Recent progress in GRB studies

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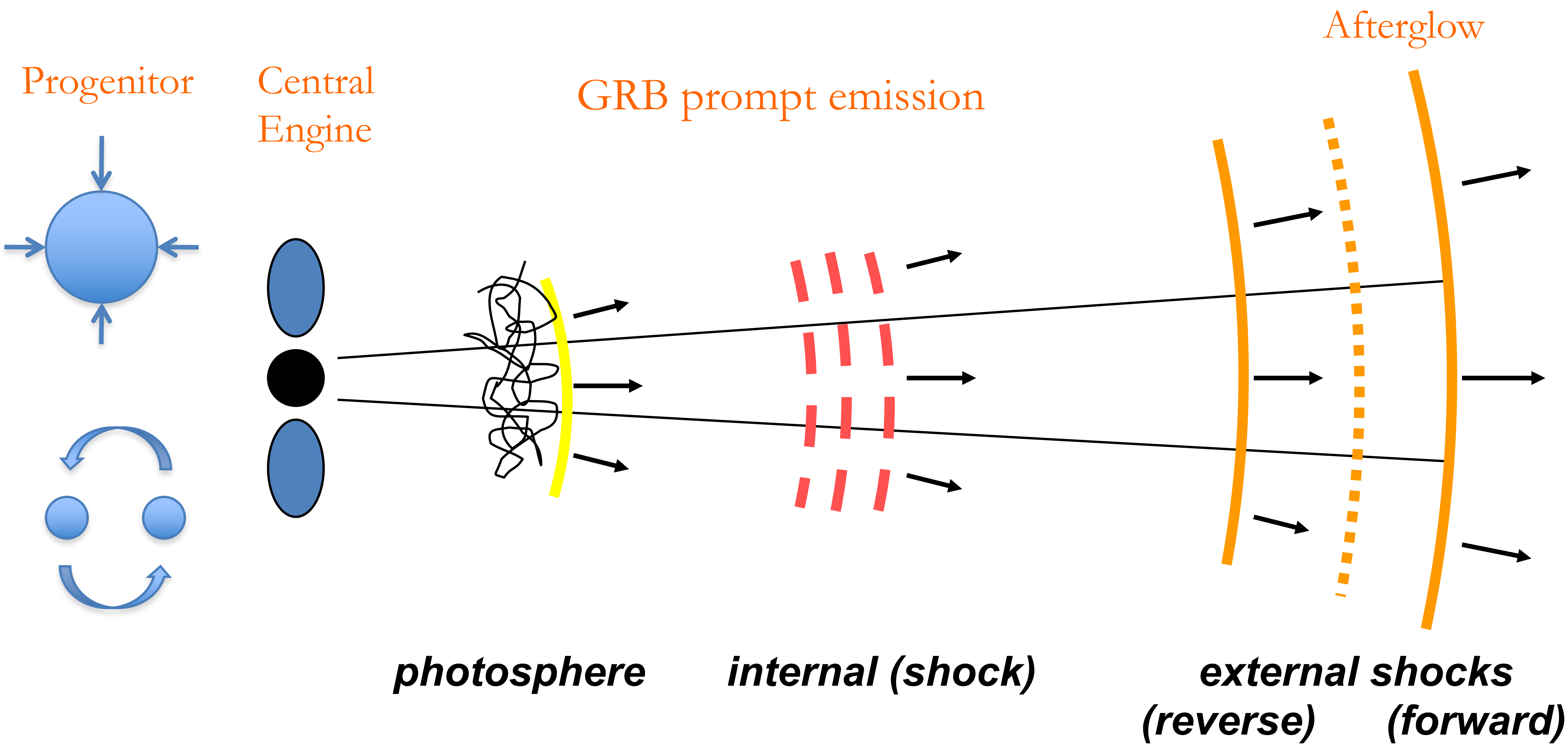
Jan. 12, 2022
(remote talk)

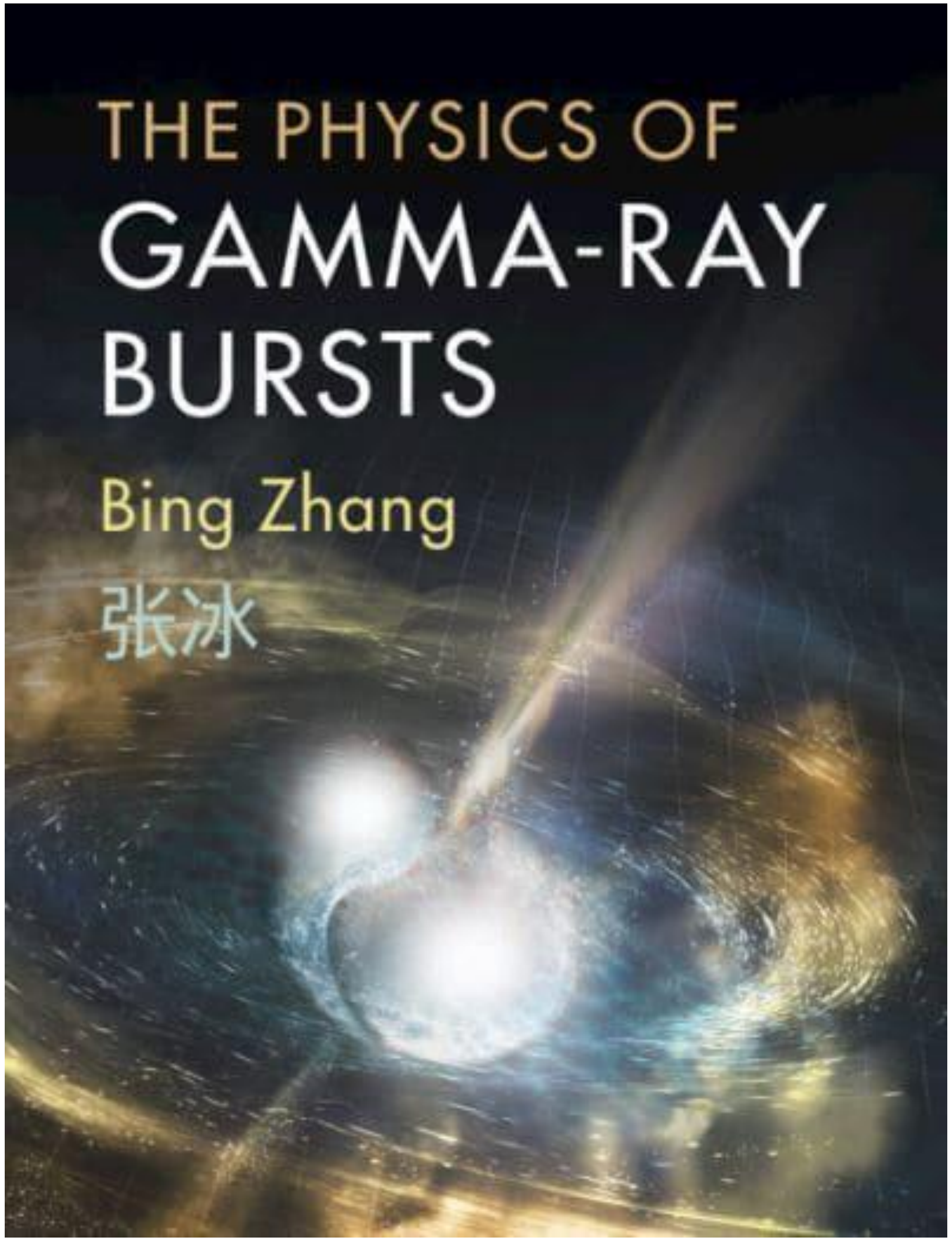
XXVII Cracow EPIPHANY Conference on
Recent Advances in Astroparticle Physics
Jan. 10-14, 2022

A Sketch of Physical Picture of GRBs



Open Questions in GRB Physics

- Progenitor (massive star core collapse vs. compact star mergers)
- Central engine (black hole vs millisecond magnetar)
- Ejecta composition (fireball vs. Poynting flux)
- Energy dissipation mechanism (shock vs. magnetic reconnection)
- Particle acceleration & radiation mechanisms (synchrotron, inverse Compton, quasi-thermal)
- Afterglow



Selected topics

Disclaimer: not a complete review, personal taste and involvement

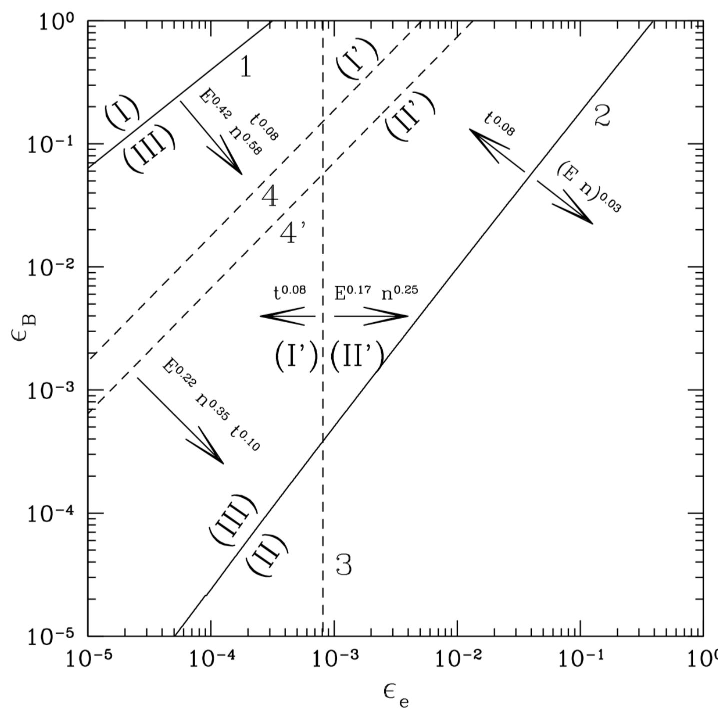
- TeV afterglow emission
- Oddball GRBs with special progenitors
- GRB prompt emission: jet composition, energy dissipation and radiation mechanisms

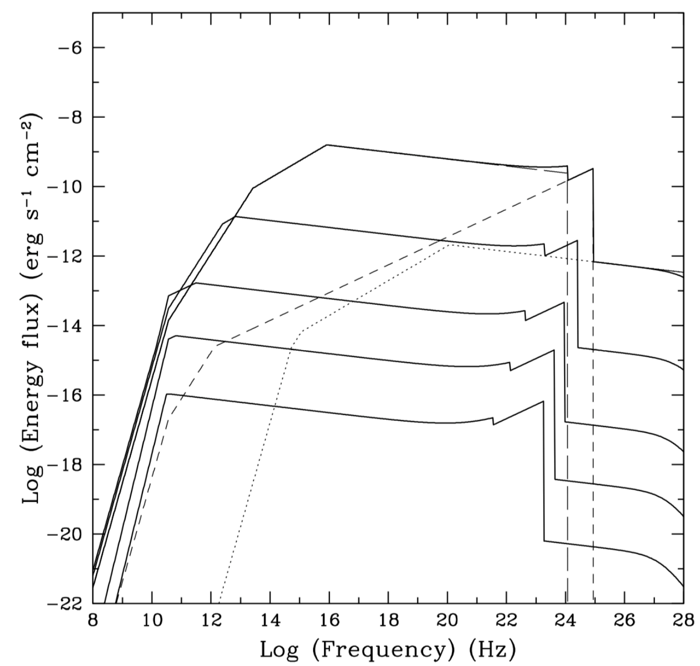
1. TeV afterglow emission from GRBs

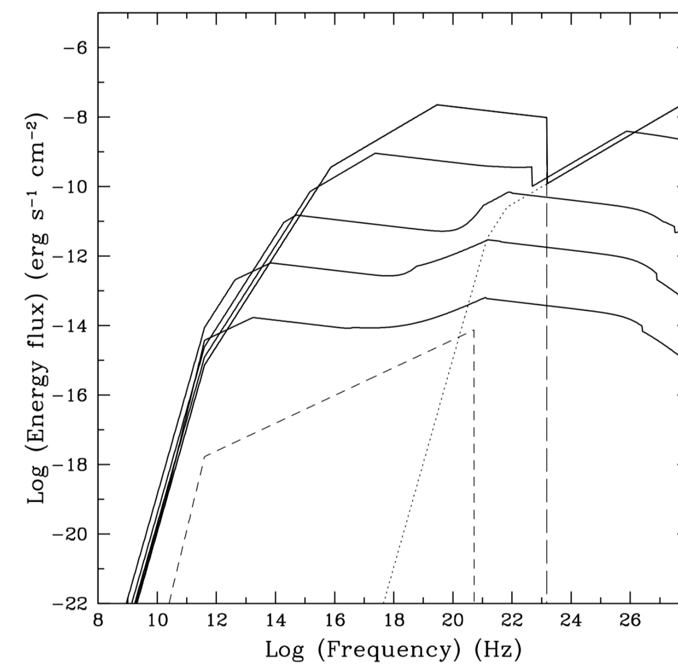
GRB 190114C, GRB 180720B, GRB 190829A

High-Energy Afterglow: Which component is more important?

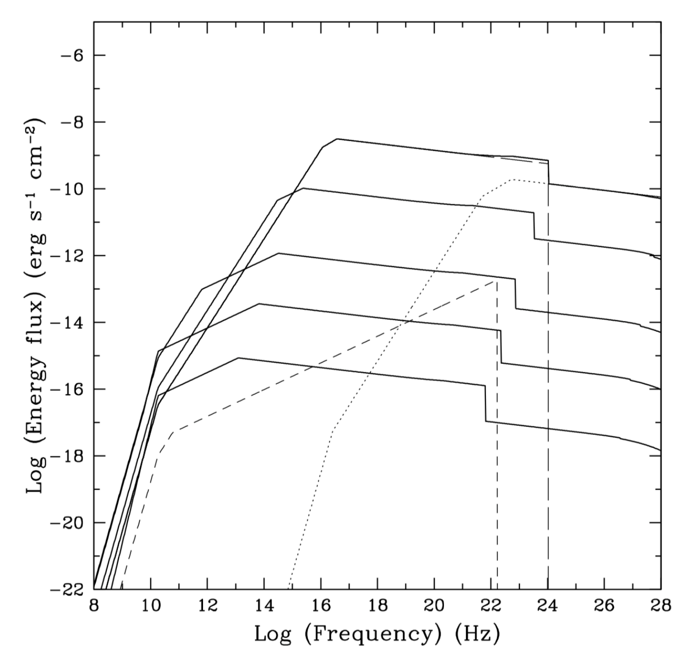
Zhang & Meszaros (2001)



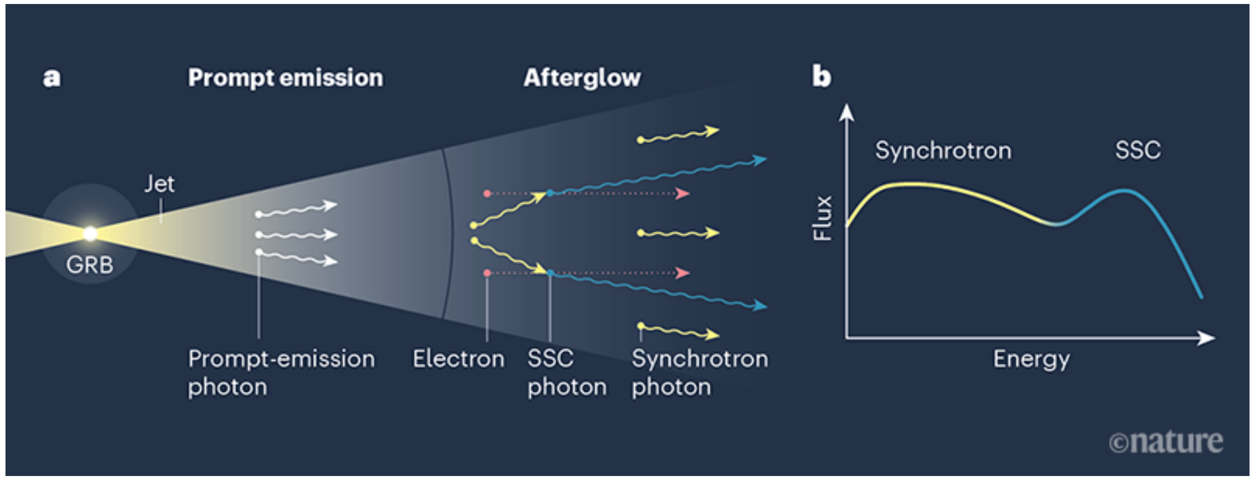




- Three HE components:
  - Electron synchrotron
  - Electron SSC
  - Proton synchrotron (and other hadronic emission)
- All three components always exist, it is a matter of which one dominates
- The largest parameter space is the SSC-dominated regime



