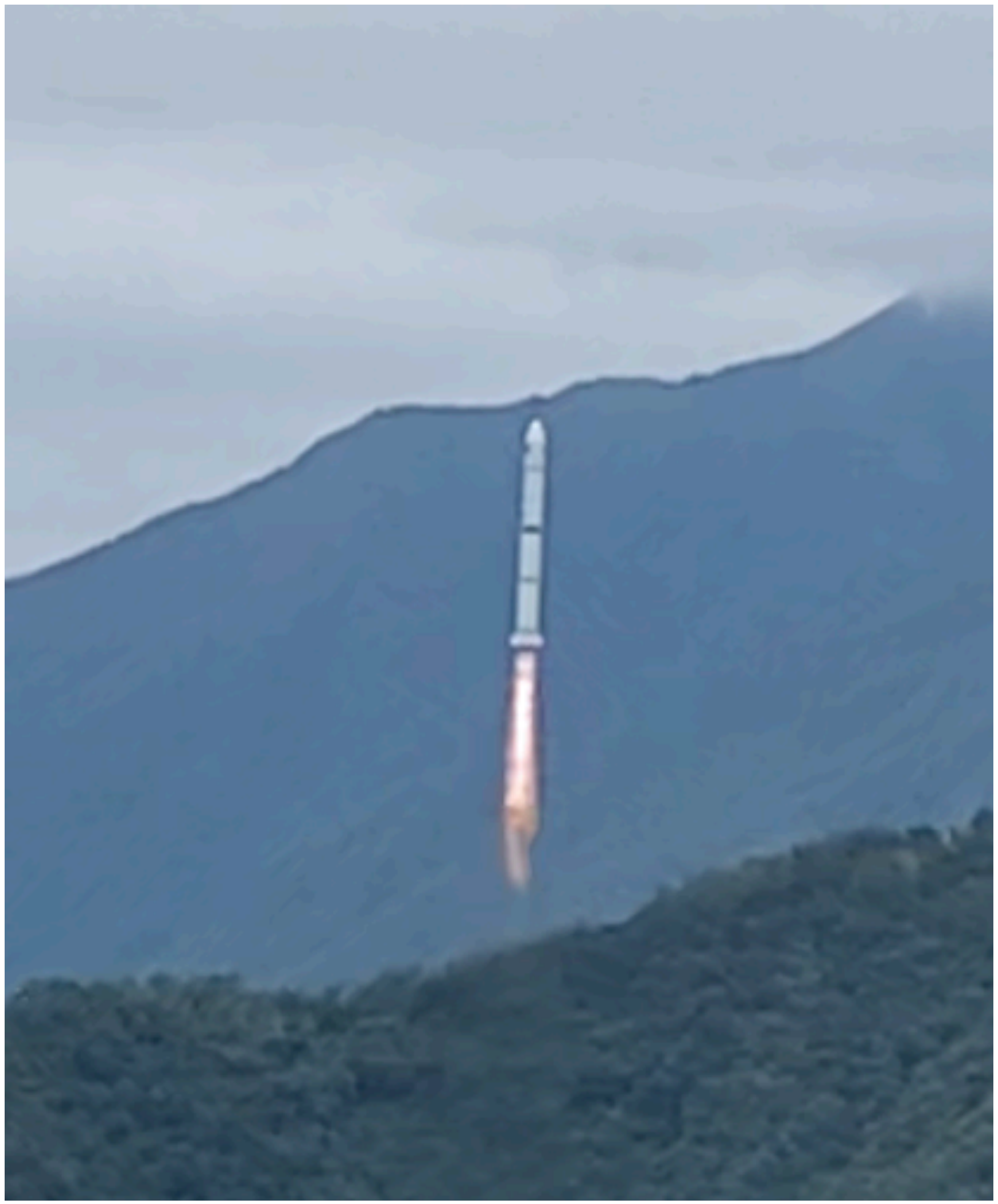
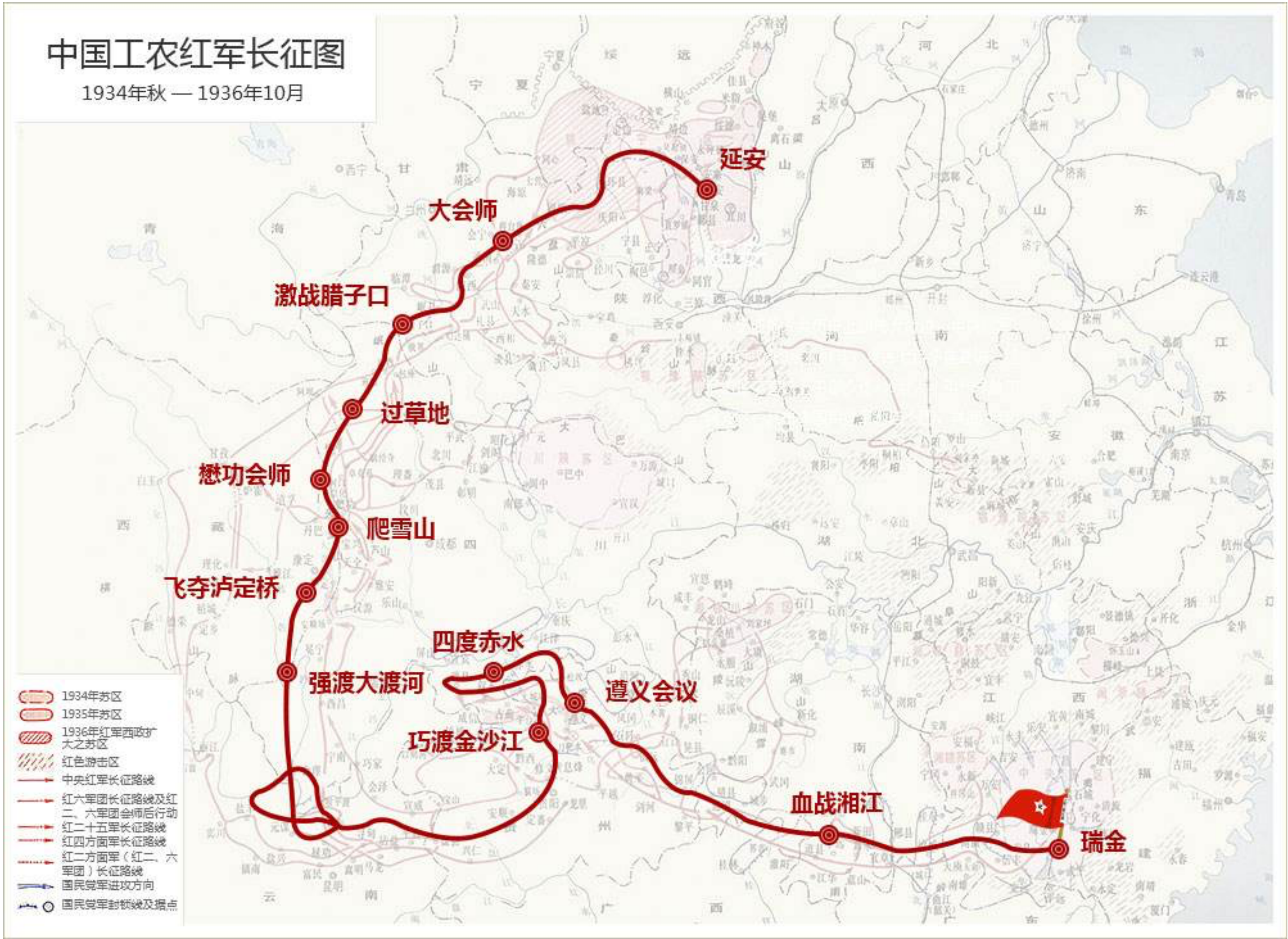
# Congratulations, SVOM!



June 22, 2024

# Historical “Red Army” Long March in Guizhou




2017, Second SVOM workshop, Qiannan

# SVOM's happy "Long March"

2017, Second SVOM workshop, Qiannan

# Gamma-Ray Bursts: What do we know?

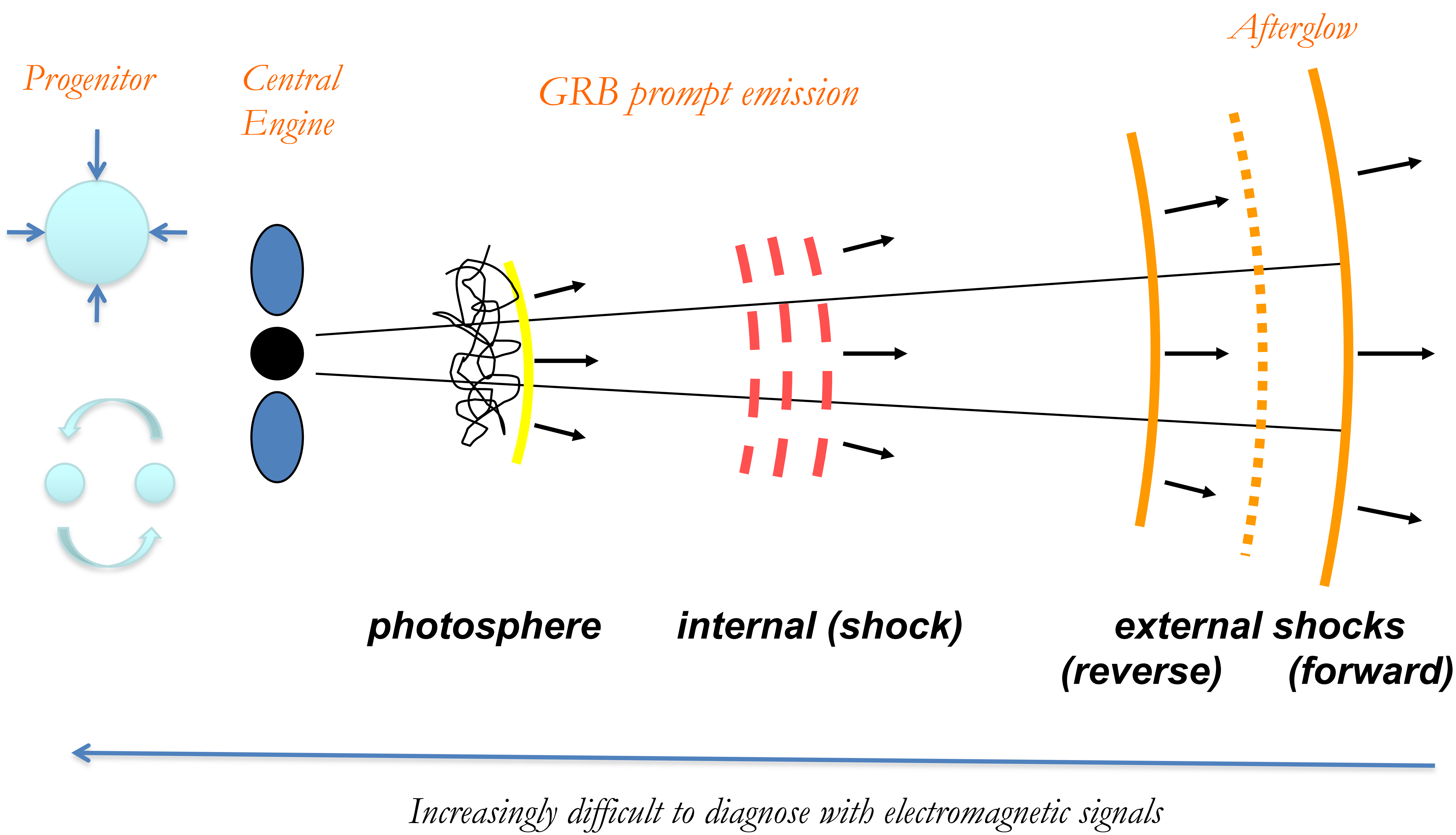
Bing Zhang

Nevada Center for Astrophysics
University of Nevada, Las Vegas

**June 23, 2024**

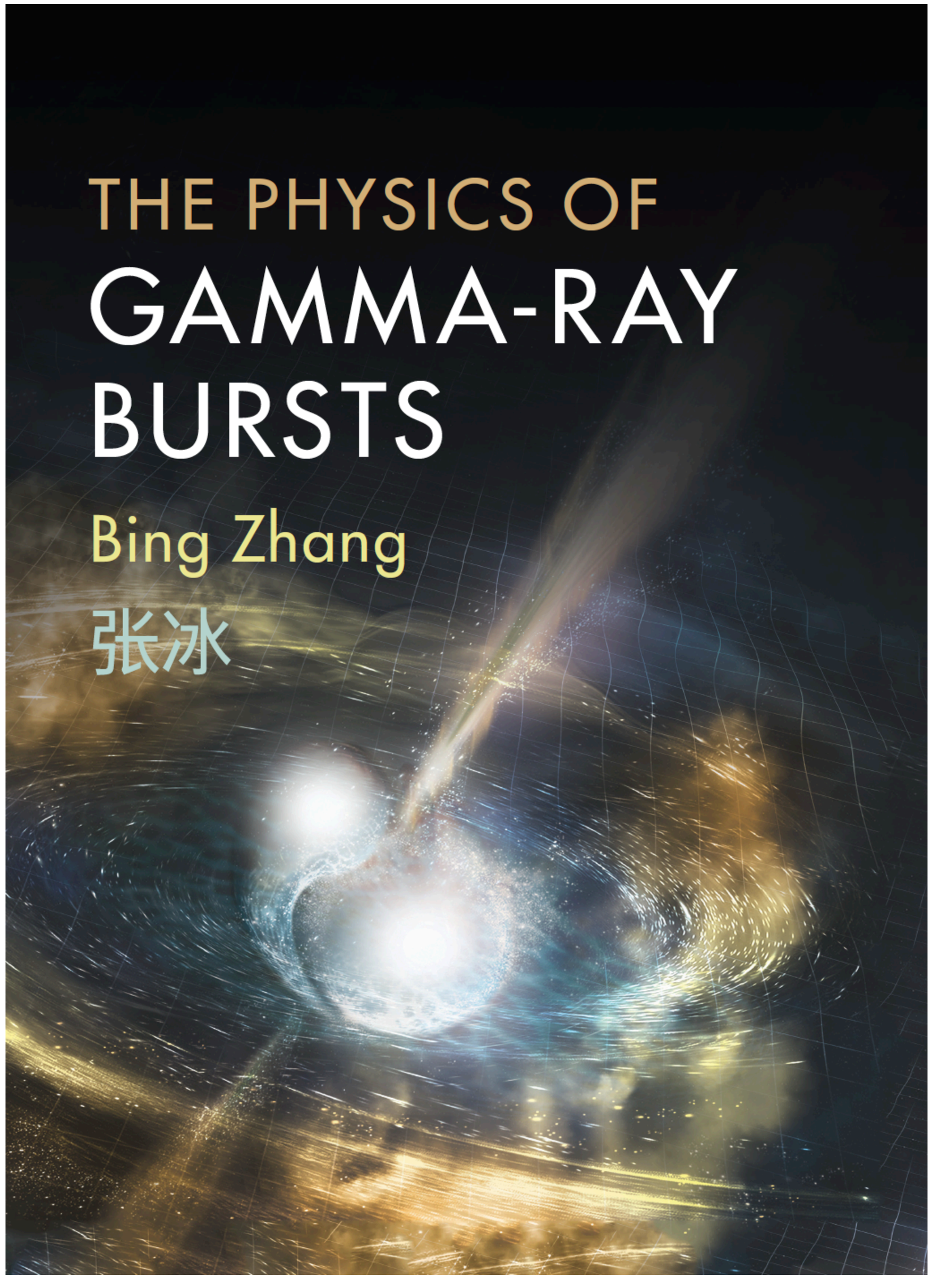
SVOM Scientific Workshop
June 23-28, Xichang, China

# The Physics of Gamma-Ray Bursts



# Open Questions in GRB Physics

- Progenitors & classification (massive stars vs. compact stars; others? how many physically distinct types?)
- Central engine (black hole, magnetar?)
- Ejecta composition (baryonic, leptonic, magnetic?)
- Energy dissipation mechanism (shock vs. magnetic reconnection)
- Particle acceleration & radiation mechanisms (synchrotron, inverse Compton, quasi-thermal)
- Afterglow physics (medium interaction vs. long-term engine activity)

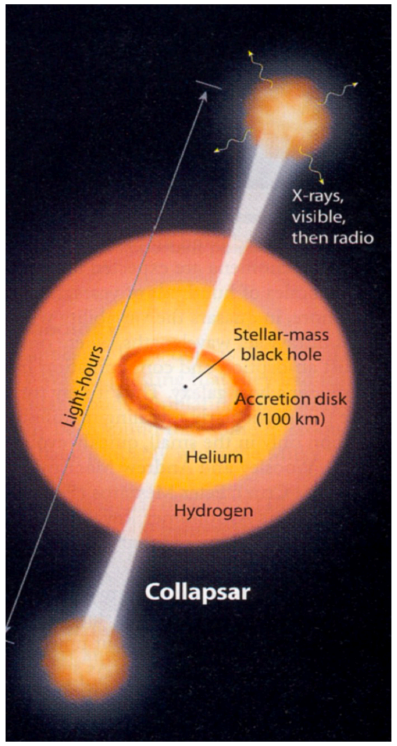


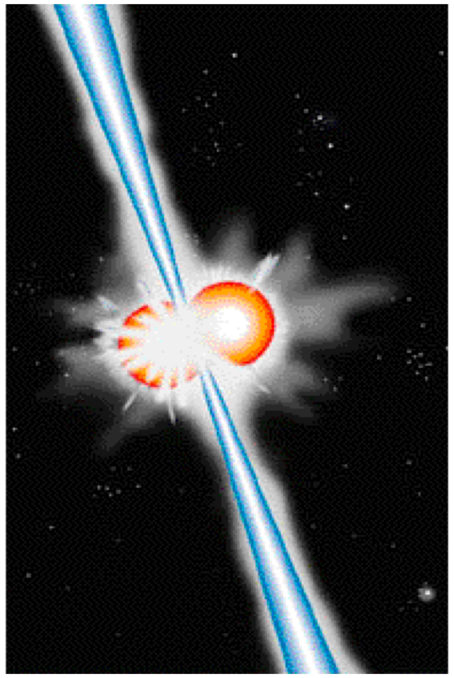

https://www.physics.unlv.edu/~bzhang/erratum.html

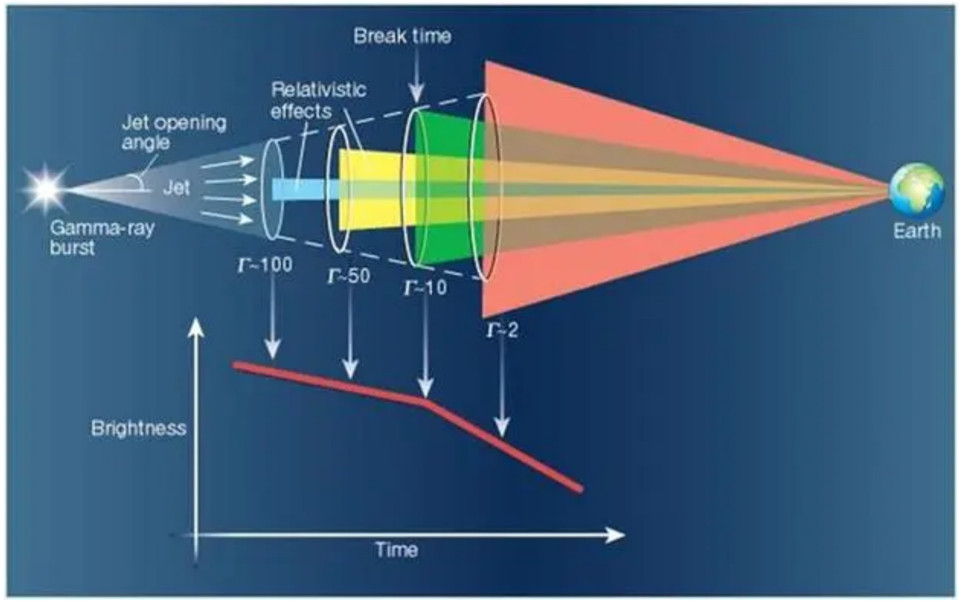
# What do we know about GRBs?

