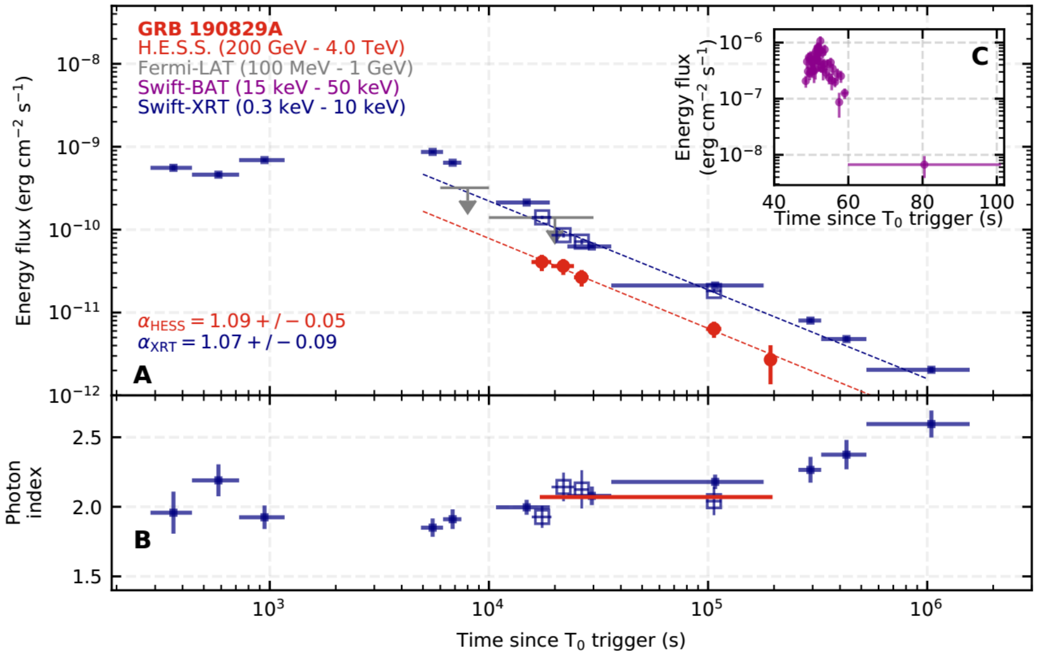
GRB 221009A

- Why is GRB 221009A so bright ?

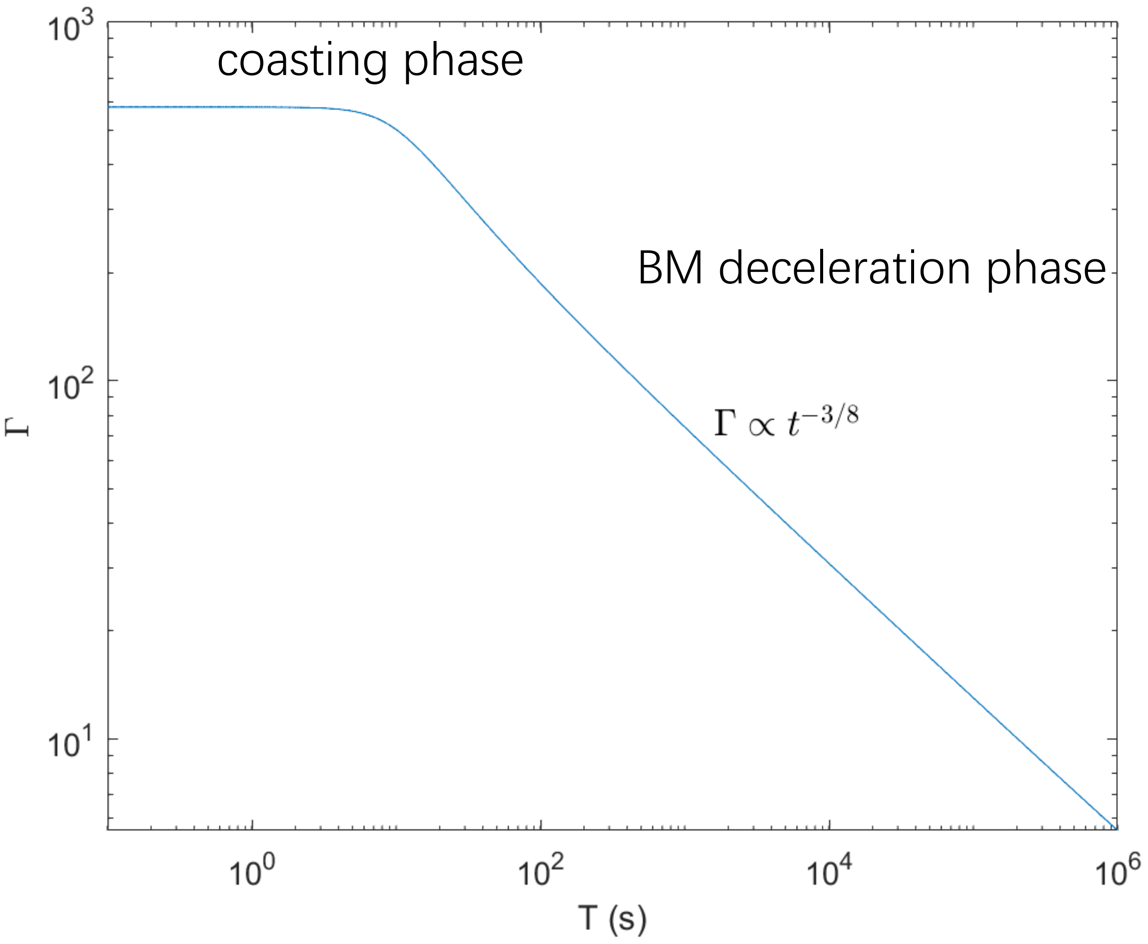
- What do TeV observations tell us ?

Decaying TeV afterglow





How about TeV emission before deceleration?



- **TeV emission during the coasting phase ?**
- **Any TeV emission during the prompt emission?**

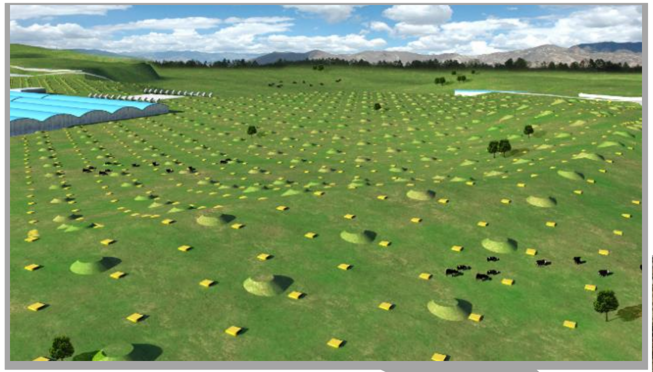
✓ IACTs are pointed instruments that need time to slew to the GRB

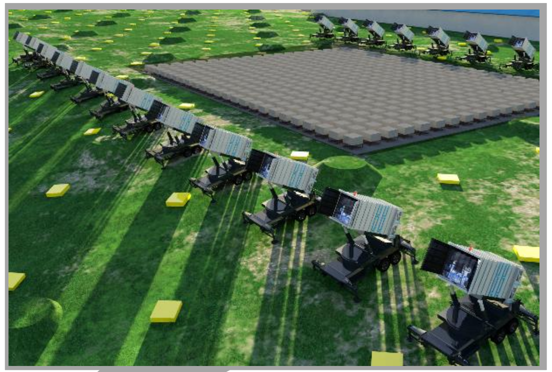
✓ Extensive air shower detectors allow observations during the prompt GRB and the afterglow onset

- LHAASO bird view in Oct. 2019

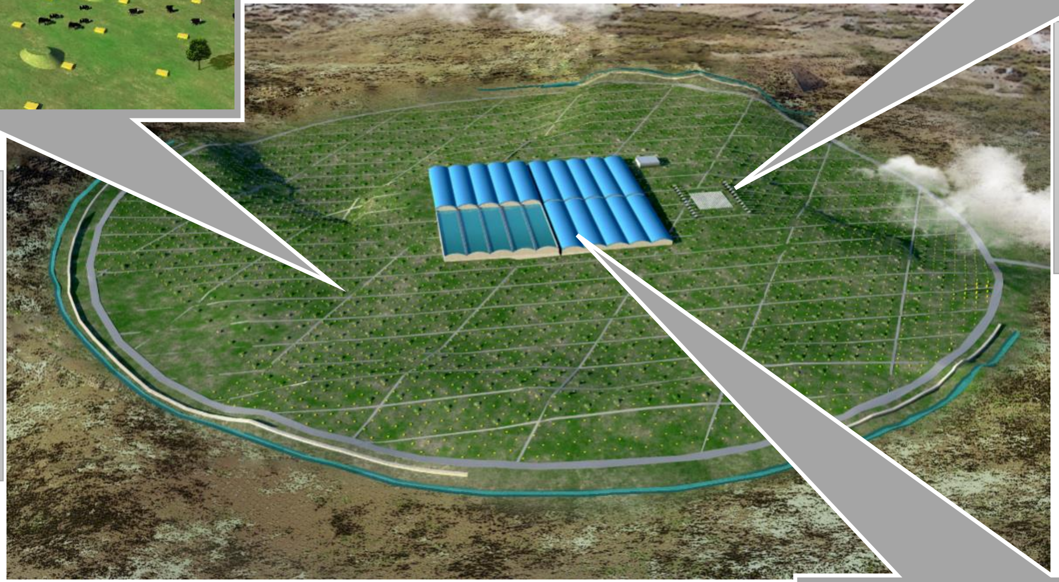
Daochen, 4410 m a.s.l., 600 g/cm^2
(29^{o}21’ 31” N, 100^{o}08’15” E)