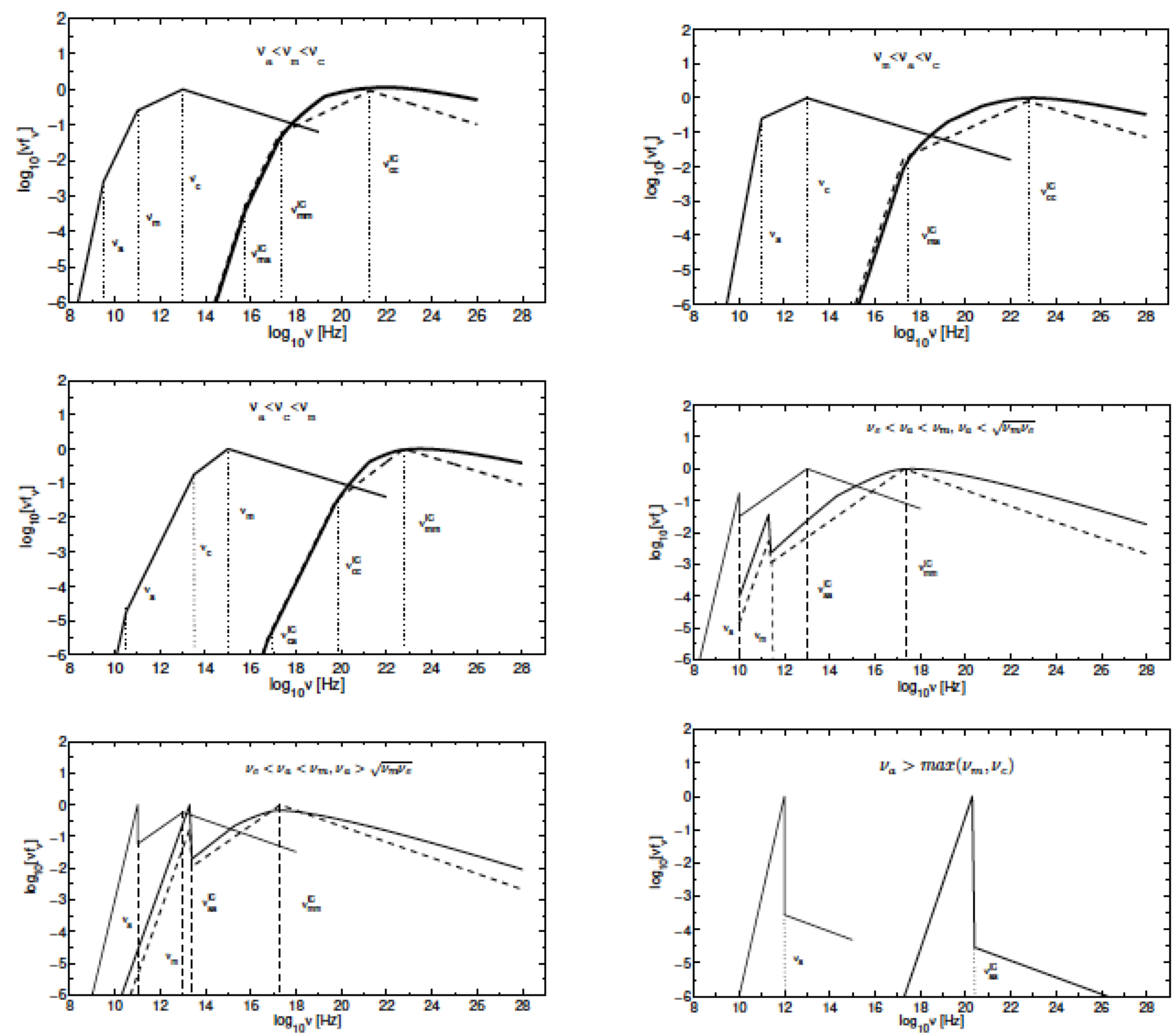
SSC in GRB afterglow



BZ, 2020, Nature, 575, 448

Wei & Lu (1998)
Dermer et al. (2000)
Panaitescu & Kumar (2000)
Sari & Esin (2001)
Zhang & Meszaros (2001)
Wang, Dai & Lu (2001a,b)
……

Gao, Lei, Wu & Zhang, 2013, MNRAS, 435, 2520-2531



TeV breakthrough in 2019

Article

Teraelectronvolt emission from the γ-ray burst GRB 190114C

https://doi.org/10.1038/s41586-019-1750-x
Received: 10 May 2019
Accepted: 2 September 2019
Published online: 20 November 2019

MAGIC Collaboration*

Long-duration γ-ray bursts (GRBs) are the most luminous sources of electromagnetic radiation known in the Universe. They arise from outflows of plasma with velocities near the speed of light that are ejected by newly formed neutron stars or black holes (of stellar mass) at cosmological distances[1,2]. Prompt flashes of megaelectronvolt-energy γ-rays are followed by a longer-lasting afterglow emission in a wide range of energies (from radio waves to gigaelectronvolt γ-rays), which originates from synchrotron radiation generated by energetic electrons in the accompanying shock waves[3,4]. Although emission of γ-rays at even higher (teraelectronvolt) energies by other radiation mechanisms has been theoretically predicted[5–8], it has not been previously detected[7,8]. Here we report observations of teraelectronvolt emission from the γ-ray burst GRB 190114C. γ-rays were observed in the energy range 0.2–1 teraelectronvolt from about one minute after the burst (at more than 50 standard deviations in the first 20 minutes), revealing a distinct emission component of the afterglow with power comparable to that of the synchrotron component. The observed similarity in the radiated power and temporal behaviour of the teraelectronvolt and X-ray bands points to processes such as inverse Compton upscattering as the mechanism of the teraelectronvolt emission[9–11]. By contrast, processes such as synchrotron emission by ultrahigh-energy protons[10,12,13] are not favoured because of their low radiative efficiency. These results are anticipated to be a step towards a deeper understanding of the physics of GRBs and relativistic shock waves.

Article

A very-high-energy component deep in the γ-ray burst afterglow

https://doi.org/10.1038/s41586-019-1743-9
Received: 5 June 2019
Accepted: 30 September 2019
Published online: 20 November 2019

A list of authors and affiliations appears at the end of the paper.

Gamma-ray bursts (GRBs) are brief flashes of γ-rays and are considered to be the most energetic explosive phenomena in the Universe[1]. The emission from GRBs comprises a short (typically tens of seconds) and bright prompt emission, followed by a much longer afterglow phase. During the afterglow phase, the shocked outflow—produced by the interaction between the ejected matter and the circumburst medium—slows down, and a gradual decrease in brightness is observed[2]. GRBs typically emit most of their energy via γ-rays with energies in the kiloelectronvolt-to-megaelectronvolt range, but a few photons with energies of tens of gigaelectronvolts have been detected by space-based instruments[3]. However, the origins of such high-energy (above one gigaelectronvolt) photons and the presence of very-high-energy (more than 100 gigaelectronvolts) emission have remained elusive[4]. Here we report observations of very-high-energy emission in the bright GRB 180720B deep in the GRB afterglow—ten hours after the end of the prompt emission phase, when the X-ray flux had already decayed by four orders of magnitude. Two possible explanations exist for the observed radiation: inverse Compton emission and synchrotron emission of ultrarelativistic electrons. Our observations show that the energy fluxes in the X-ray and γ-ray range and their photon indices remain comparable to each other throughout the afterglow. This discovery places distinct constraints on the GRB environment for both emission mechanisms, with the inverse Compton explanation alleviating the particle energy requirements for the emission observed at late times. The late timing of this detection has consequences for the future observations of GRBs at the highest energies.

Article

Observation of inverse Compton emission from a long γ-ray burst

https://doi.org/10.1038/s41586-019-1754-6
Received: 20 July 2019
Accepted: 18 October 2019
Published online: 20 November 2019

A list of authors and affiliations appears at the end of the paper.

Long-duration γ-ray bursts (GRBs) originate from ultra-relativistic jets launched from the collapsing cores of dying massive stars. They are characterized by an initial phase of bright and highly variable radiation in the kiloelectronvolt-to-megaelectronvolt band, which is probably produced within the jet and lasts from milliseconds to minutes, known as the prompt emission[1,2]. Subsequently, the interaction of the jet with the surrounding medium generates shock waves that are responsible for the afterglow emission, which lasts from days to months and occurs over a broad energy range from the radio to the gigaelectronvolt bands[1–6]. The afterglow emission is generally well explained as synchrotron radiation emitted by electrons accelerated by the external shock[7–9]. Recently, intense long-lasting emission between 0.2 and 1 teraelectronvolts was observed from GRB 190114C[10,11]. Here we report multi-frequency observations of GRB 190114C, and study the evolution in time of the GRB emission across 17 orders of magnitude in energy, from 5×10^{-6} to 10^{12} electronvolts. We find that the broadband spectral energy distribution is double-peaked, with the teraelectronvolt emission constituting a distinct spectral component with power comparable to the synchrotron component. This component is associated with the afterglow and is satisfactorily explained by inverse Compton up-scattering of synchrotron photons by high-energy electrons. We find that the conditions required to account for the observed teraelectronvolt component are typical for GRBs, supporting the possibility that inverse Compton emission is commonly produced in GRBs.

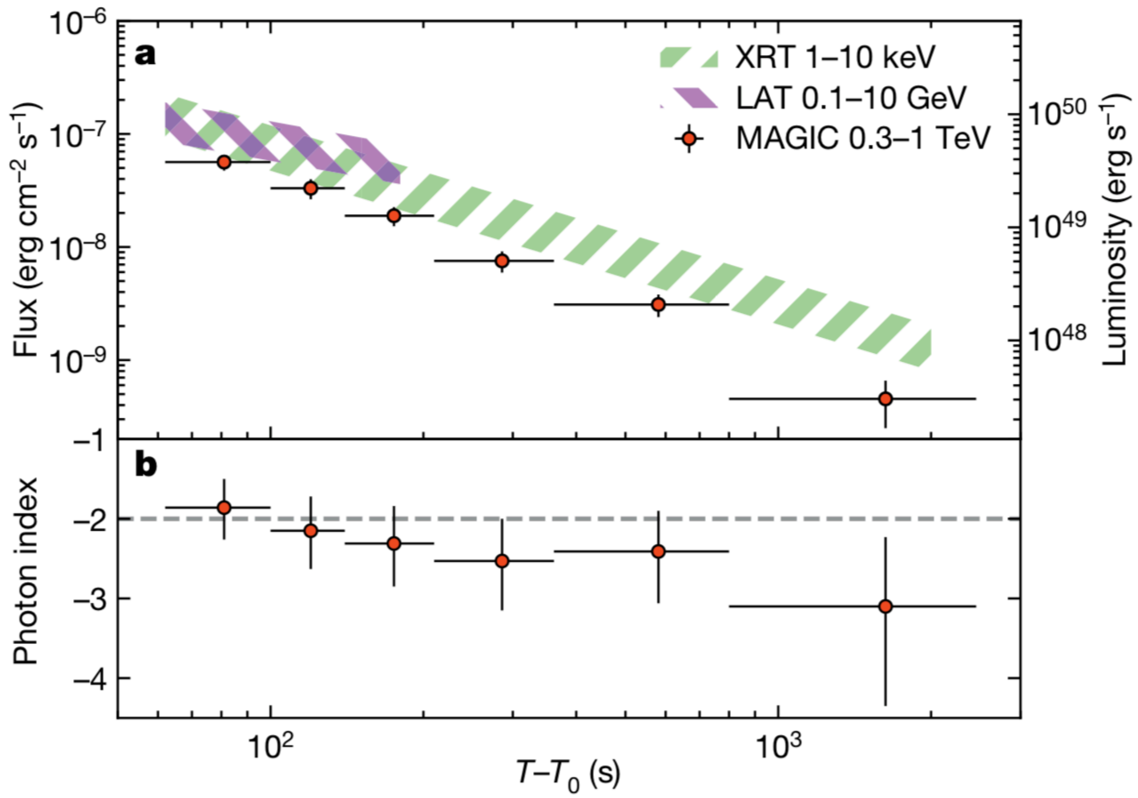
Astrophysics

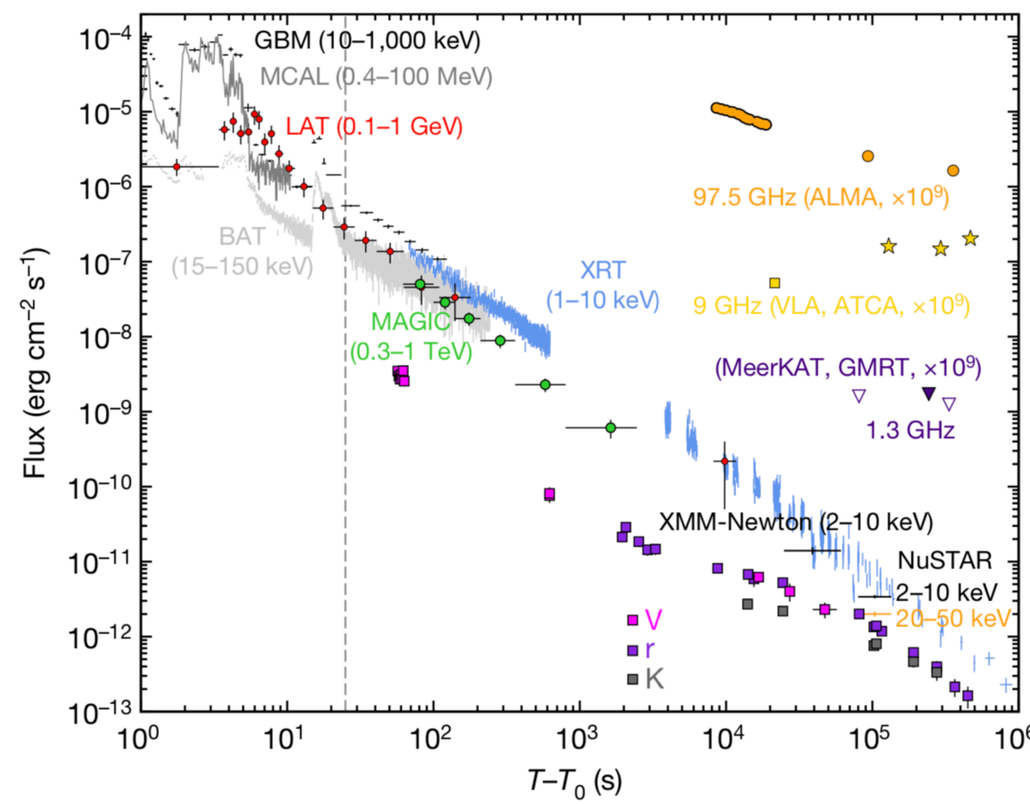
Extreme emission seen from γ-ray bursts

Bing Zhang

Cosmic explosions called γ-ray bursts are the most energetic bursting events in the Universe. Observations of extremely high-energy emission from two γ-ray bursts provide a new way to study these gigantic explosions. **See p.455, p.459 & p.464**

GRB 190114C

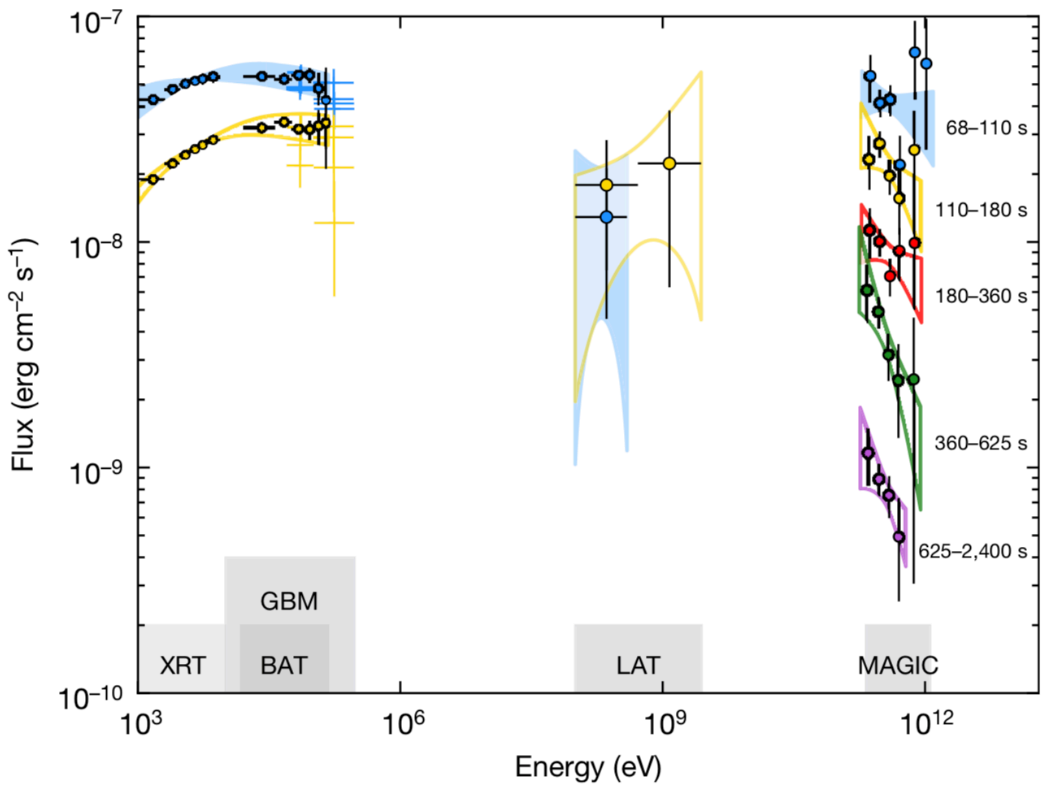


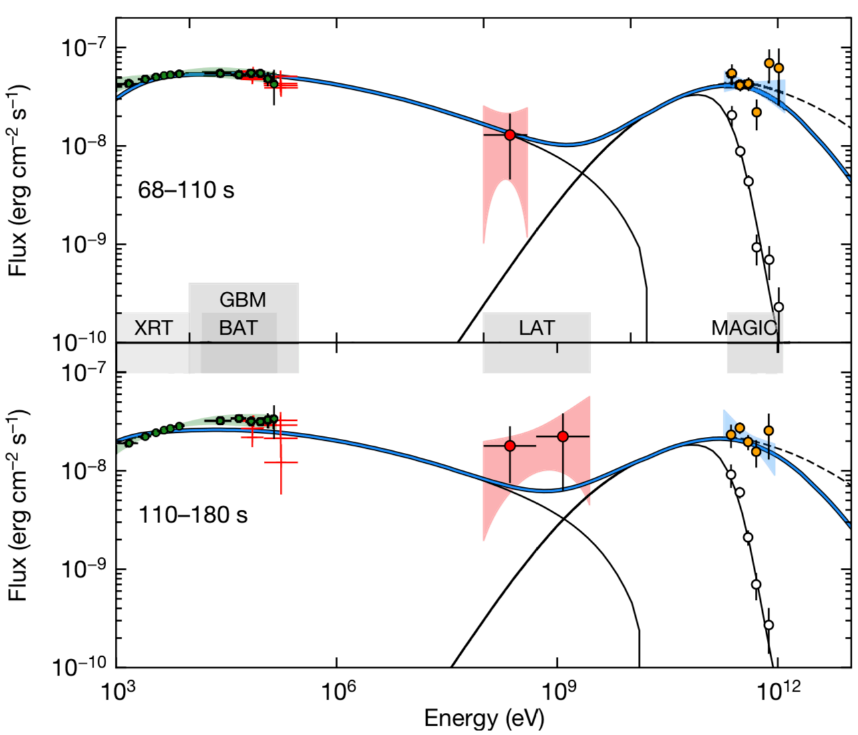


z=0.4245

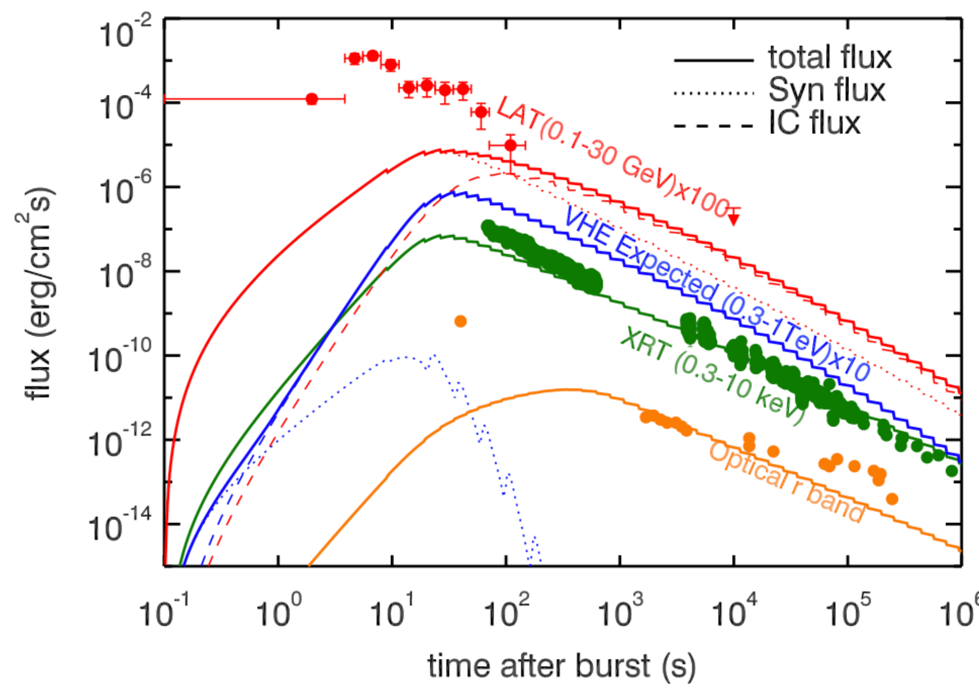
MAGIC Collaboration, 2019a, Nature, 575, 455
MAGIC Collaboration, 2019b, Nature, 575, 459