# What do we know for certain?

- **GRBs are the most luminous explosions in the universe.**
  - Highest isotropic luminosity.
  - Catastrophic events.
- **There are at least two physically distinct types.**
  - Those associated with massive star core-collapse (supernova association)
  - Those associated with NS-NS mergers (gravitational wave association)
- **They are relativistic jets beaming toward Earth.**
  - Compactness argument, superluminal motion
  - Measurement of Lorentz factor:
    - deceleration signature
    - high-energy cutoff
    - photosphere signature …
- **They are collimated.**
  - Energy-budget argument
  - Jet break
  - Off-axis afterglow in GRB 170817A
- **The deceleration of the jet by a circumburst medium powers an afterglow due to the synchrotron radiation and inverse Compton scattering of relativistic particles. (LHAASO, talks by Wang, Daigne & Liang)**



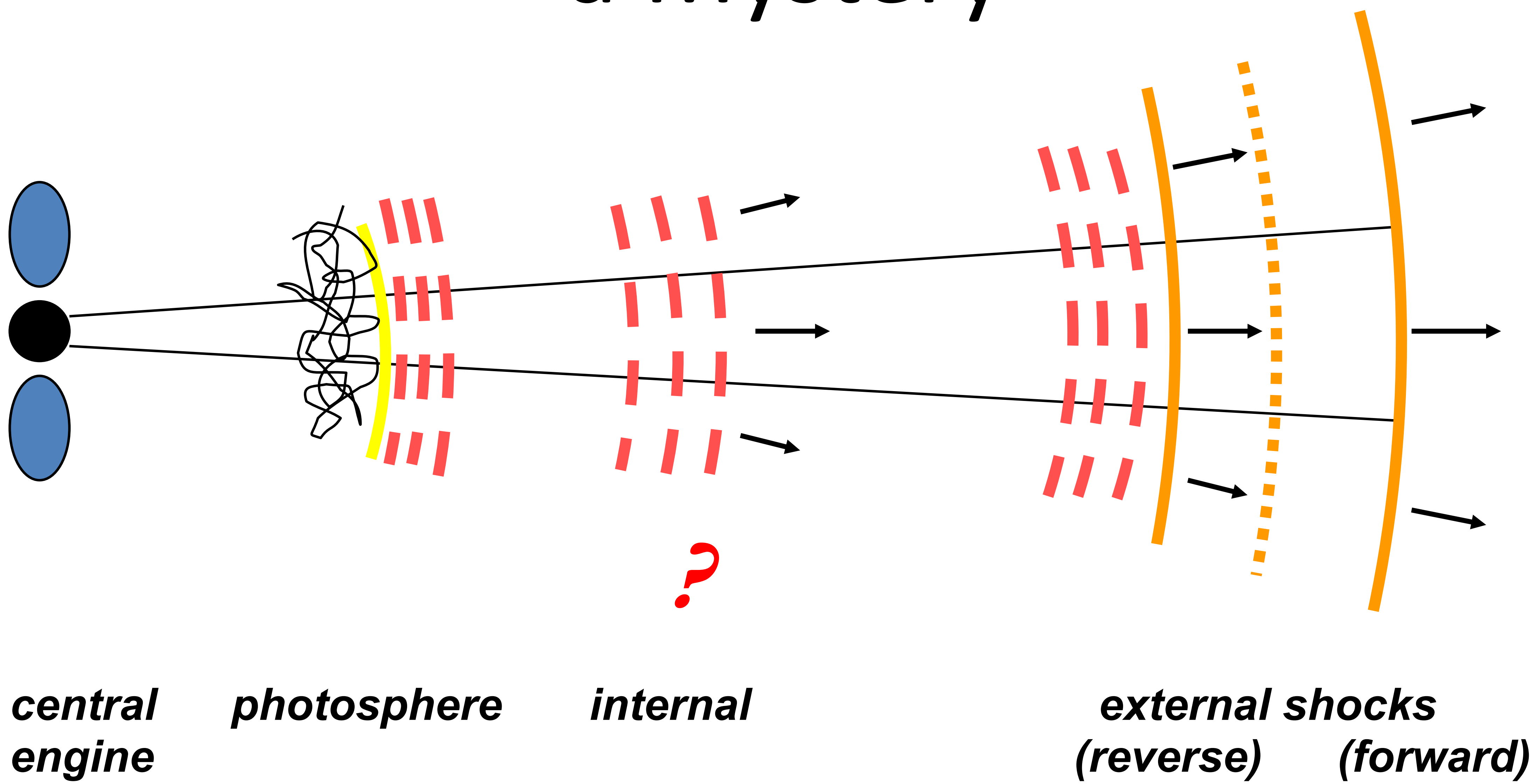





# What do we “sort of” know about GRBs?

# Jet Composition
# Energy Dissipation Mechanisms
# Radiation 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 ($\eta$, $\sigma_0$)

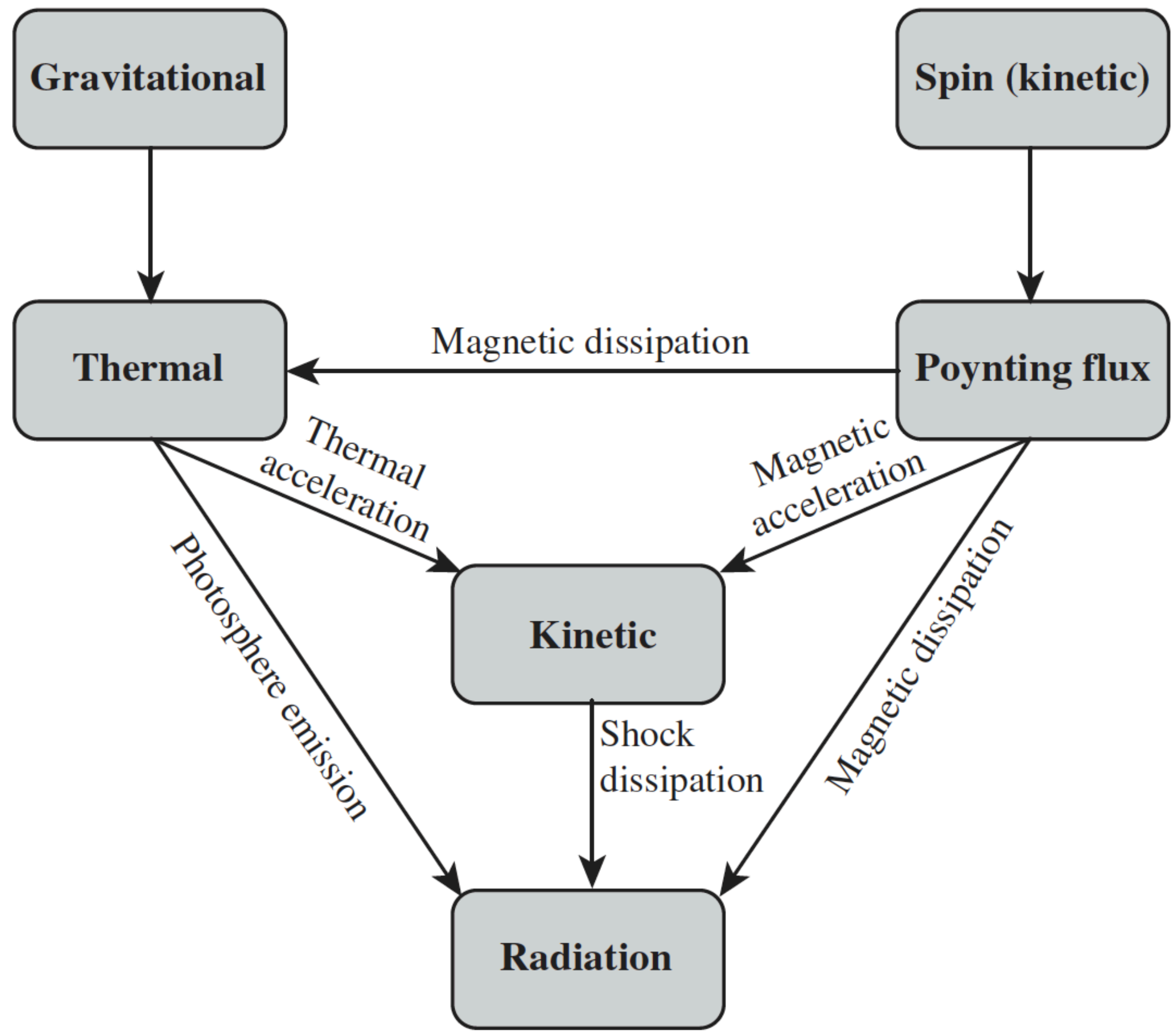
- Energy per baryon >> 1
- Energy in three forms
  - Thermal: $\eta$, $\Theta$
  - Magnetic: $\sigma$
  - Kinetic: $\Gamma$

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

Neglect radiation loss, one has

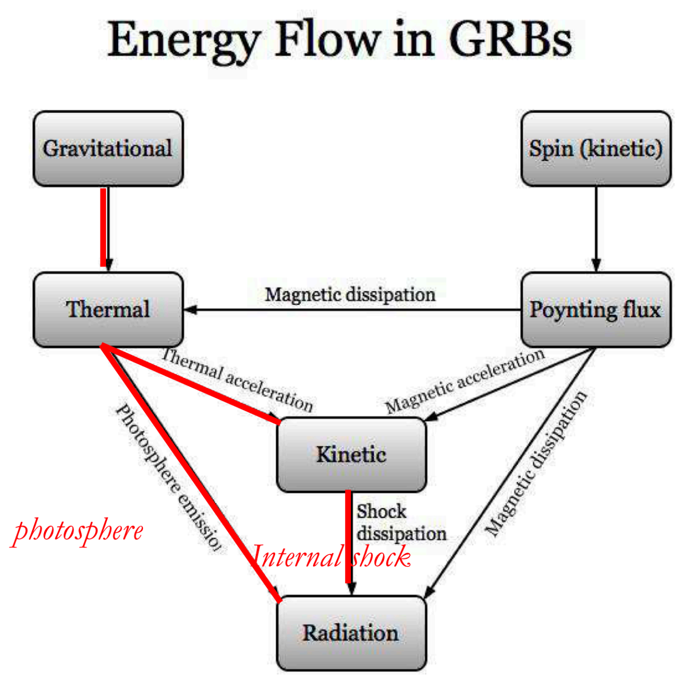
$$\mu_0 = \eta(1+\sigma_0) = \Gamma\Theta(1+\sigma).$$

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

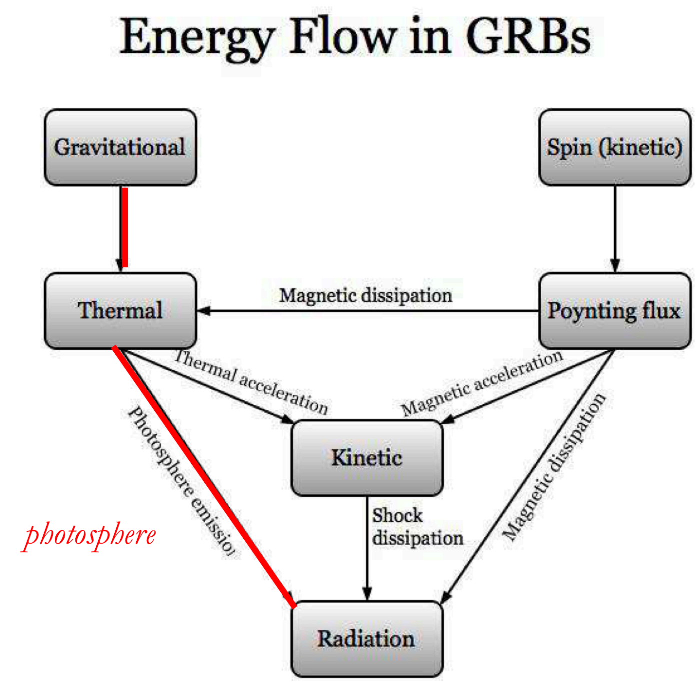



Zhang, 2018, The Physics of Gamma-Ray Bursts

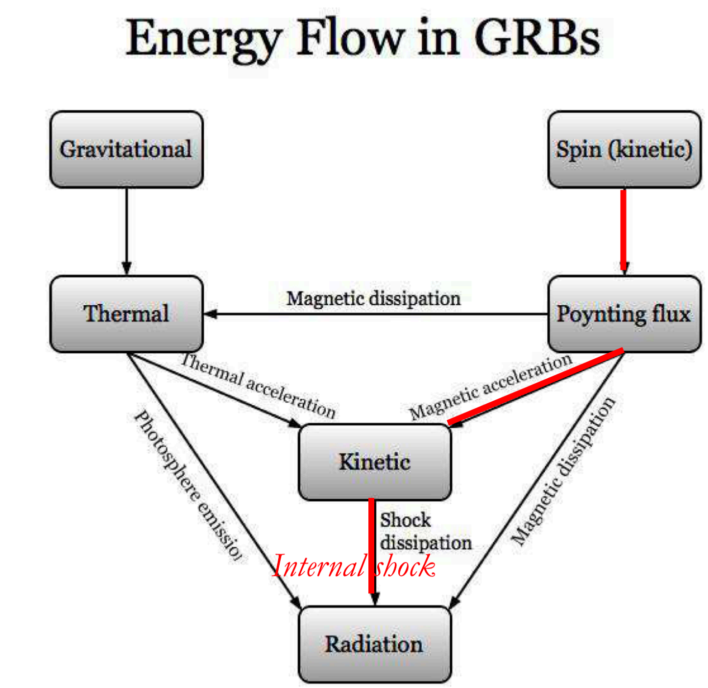
# Various prompt emission models



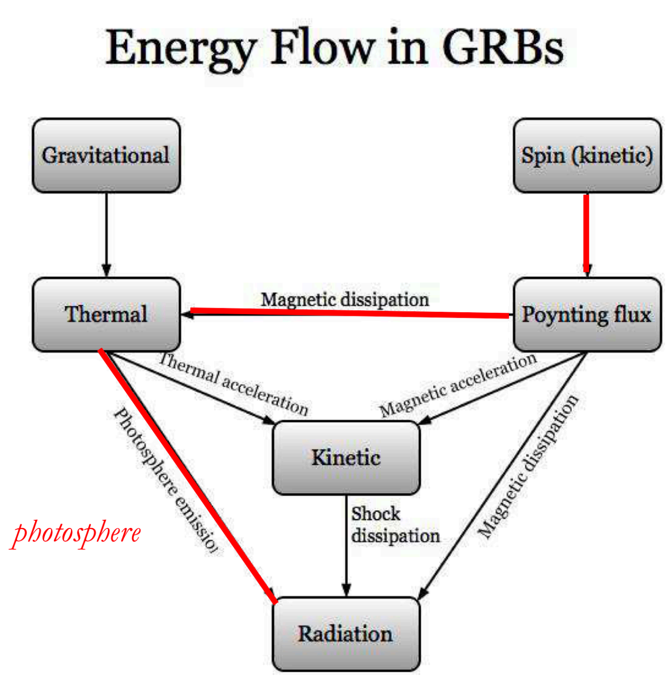

*Fireball model*



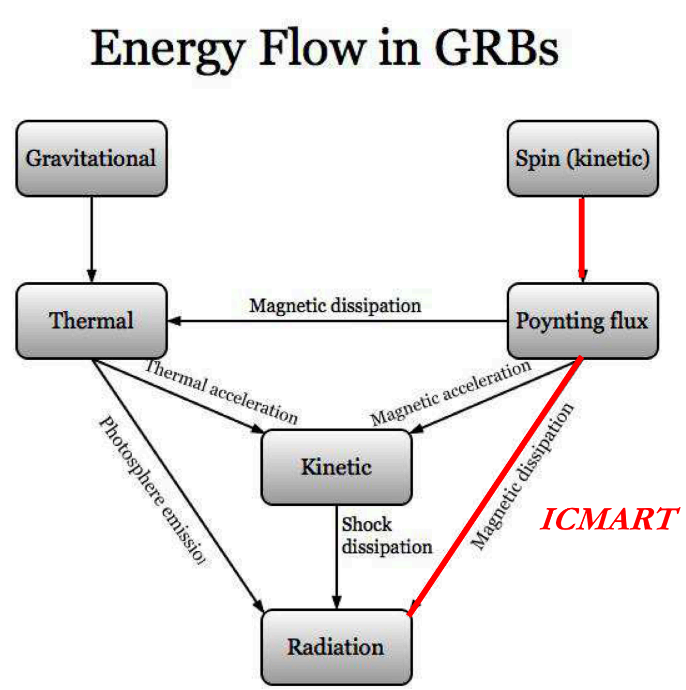

*Dissipative photosphere model*



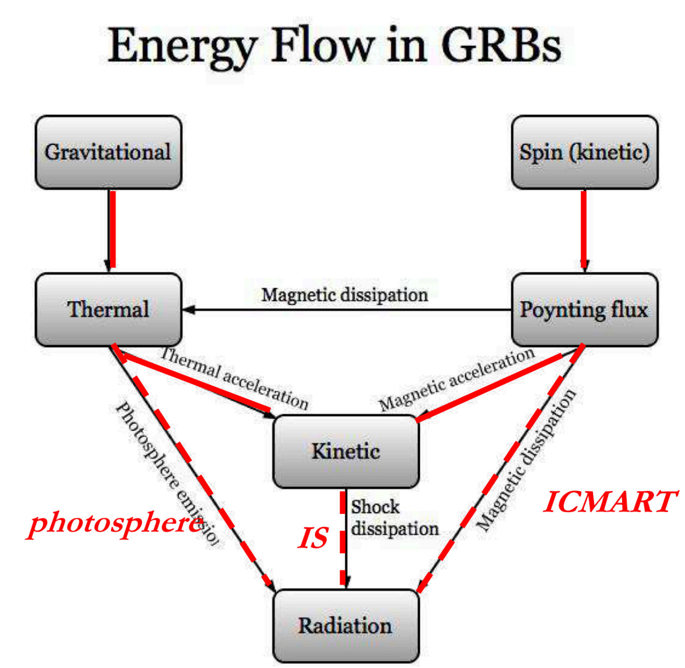

*Initially magnetized internal shock model*




*Magnetically dissipative photosphere model*




*ICMART model*

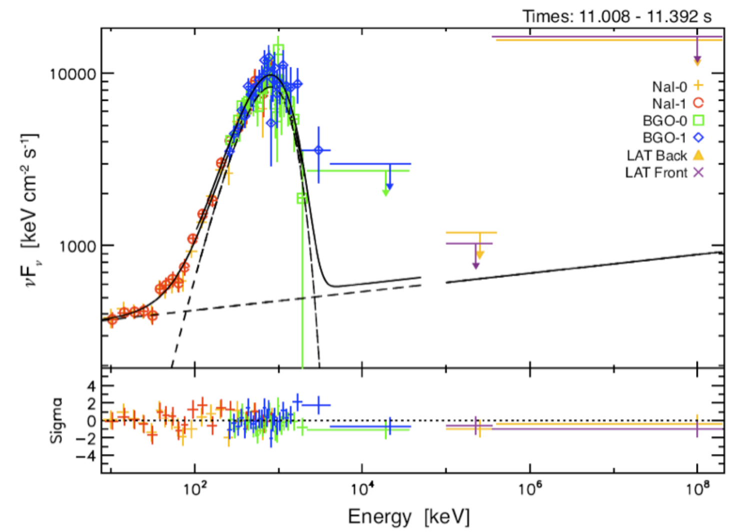



*Hybrid models*

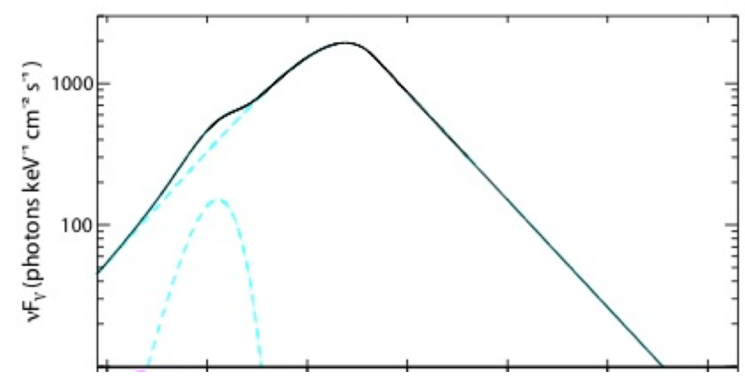
# Big Picture: GRB jet composition

- GRB jets have diverse compositions:
  - Photosphere dominated (GRB 090902B), rare
  - Intermediate bursts (weak but not fully suppressed photosphere, GRB 100724B, 110721A)
  - Photosphere suppressed, Poynting flux dominated (GRB 080916C)