LHAASO





KM2A:
• 5195 Scin's: 1 m^2, 15m spacing
• 1171 MDs: 36 m^2, 30m spacing



WFCTA:
18 Cherenkov telescopes (1024 pixels/telescope)

WCDA:
3120 cells ($25m^2$/cell)

A dual-task facility designed for CR and γ-ray studies

1) KM2A : Kilometer Square Array
2) WCDA : Water Cherenkov Detector Array
3) WFCTA: Wide Field-of-view Cherenkov Telescope Array

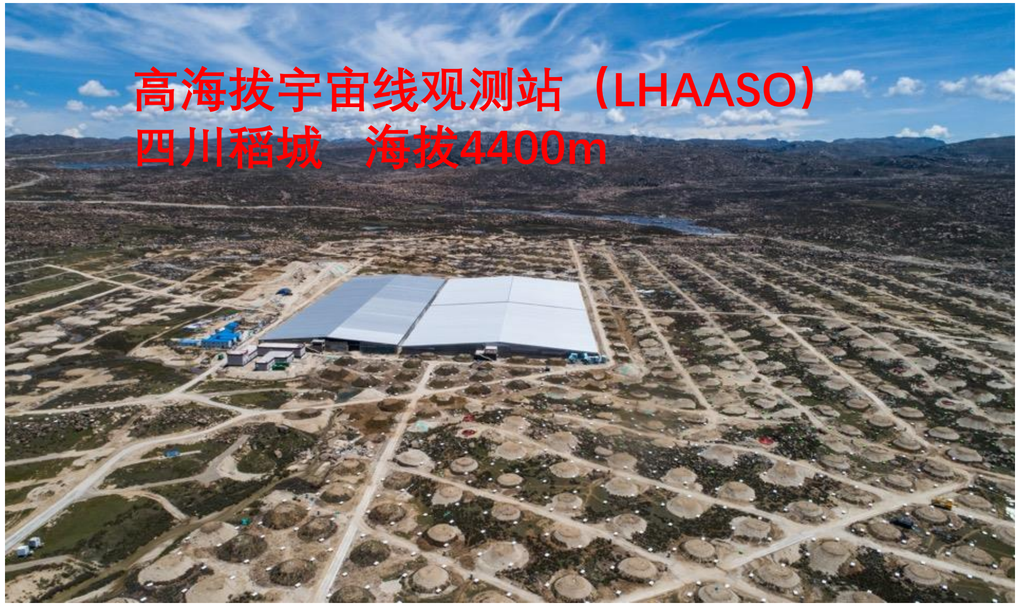
LHAASO对GRB221009A的探测

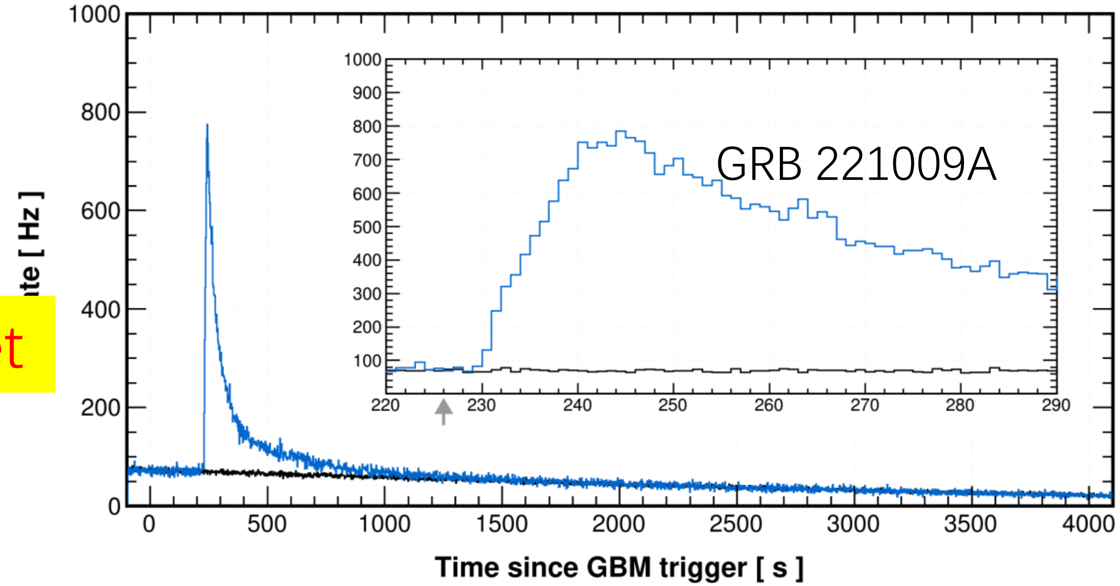
- LHAASO detection of GRB 221009A: first GRB seen by a extensive air shower detector

- High statistics: >60,000 photons above 0.2TeV (LHAASO-WCDA)

- TeV count rate light curve: Smooth temporal profile – **external shock origin**