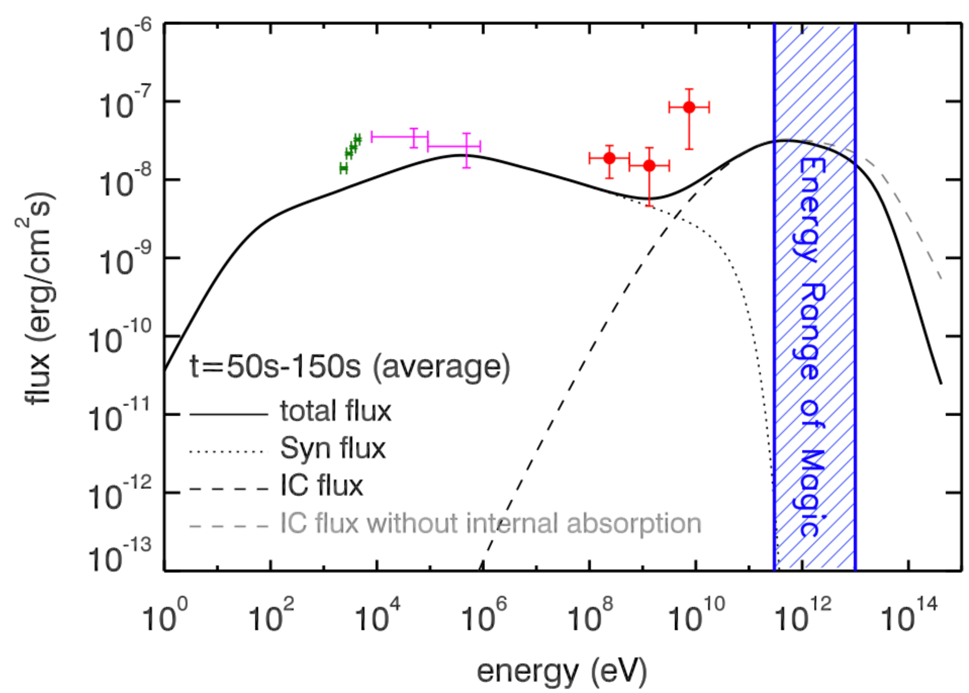
GRB 190114C





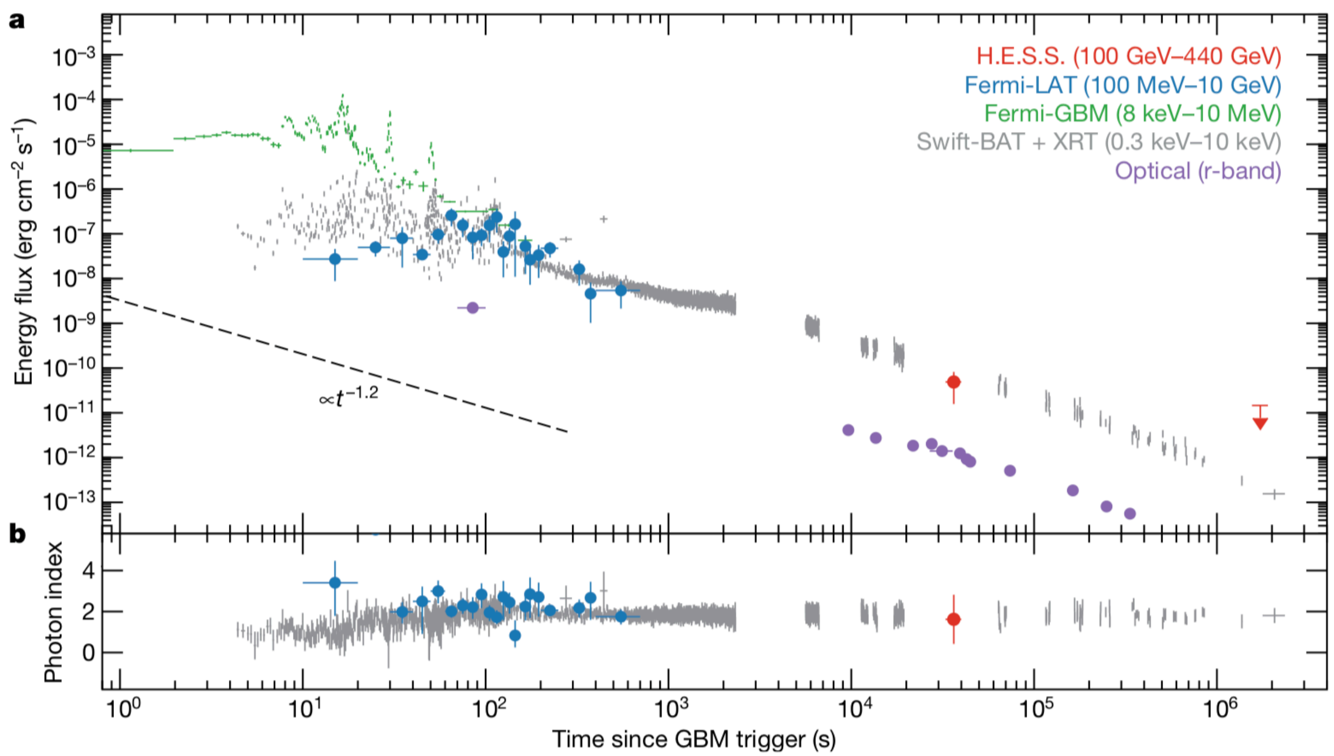
MAGIC Collaboration, 2019b, Nature, 575, 459

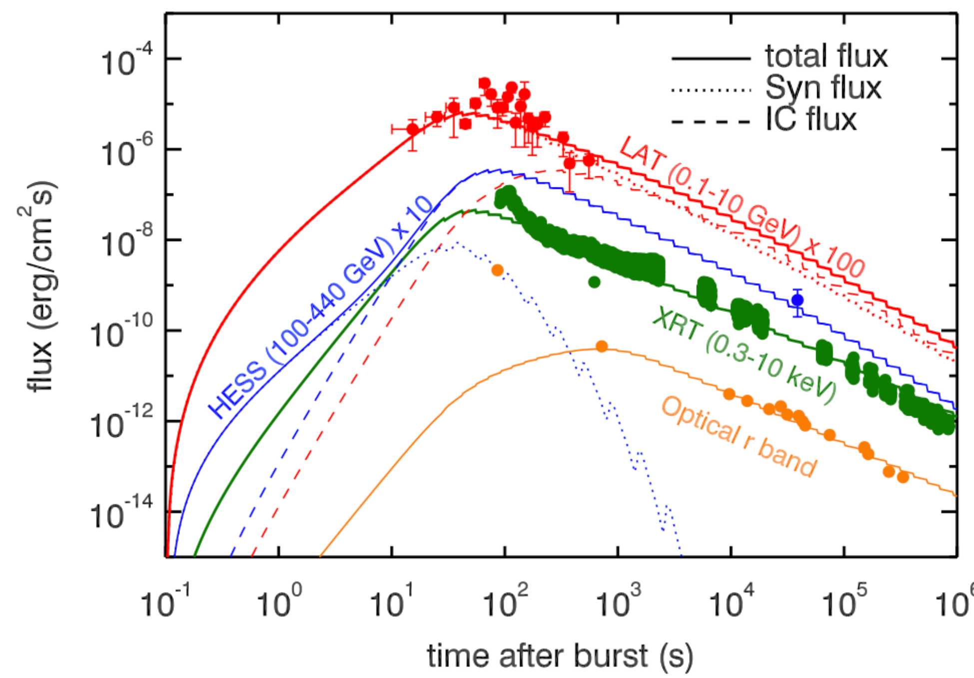




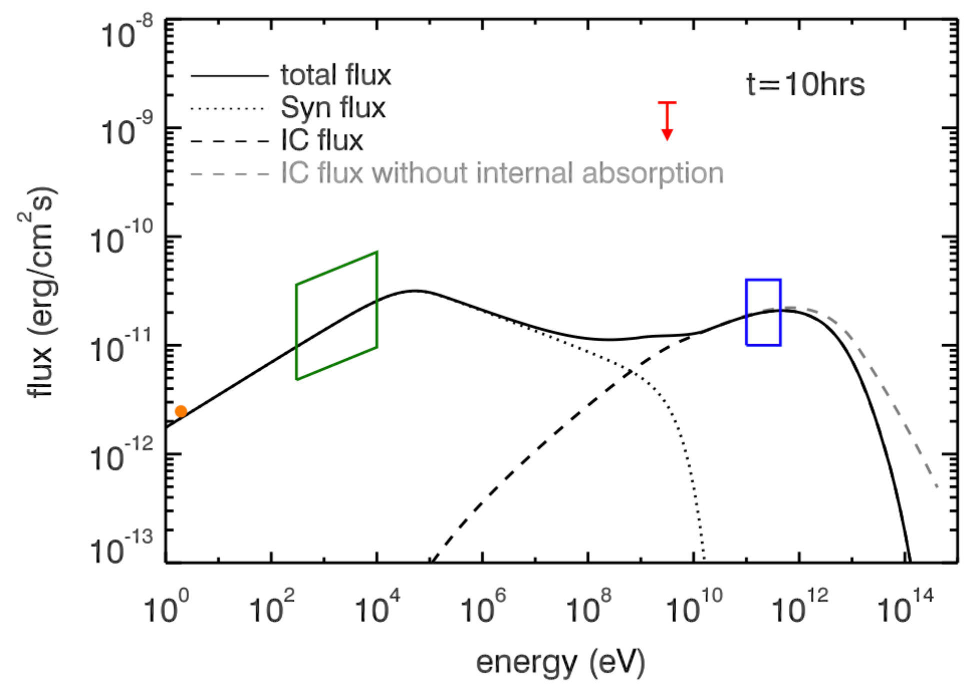
Wang et al. 2019, ApJ, 884, 117

GRB 180720B





z=0.653

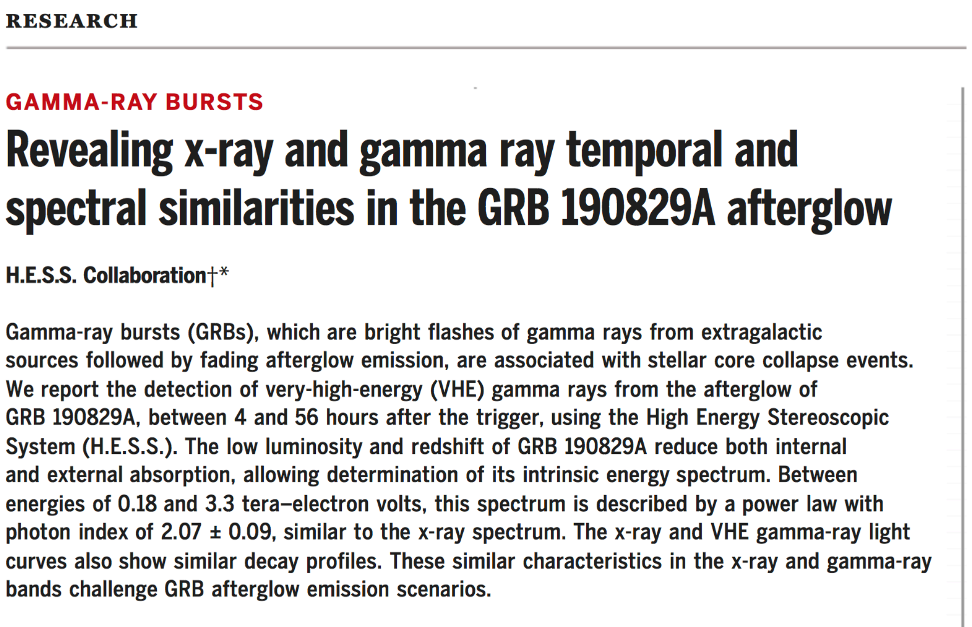


Abdallah et al., 2019, Nature, 575, 467

Wang et al. 2019, ApJ, 884, 117

GRB 190829A

Abdalla et al., 2021, Science, 6546, 1081-1085

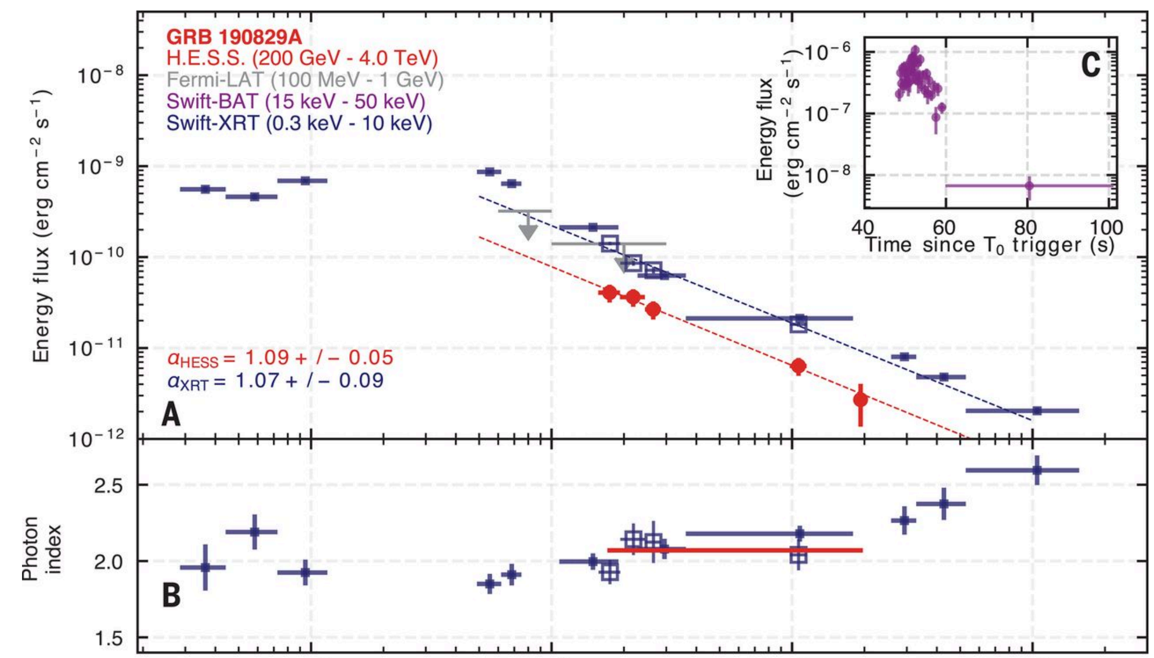

RESEARCH

GAMMA-RAY BURSTS

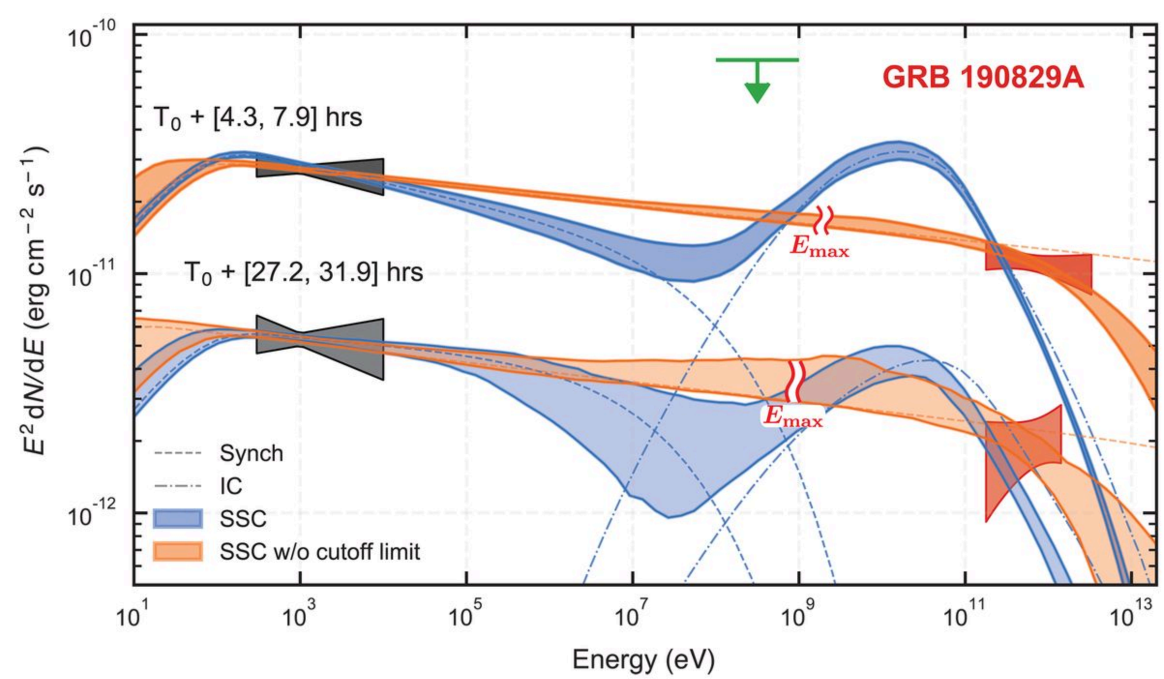
Revealing x-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow

H.E.S.S. Collaboration†*

Gamma-ray bursts (GRBs), which are bright flashes of gamma rays from extragalactic sources followed by fading afterglow emission, are associated with stellar core collapse events. We report the detection of very-high-energy (VHE) gamma rays from the afterglow of GRB 190829A, between 4 and 56 hours after the trigger, using the High Energy Stereoscopic System (H.E.S.S.). The low luminosity and redshift of GRB 190829A reduce both internal and external absorption, allowing determination of its intrinsic energy spectrum. Between energies of 0.18 and 3.3 tera–electron volts, this spectrum is described by a power law with photon index of 2.07 ± 0.09, similar to the x-ray spectrum. The x-ray and VHE gamma-ray light curves also show similar decay profiles. These similar characteristics in the x-ray and gamma-ray bands challenge GRB afterglow emission scenarios.