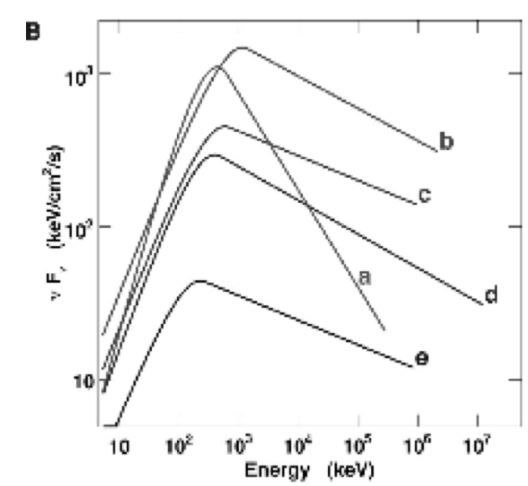
Most GRBs have significant magnetization




*GRB 090902B*




*GRB 110721A*

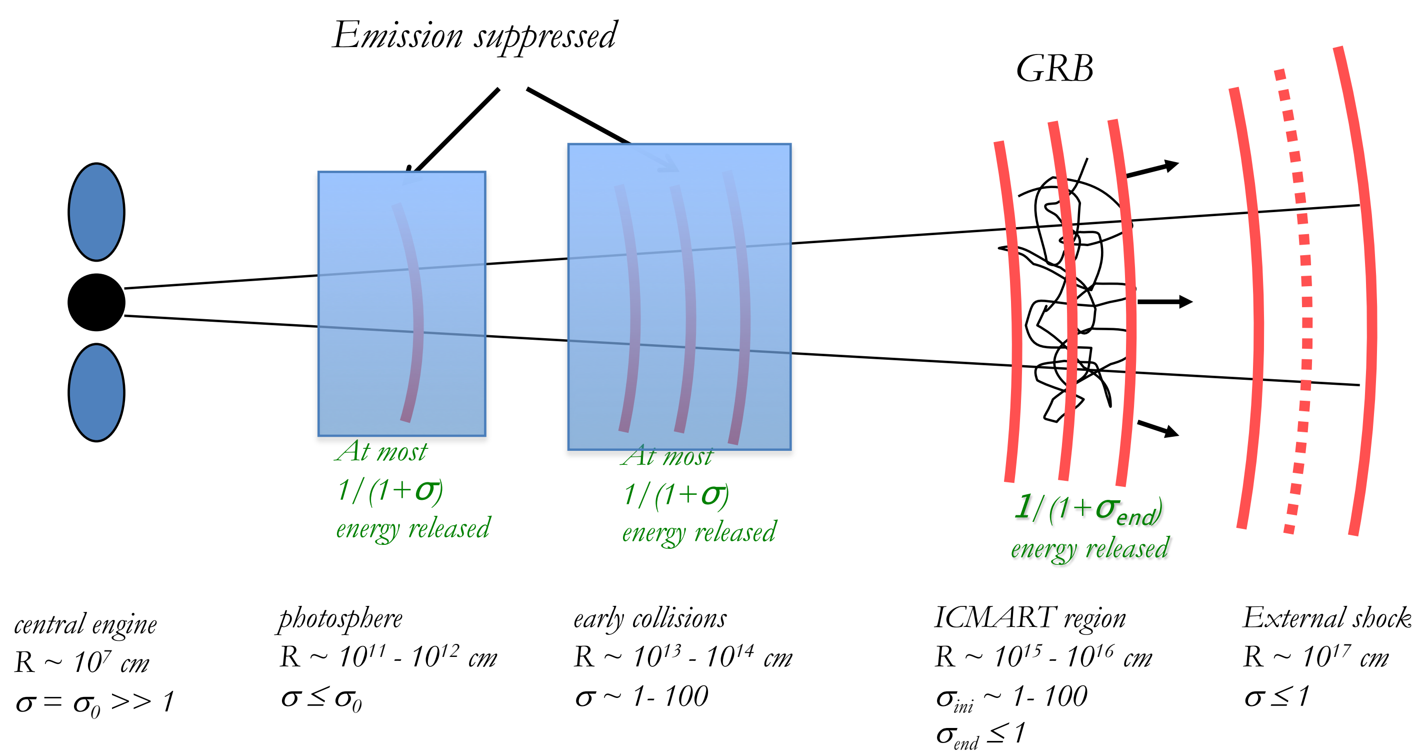


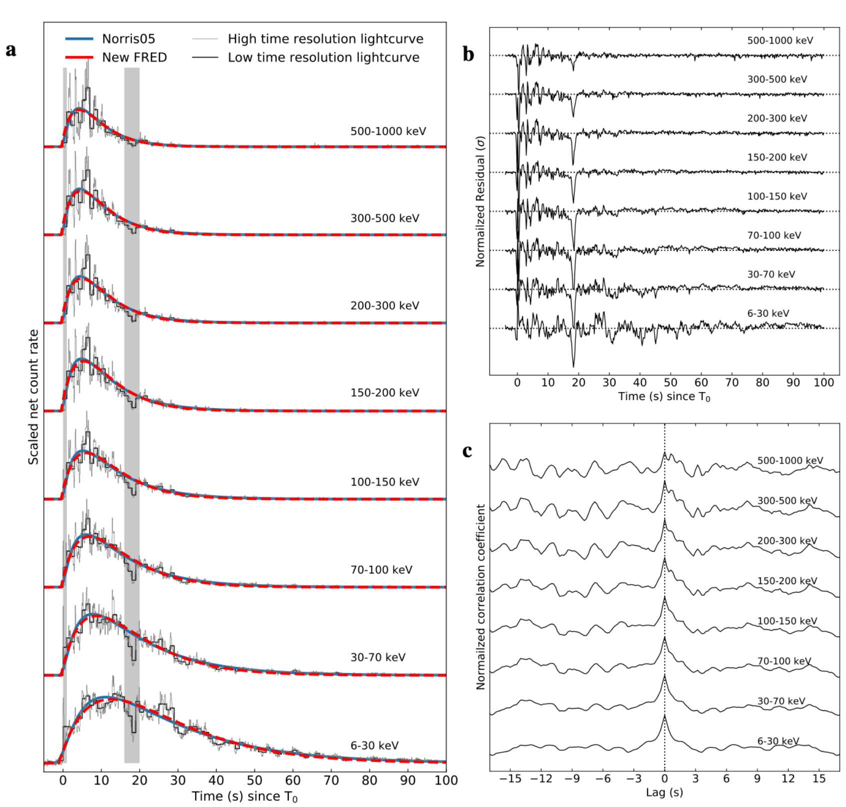

*GRB 080916C*

# The ICMART Model

(Internal Collision-induced MAgnetic Reconnection & Turbulence)

*Zhang & Yan (2011)*



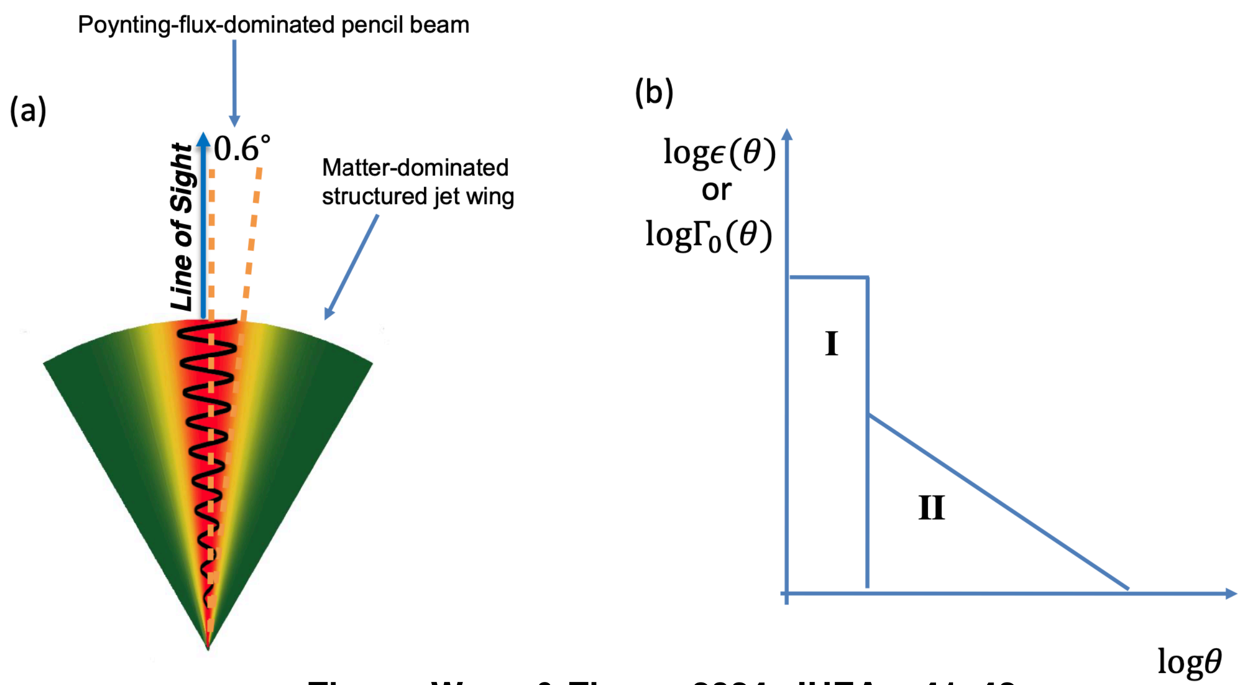

**Yi et al., 2023, arXiv:2310.07205**

## ICMART Predictions

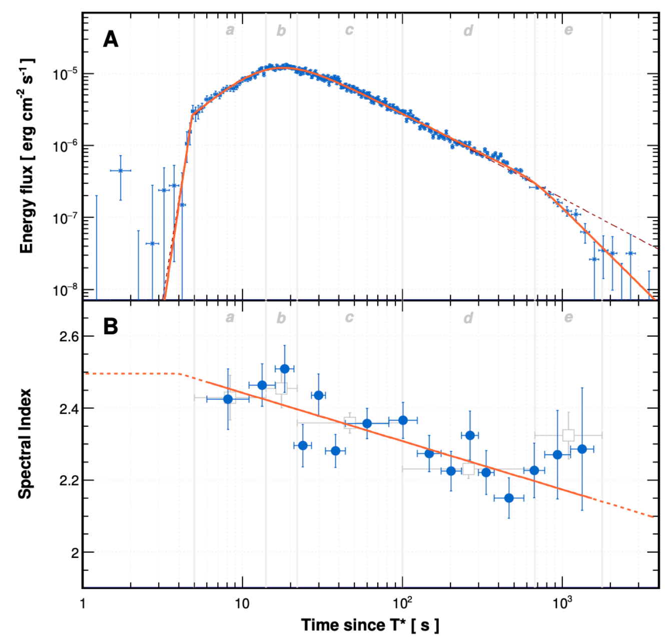
- No-thermal component
- Spectral lag & Ep evolution
- **Two-component variability**
- High-latitude emission
- Neutrino non-detection
- Polarized gamma-rays
- Polarized early optical

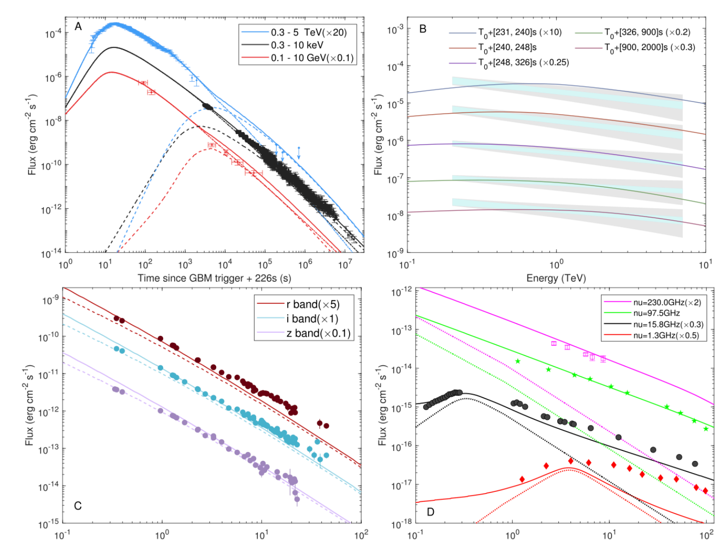
# Hybrid compositions in the BOAT GRB 221009A

- **Poynting-flux-dominated pencil beam**
  - No thermal prompt emission
  - No TeV prompt emission
  - No reverse shock emission associated with the narrow jet
  - No neutrino detection
  - Clear jet break on TeV lightcurve
  - $\Gamma \theta_j \sim \mathrm{a\ few}$
- **Matter-dominated structured jet wing**
  - Broad-band afterglow requires a structured jet
  - Early radio emission requires reverse shock emission
  - Thermal component during the quiescent phase of prompt emission
  - TeV spectral hardening




**Zhang, Wang & Zheng, 2024, JHEAp, 41, 42**




**LHAASO Collaboration, 2023, Science, 380, 1390** **Zheng et al. 2024, ApJ, 966, 141**

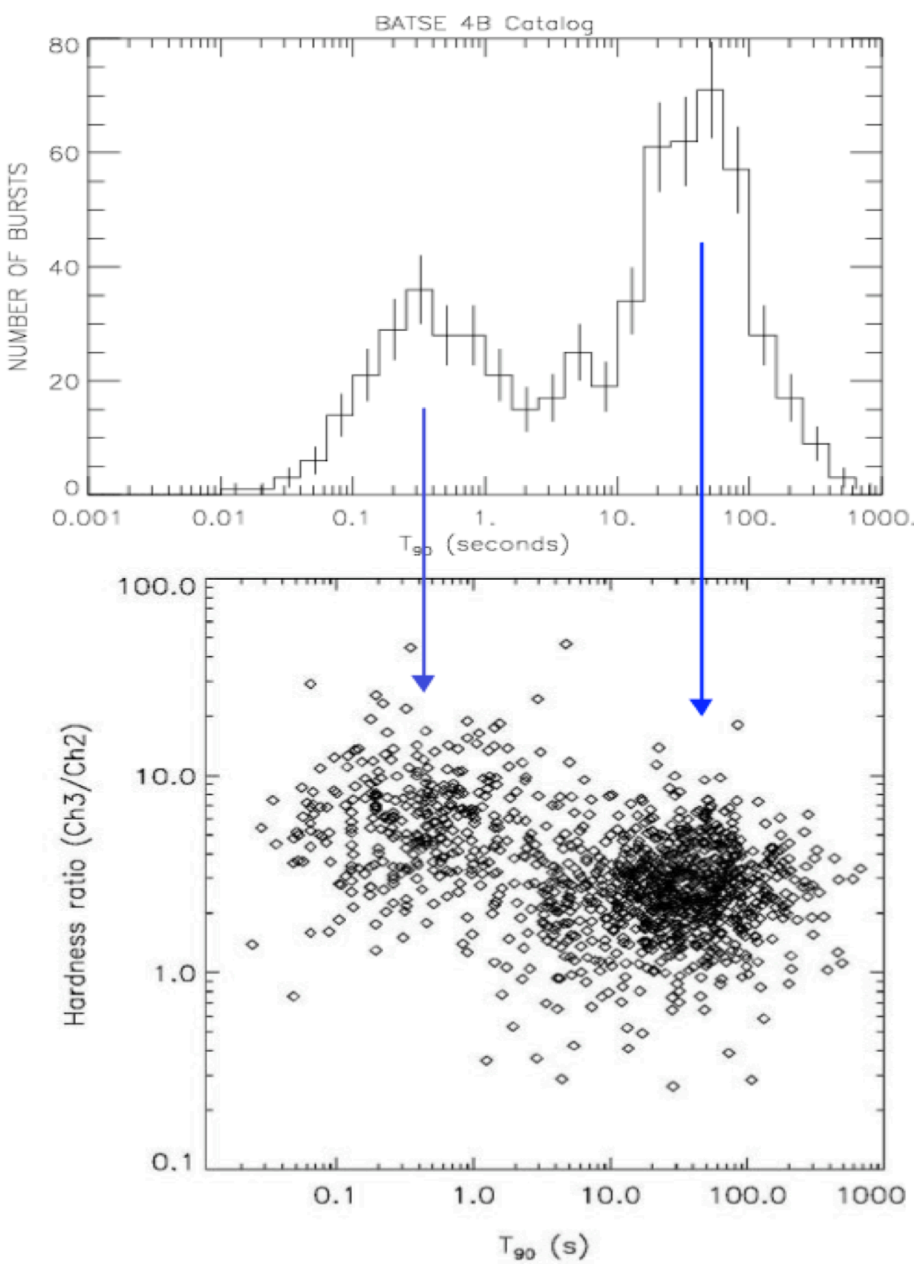
**See also Laskar et al. 2023; O'Connor et al. 2023; Gill & Granot 2023**

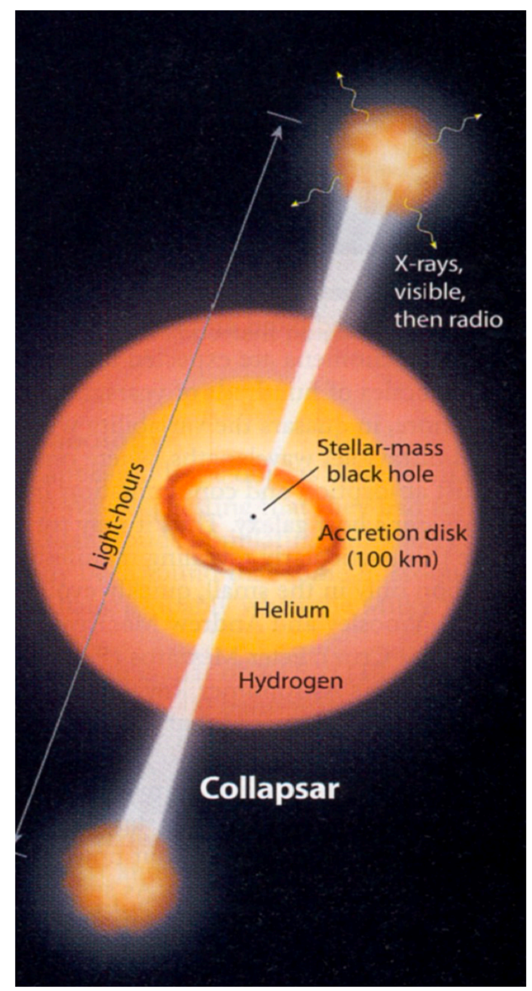
**See also Xiangyu Wang's talk**

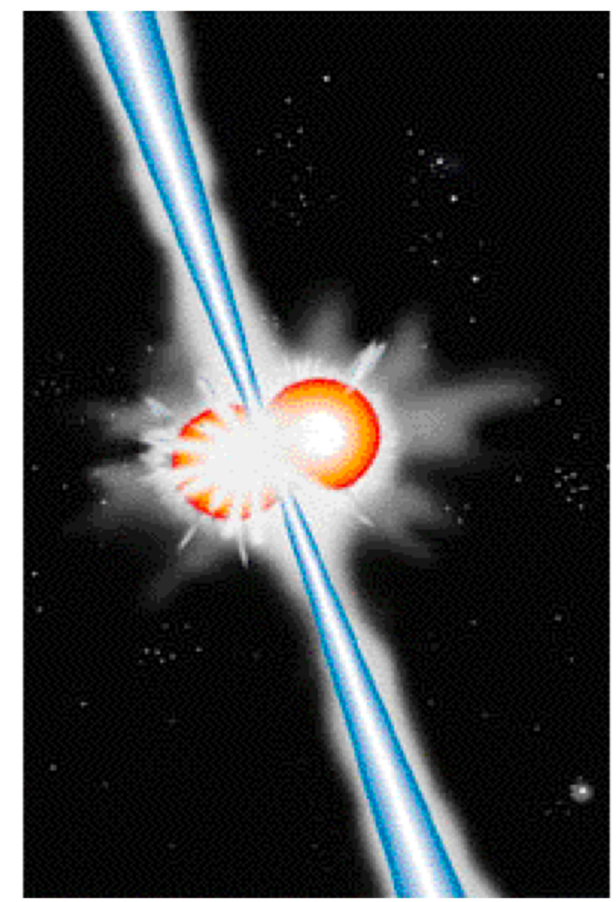
# Classification

# Progenitor Systems

# Long vs. Short
# Massive star (collapsar) GRBs (Type II)
# vs. Compact Star (merger) GRBs (Type I)



ASTROPHYSICS

# A burst of new ideas

Bing Zhang

**Gigantic cosmological γ-ray bursts have fallen into a dichotomy of long and short bursts, each with a very different origin. The discovery of an oddball burst calls for a rethink of that classification.**

| | Type Ia | Type II (Type Ib/c) |
|---|---|---|
| Stellar population | Old | Young |
| Host galaxy | All types of galaxy | Late-type galaxies |
| Progenitor | Binary systems (accretion-induced collapse of white dwarfs) | Single-star systems (core collapse of massive stars) |

**Figure 1 | The classification of supernovae[18].**

| | Type I (short–hard) | Type II (long–soft) |
|---|---|---|
| Duration | Usually short (may have a long tail?) | Usually long |
| Spectrum | Usually hard (tail is soft) | Usually soft |
| Spectral lag | Short | Long |
| Associated supernova | No | Yes |
| Stellar population | Old | Young |
| Host galaxy | All types of galaxies (predominantly in regions of low star formation rate) | Late-type galaxies (predominantly in irregular, dwarf galaxies) |
| Location in the host galaxy | Outskirts | Central |
| Progenitor | Mergers of compact objects in binary systems? | Single-star systems? (Core collapse of massive stars) |

**Figure 2 | A classification scheme for γ-ray bursts.** The red rows show the analogy with the supernova classification scheme. Blue cells show the properties of GRB 060614 (refs 7–10).