First time detecting the TeV aftreglow onset



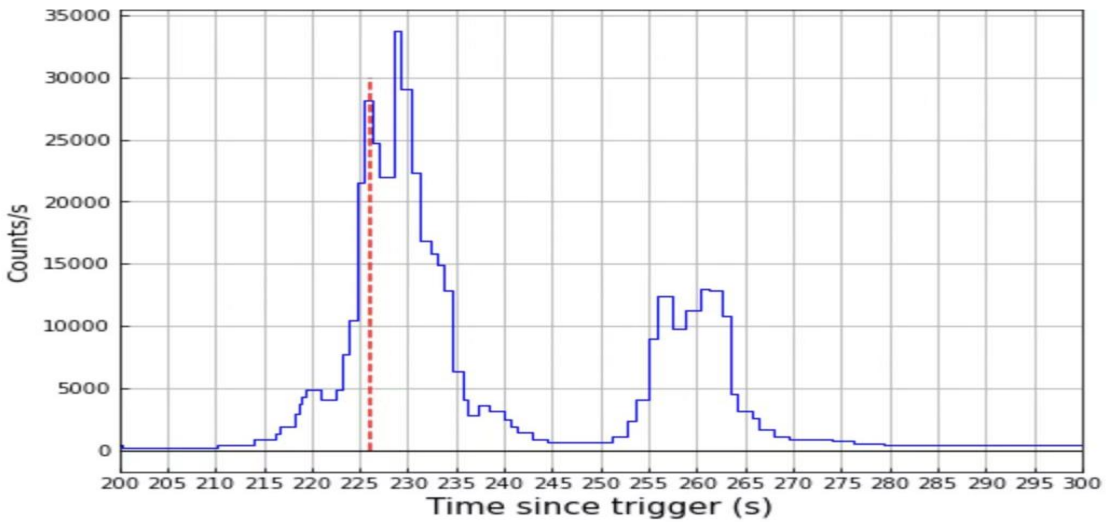


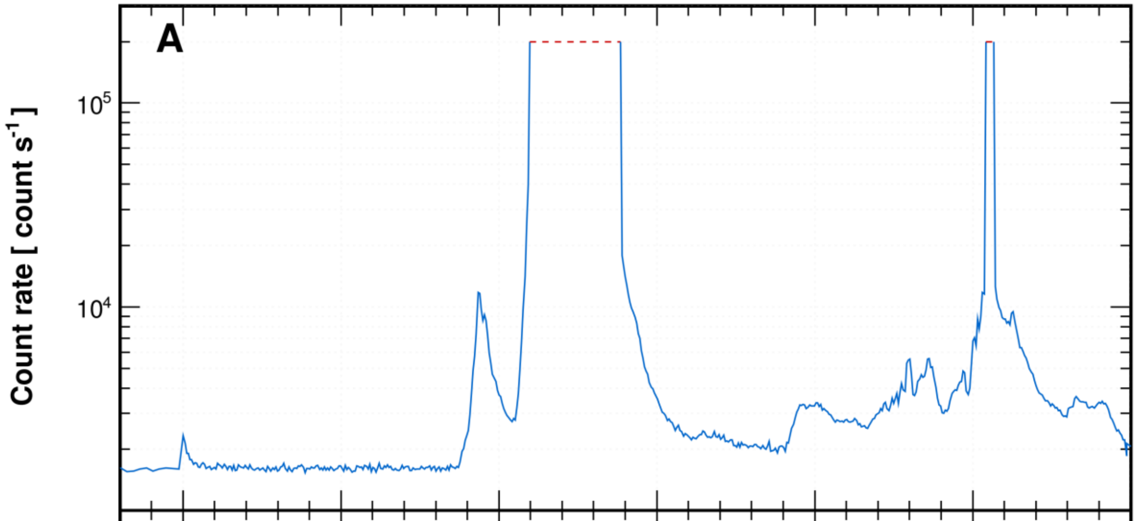
Afterglow starting time: T*

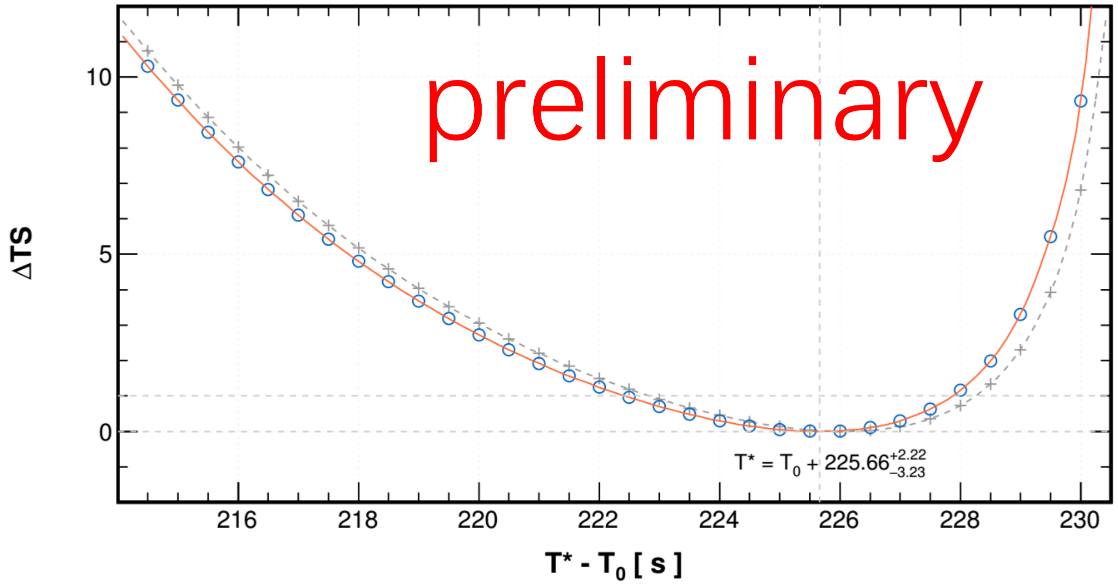
- Triggered on a weak precursor
- Numerical studies have found that measuring times from the beginning of the main burst emission is a good approximation (Lazzati, Zhang…):

$T^* \approx 225$–228 s

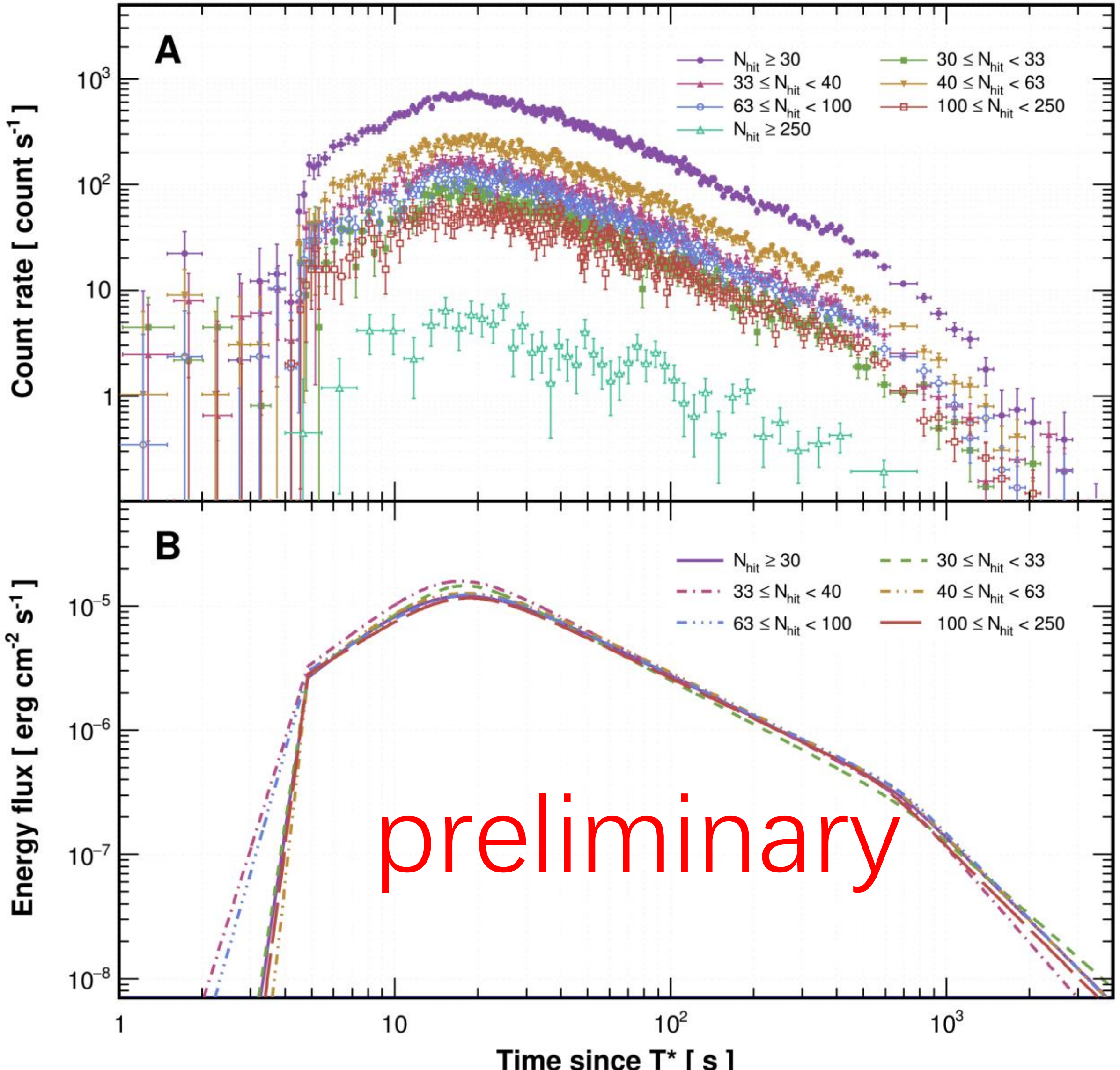
- Fitting of LHAASO light curve: $T^* \approx 226_{-3}^{+2}$ s



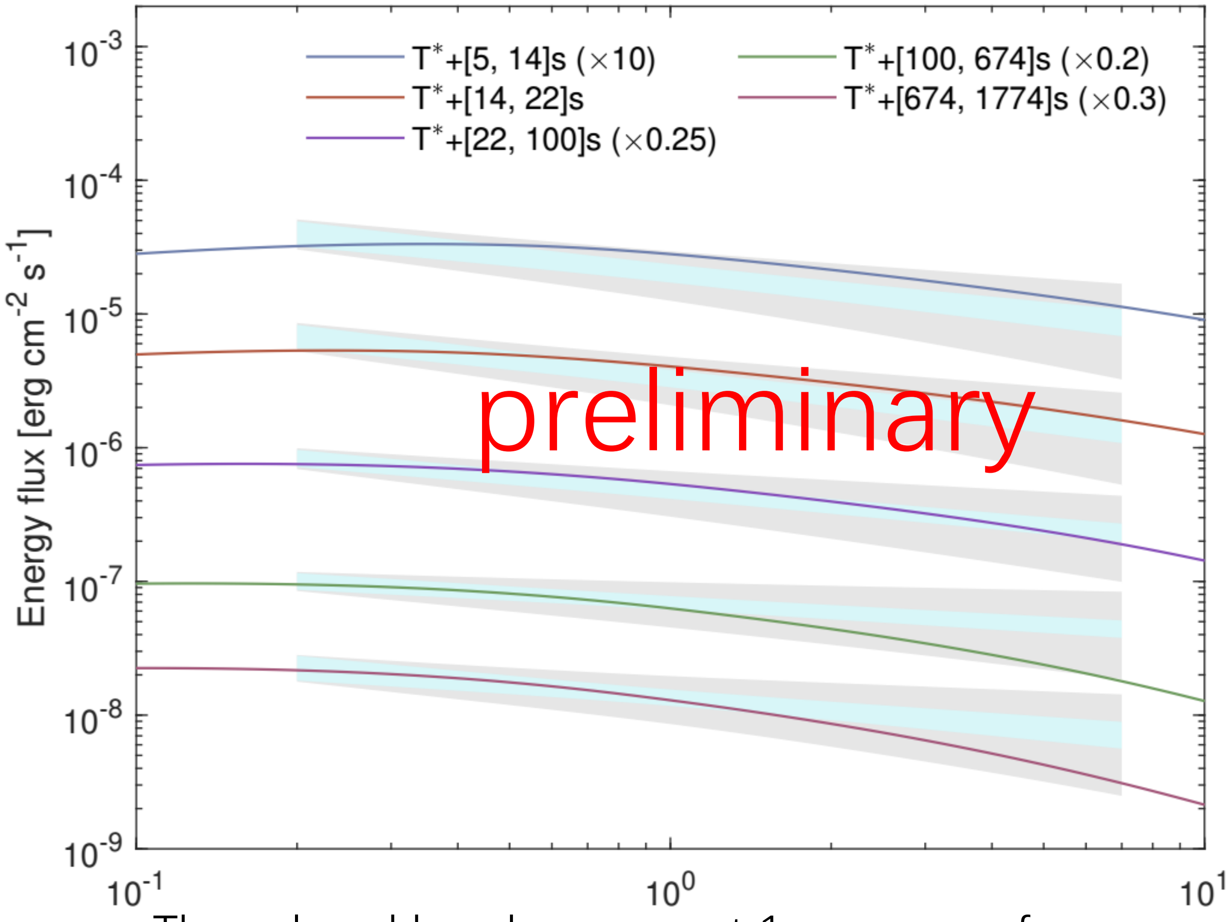




4-segement Power-law



SED measured by LHAASO-WCDA



The colored bands represent 1 σ ranges of statistical errors (the inner band) and systematic uncertainties (outer bands).