- A nearby, low-luminosity GRB ($z=0.0785$)
- Same decay law in TeV and X-rays
- Consistent with one single spectral component
- Simple one-zone SSC model fails
- Synchrotron model extends the maximum energy by three orders of magnitude



Evidence of EIC?

GRB 190829A

Evidence of external IC in GRBs

- X-ray flare at ~ 10^3 s, suggesting a long-lasting engine
- X-rays are upscattered by electrons from external shocks
- Reasonable burst parameters

THE ASTROPHYSICAL JOURNAL, 920:55 (10pp), 2021 October 10 https://doi.org/10.3847/1538-4357/ac0cfc

CrossMark

External Inverse-Compton Emission from Low-luminosity Gamma-Ray Bursts: Application to GRB 190829A

B. Theodore Zhang[1,2,3], Kohta Murase[1,2,3,4], Péter Veres[5], and Péter Mészáros[1,2,3]
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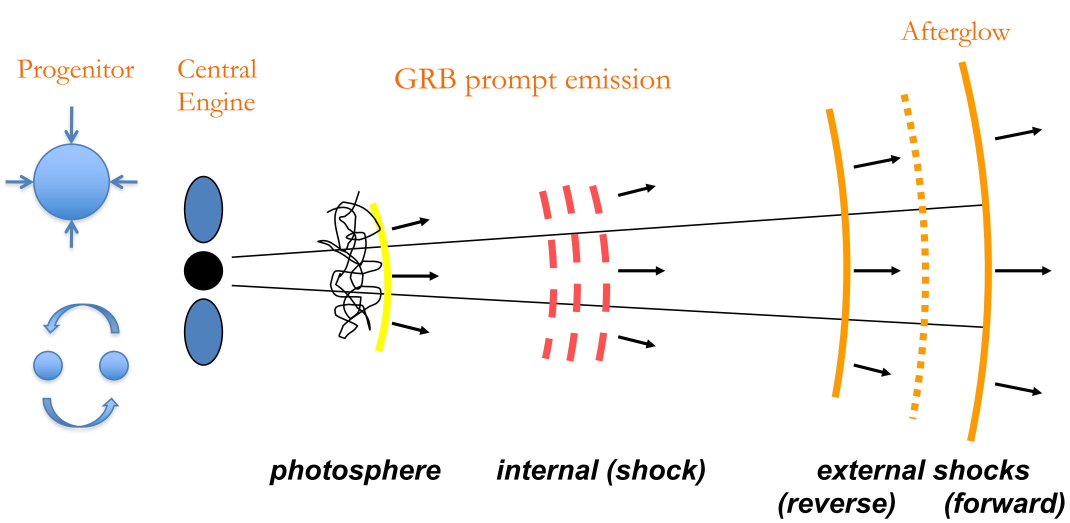
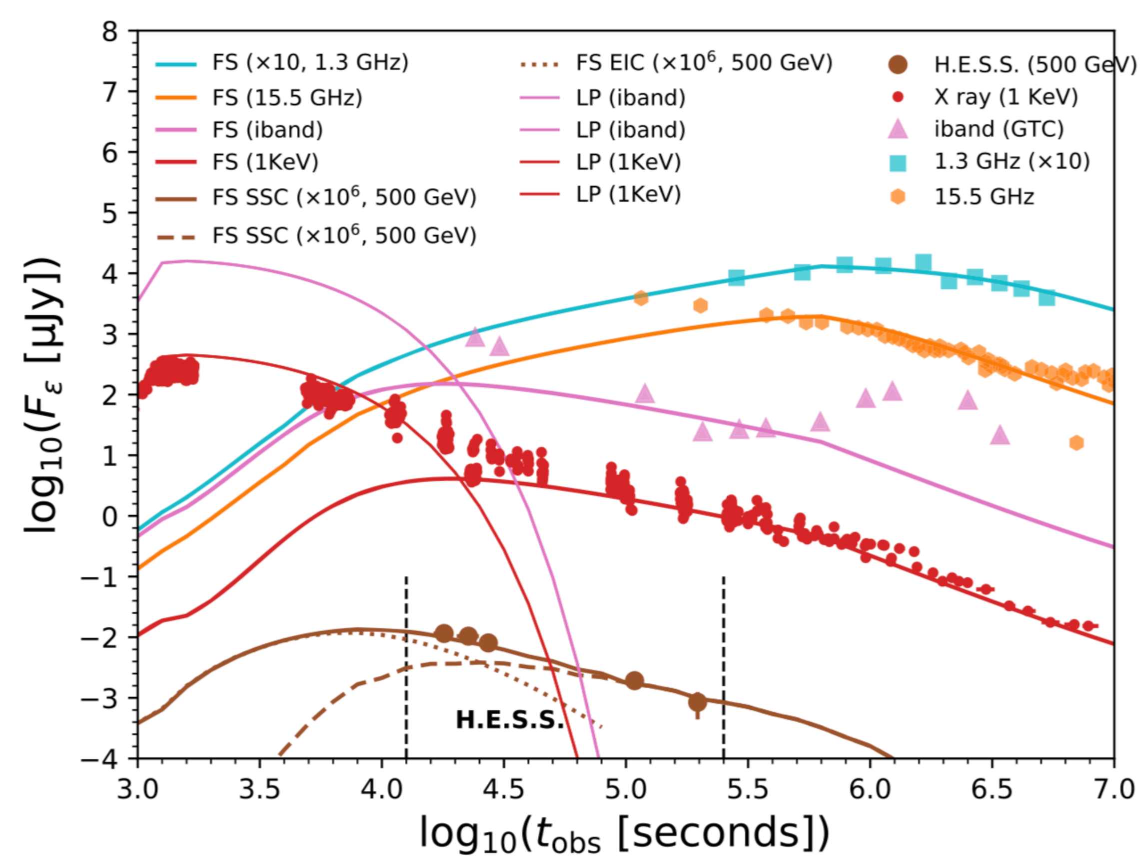
Received 2020 December 18; revised 2021 June 16; accepted 2021 June 19; published 2021 October 12

Abstract

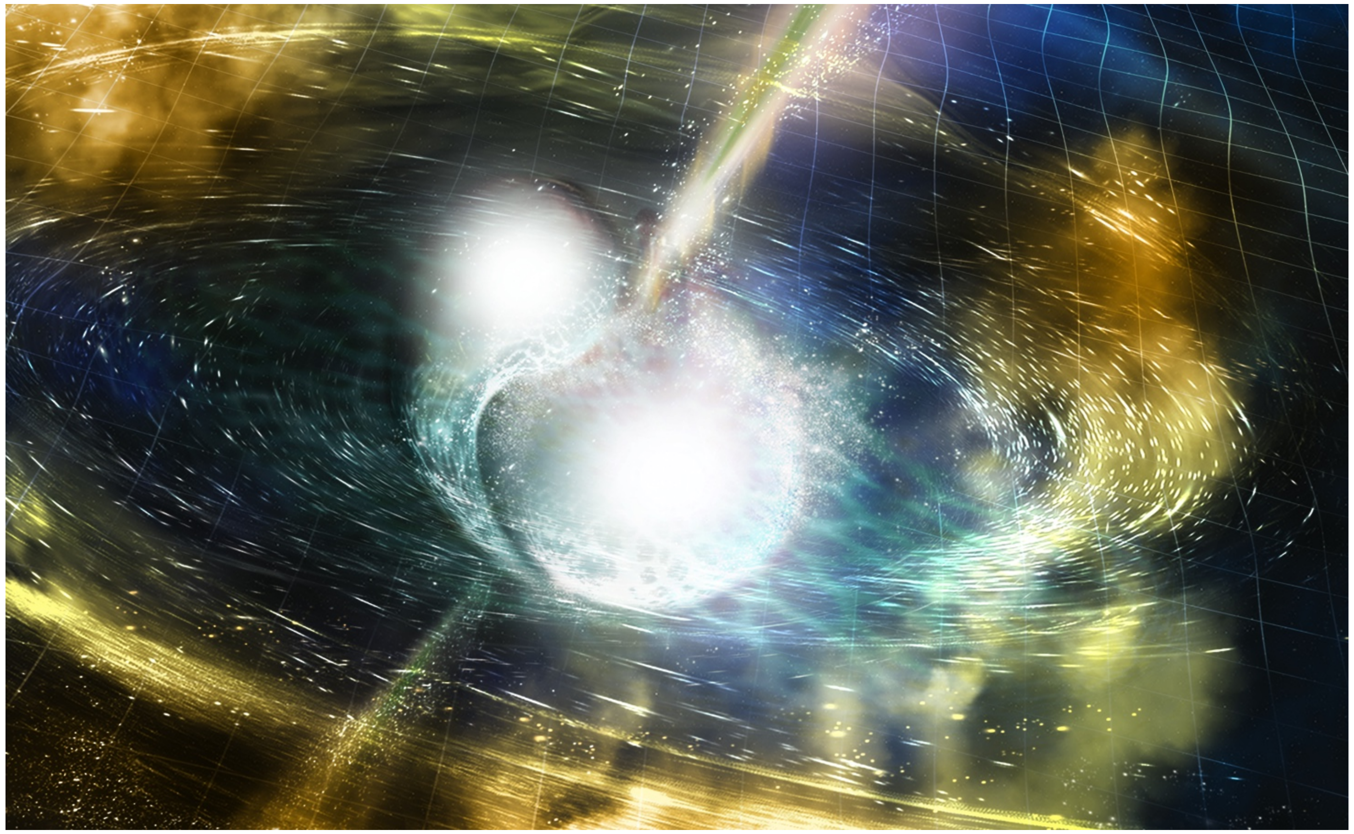
The detection of TeV gamma-ray bursts (GRBs) brought new opportunities for studying the physics of particle acceleration at relativistic shocks. The High Energy Stereoscopic System (H.E.S.S.) telescopes recently observed very-high-energy (VHE) emission from a nearby low-luminosity GRB, GRB 190829A. Follow-up observations with, e.g., Swift-XRT, revealed unusual flare activities at $\sim 10^3$ s, which can be caused by a long-lasting central engine. We show that the VHE emission during the H.E.S.S. observation time is naturally produced in the external inverse-Compton (EIC) scenario, where seed photons supplied by the flares or other late-time dissipations are upscattered to VHE energies by the nonthermal electrons accelerated at the external forward shock. Our calculations show that the EIC flare nearly coincides with the late-prompt flare, but extends ~3–4 times longer than the duration of the late-prompt flare. The preferred kinetic energy and initial Lorentz factor used in our model are $\sim 10^{52}$ erg and ~20, respectively. Understanding the mechanisms of the VHE emission from low-luminosity GRBs will help us constrain the properties of the outflow and the central engine activities, as well as the particle acceleration mechanism.