BZ, 2006, Nature, 444, 1010

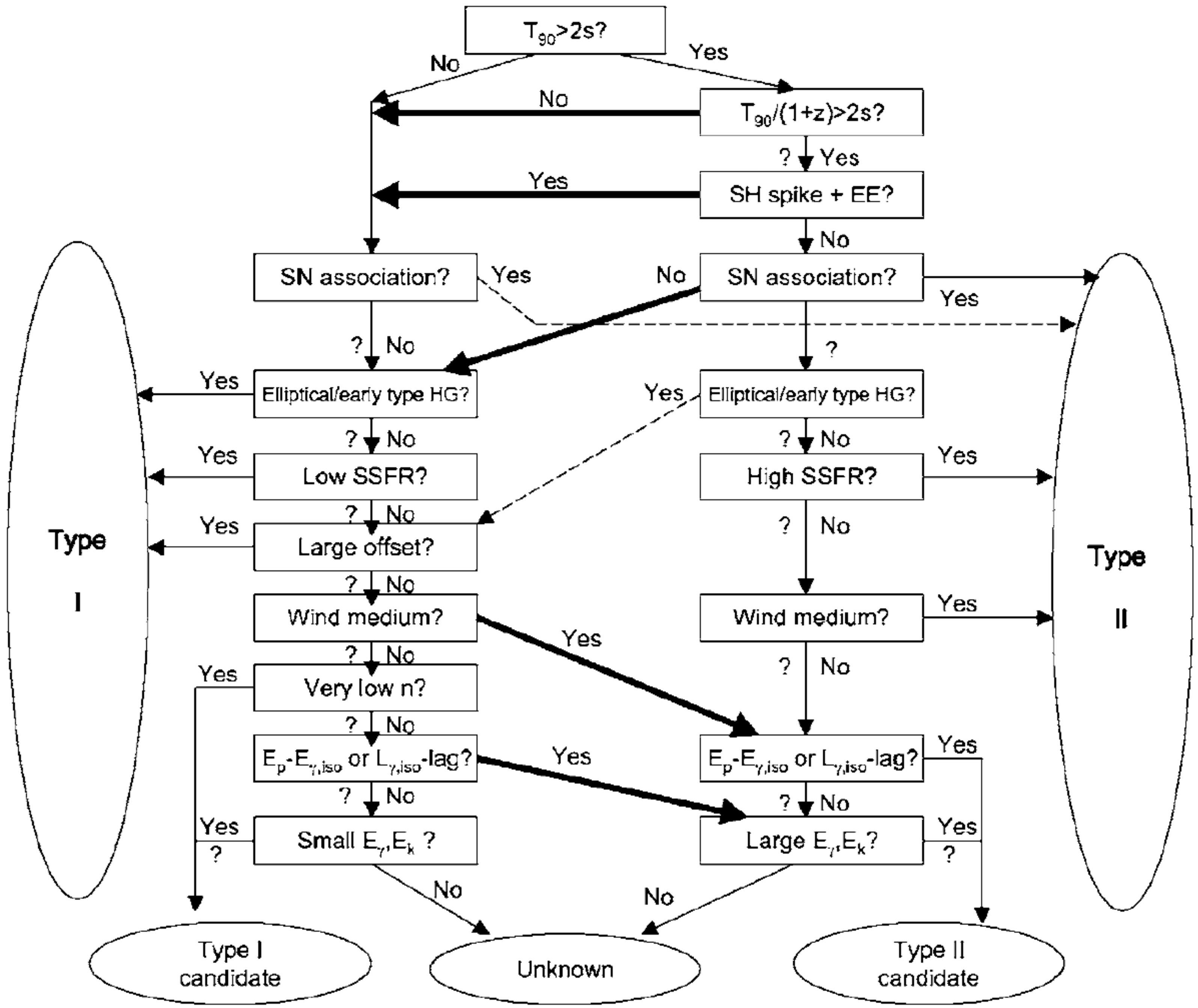
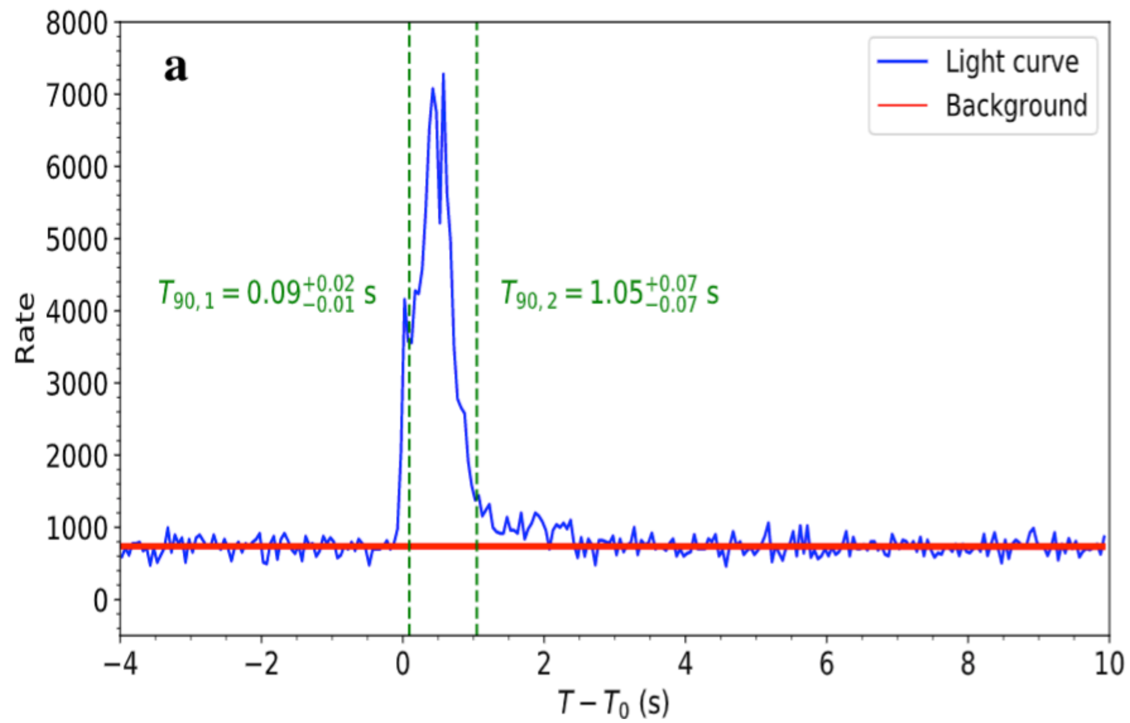
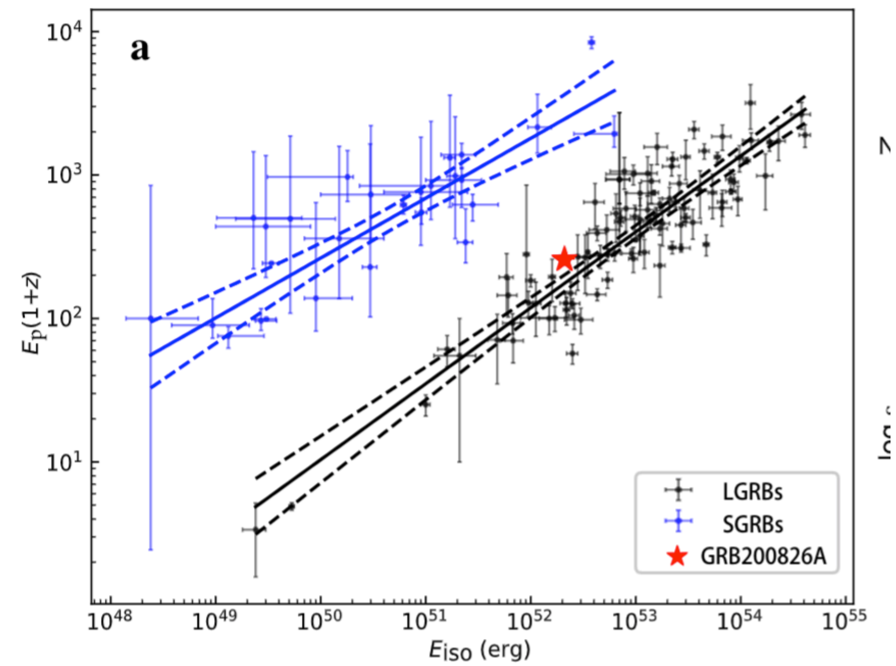


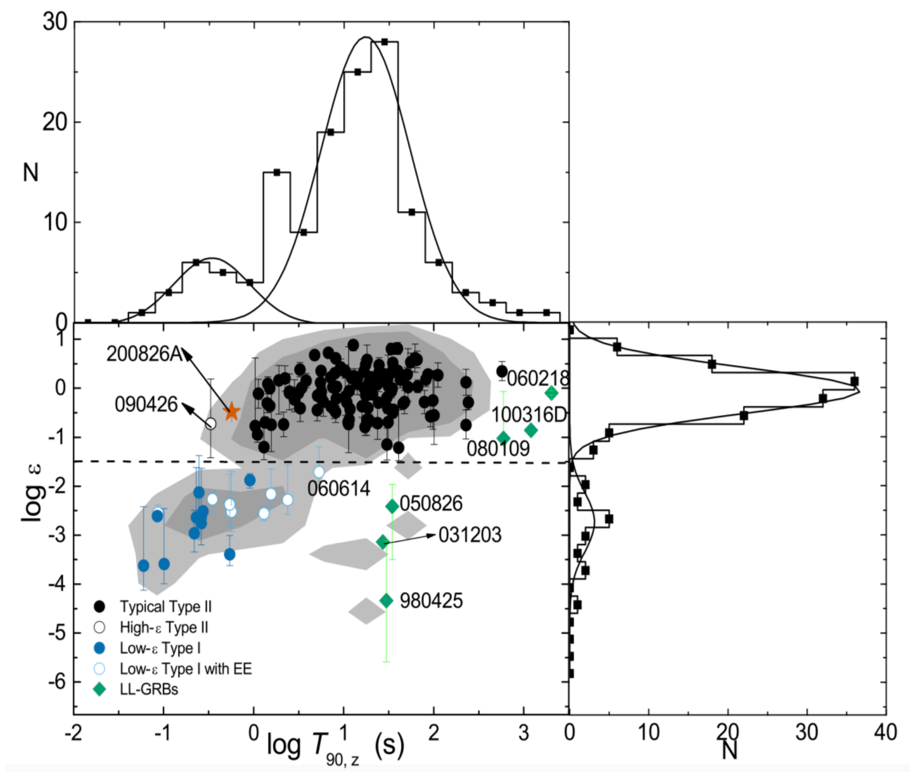

**Figure 8.** Recommended procedure to judge the association of a particular GRB to a particular physical model category. Multiple observational criteria have been applied. Question marks stand for no information being available to judge the validity of the criterion. The two dotted arrows stand for the possibilities that are in principle possible but have never been observed. Five thick arrows bridge the long-duration and short-duration GRBs, suggesting that the there can be long-duration Type I and short-duration Type II GRBs.

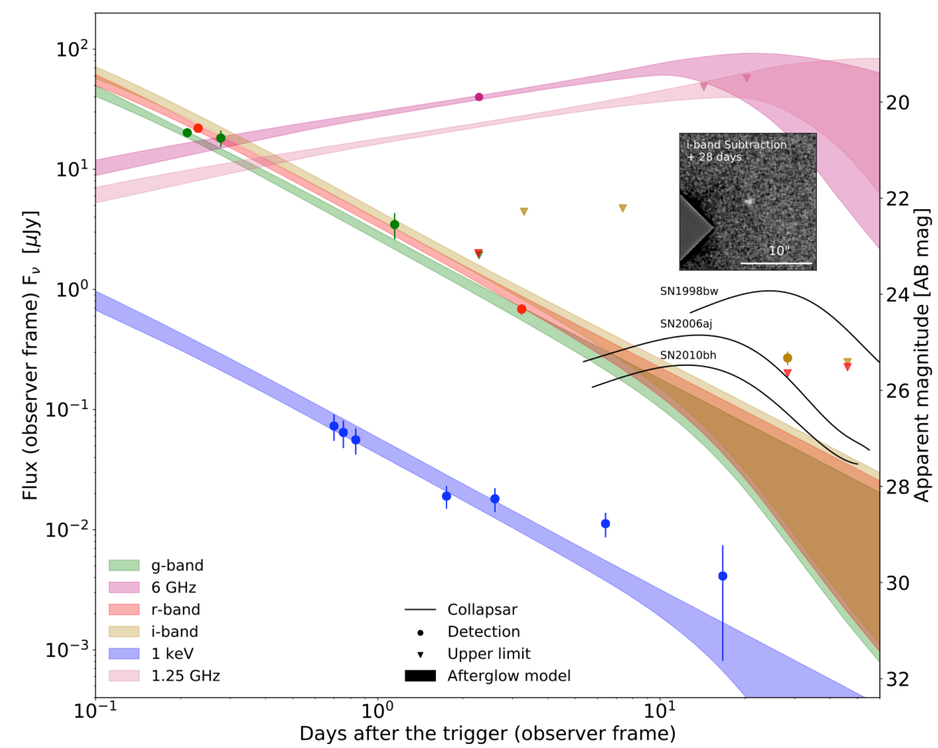
BZ et al., 2009, ApJ, 703, 1696-1724
See also Y. Li et al. 2016, 2020

# GRB 200826A: A short Type II GRB



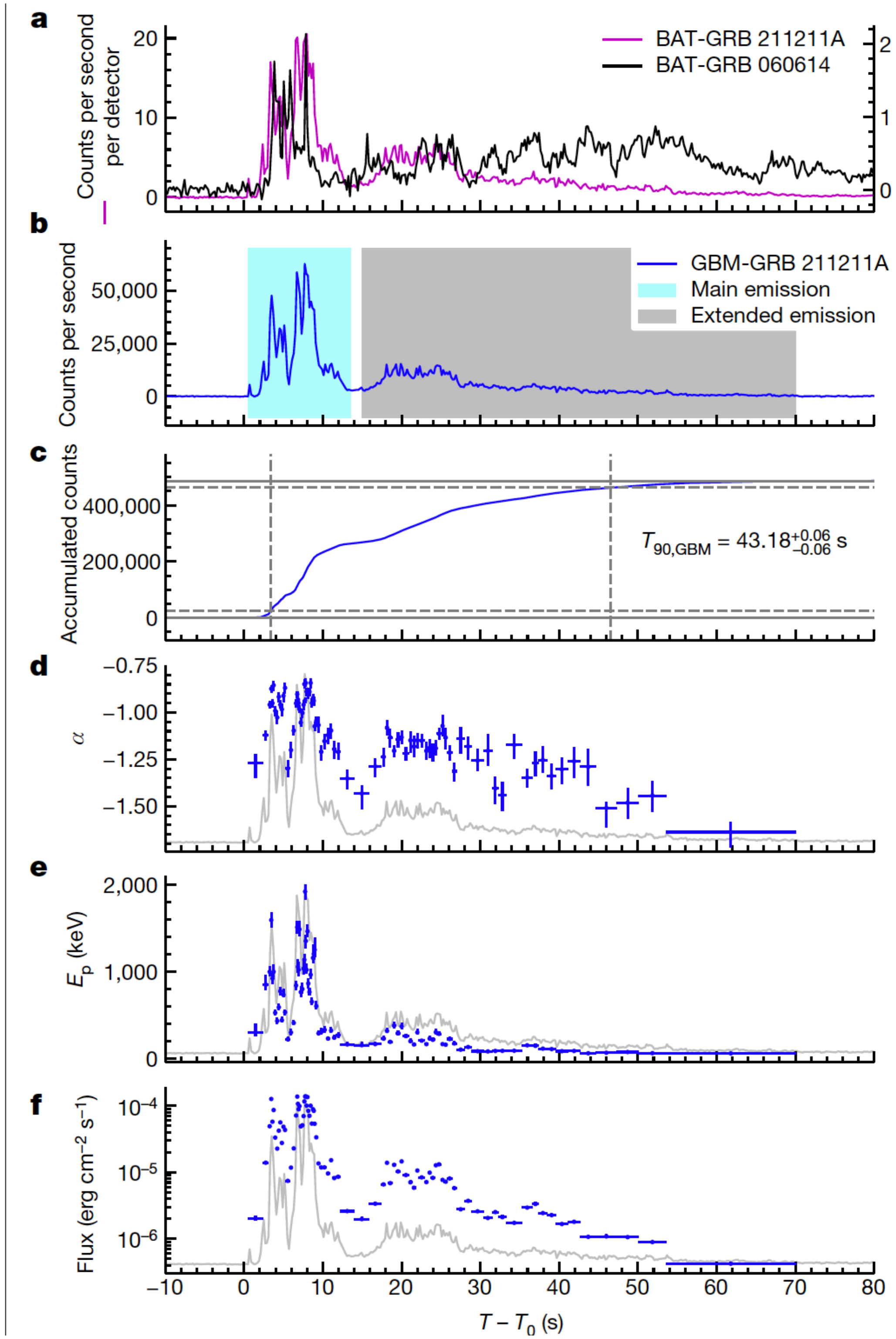



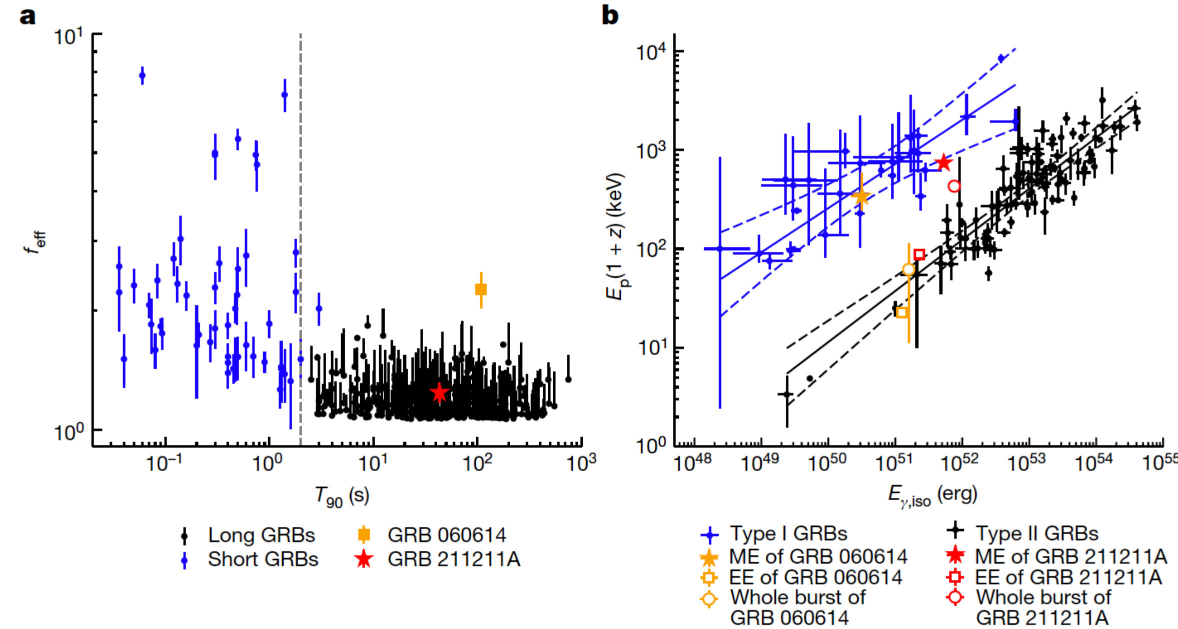



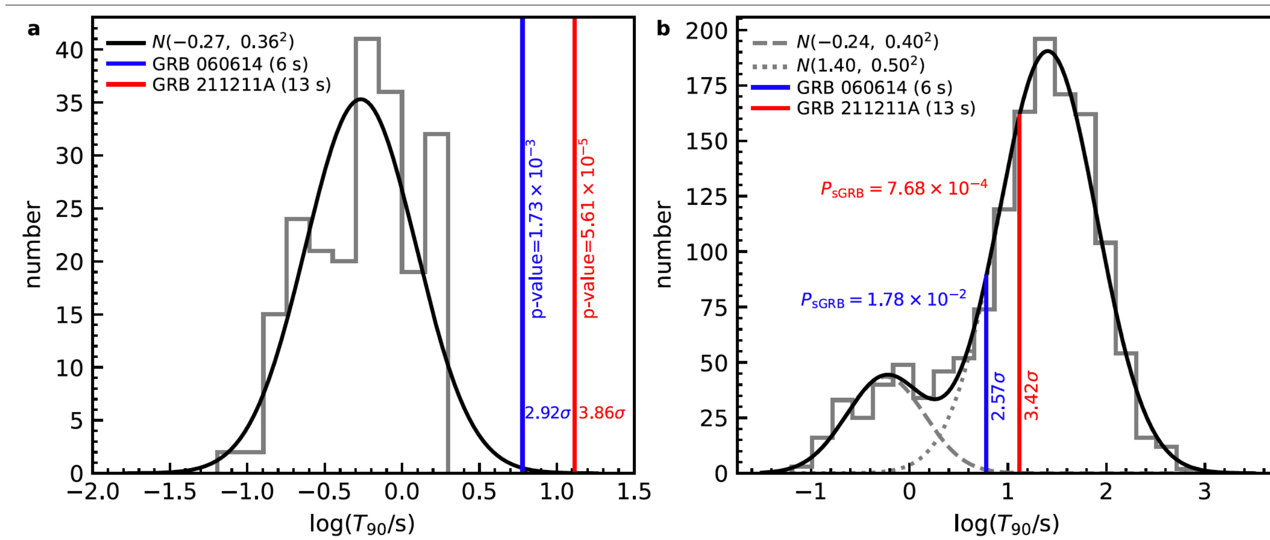




Zhang, B.-B. et al 2021, Nature Astronomy, 5, 911-916
Ahumada et al. 2021, Nature Astronomy, 5, 917-927