- .EBL model: A. Saldana-Lopez et al., Mon. Not. R. Astron. Soc. 507, 5144-5160 (2021)

Time interval (seconds after T_0)	A (10^{-8} TeV^{-1} cm^{-2} s^{-1})	γ	$E_{\rm cut}$ TeV	χ^2/dof
Observed spectrum				
231–240	42.9 ± 2.7	2.983 ± 0.061	3.14 (fixed)	4.6/6
240–248	70.1 ± 3.8	3.006 ± 0.052	3.14 (fixed)	8.0/6
248–326	39.9 ± 1.0	2.911 ± 0.028	3.14 (fixed)	14.8/6
326–900	7.35 ± 0.16	2.788 ± 0.026	3.14 (fixed)	8.9/6
900–2000	0.959 ± 0.043	2.880 ± 0.067	3.14 (fixed)	2.9/5
Intrinsic spectrum, *standard* EBL				
231–240	127.3 ± 7.9	2.429 ± 0.062	\	3.1/6
240–248	208 ± 11	2.455 ± 0.054	\	6.5/6
248–326	117.8 ± 3.0	2.359 ± 0.028	\	8.7/6
326–900	21.77 ± 0.47	2.231 ± 0.026	\	3.4/6
900–2000	2.84 ± 0.13	2.324 ± 0.065	\	2.2/5

1.Rising phase

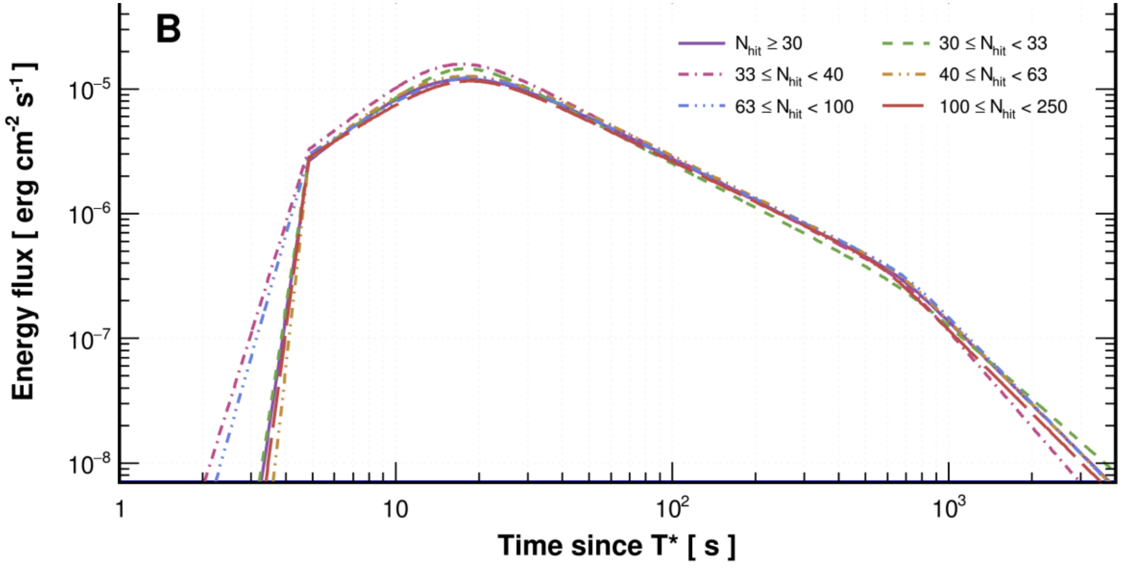
$$\alpha_0 = 14.9^{+5.7}_{-4.0}$$

$$\alpha_1 = 1.82^{+0.21}_{-0.18}$$

- The rising phase: free expansion
- TeV: assuming synchrotron Self-Compton emission
- Expected light curve: agrees with t^2 for

k=0 (ISM)

$$\boxed{n \propto R^{-k}}$$



$$F_\nu = \begin{cases} F_m^{\rm IC}\left(\frac{\nu}{\nu_m^{\rm IC}}\right)^{-\frac{p-1}{2}} \propto t^{\frac{16-(9+p)k}{4}}\nu^{-\frac{p-1}{2}}, & \nu_m^{\rm IC} < \nu < \nu_c^{\rm IC} \\ F_m^{\rm IC}\left(\frac{\nu}{\nu_c^{\rm IC}}\right)^{-\frac{1}{2}} \propto t^{\frac{8-3k}{4}}\nu^{-1/2}, & \nu_c^{\rm IC} < \nu < \nu_m^{\rm IC} \\ F_m^{\rm IC}(\nu_m^{\rm IC})^{\frac{p-1}{2}}(\nu_c^{\rm IC})^{\frac{1}{2}}\nu^{-\frac{p}{2}} \propto t^{\frac{8-(2+p)k}{4}}\nu^{-\frac{p}{2}}. & \nu > \max(\nu_m^{\rm IC}, \nu_c^{\rm IC}) \end{cases} \quad (12)$$

What we've learnt from the GRB 221009A

1. Initial Lorentz Factor Γ_0

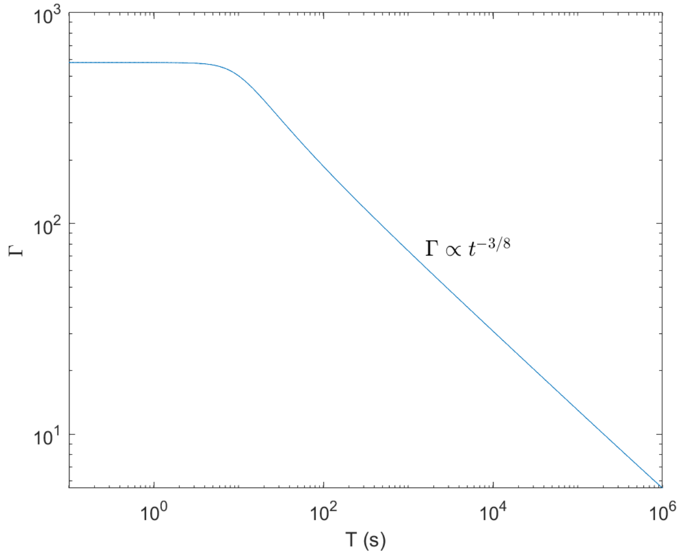
- From **T*** to the peak (energy-independent peak time), it takes

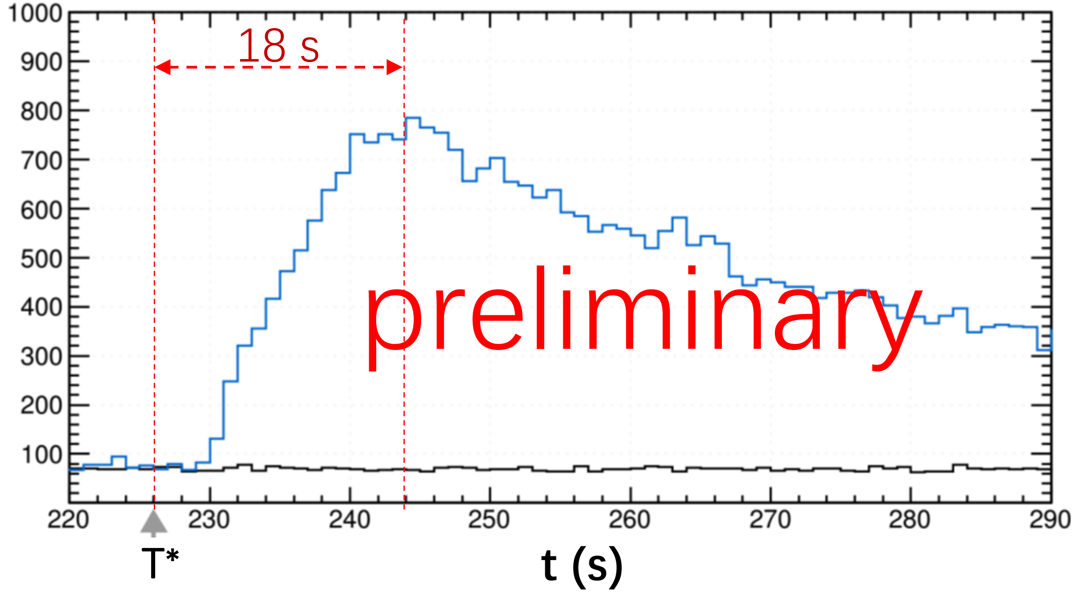
~18 s

- The bulk Lorentz factor is estimated as

$$\Gamma_0 = \left(\frac{3E_k}{32\pi n m_p c^5 t_{\rm peak}^3}\right)^{1/8} = \boxed{440} E_{k,55}^{1/8} n_0^{-1/8} \left(\frac{t_{\rm peak}}{18\,{\rm s}}\right)^{-3/8}$$