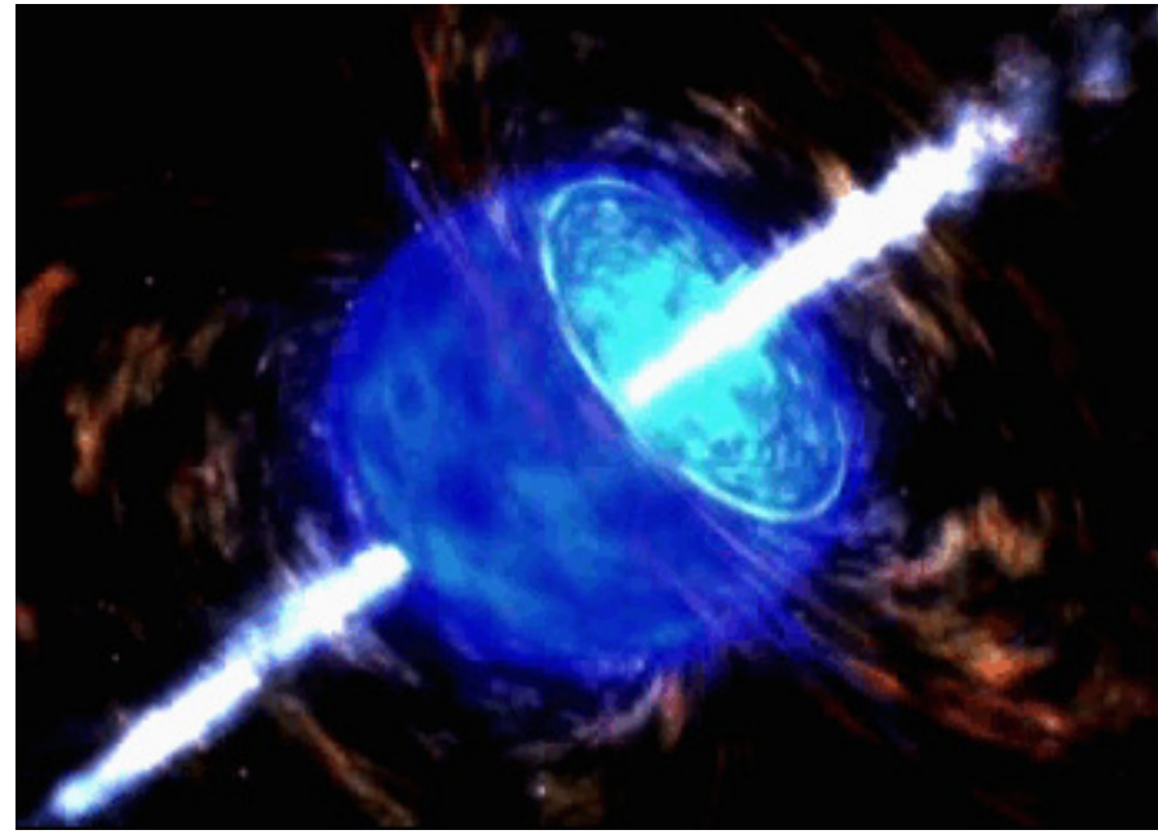
A Sketch of Physical Picture of GRBs

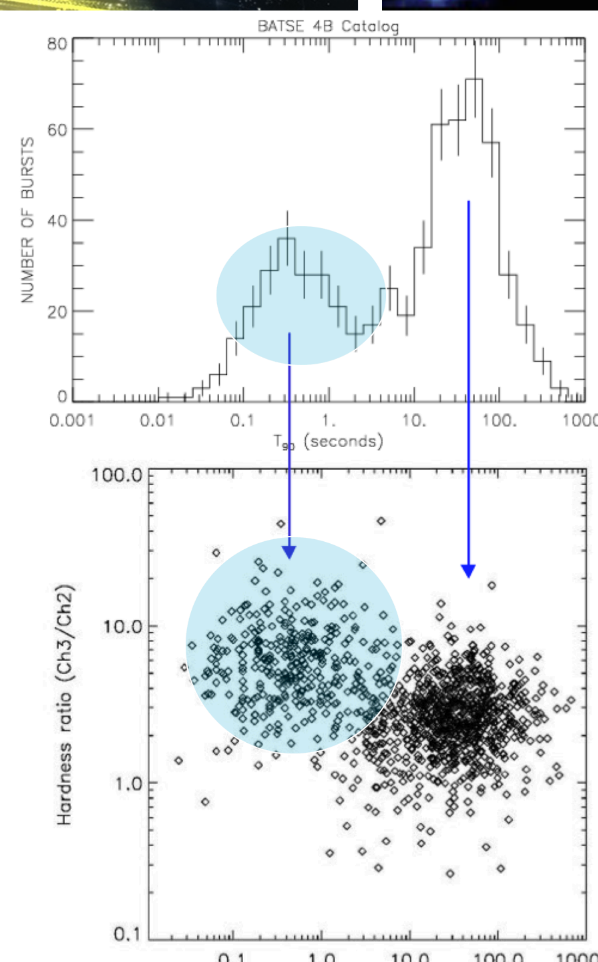




2. Oddball GRB progenitors



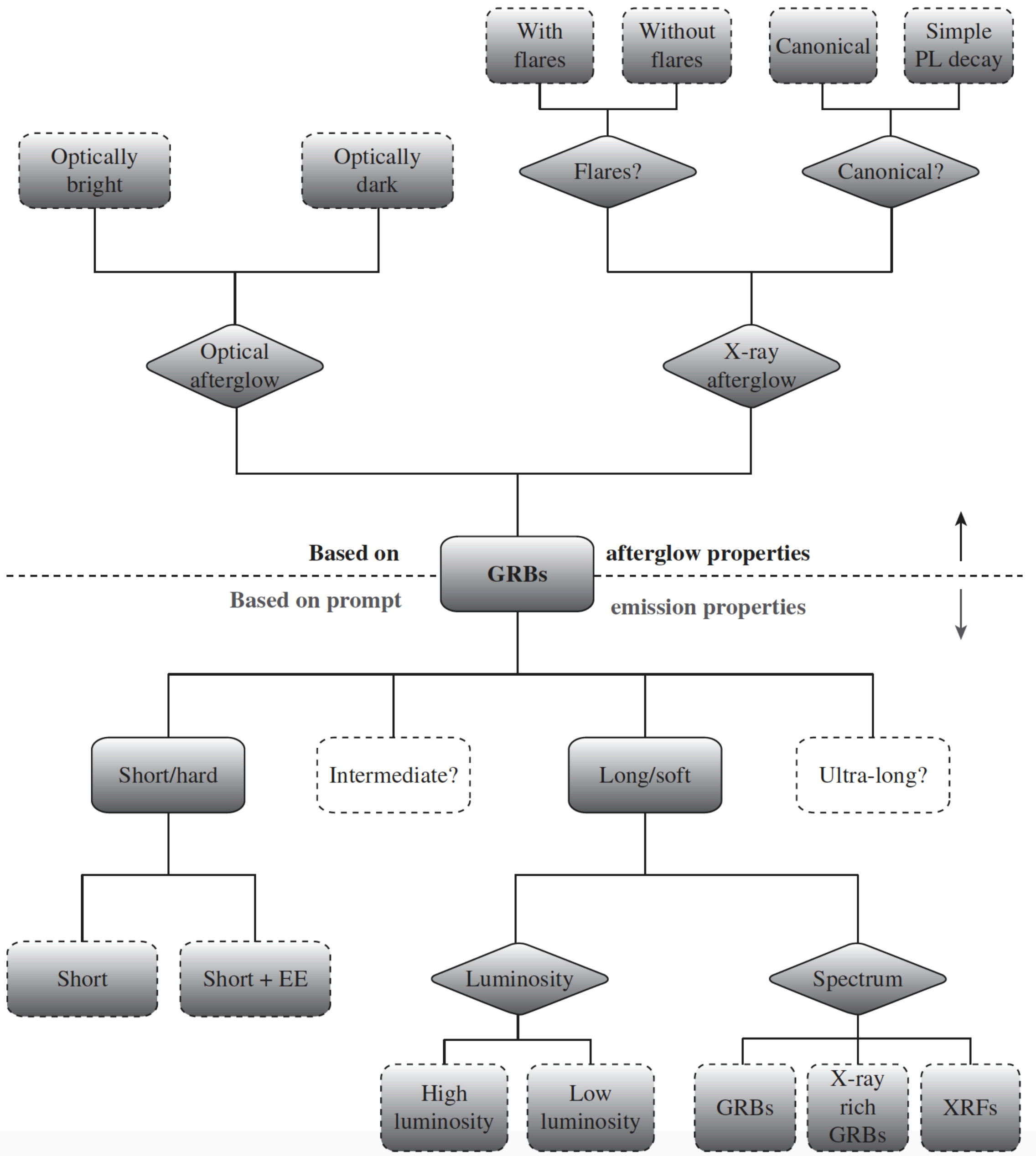


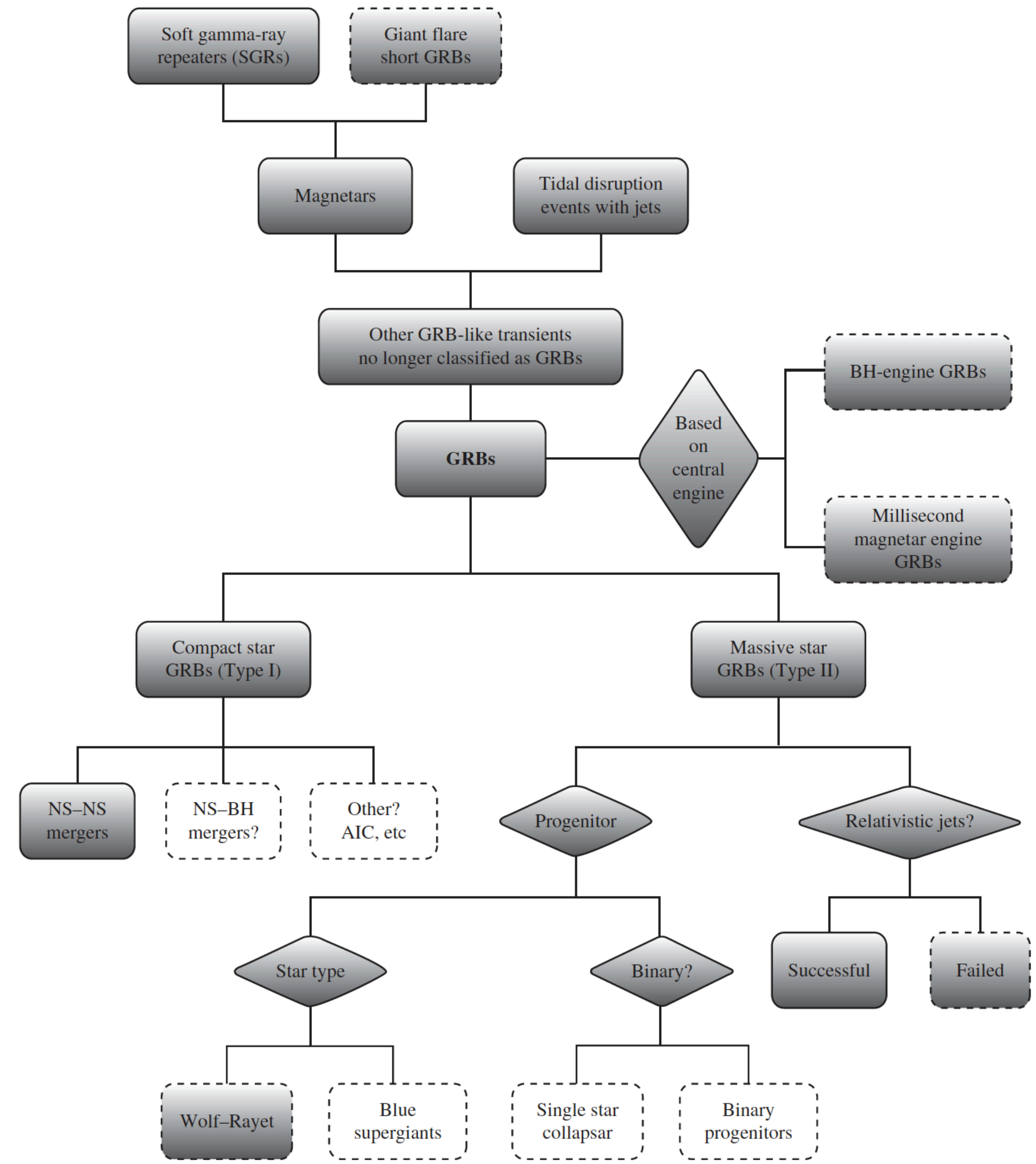


Short / hard

Long / soft

GRB classification schemes





Zhang, 2018, The Physics of Gamma-Ray Bursts, Cambridge University Press

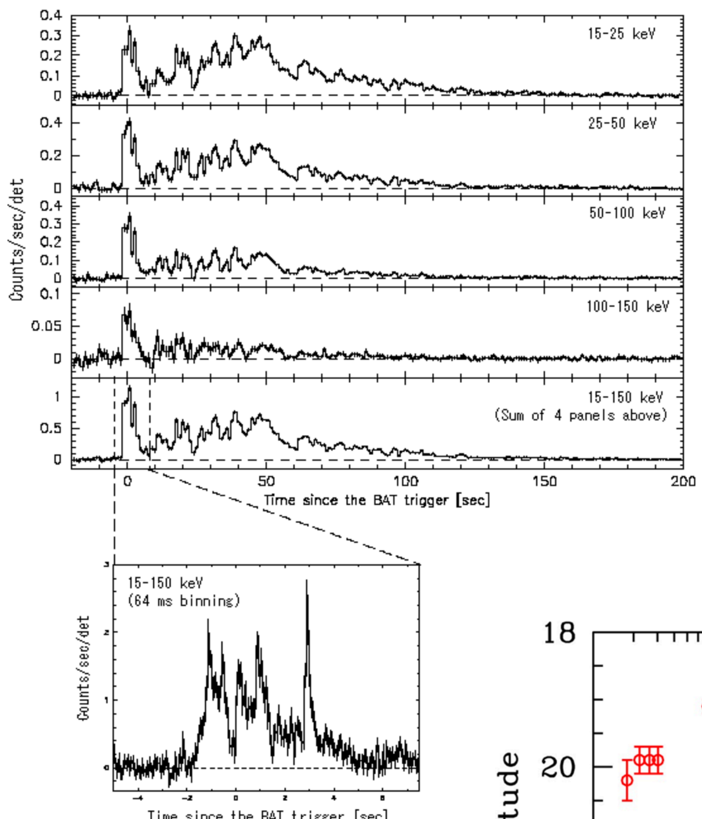
An elegant picture:

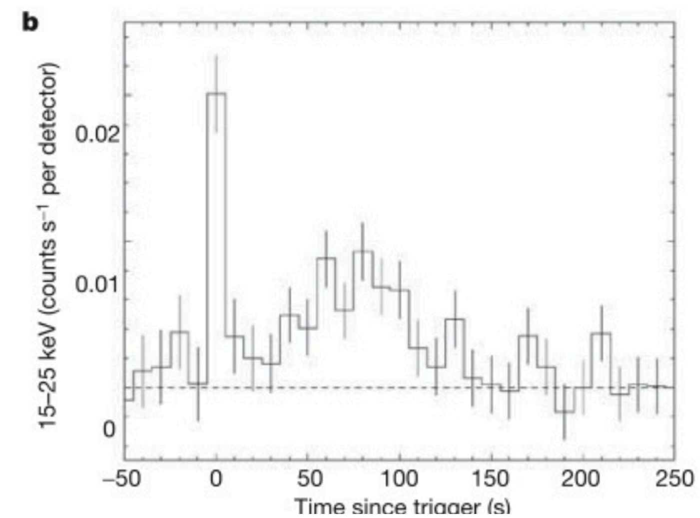
Long GRBs = massive star GRBs (Type II)

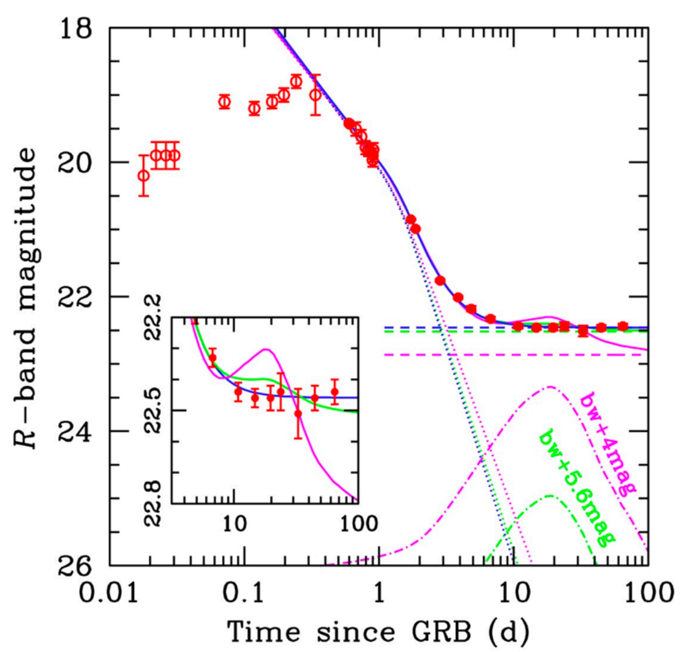
Short GRBs = compact star GRBs (Type I)

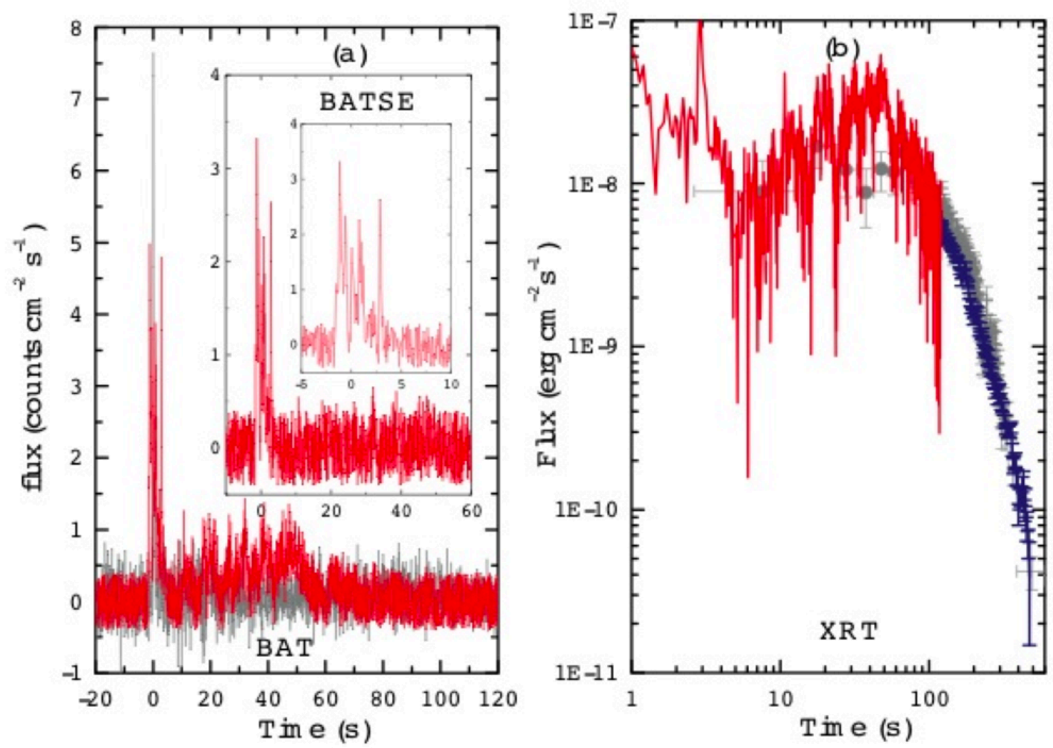
But is it that simple?

Oddball GRB 060614: a long burst with a compact star (Type I) origin









Gehrels et al. 2006; Gal-Yam et al. 2006; Fynbo et al. 2006; Della Valle et al. 2006
Zhang 2006; Zhang et al. 2007

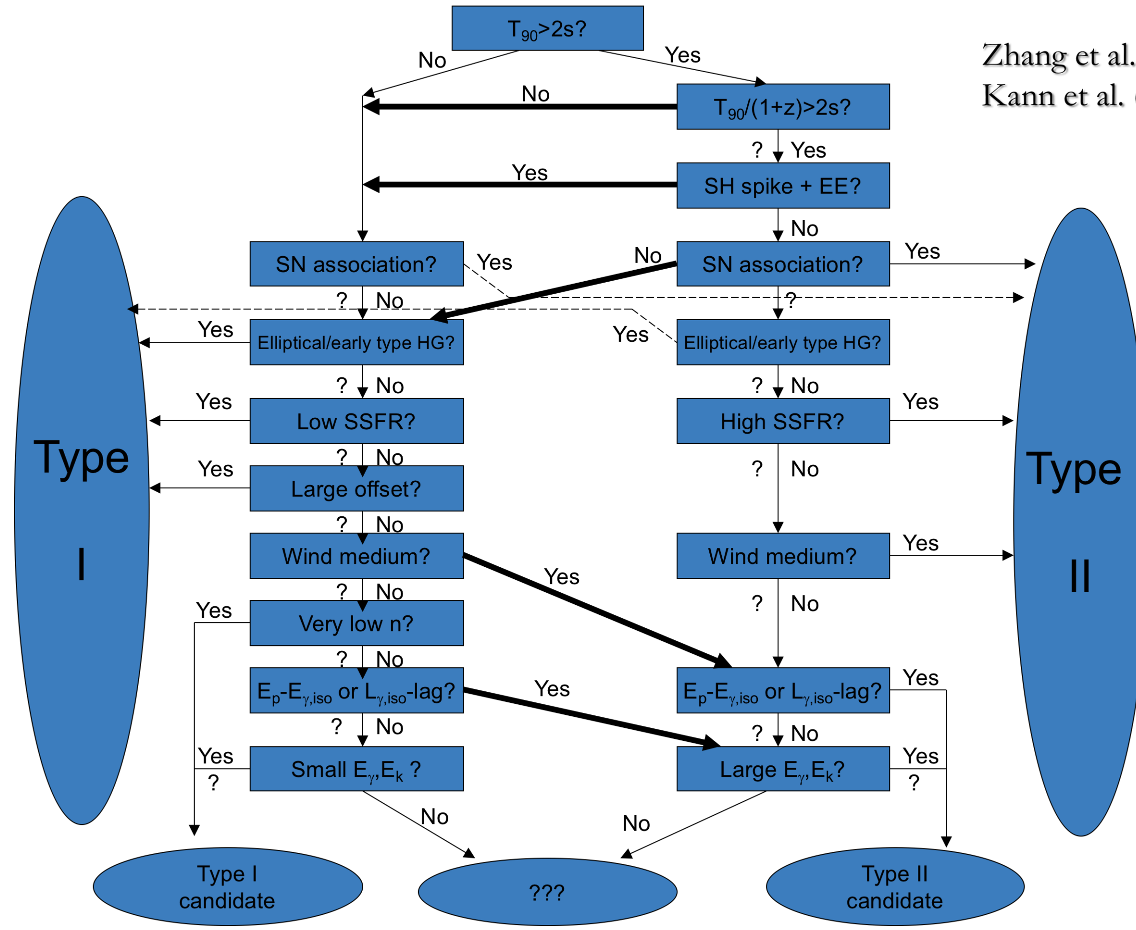
Multi-wavelength observational criteria

How to tell the physical category from the observations?

Multiple observational criteria needed!

TABLE 2
OBSERVATIONAL CRITERIA FOR PHYSICALLY CLASSIFYING GRBS.

Criterion	Type I	Type II	Issues
Duration	Usually short, but can have extended emission.	Long without short/hard spike, can be shorter than 1s in rest frame.	No clear separation line.
Spectrum	Usually hard (soft tail)	Usually soft	Large dispersion
Spectral Lag	Usually short	Usually long, can be short.	Related to variability time scale
$E_{\gamma,iso}$	Low (on average)	High (on average)	Wide dstribution in both
$E_p - E_{\gamma,iso}$	Usually off the track.	Usually on the track.	Some Type II off the track.
$L^p_{\gamma,iso}$−lag	Usually off the track.	Usually on the track.	Some Type II off the track.
SN association	No.	**Yes.**	Some Type II may have no association.
Medium type	Low-n ISM.	**Wind** or High-n ISM.	Large scatter of n distribution.
$E_{K,iso}$	Low (on average)	High (on average)	Large dispersion
Jet angle	Wide (on average)	Narrow (on average)	Difficult to identify jet breaks
E_γ and E_K	Low (on average)	High (on average)	Type I BZ model ∼ Type II.
Host galaxy type	**Elliptical, early** and late	Late	Deep spectroscopy needed.
SSFR	**Low** or high	High (exception GRB 070125)	
Offset	Outskirt or outside	Well inside	How to claim association if outside?
z-distribution	Low average z	High average z	
L-function	?	Broken power law, 2-component	



Zhang et al. (2009)
Kann et al. (2011)

Multi-wavelength GRB Classifier

This Multi-wavelength GRB Classifier physically classify Gamma Ray Bursts (GRBs) as Type II (massive star core collapse) and Type I GRB (compact star merger) based on multi-wavelength criteria, with Naive Bayes method ultilized. Both the prompt emission information and host galaxy information are taken into consideration. This method is based on Li, Zhang & Yuan, 2020, The Astrophysical Journal, Volume 897, page 154, also available at arXiv:2005.13663.