# GRB 211211A: A long Type I GRB

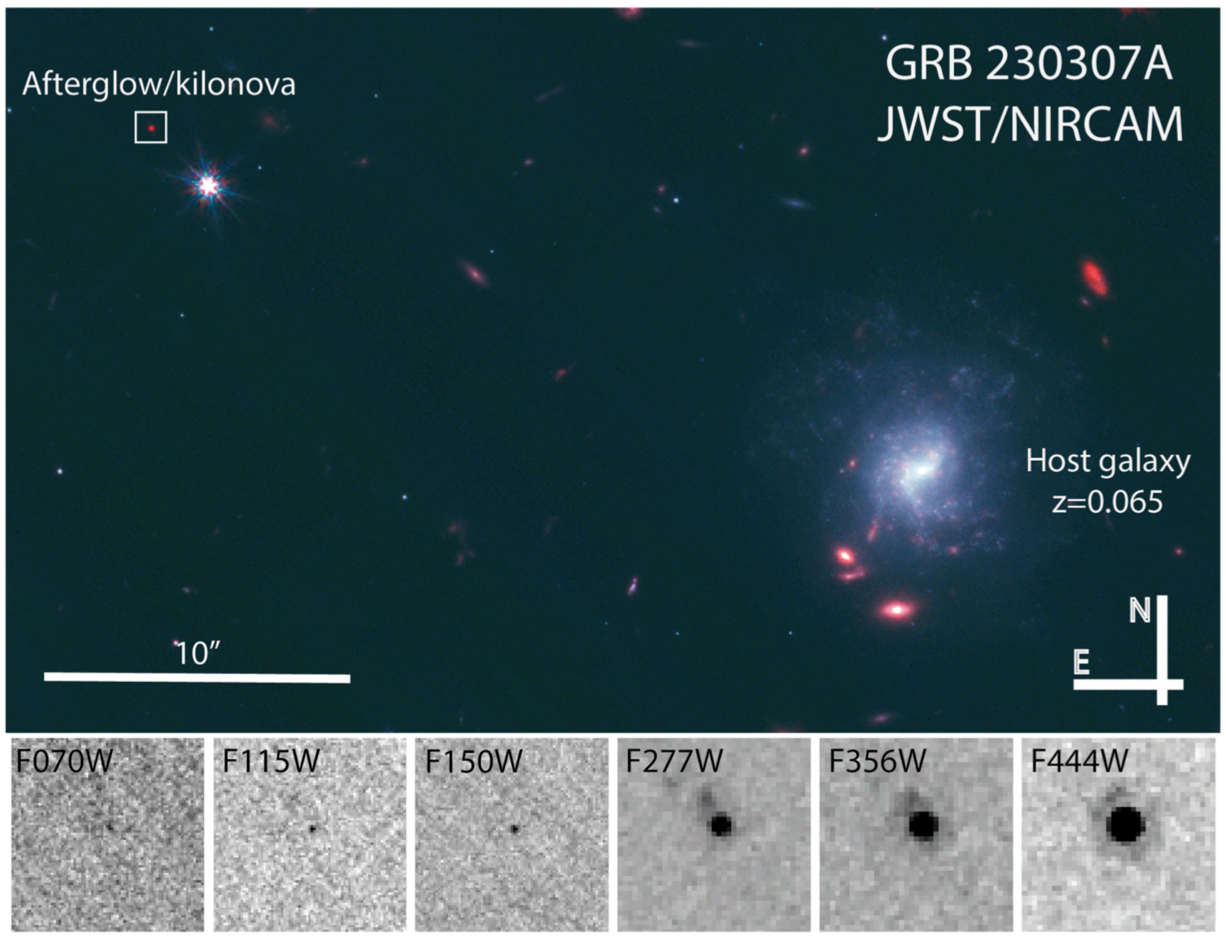


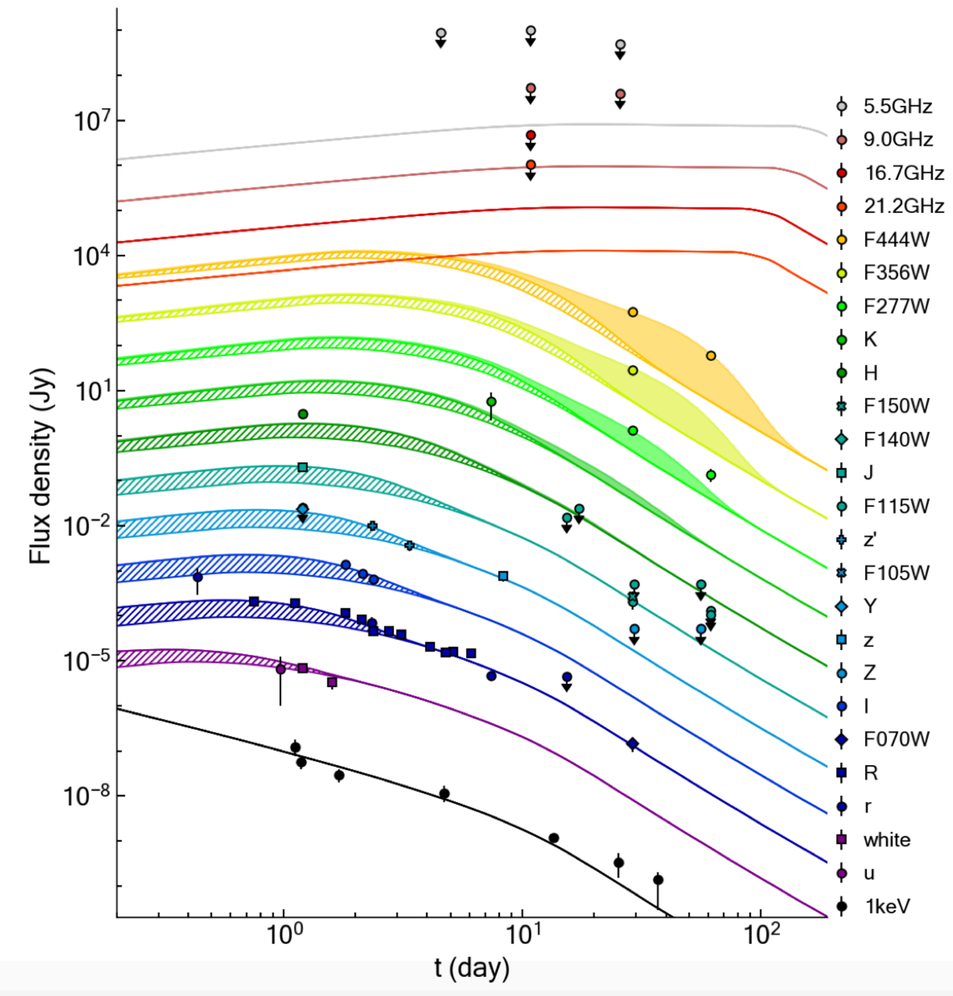




Rastinejad, et al. 2022, Nature, 612, 223-227
Troja et al. 2022, Nature, 612, 228-231
Yang, J. et al 2022, Nature, 612, 232-235
Mei et al, 2022, Nature, 612, 236-239
Gompertz et al, 2022, Nature Astronomy

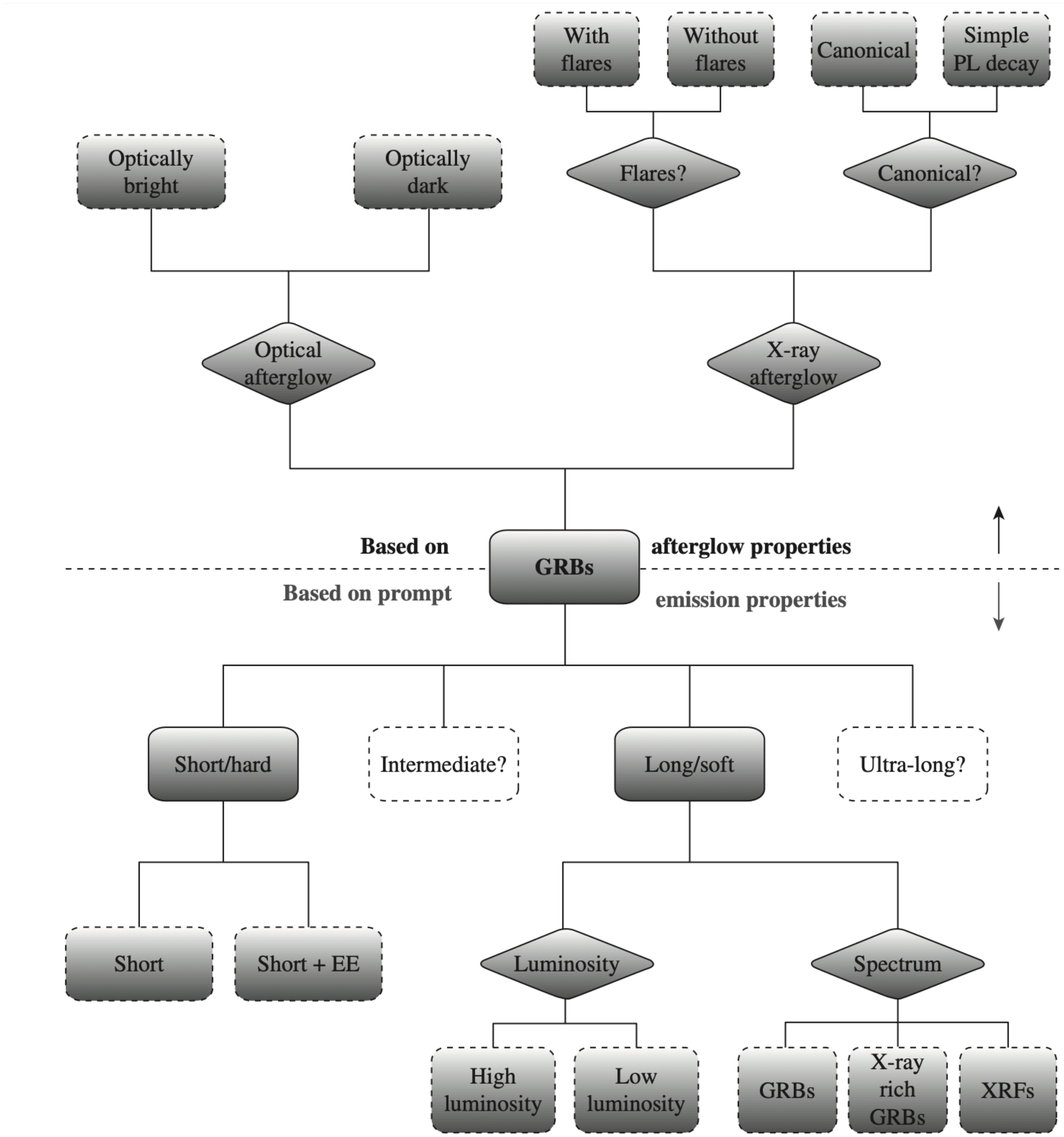
# GRB 230307A: Another long Type I GRB



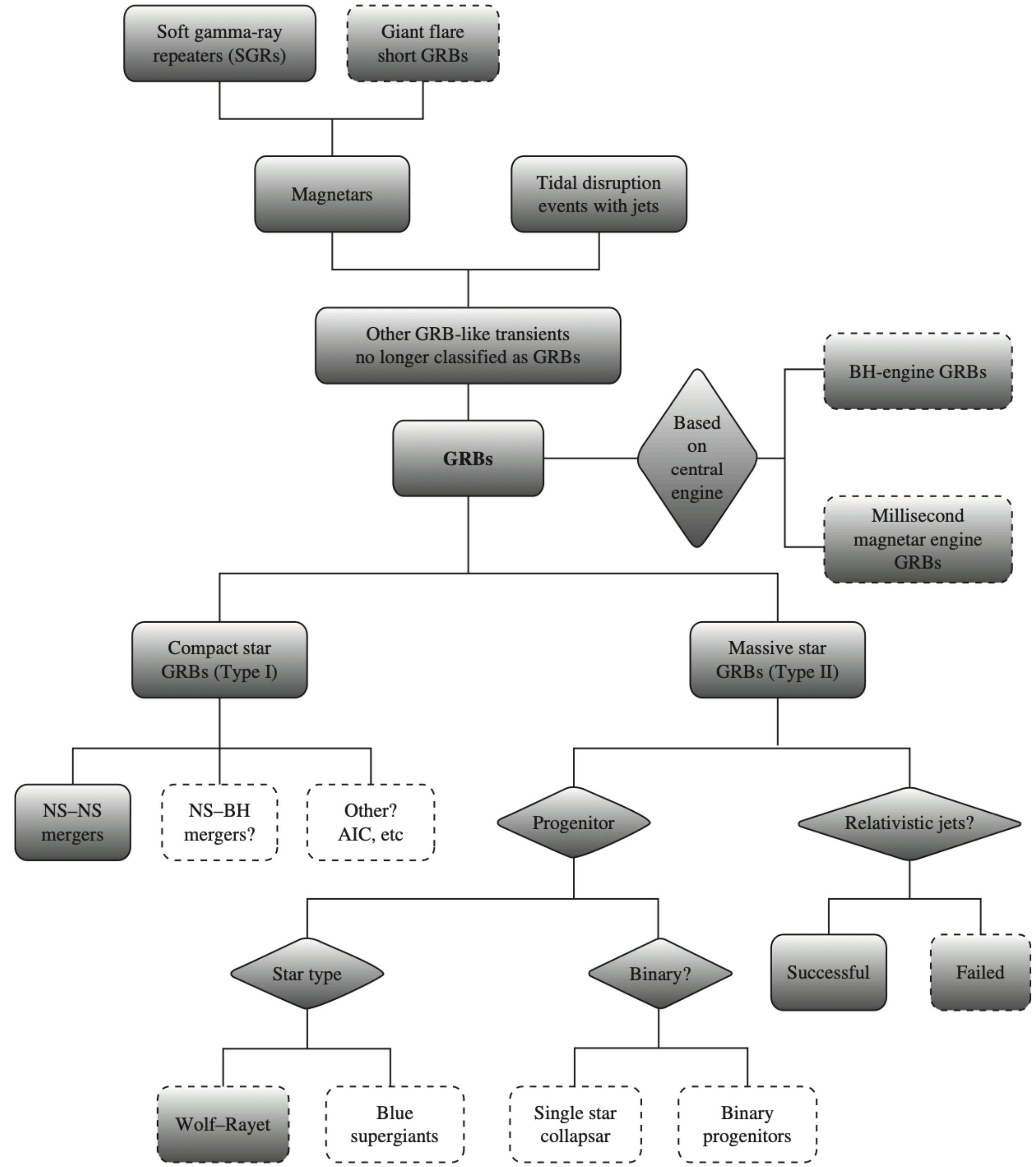




Levan et al. 2024, Nature, 612, 223-227
Yang et al. 2024, Nature, 612, 228-231
Sun et al. 2023, arXiv: 2307.05689

See also the talk by Binbin Zhang




Phenomenological classification schemes

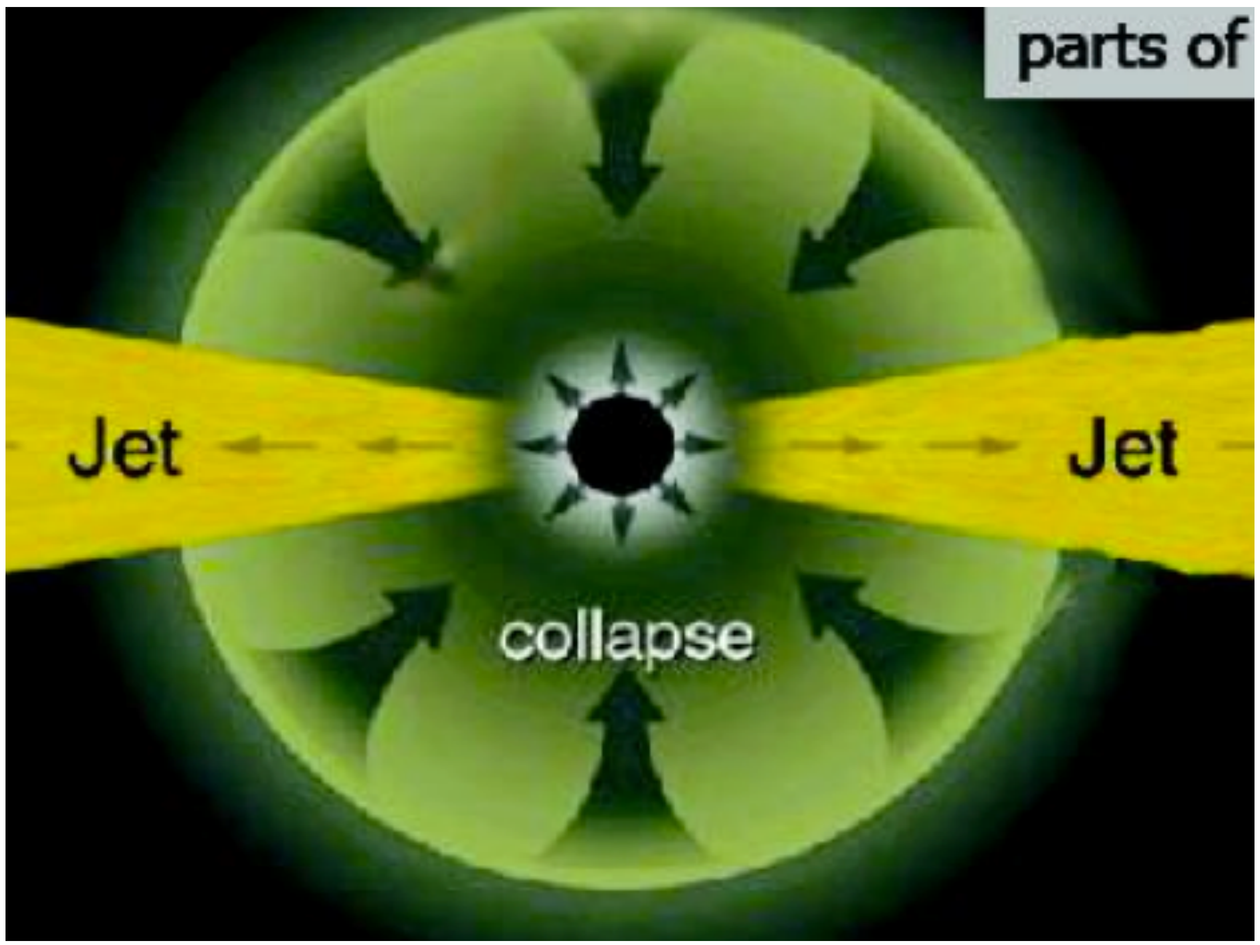



Physical classification schemes

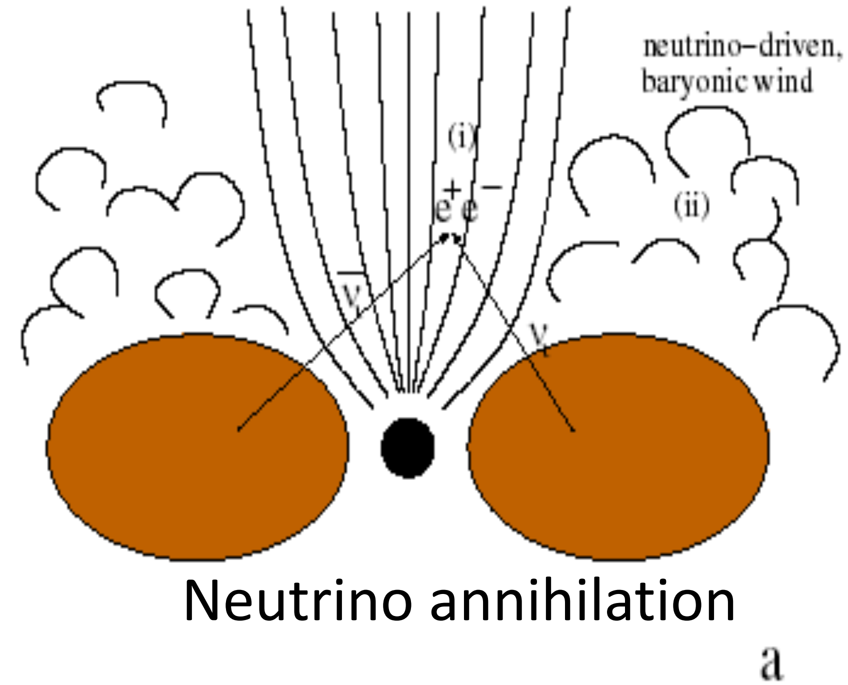
BZ, 2018, The Physics of Gamma-Ray Bursts