it is among the highest values for all GRBs





2. Slow decay phase:

$$\boxed{\alpha_2 = -1.115^{+0.012}_{-0.012}}$$

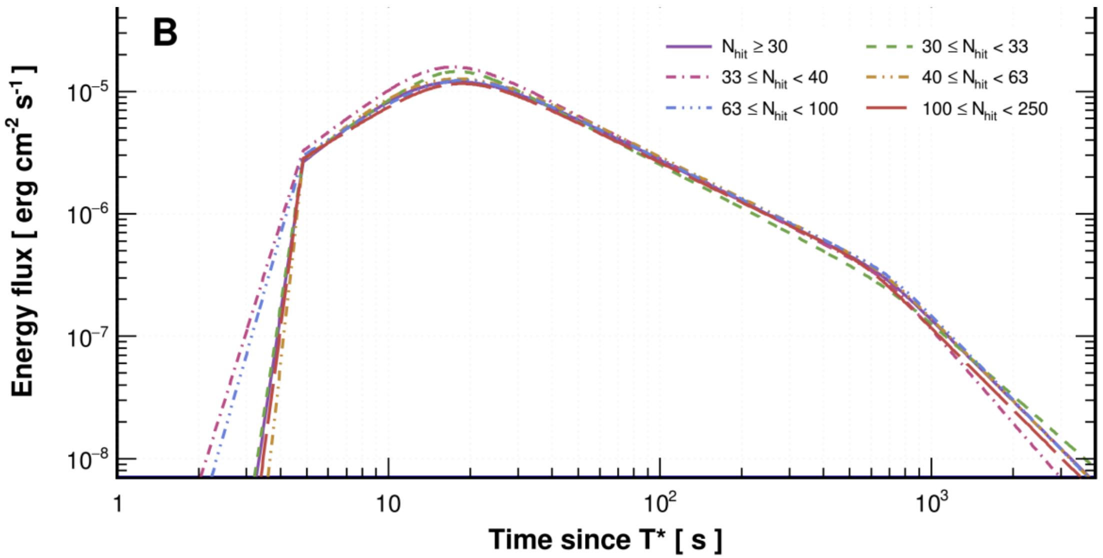
- slow decay

Thomson scattering regime

$$F_\nu = \begin{cases} F_m^{\rm IC}\left(\frac{\nu}{\nu_m^{\rm IC}}\right)^{-\frac{p-1}{2}} \propto t^{\frac{11-9p}{8}}, & \nu_m^{\rm IC} < \nu < \nu_c^{\rm IC} \\ F_m^{\rm IC}\left(\frac{\nu}{\nu_c^{\rm IC}}\right)^{-\frac{1}{2}} \propto t^{\frac{1}{8}}, & \nu_c^{\rm IC} < \nu < \nu_m^{\rm IC} \\ F_m^{\rm IC}(\nu_m^{\rm IC})^{\frac{p-1}{2}}(\nu_c^{\rm IC})^{\frac{1}{2}}\nu^{-\frac{p}{2}} \propto \boxed{t^{\frac{10-9p}{8}},} & \nu > \max(\nu_m^{\rm IC}, \nu_c^{\rm IC}) \end{cases}$$

Klein-Nishina regime

$$F_\nu = F_m^{\rm IC}(\nu_m^{\rm IC})^{\frac{p-1}{2}}(\nu_{\rm peak}^{\rm IC})^{\frac{p-1}{2}}\nu^{-(p-1)} \propto t^{\boxed{\left(\frac{3}{2}-\frac{5p}{4}\right)}}\nu^{-(p-1)}$$

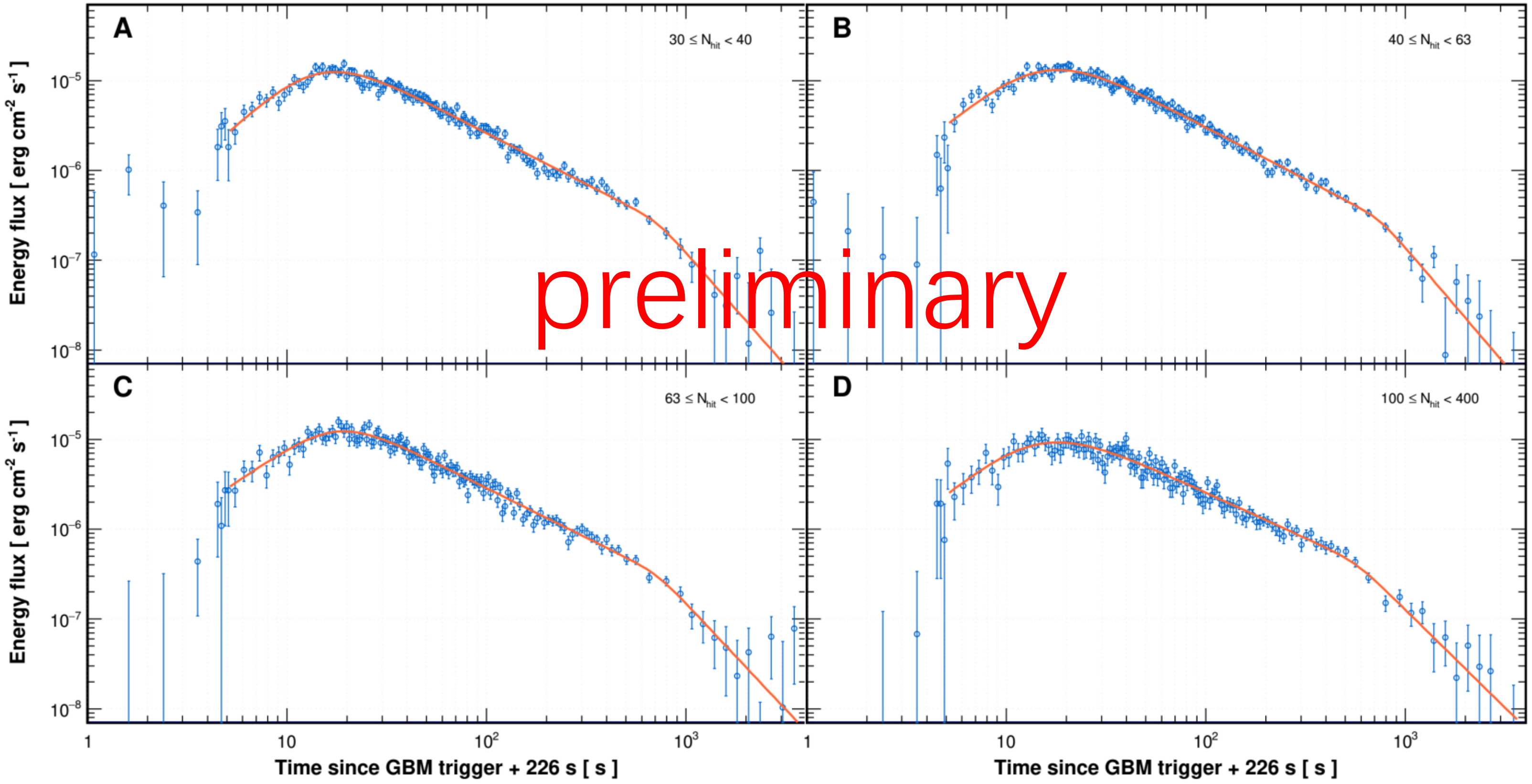


$$dN_e/dE \propto E_e^{-p}$$

$$p \sim 2.1$$

3. Fast decay phase

$$\alpha_3 = -2.21^{+0.30}_{-0.83}$$

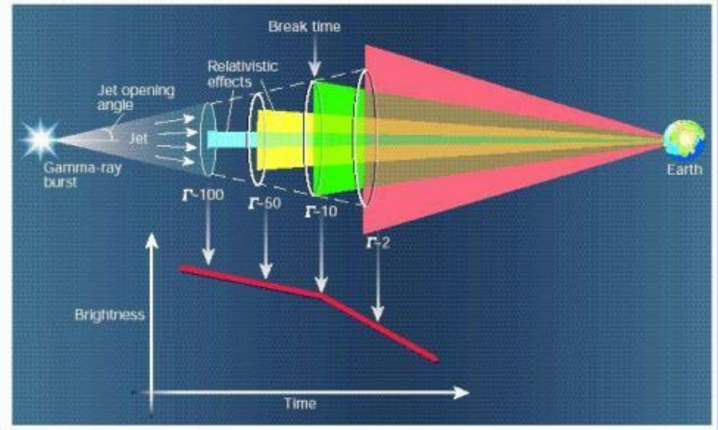


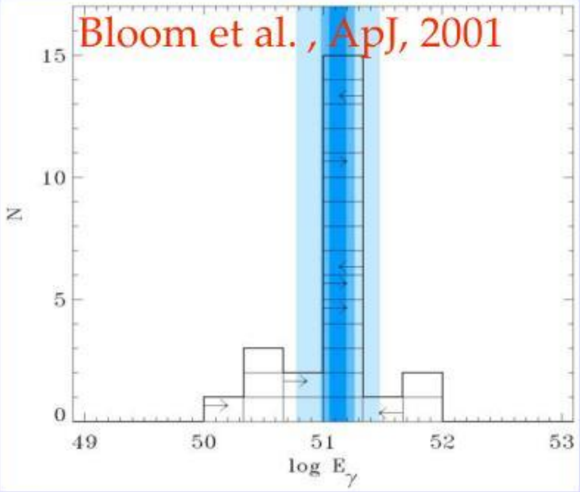
Revealing a jet break at the earliest time.