Input parameter

(keep the unknown parameters blank)

name (not required):	GRB 130603B	log T_90 (s):	-0.745
log E_iso (erg):	51.305	alpha:	-0.730
log E_p (keV):	2.820	log (f_eff-1):	
log sSFR (Gyr^-1):	0.456	log M (M_sun):	9.230
[X/H]:	-0.240	log R_50 (kpc):	0.702
log r_off (=R_off/R_50):	0.021	F_light:	0.35

submit

Zhang et al. 2009; Kann et al. 2011; Li, Zhang & Yuan 2020;
https://www.physics.unlv.edu/~liye/GRB/grb_cls.html

Oddball GRB 200826A: a short burst with a massive star (Type II) origin

nature astronomy

LETTERS

https://doi.org/10.1038/s41550-021-01395-z

Check for updates

A peculiarly short-duration gamma-ray burst from massive star core collapse

B.-B. Zhang[1,2,3,13] ✉, Z.-K. Liu[1,2,13], Z.-K. Peng[1,2,13], Y. Li[4,5], H.-J. Lü[6], J. Yang[1,2], Y.-S. Yang[1,2], Y.-H. Yang[1,2], Y.-Z. Meng[1,2], J.-H. Zou[1,2,7], H.-Y. Ye[1], X.-G. Wang[6], J.-R. Mao[8], X.-H. Zhao[8], J.-M. Bai[8], A. J. Castro-Tirado[9,10], Y.-D. Hu[9,11], Z.-G. Dai[1,2,12], E.-W. Liang[6] and B. Zhang[3] ✉

nature astronomy

LETTERS

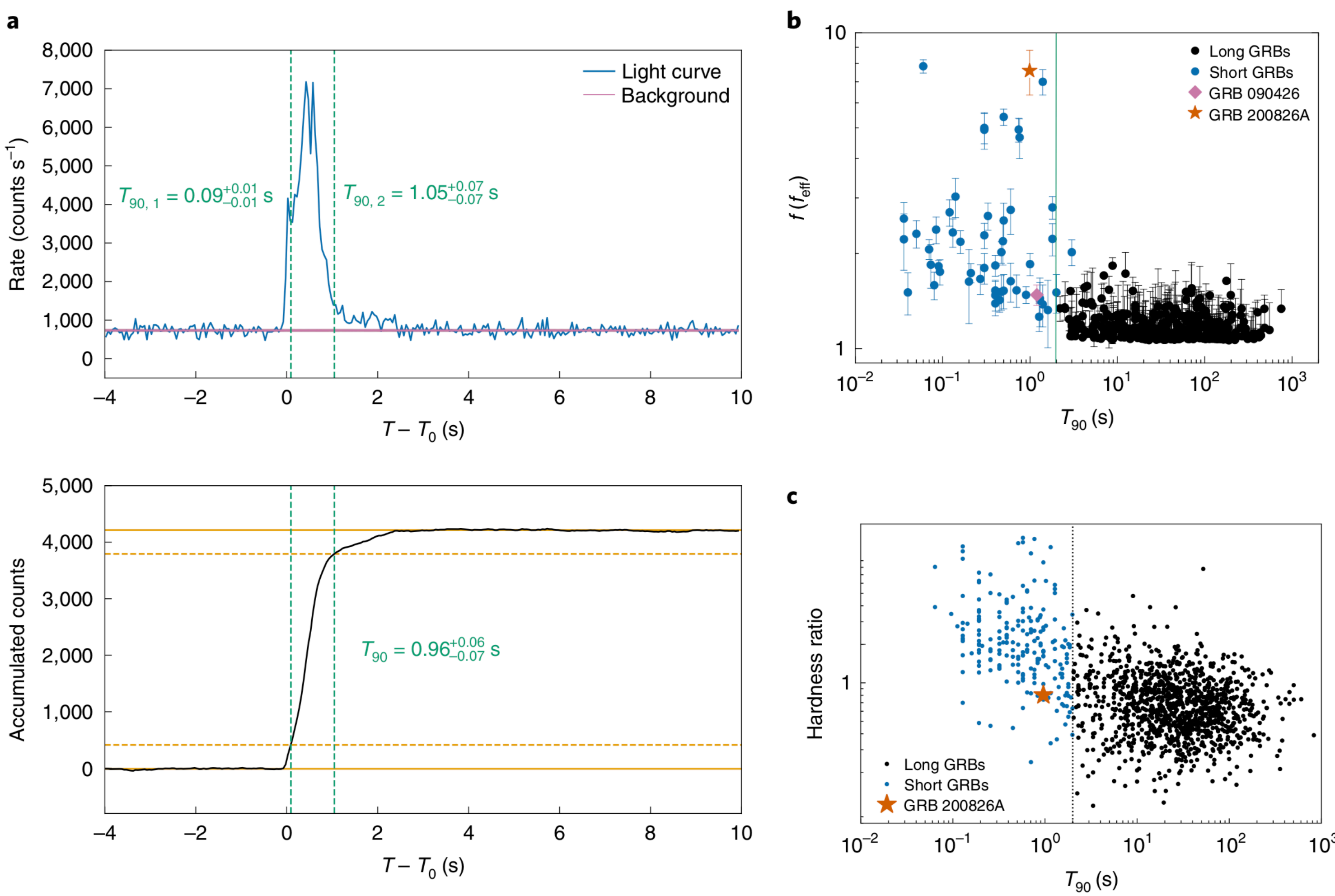
https://doi.org/10.1038/s41550-021-01428-7

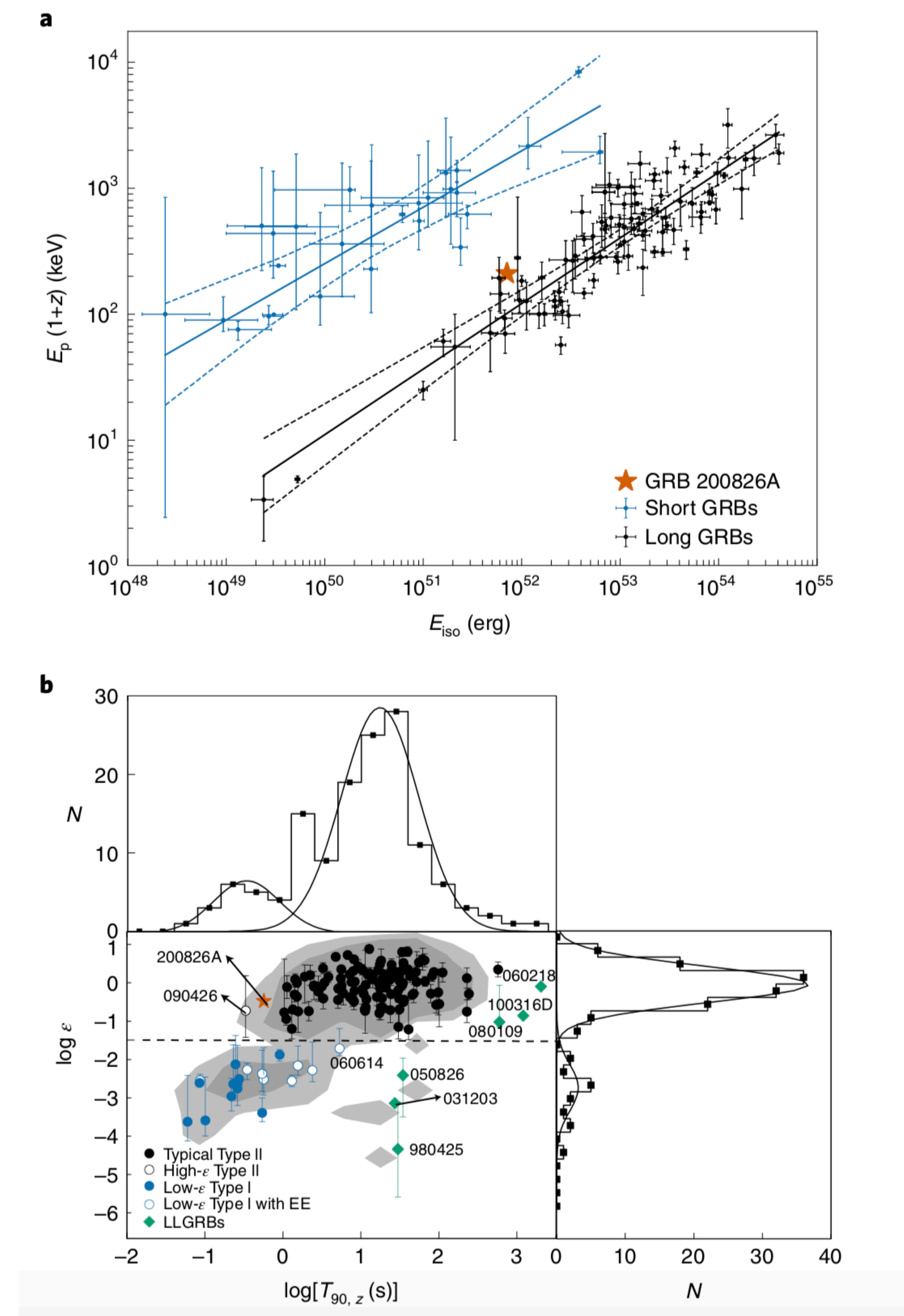
Check for updates

Discovery and confirmation of the shortest gamma-ray burst from a collapsar

Tomás Ahumada[1,2,3] ✉, Leo P. Singer[2,4], Shreya Anand[5], Michael W. Coughlin[6], Mansi M. Kasliwal[5], Geoffrey Ryan[1,2], Igor Andreoni[5], S. Bradley Cenko[2,4], Christoffer Fremling[5], Harsh Kumar[7], Peter T. H. Pang[8,9], Eric Burns[10], Virginia Cunningham[1,2], Simone Dichiara[1,2], Tim Dietrich[11,12], Dmitry S. Svinkin[13], Mouza Almualla[14], Alberto J. Castro-Tirado[15,16], Kishalay De[5], Rachel Dunwoody[17], Pradip Gatkine[5], Erica Hammerstein[1], Shabnam Iyyani[18], Joseph Mangan[17], Dan Perley[19], Sonalika Purkayastha[20], Eric Bellm[21], Varun Bhalerao[7], Bryce Bolin[5], Mattia Bulla[22], Christopher Cannella[23], Poonam Chandra[20], Dmitry A. Duev[5], Dmitry Frederiks[13], Avishay Gal-Yam[24], Matthew Graham[5], Anna Y. Q. Ho[25,26], Kevin Hurley[27], Viraj Karambelkar[5], Erik C. Kool[28], S. R. Kulkarni[5], Ashish Mahabal[5], Frank Masci[29], Sheila McBreen[17], Shashi B. Pandey[30], Simeon Reusch[31,32], Anna Ridnaia[12], Philippe Rosnet[33], Benjamin Rusholme[29], Ana Sagués Carracedo[34], Roger Smith[35], Maayane Soumagnac[24,36], Robert Stein[31,32], Eleonora Troja[1,2], Anastasia Tsvetkova[13], Richard Walters[35] and Azamat F. Valeev[37,38]

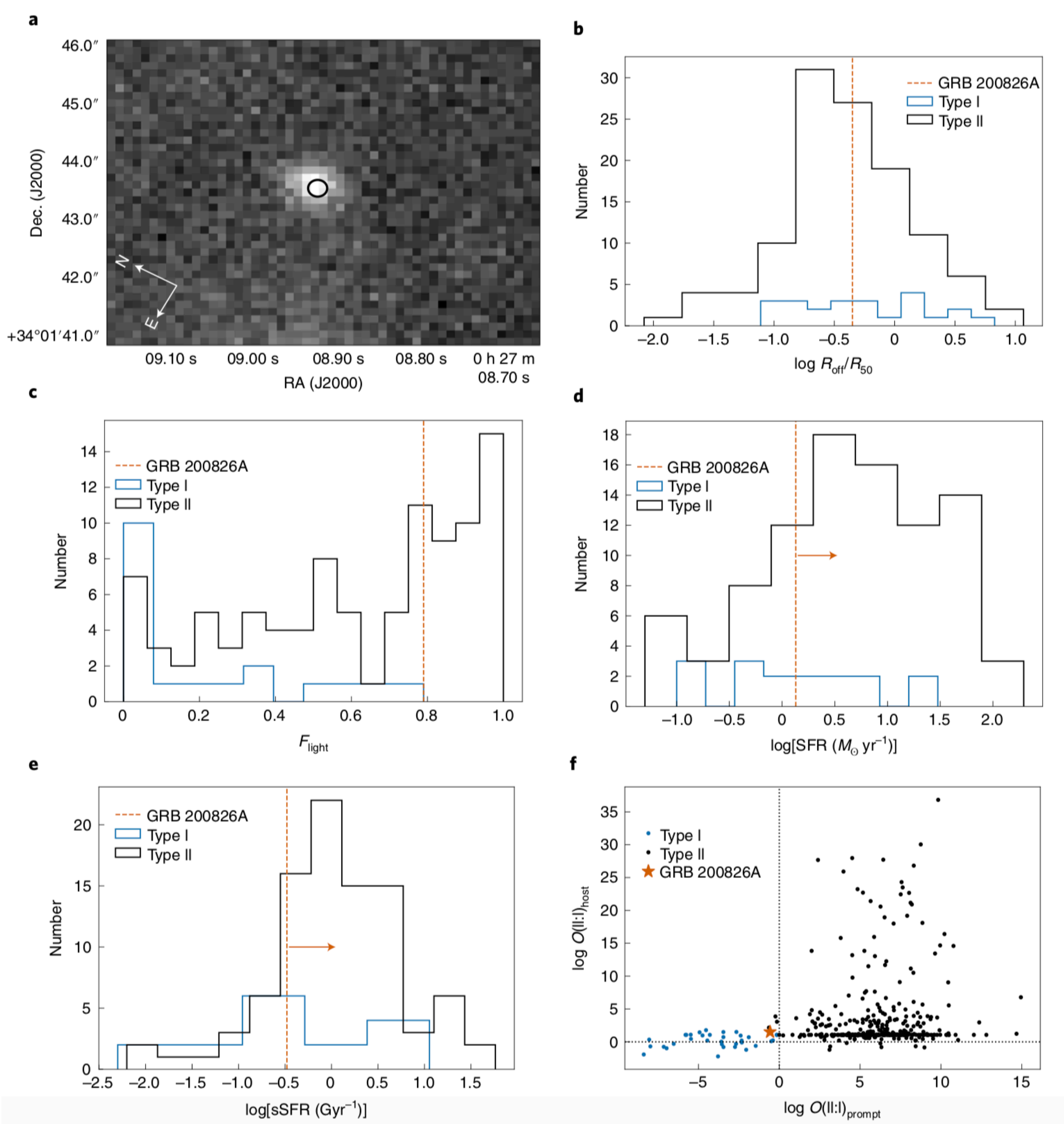
GRB 200826A: a short burst with a massive star (Type II) origin