# Central Engine

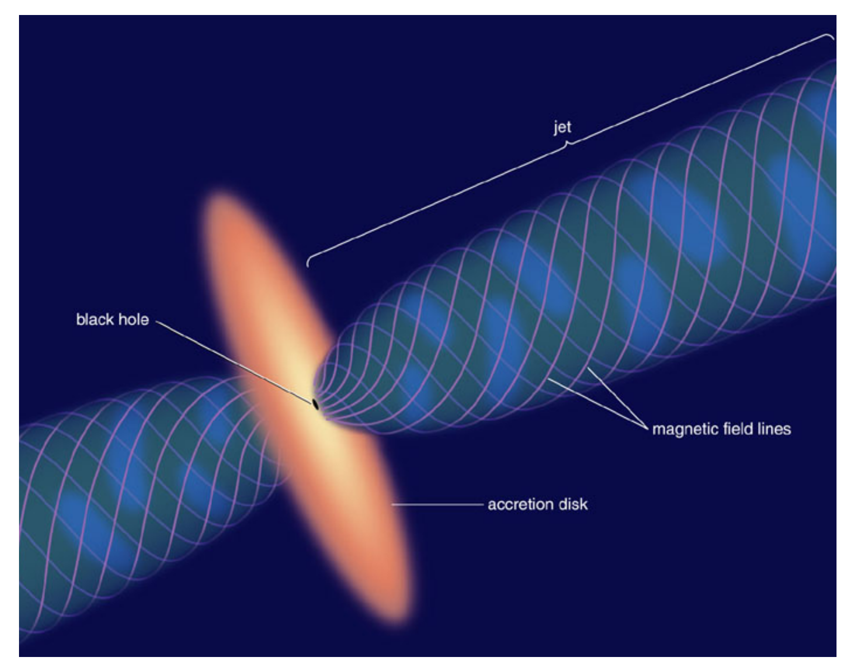
# Hyper-Accreting Black Holes




Hyper-Accreting Black Hole

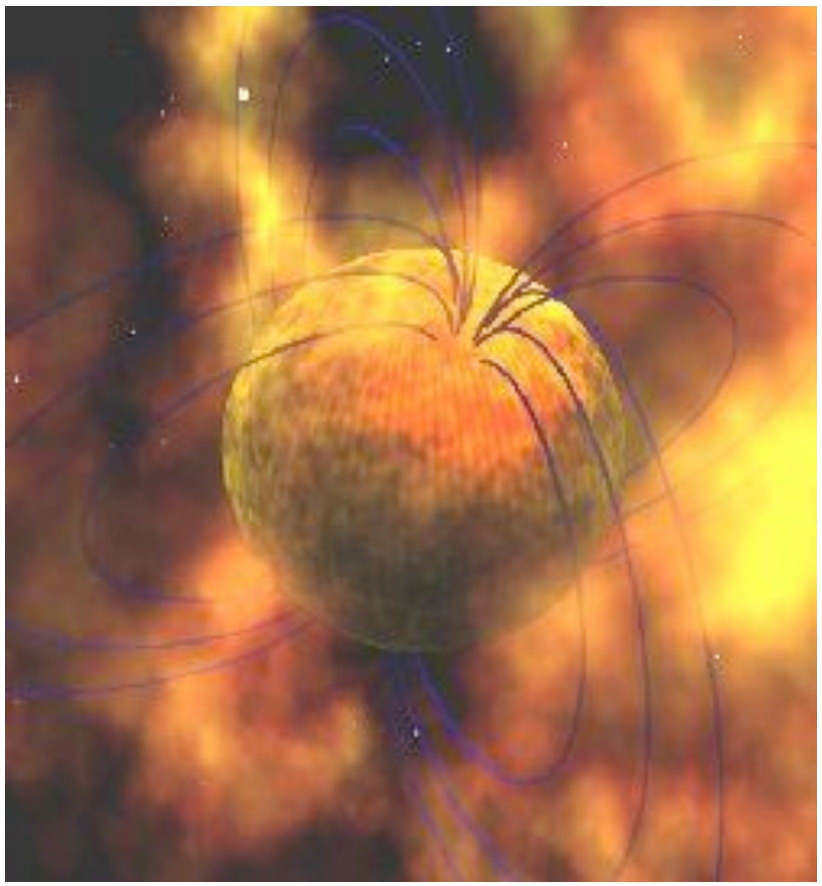



Neutrino annihilation



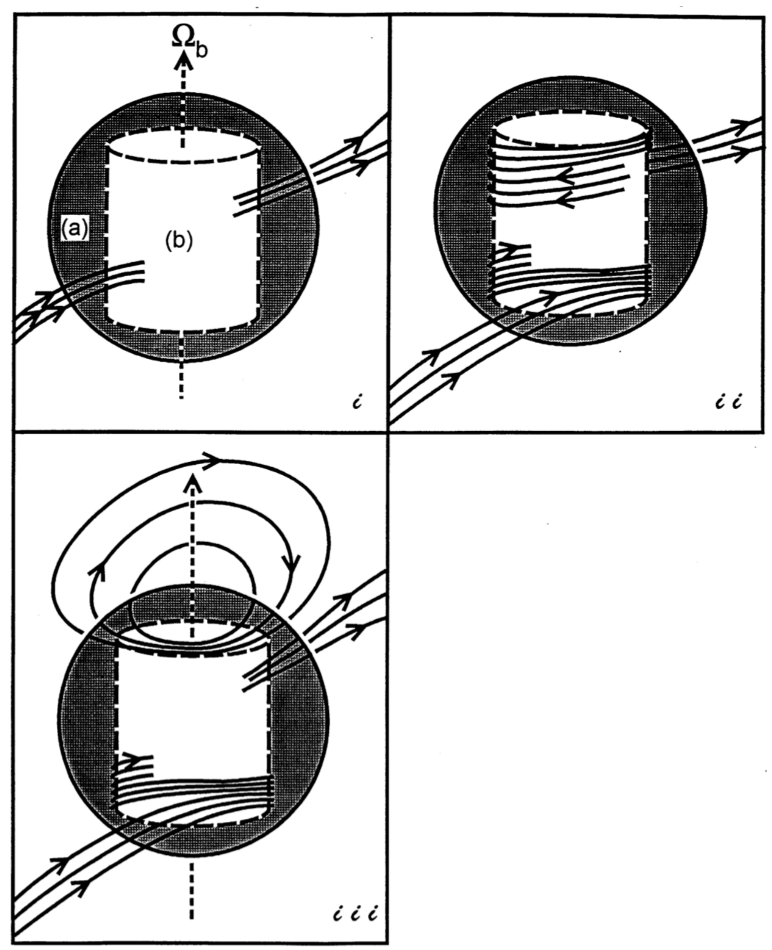

Magnetically tapping BH spin energy (Blandford-Znajek)

# Three ways of making a GRB from a magnetar



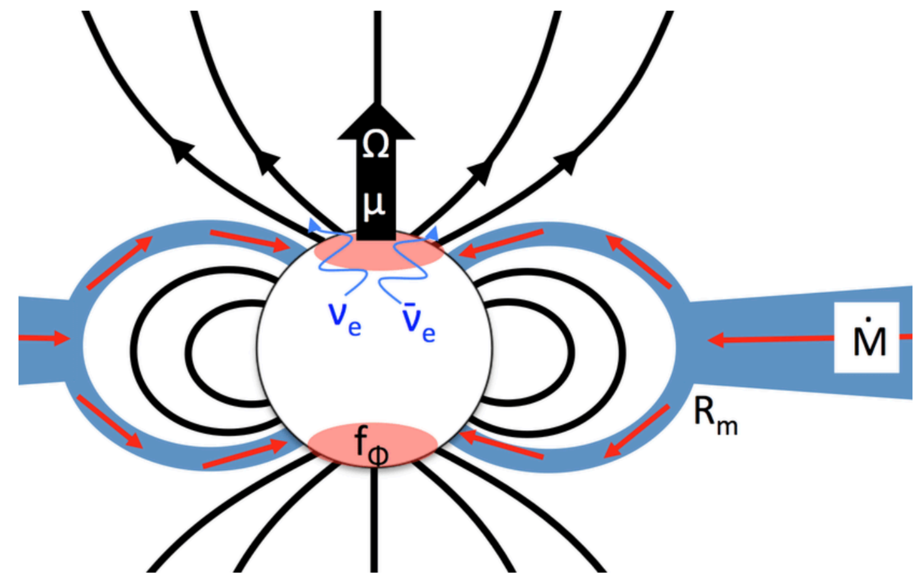
Usov 1992

Spin down




Kluzniak & Ruderman 1998

Differential rotation

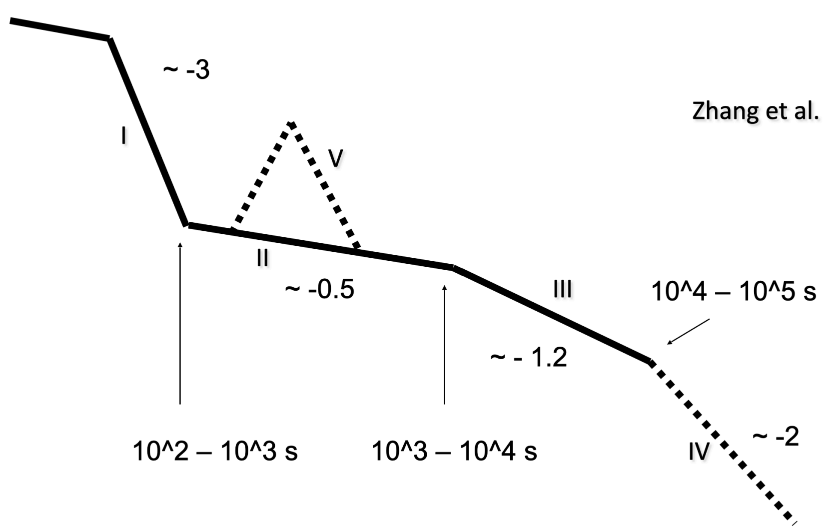



Metzger et al. 2018

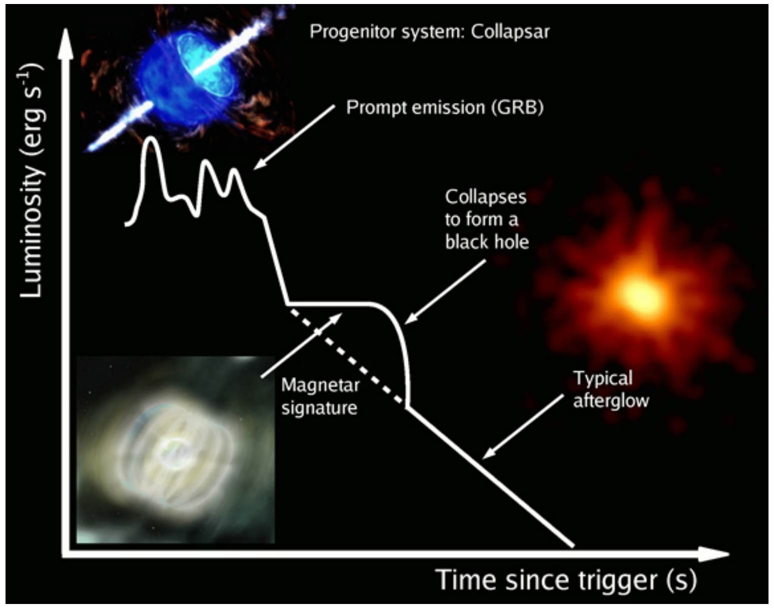
Accretion

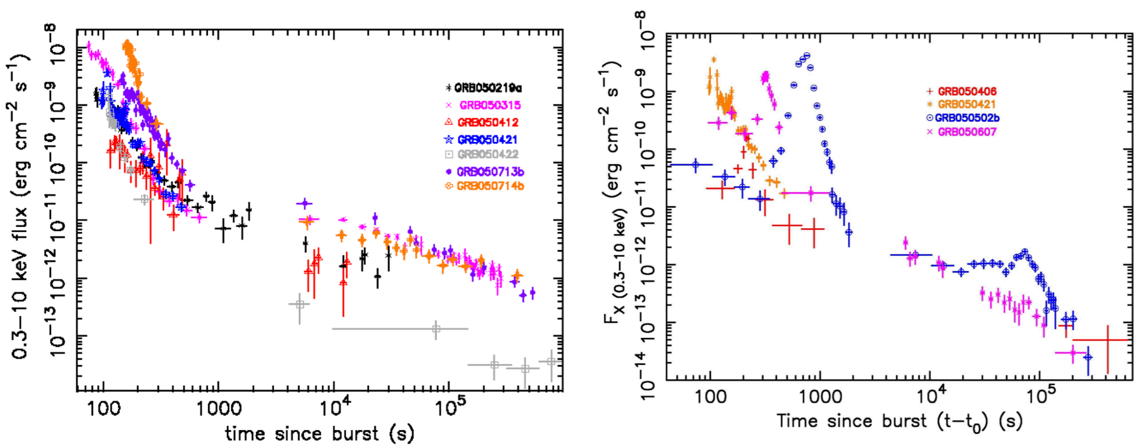
# Magnetar signature: Energy injection due to spindown

(Dai & Lu 1998; Zhang & Meszaros 2001 …)

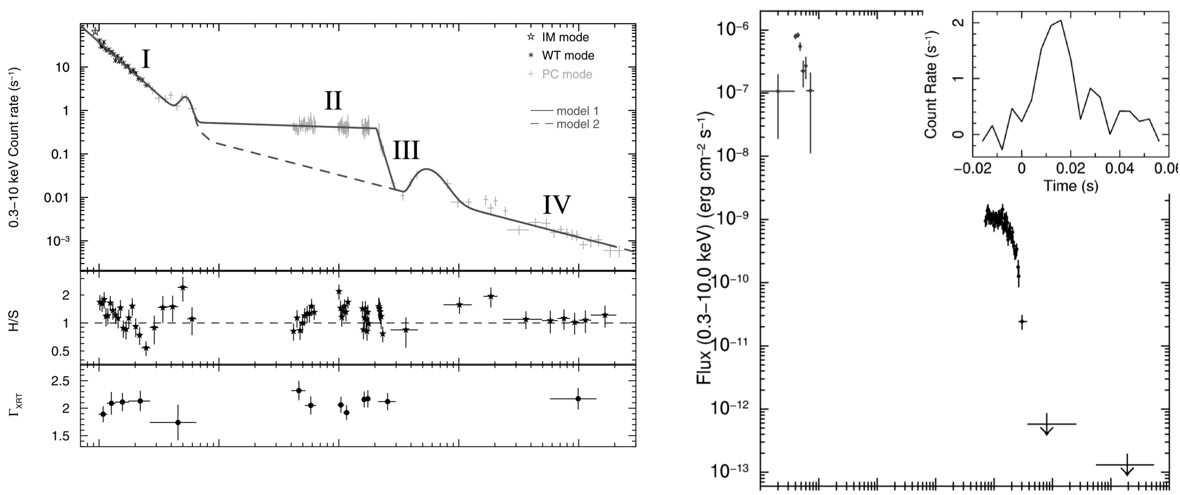



Zhang et al. (2006)




Nousek et al. 2006

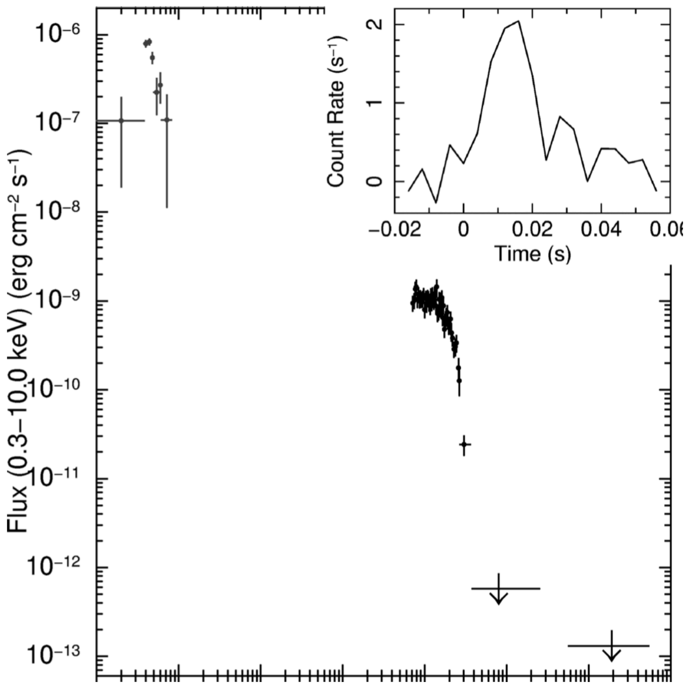



Troja et al. 2007; Lyons et al. 2010; Rowlinson et al. 2010

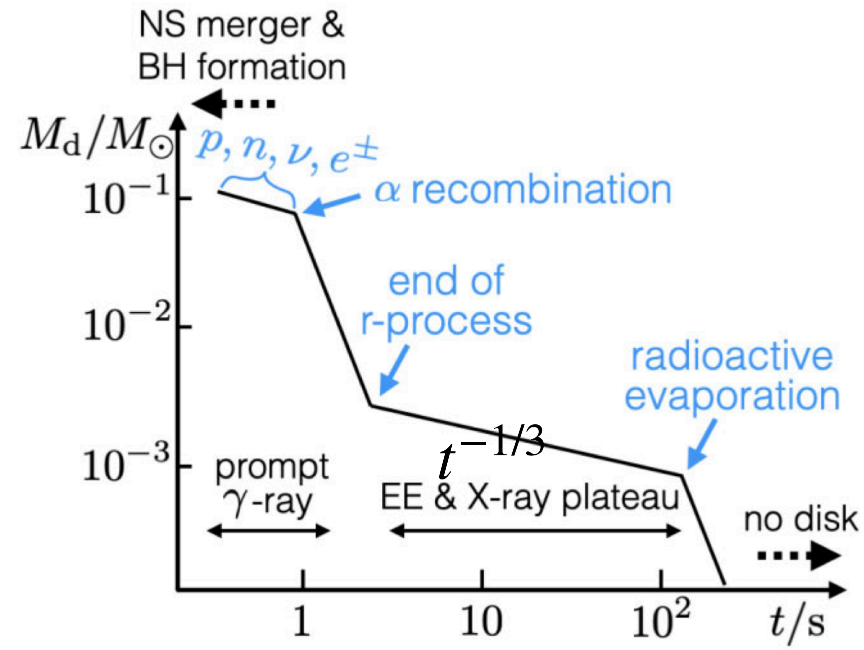
## External plateaus

## “Internal” plateaus

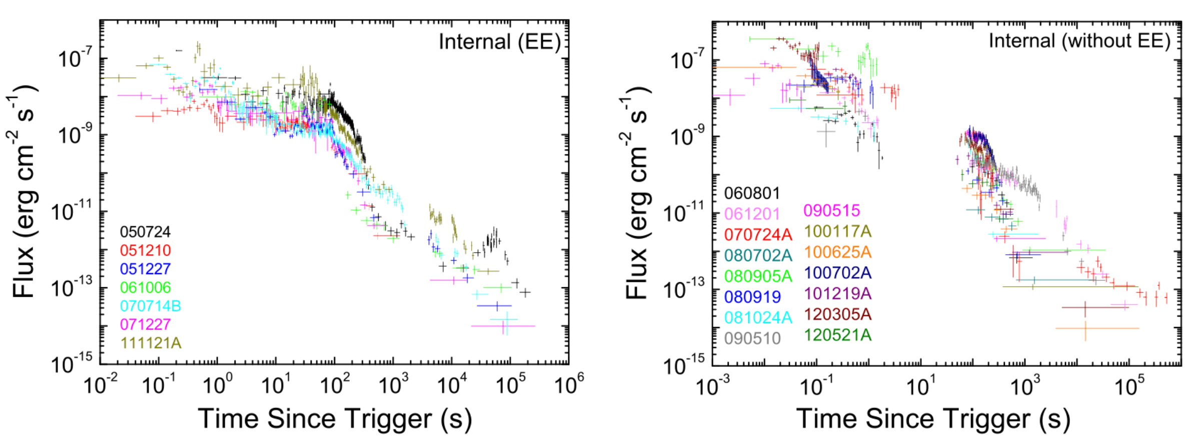
# Magnetar engine from NS-NS mergers?
# Can a BH engine do it?