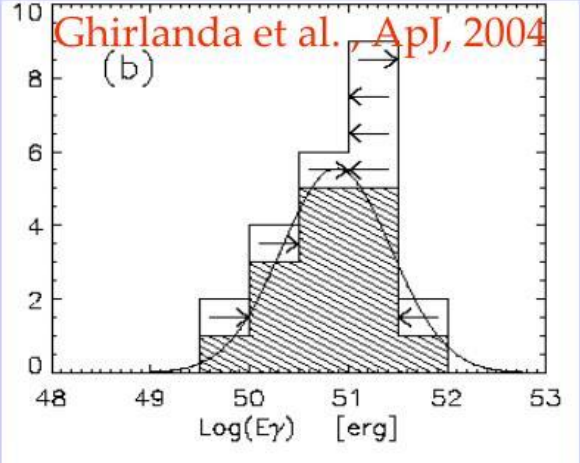
A narrow GRB jet

- Jet breaks have been seen in optical/X-ray bands
- First time seeing a jet break at TeV band
- Helps to understand the total energy of the GRB

➢ assuming jet angles derived from the break time of the optical afterglow light curve, the collimation-corrected radiated energy is clustered around ~10^{51} erg.







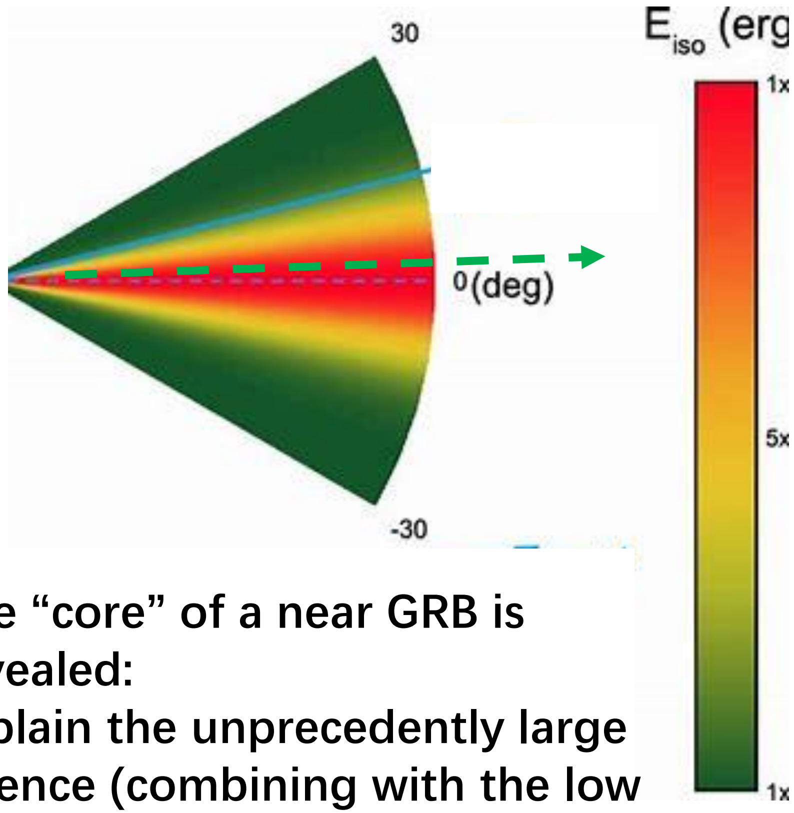
$$\theta_0 \sim 0.6^\circ E_{k,55}^{-1/8} n_0^{1/8} \left(\frac{t_{\mathrm{b},2}}{670\,\mathrm{s}}\right)^{3/8}$$

$$\boxed{E_{\gamma,j} \;=\; E_{\gamma,\mathrm{iso}}\theta_0^2/2 \;\sim\; 7.5 \times 10^{50}\ \ \mathrm{erg}\, E_{\gamma,\mathrm{iso},55}(\theta_0/0.7^\circ)^2}$$

Consistent with seeing the brightest core of a structured jet (if jet structure is universal)

structured jet model (Rossi & Rees, 2001, Zhang & Meszaros 2001)

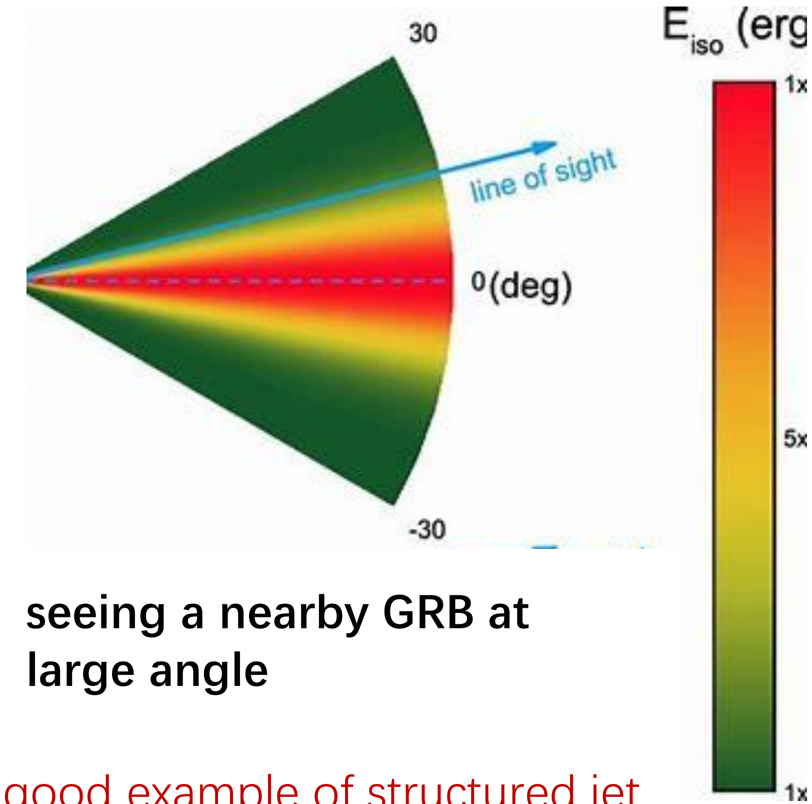
- GRB 221009A



- **The "core" of a near GRB is revealed:**
- **Explain the unprecedently large fluence (combining with the low redshift)**
- **Low chance probability**

Versus

GRB 170817A (off-axis)