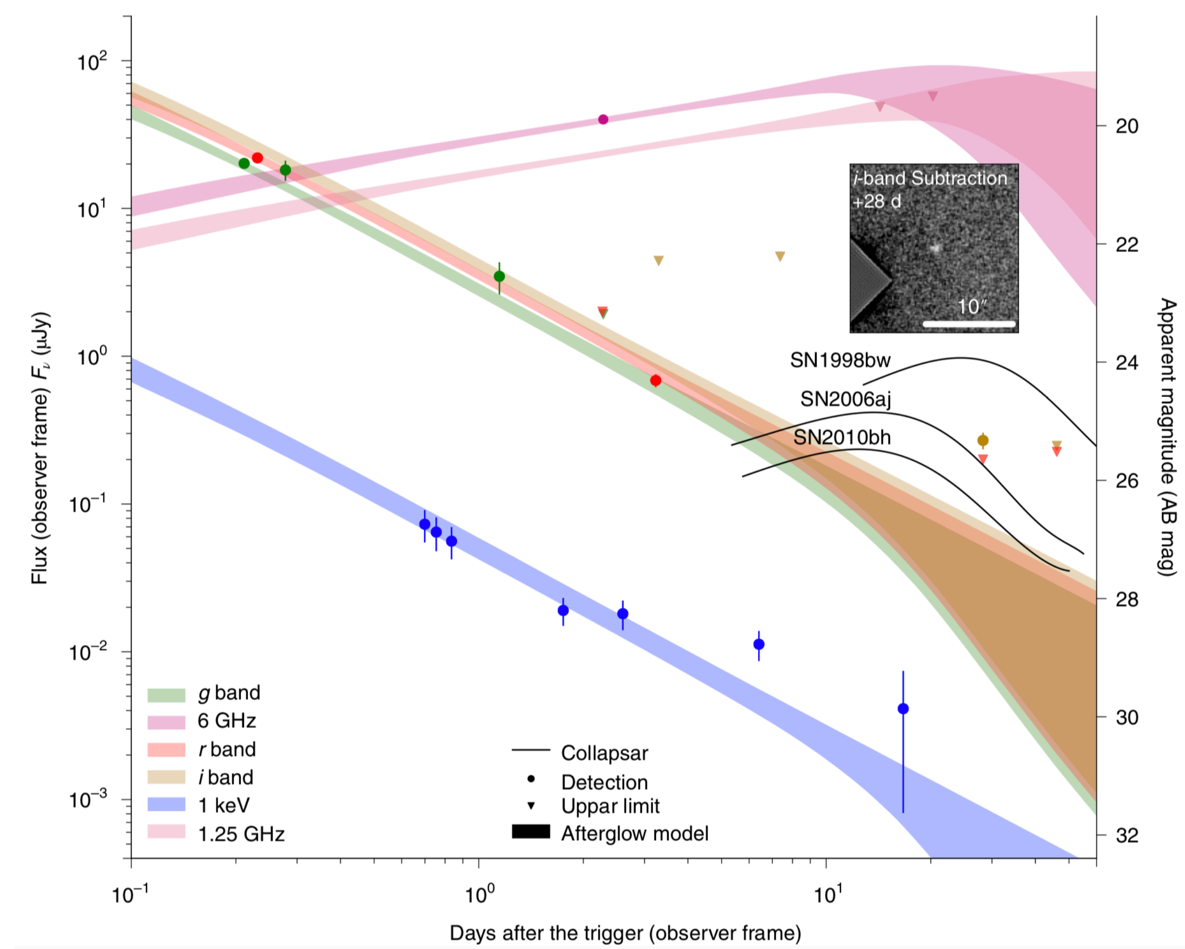




B. B. Zhang et al. 2020, NatAst, 5, 911-916; Ahumada et al. 2020, NatAst, 5, 917-927

GRB 200826A: a short burst with a massive star (Type II) origin

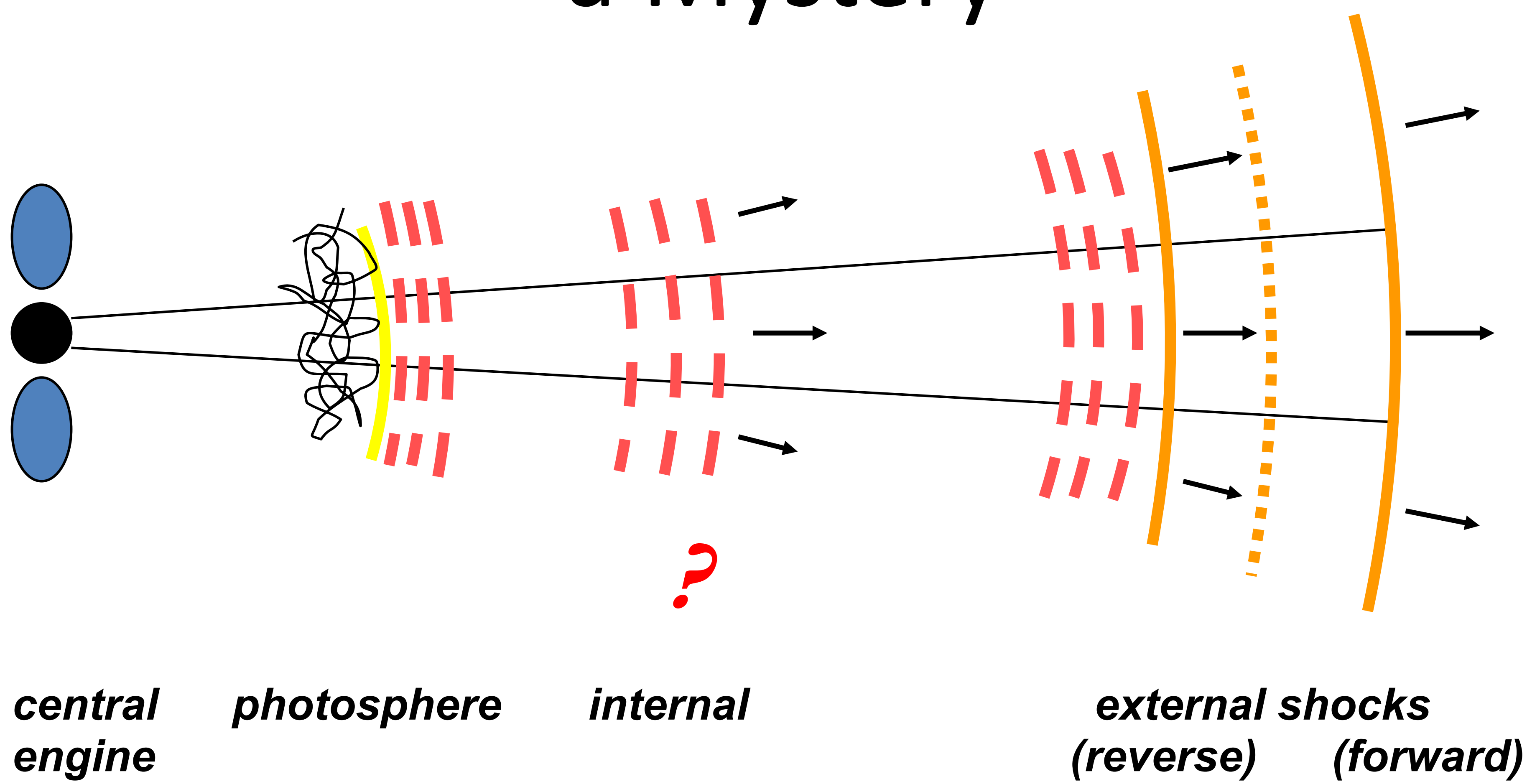




B. B. Zhang et al. 2020, NatAst, 5, 911-916; Ahumada et al. 2020, NatAst, 5, 917-927

3. GRB Prompt Emission: Jet Composition, dissipation and emission mechanisms

Prompt GRB Emission: a Mystery



What is the jet composition (baryonic vs. Poynting flux)?
Where is (are) the dissipation radius (radii)?
How is the radiation generated (synchrotron, thermal Comptonization)?

GRB Jet Composition & Energy Dissipation Processes

GRB central engine defined by (η, σ_0)

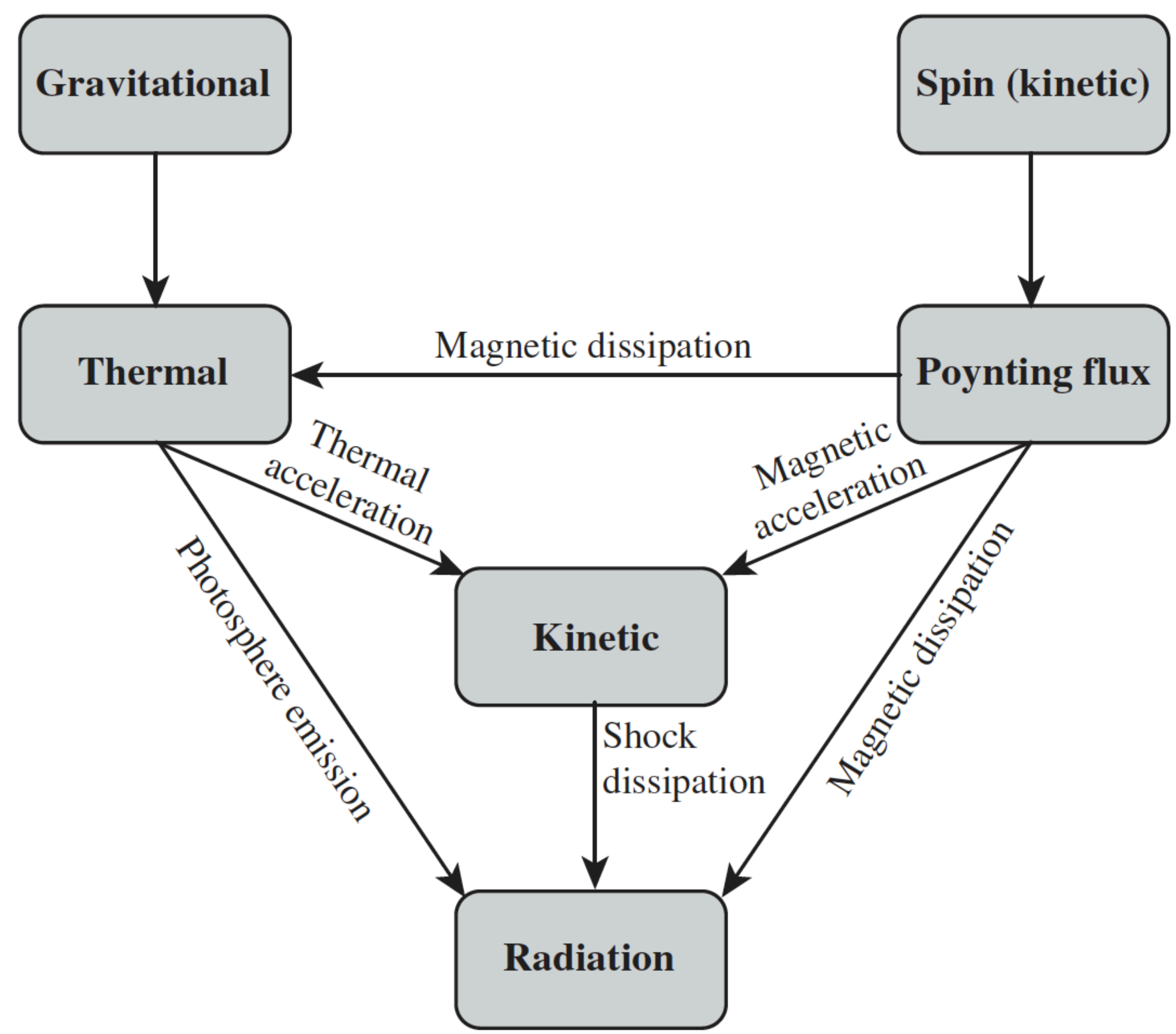
- Energy per baryon >> 1
- Energy in three forms
  - Thermal: η, Θ
  - Magnetic: σ
  - Kinetic: Γ

$$\mu_0 = \frac{E_{\rm tot,0}}{Mc^2} = \frac{E_{th,0} + E_{\rm P,0}}{Mc^2} = \eta(1+\sigma_0).$$

Neglect radiation loss, one has

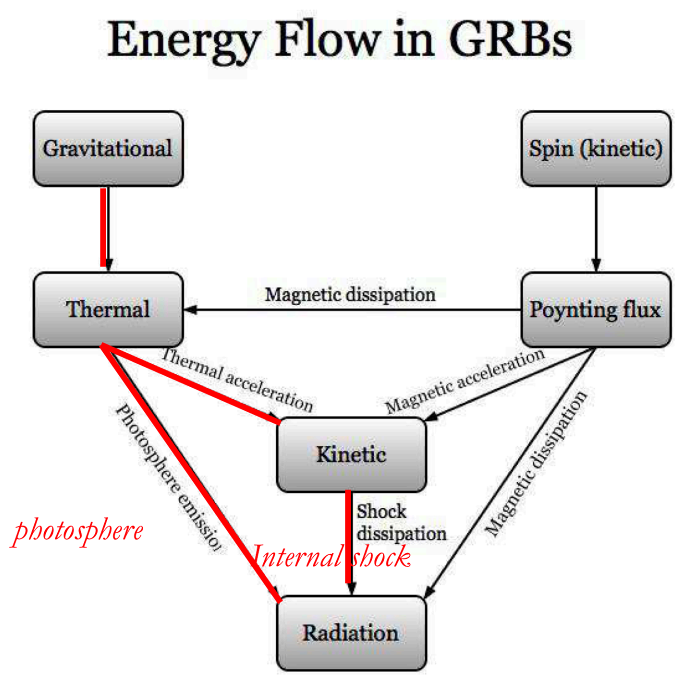
$$\mu_0 = \eta(1+\sigma_0) = \Gamma\Theta(1+\sigma).$$

$$\Gamma_{\rm max} = \mu_0 \simeq \begin{cases} \eta, & \sigma_0 \ll 1; \\ \sigma_0, & \eta \sim 1, \sigma_0 \gg 1. \end{cases}$$

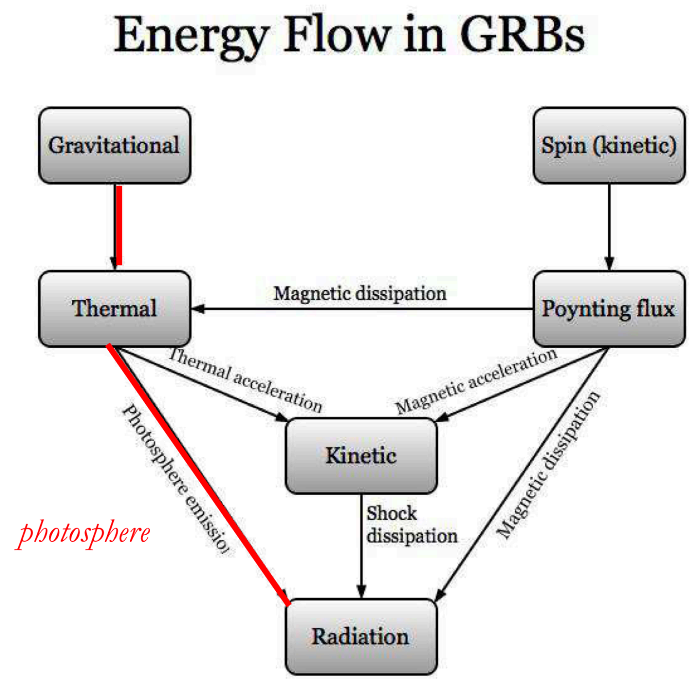


Zhang, 2018, The Physics of Gamma-Ray Bursts

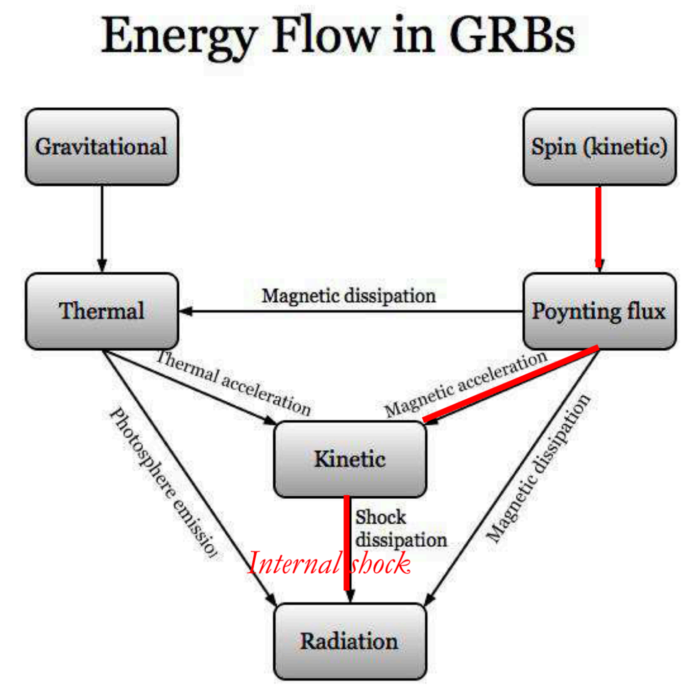
Various prompt emission models



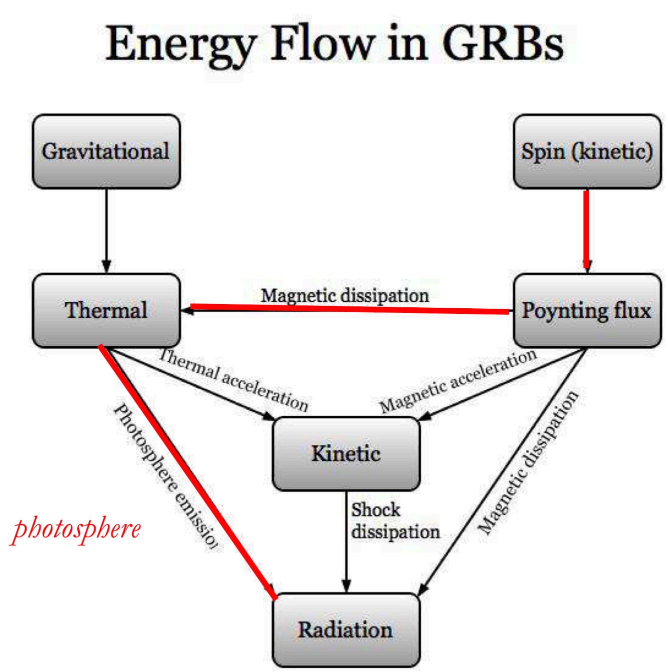
Fireball model



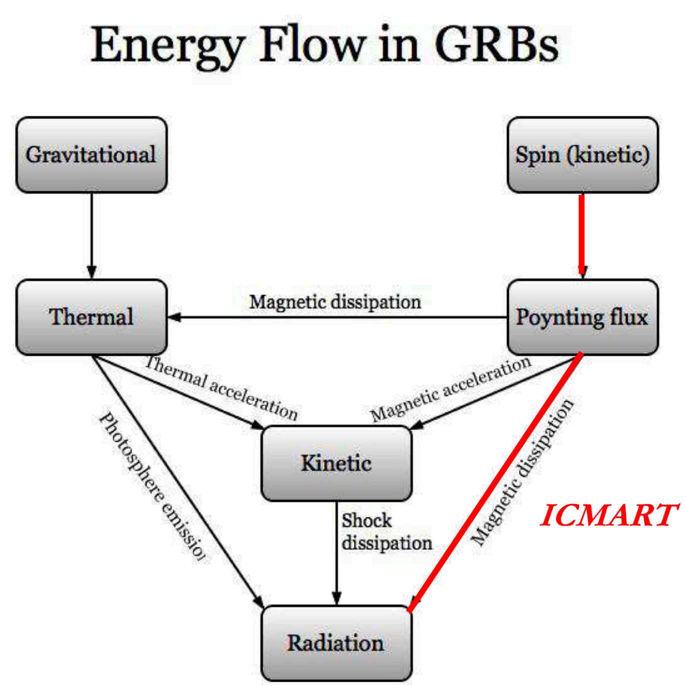
Dissipative photosphere model



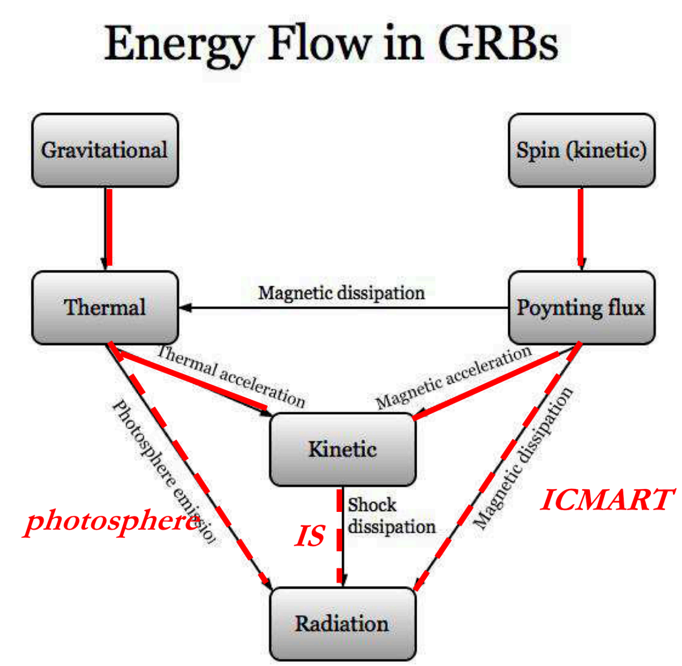
Initially magnetized internal shock model