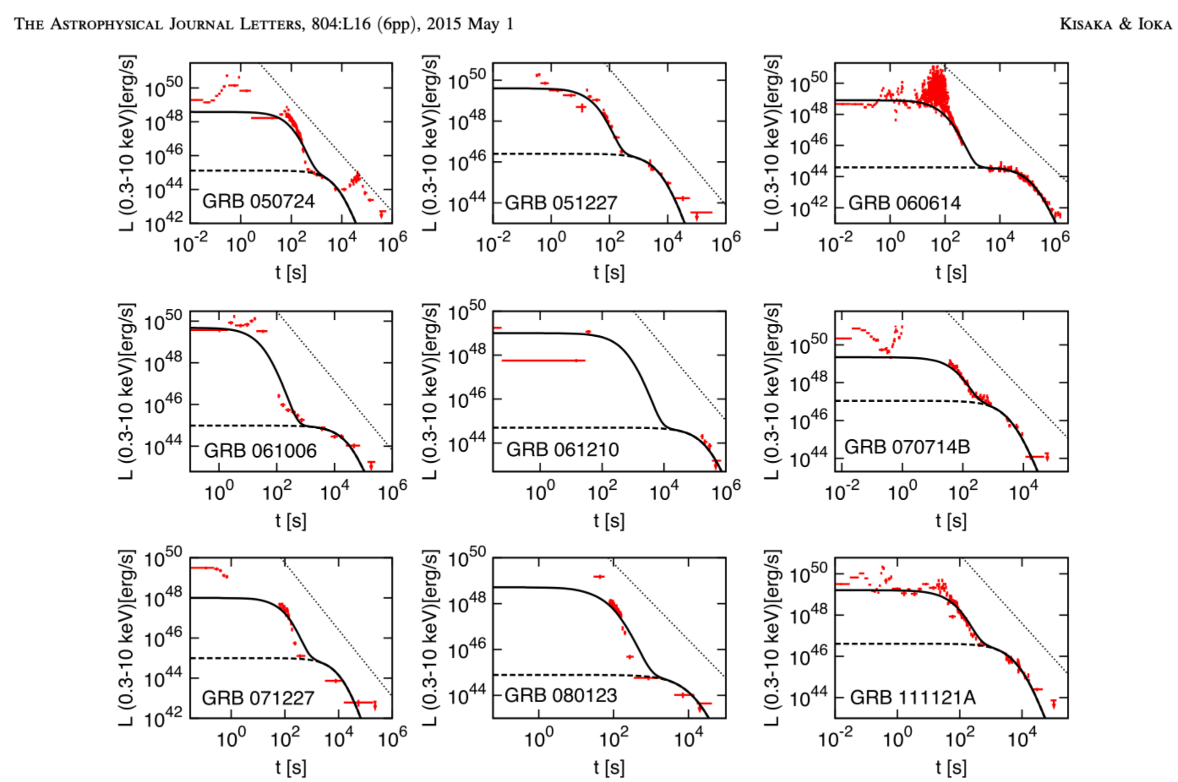

Rowlinson et al. (2010)




Lu & Quataert (2023)




Lü et al. (2015)

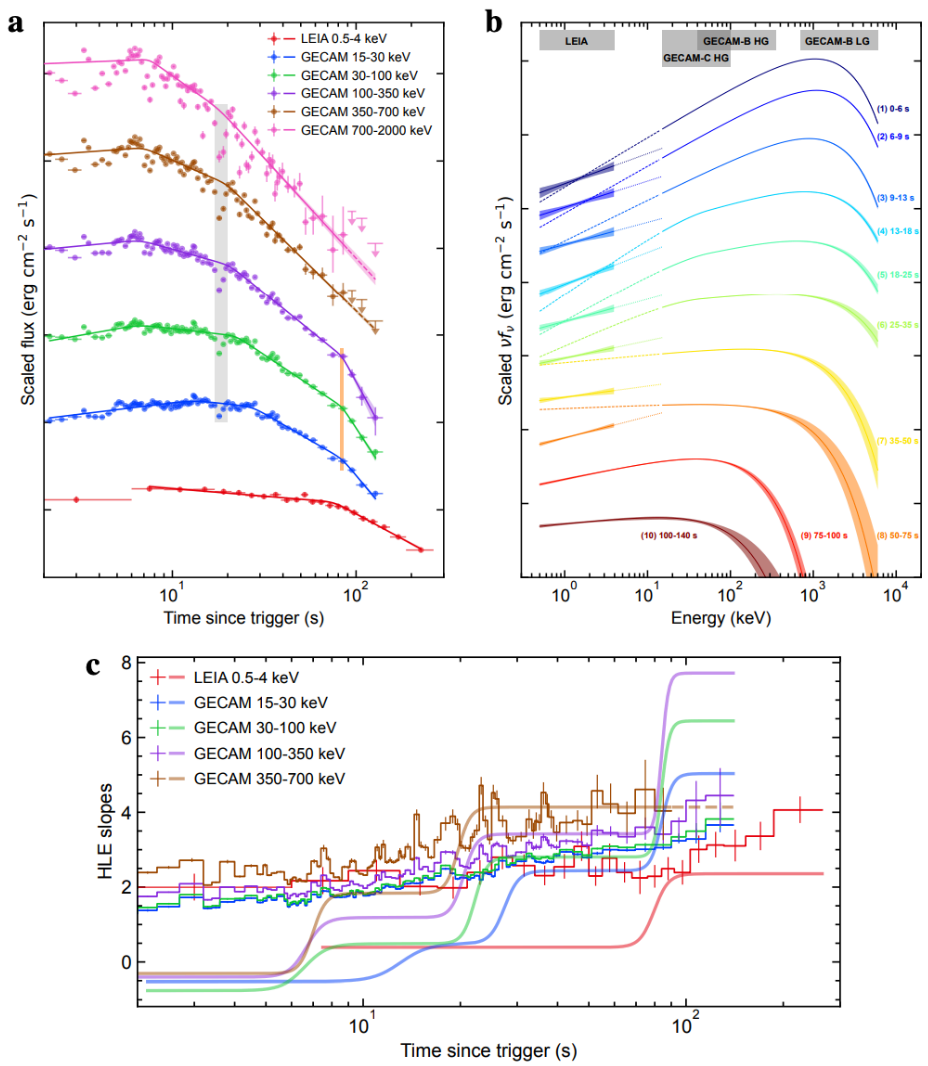


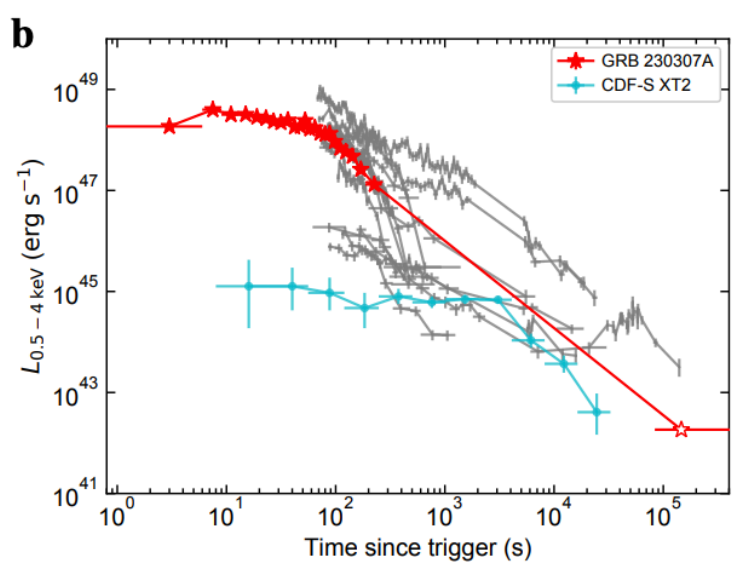

Kisaka & Ioka (2015)

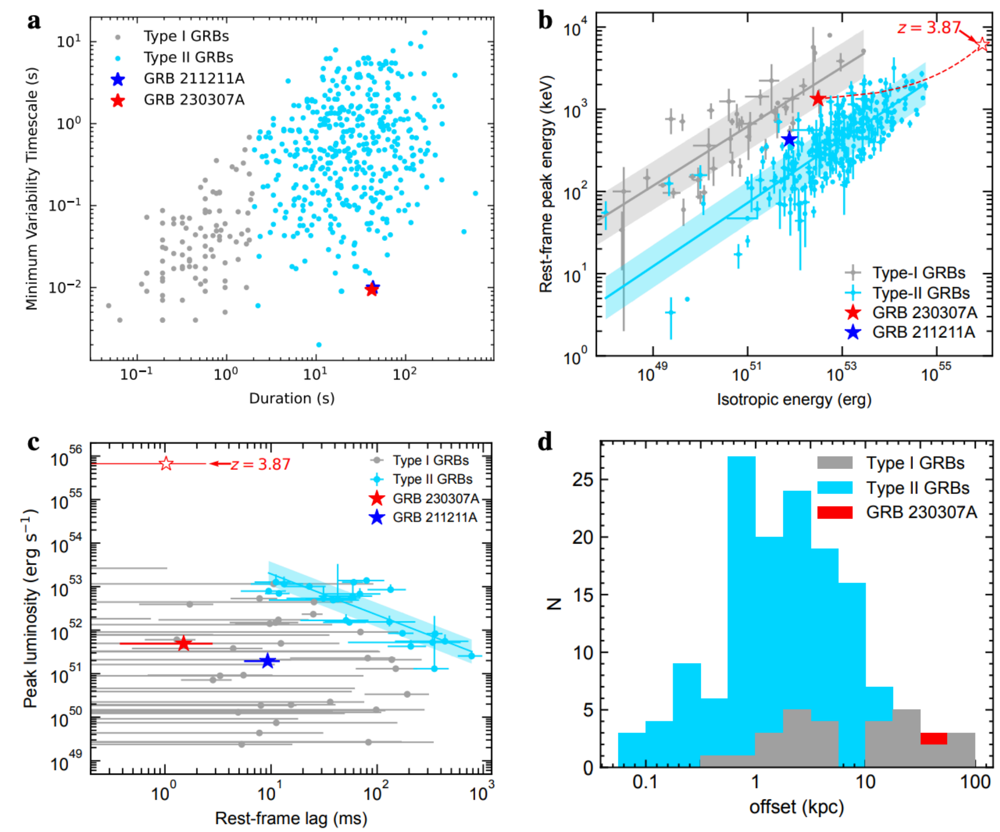
**Evidence**

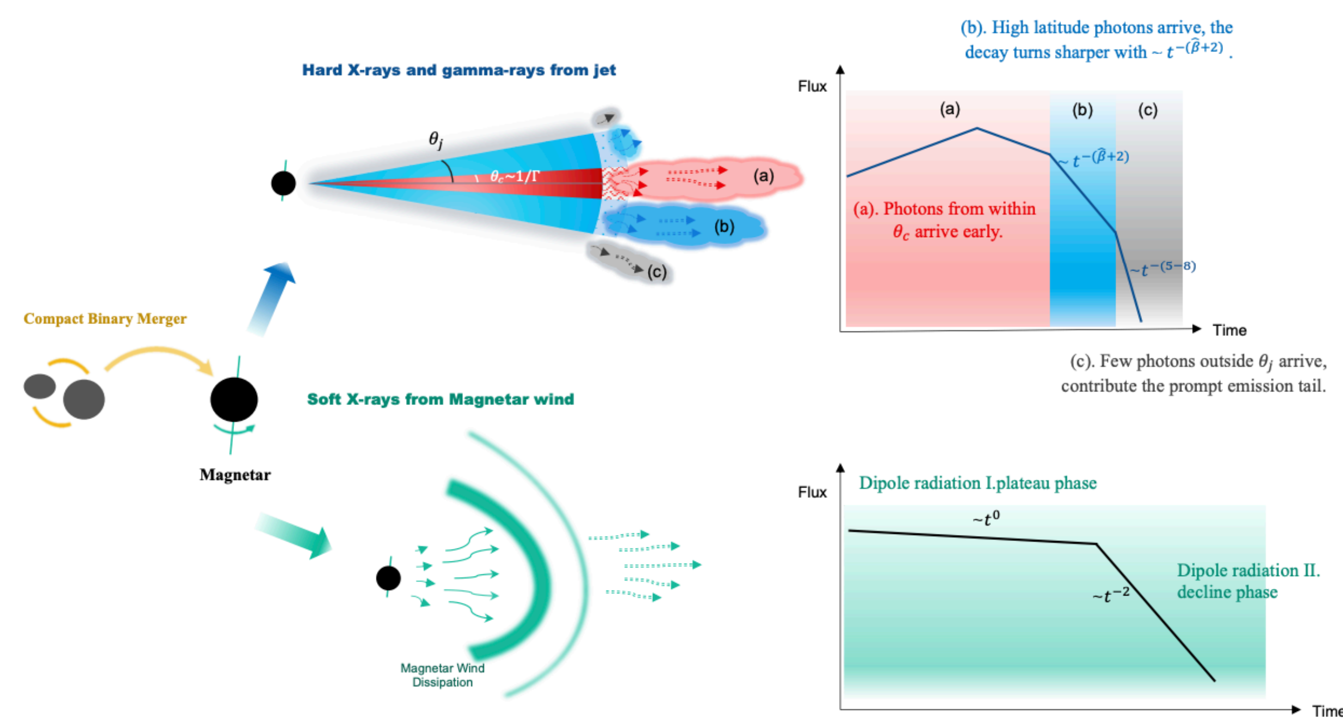
# Smoking gun: GRB 230307A

Sun et al. arXiv:2307.05689

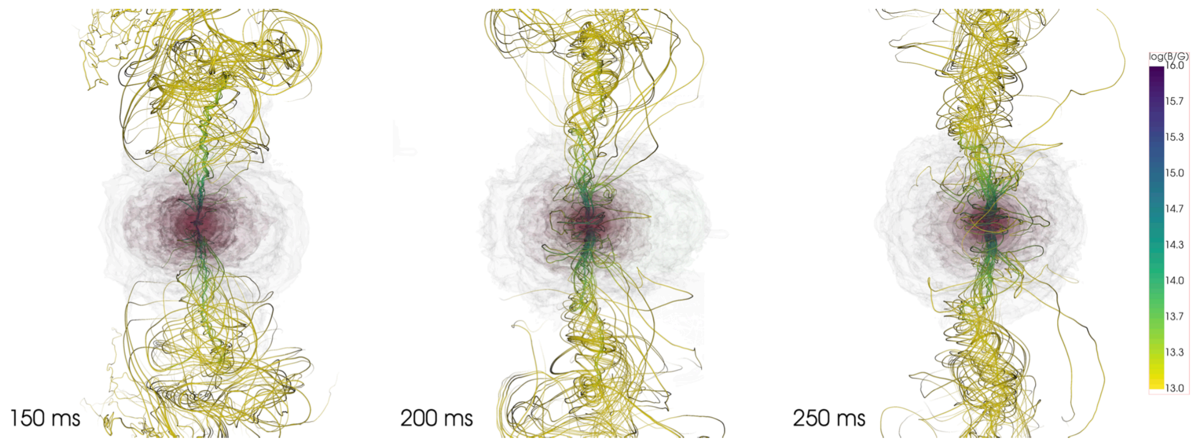


# Magnetar engine from NS-NS mergers?
# Theoretical difficulty: I. Can a relativistic jet be launched?

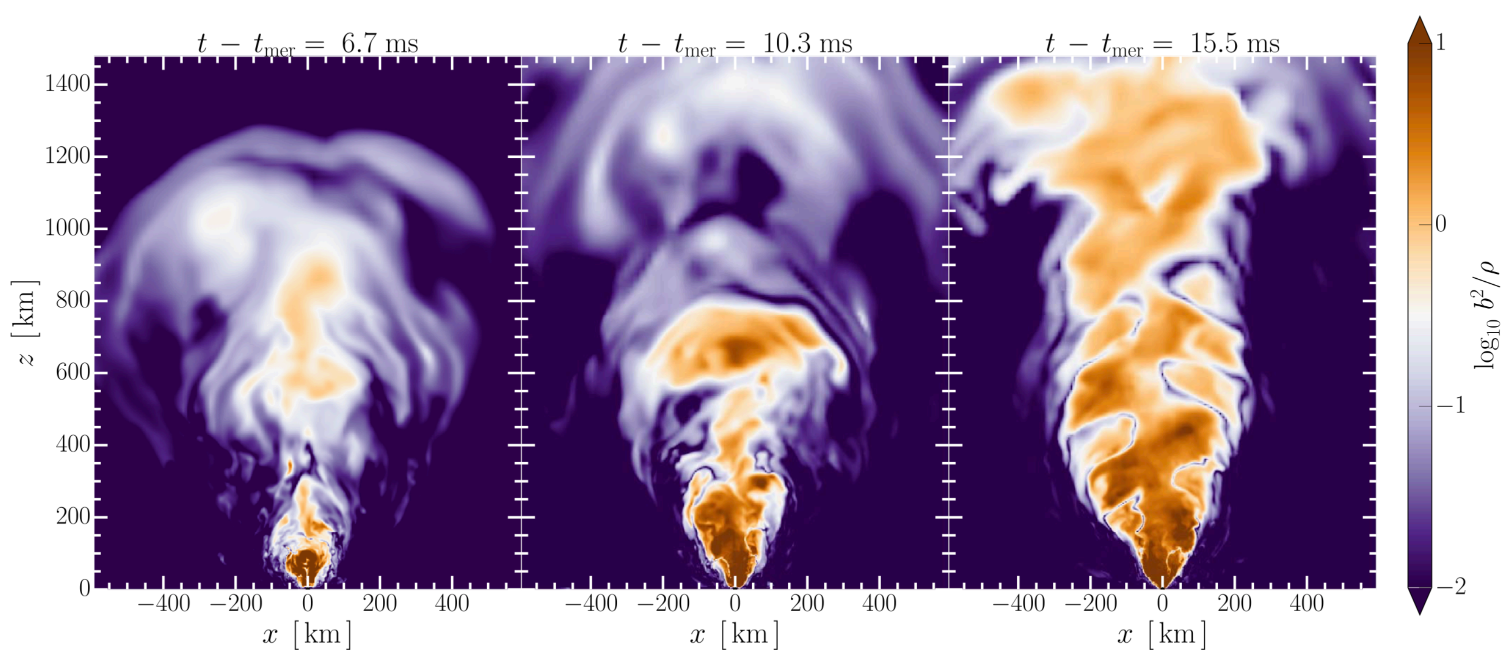



**Magnetically collimated outflow but not a short GRB jet yet (heavy baryon loading)**

Ciolfi (2020)