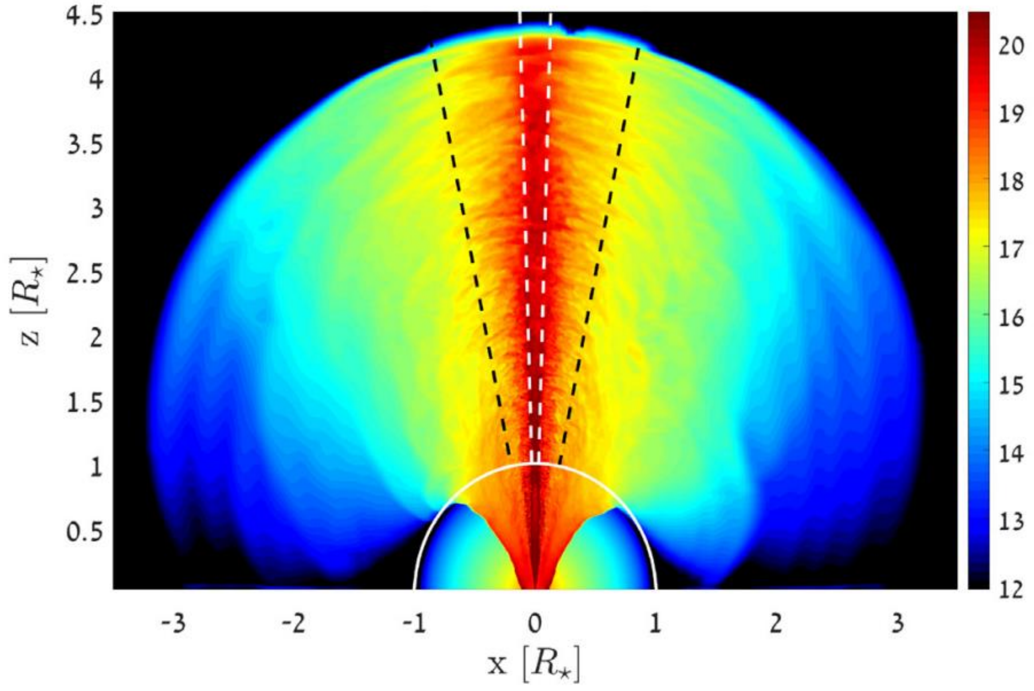


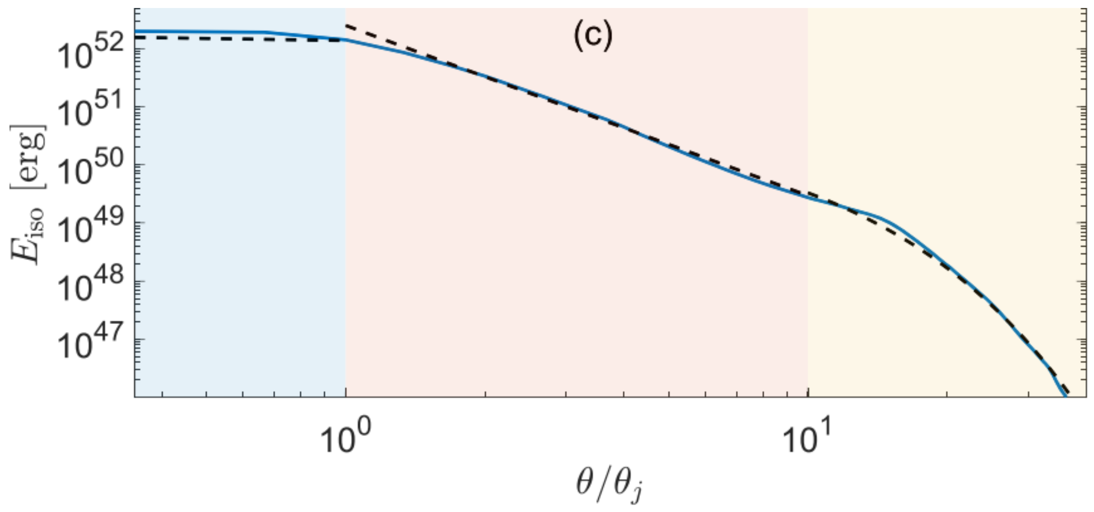
seeing a nearby GRB at large angle

A good example of structured jet

Numerical simulation: structured jet

Gottlieb et al. 2021





Upper limit in prompt phase

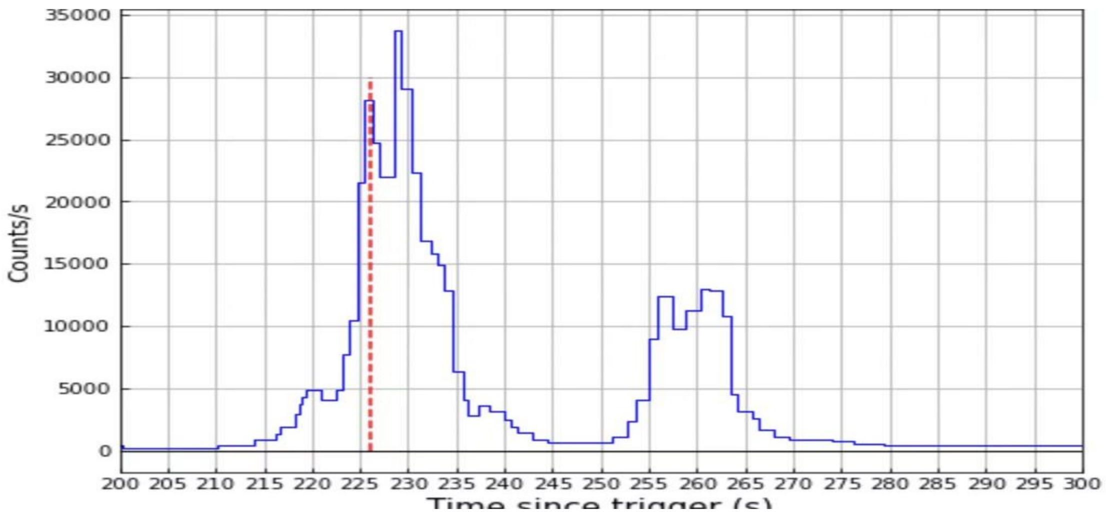
- The most strict limit on the prompt TeV emission

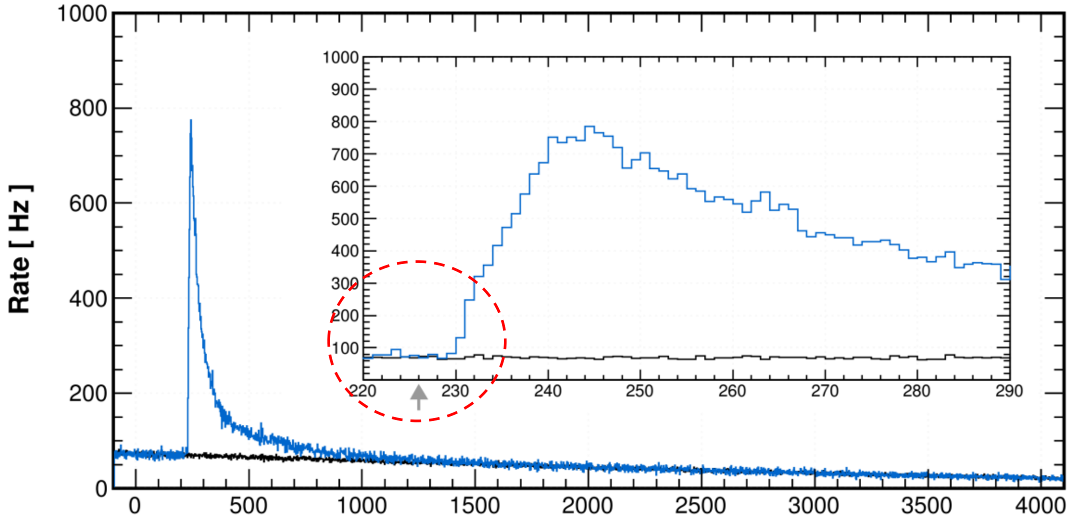
  R=$F_{\mathrm{TeV}}/F_{\mathrm{MeV}} < 2\times10^{-5}$

- A large **$\gamma\gamma$ absorption** optical depth

$$R_{\mathrm{in}} \sim 2\Gamma_0^2 c t_v = 10^{15}\,\mathrm{cm}\,(\Gamma_0/440)^2\,(t_v/0.082\,\mathrm{s})$$

$$\tau_{\gamma\gamma} \sim \sigma_{\gamma\gamma} n'_t \frac{R_{\mathrm{in}}}{\Gamma_0} \sim 190 \left(\frac{R_{\mathrm{in}}}{10^{15}\,\mathrm{cm}}\right)^{-1} \left(\frac{\Gamma_0}{440}\right)^{-2} \left(\frac{\varepsilon_t}{h\nu_m}\right)^{\beta_1+1}$$