Magnetically dissipative photosphere model

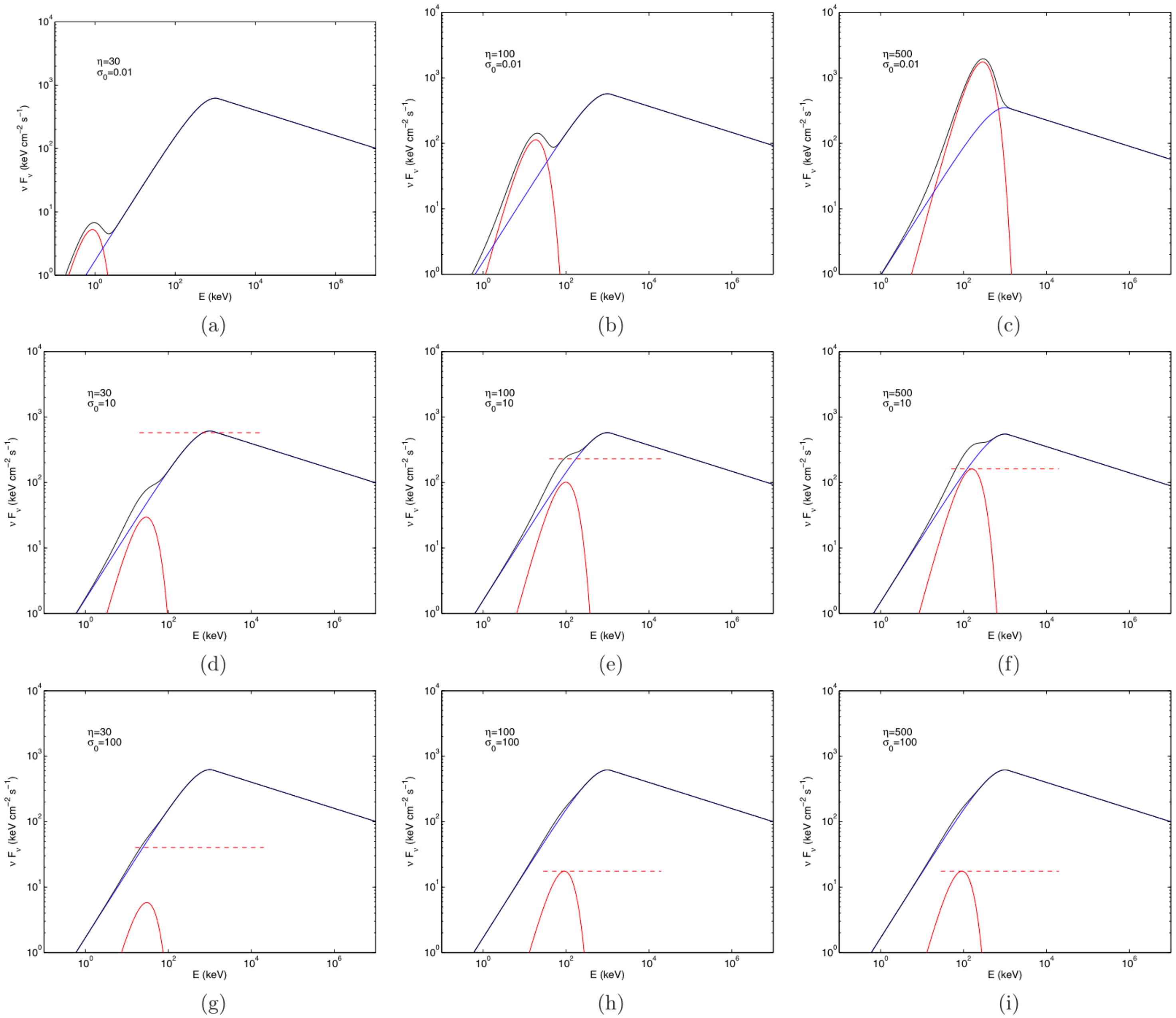


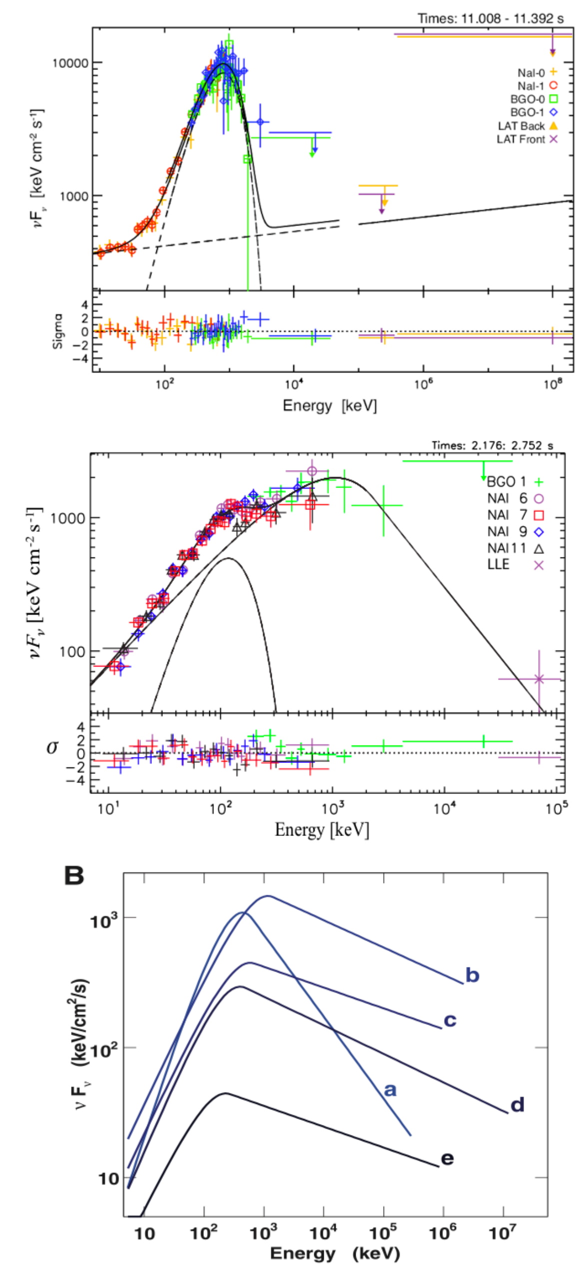
ICMART model



Hybrid models

Diverse composition in GRBs



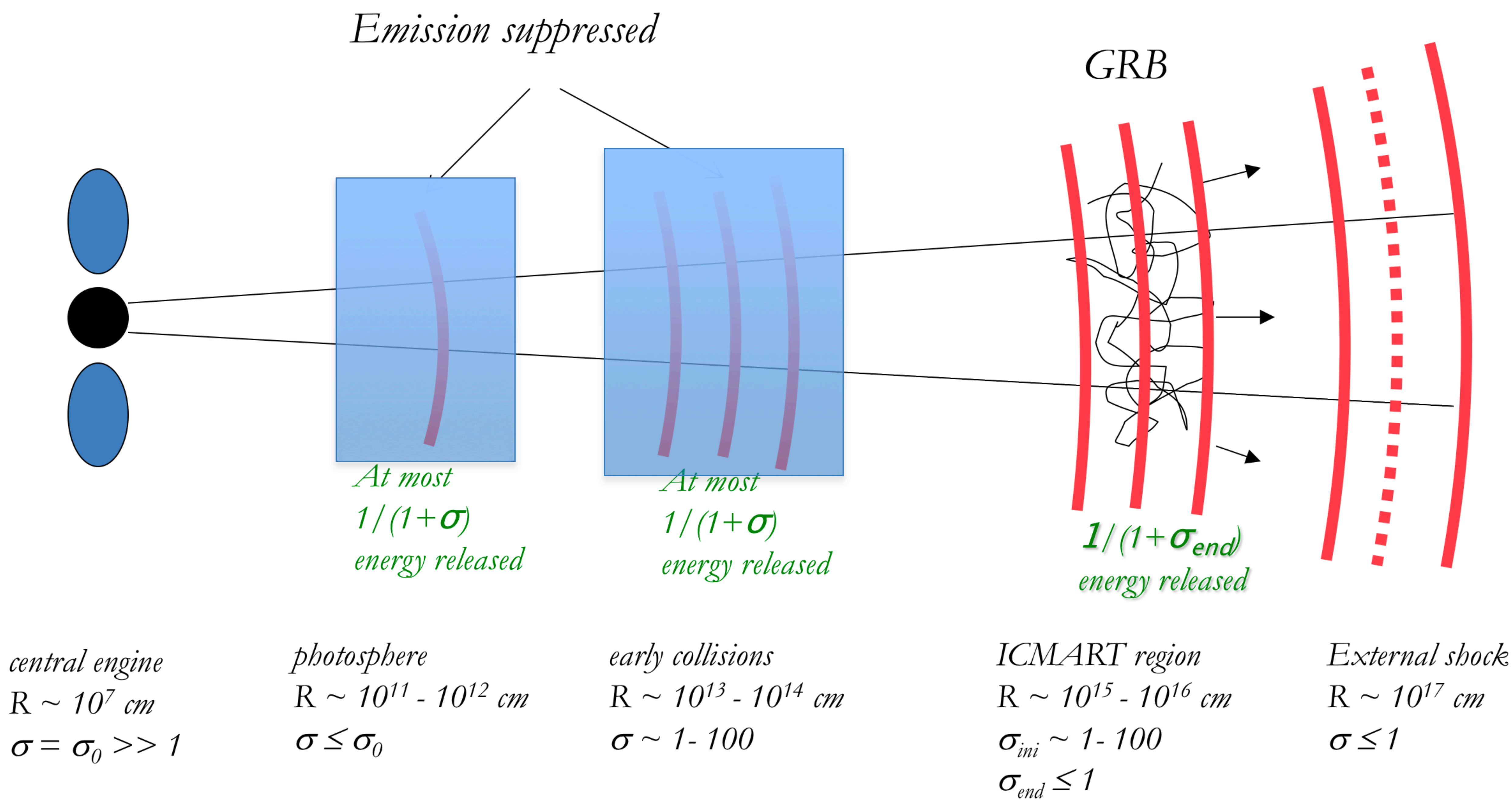


Gao & Zhang (2015, ApJ, 801: 103)

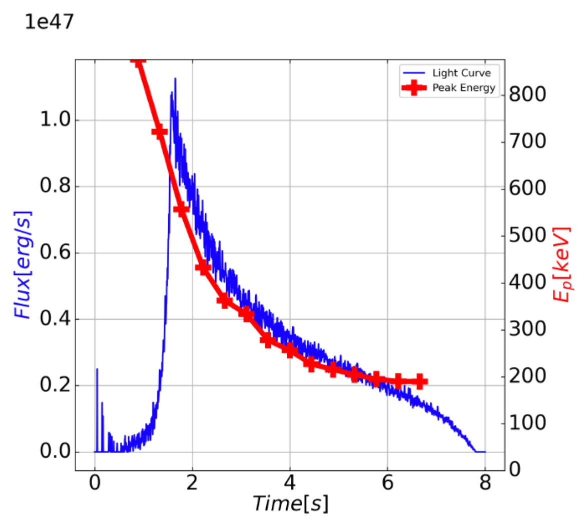
The ICMART Model

(Internal Collision-induced MAgnetic Reconnection & Turbulence)

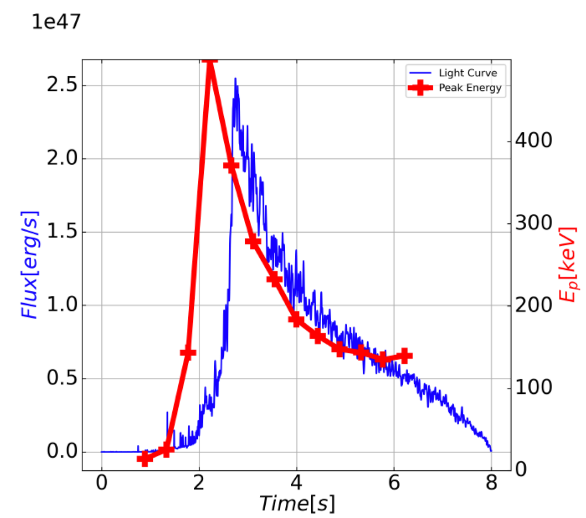
Zhang & Yan (2011)



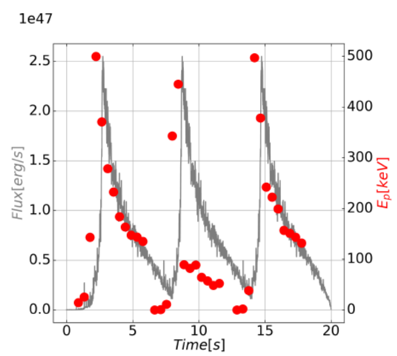
ICMART lightcurves and spectra



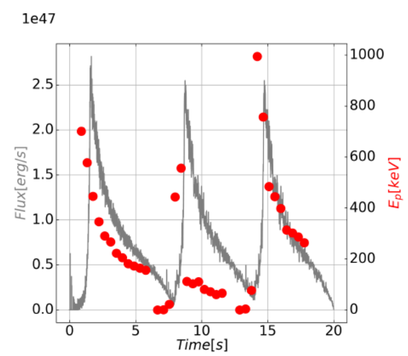
(a) Hard-to-Soft Pattern



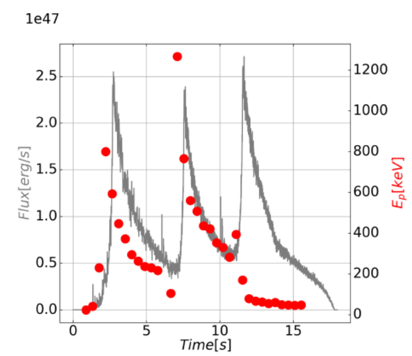
(b) Tracking Pattern



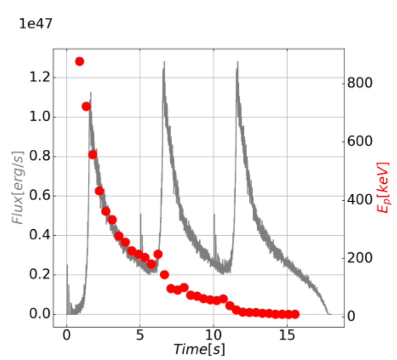
(a)



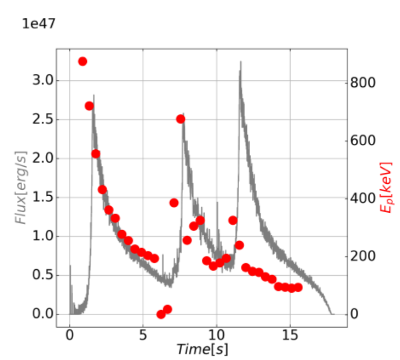
(b)



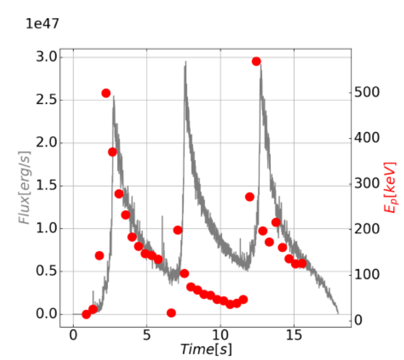
(c)



(d)

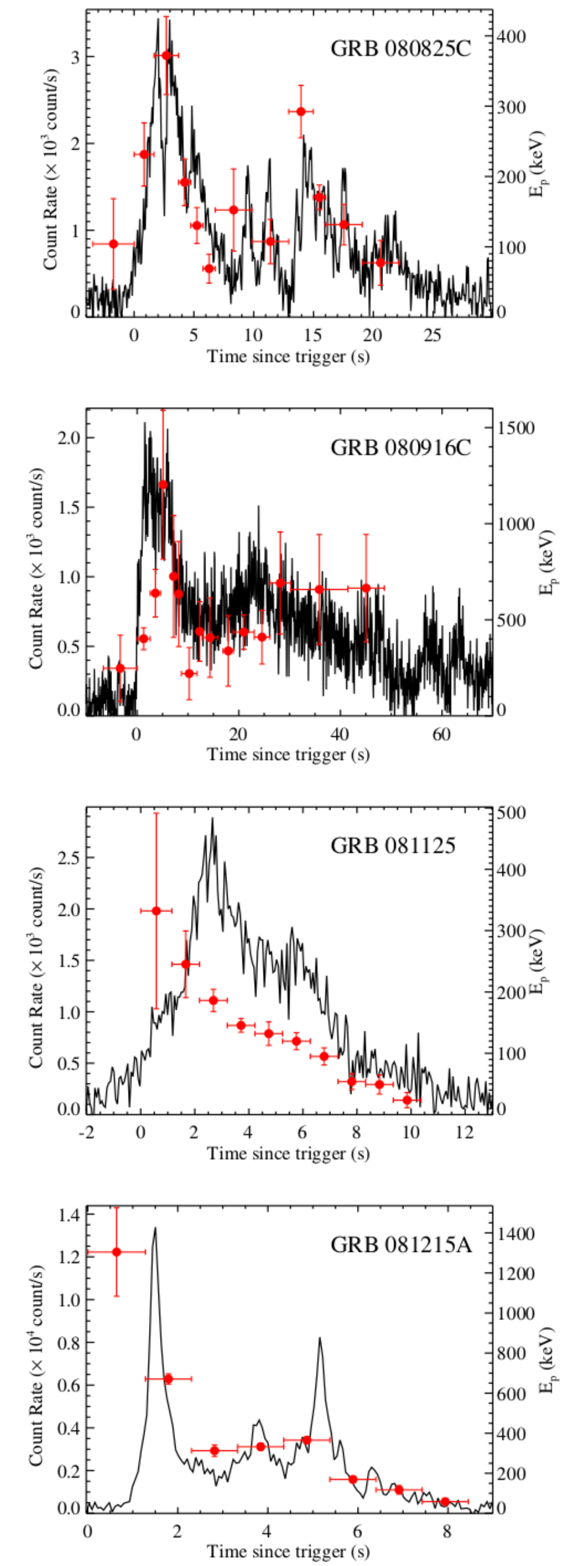


(e)



(f)

Shao & Gao, 2022, arXiv:2201.03750
(also Zhang & Zhang 2014; Uhm & Zhang 2016)



Lu et al. 2012

Summary

- TeV afterglows
  - High-energy photons have been detected from GRBs
  - The detected TeV emission likely originates from the external shock, and emitted by certain Compton scattering processes (SSC or EIC). No evidence of hadronic emission or extreme electron acceleration process yet.
- Oddball progenitors
  - Both long Type I and short Type II exist. Multi-wavelength data are needed for classification
  - There might be more diverse progenitor types
- Prompt emission
  - Diverse jet composition in GRBs. A good fraction carries a large Poynting flux.
  - The ICMART model invokes turbulent reconnection of a moderate outflow, produce highly polarized synchrotron radiation from jets in the jet. Can interpret many observations well.