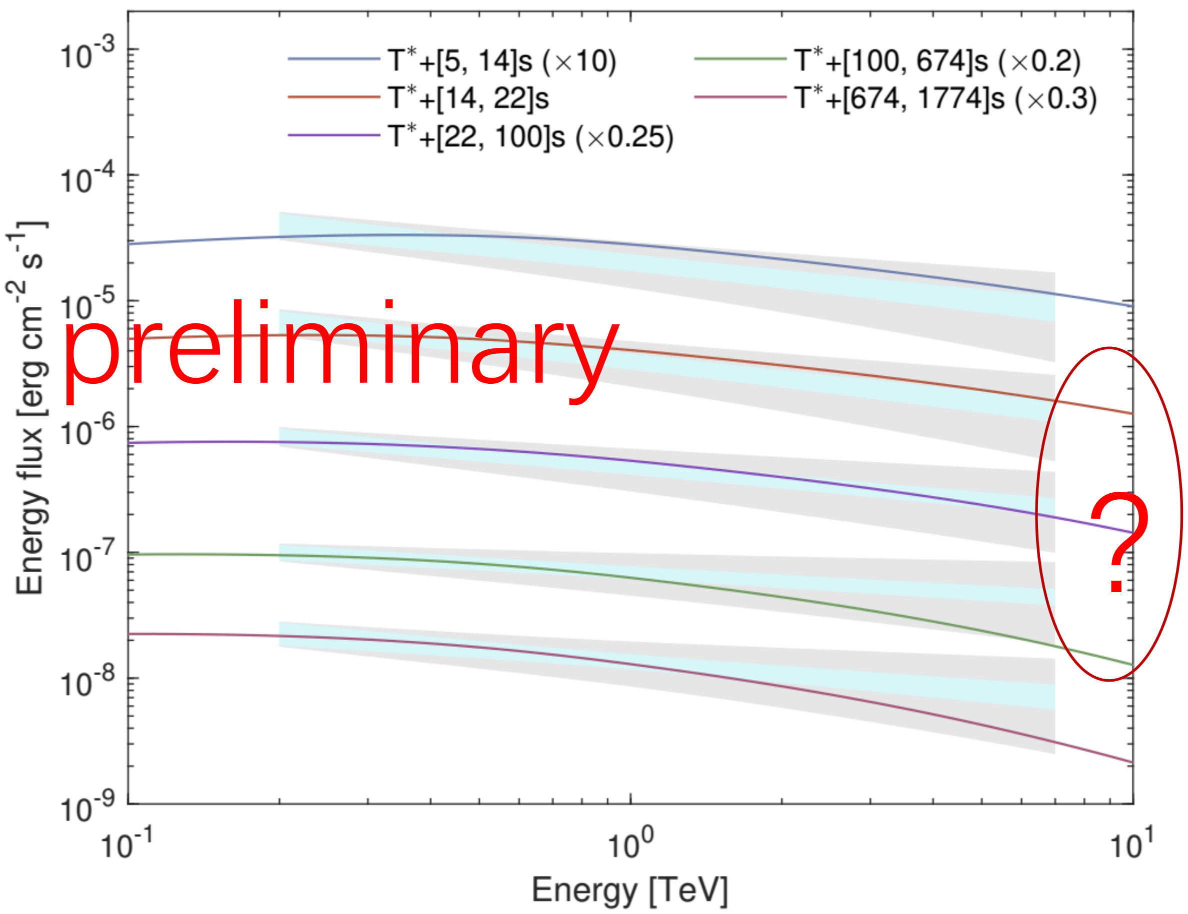


Future work: 1) >10TeV photon

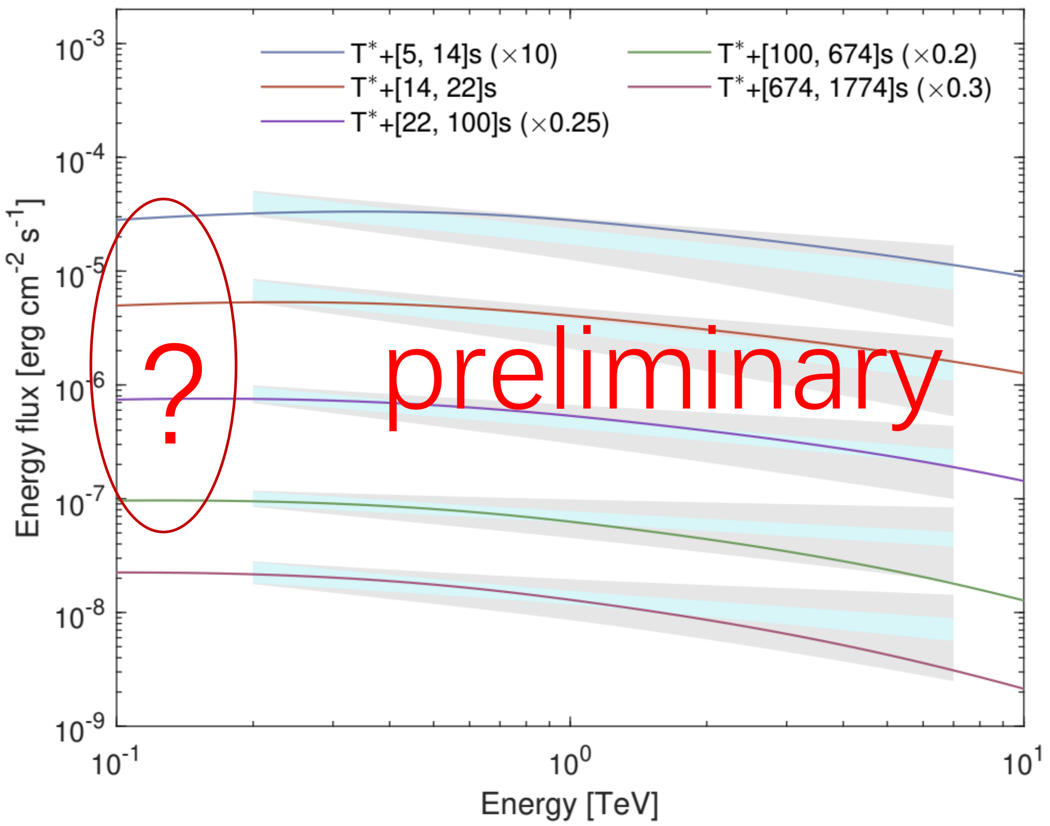
- Klein-Nishina effect in electron SSC emission
- Internal absorption

- Hadronic emission ?

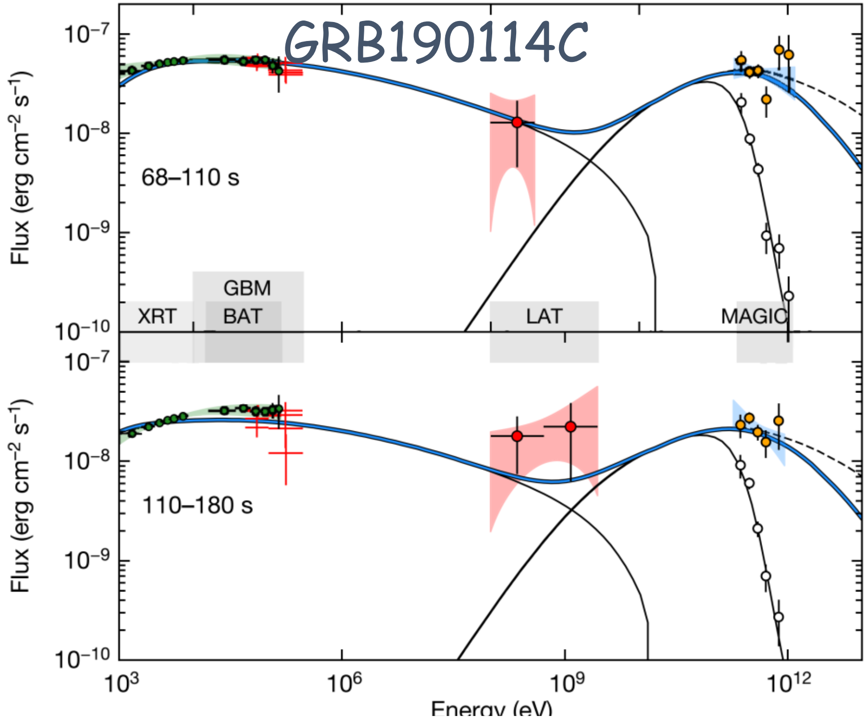
-GRB produce UHECRs

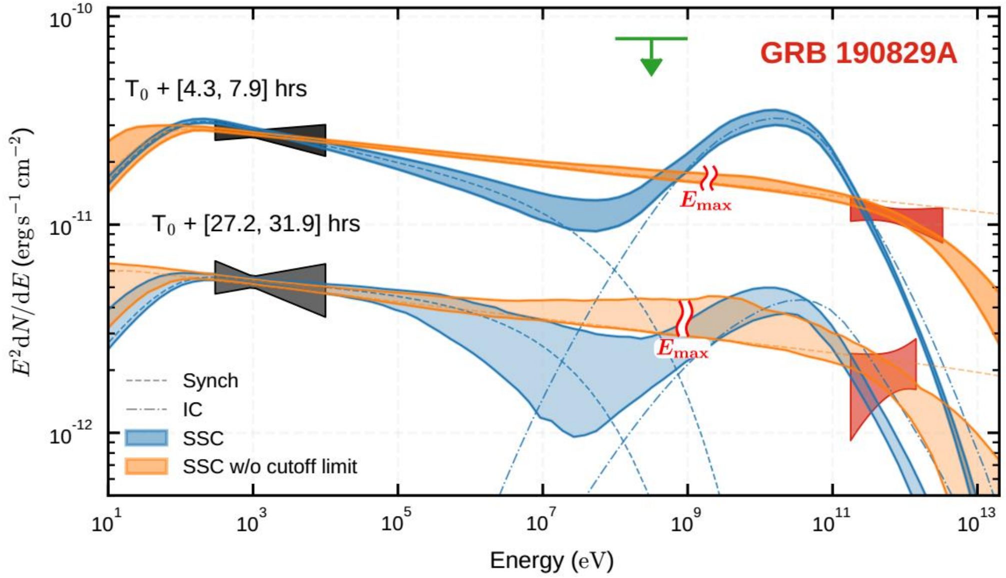


Future work: 2) <0.2TeV



Is there a SSC bump ?





Conclusions

1. First time observed the onset of the afterglow in TeV band
2. This enables
    1. Estimating the initial bulk Lorentz factor Γ_0 of the jet
    2. Setting the most strict limit on the prompt emission in TeV band
3. Finding a jet break in the TeV light curve in its decay phase
    1. The narrowest jet of 0.6° (the earliest jet break), revealing the “core” of the structured jet
    2. A reasonable $E_{\gamma,jet} \sim 10^{51}$ erg with the beam correction
    3. **The unprecedently large fluence may be due to seeing the core of a nearby GRB jet**

Thanks