Most & Quataert (2023)

Bamber et al. (2024)

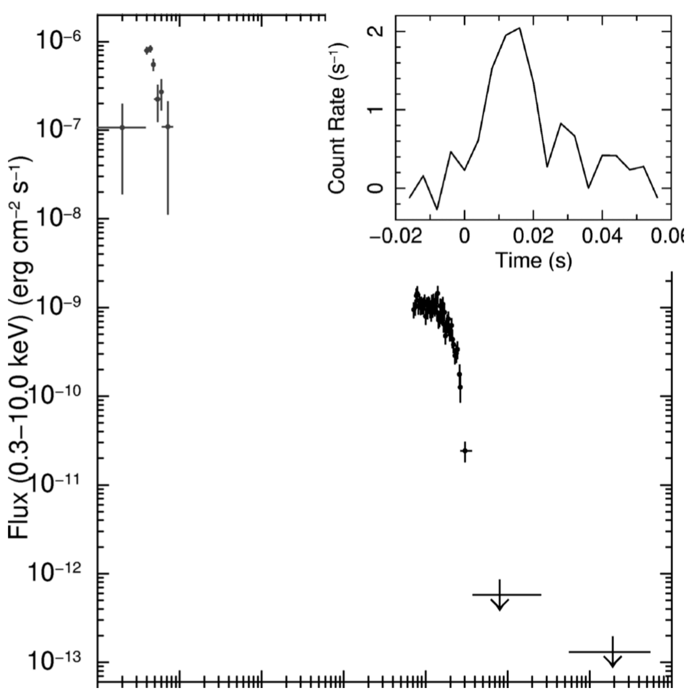



**Difficulty & Encouragement**

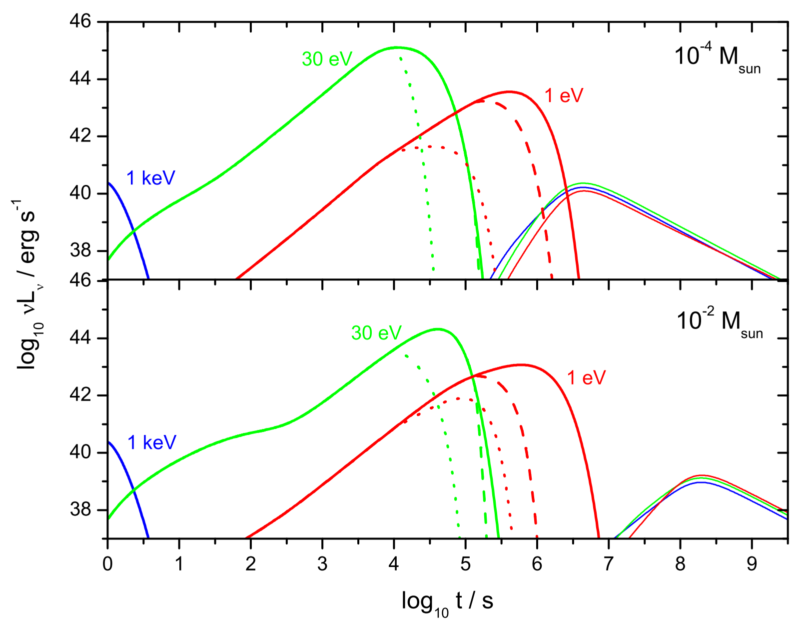
# Magnetar engine from NS-NS mergers?
# Theoretical difficulty: II. Missing energy

$$E_{\rm rot} = \frac{1}{2} I \Omega_0^2 \simeq 2 \times 10^{52}\,{\rm erg}\, M_{1.4} R_6^2 P_{0,-3}^{-2},$$

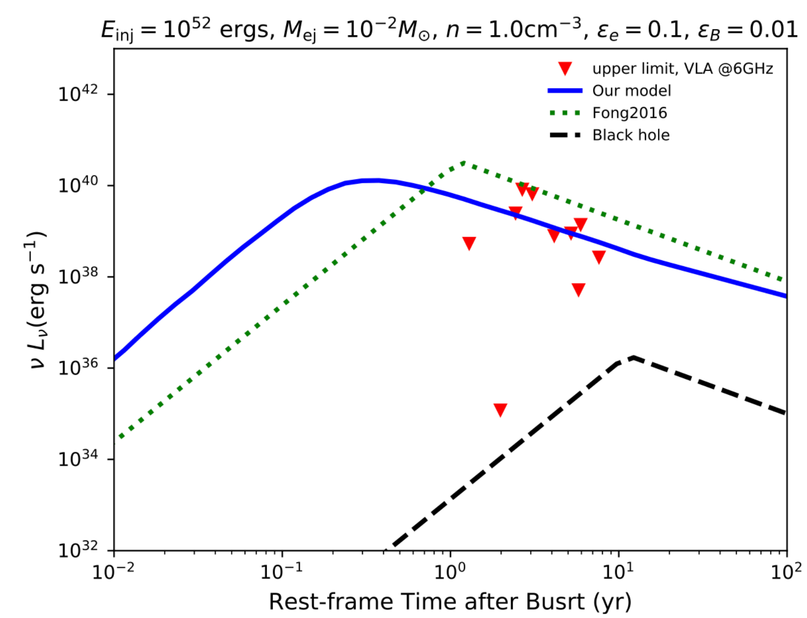
## Where does the energy go?




SGRB and plateau energy < 10^52.

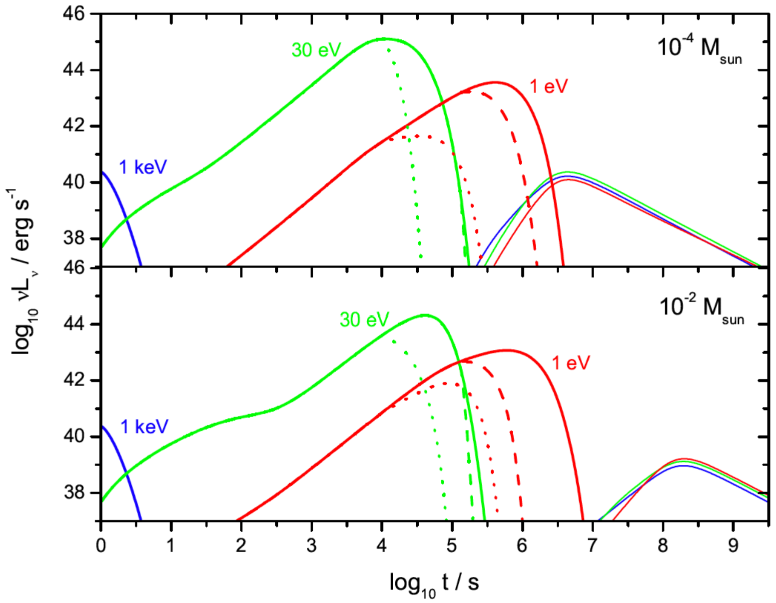


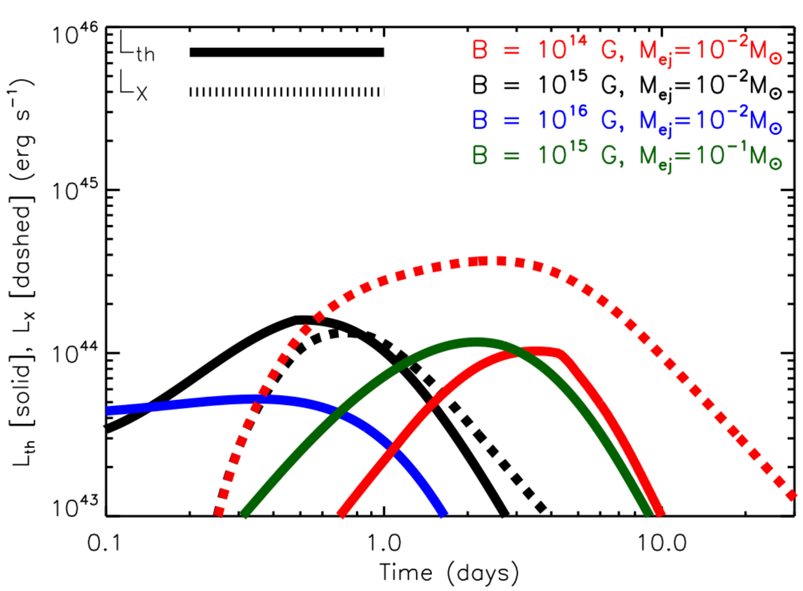

Predicted engine-driven kilonova too bright?

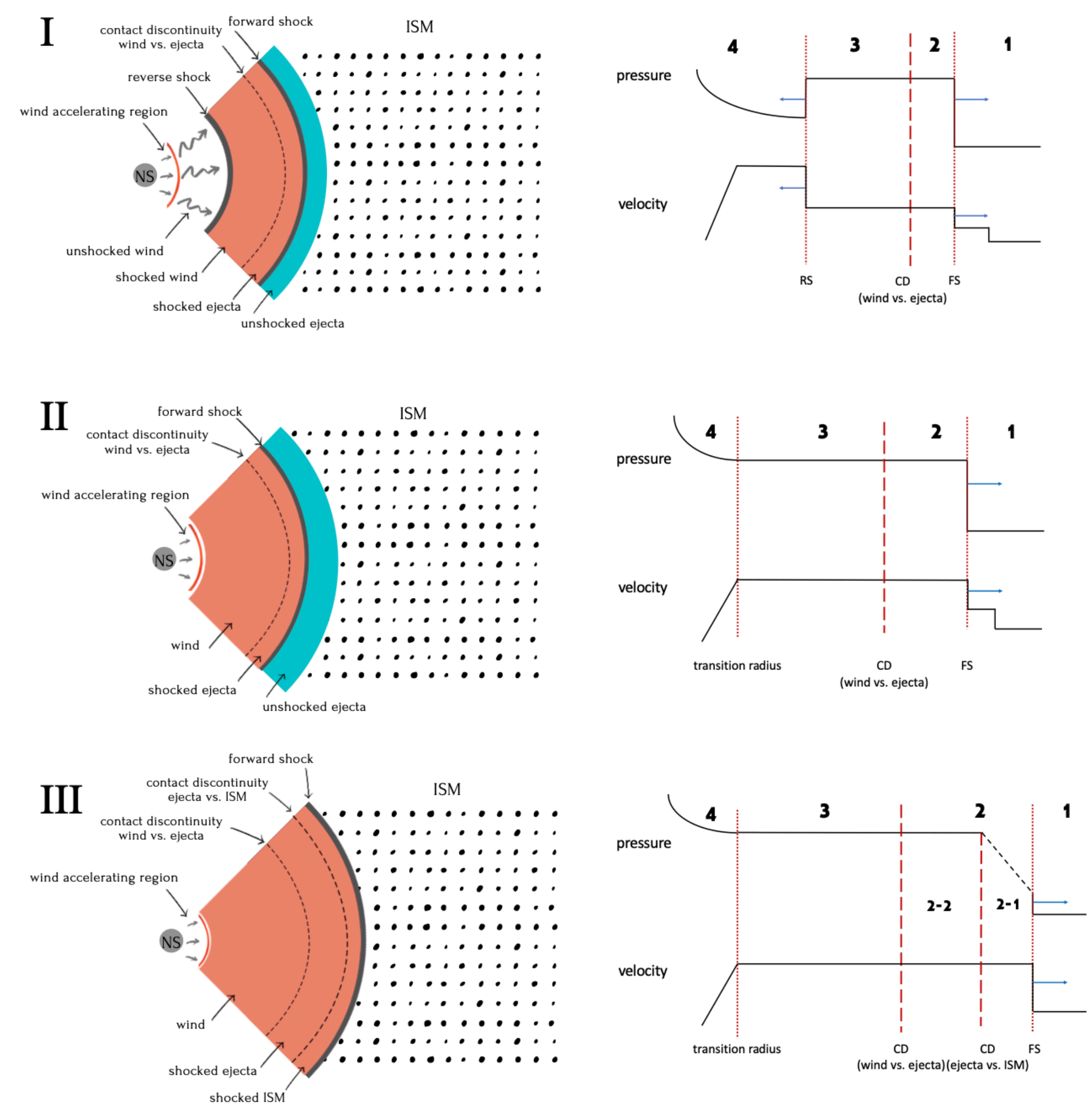



Predicted radio afterglow too bright?

# Engine-fed kilonova (mergernova)



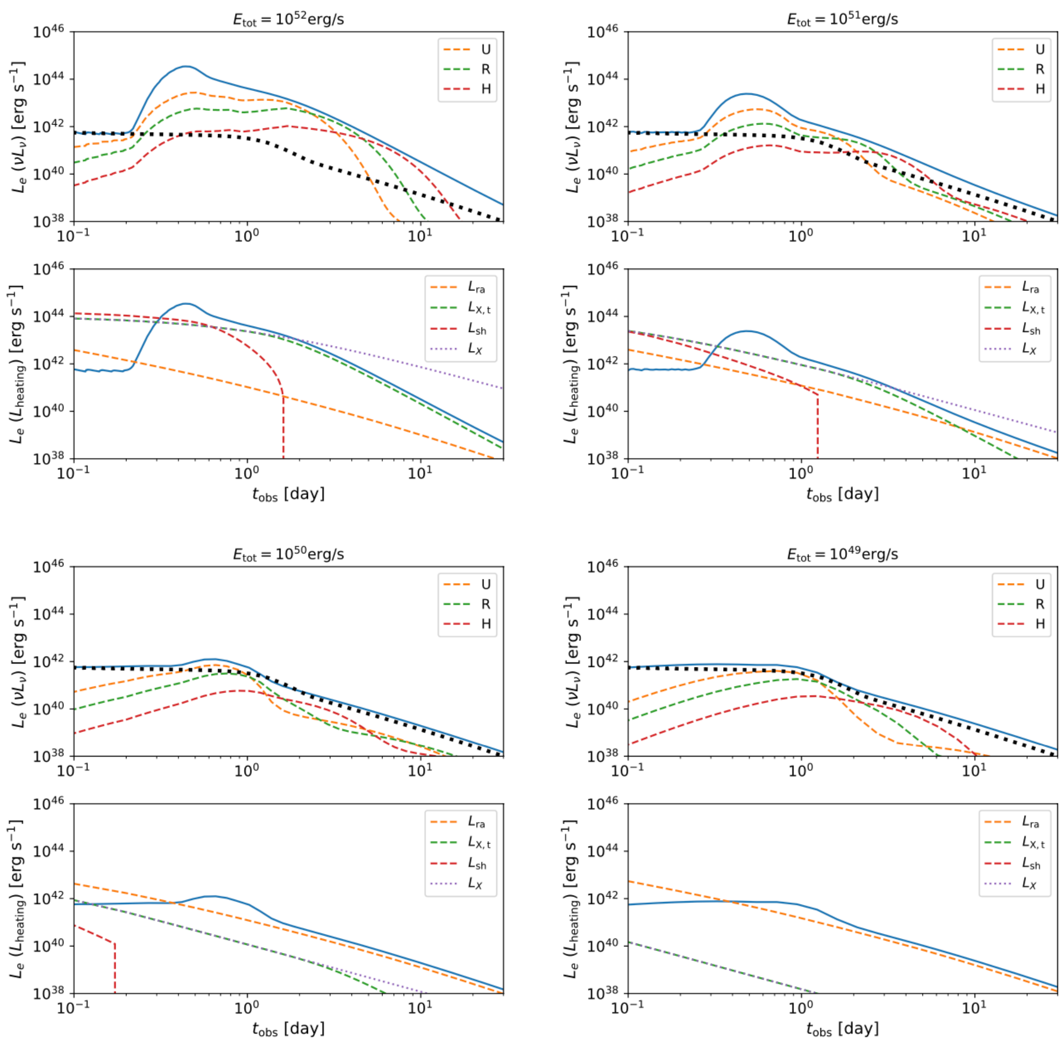



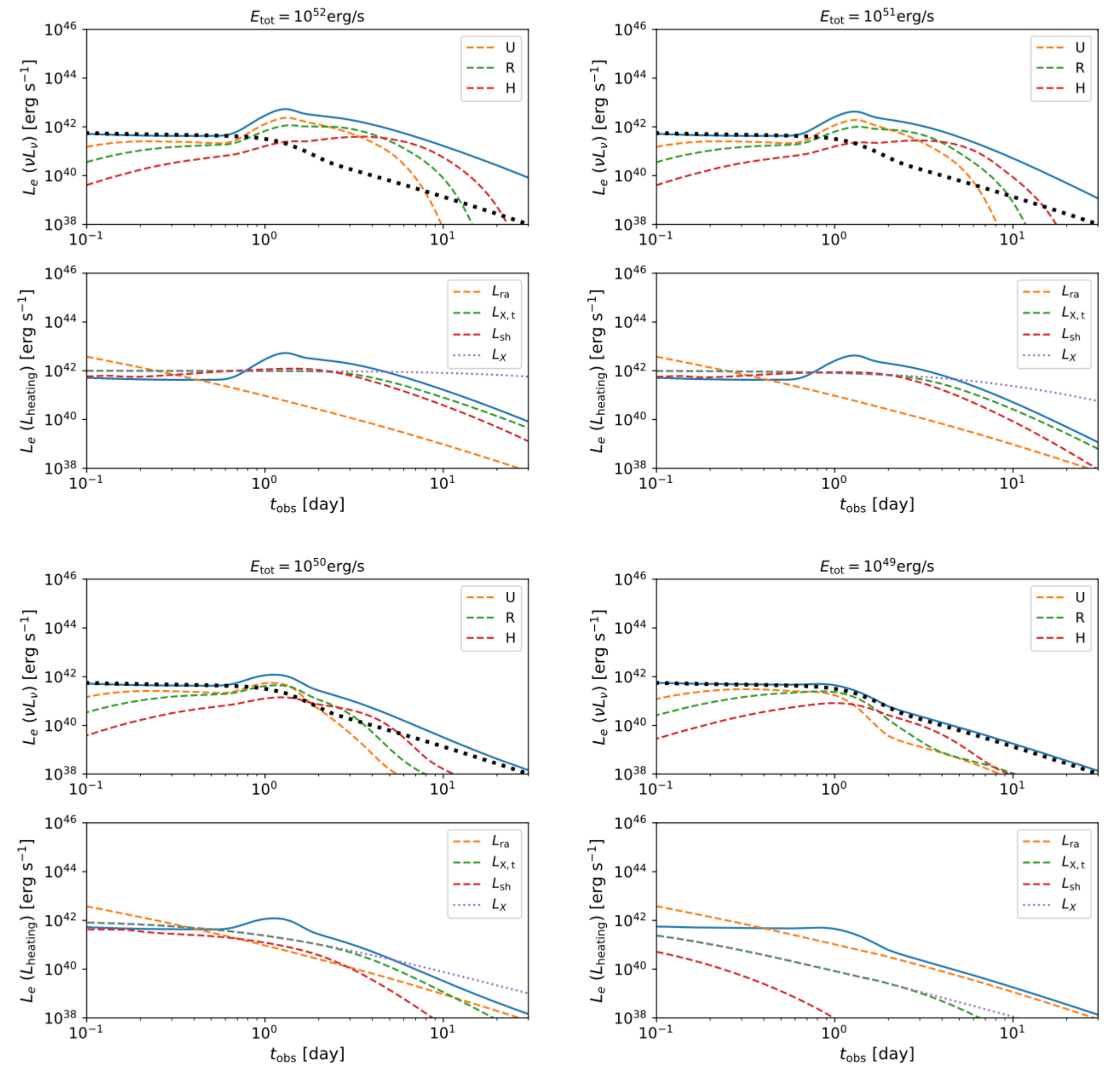

Efficient ejecta heating only happens before forward shock crossing

Yu, Zhang, Gao 2013, ApJL, 776, L40; Metzger & Piro, 2014, MNRAS, 439, 3916
Ai, Zhang & Zhu, 2022, MNRAS, 516, 2614

# Engine-fed kilonova (mergernova)



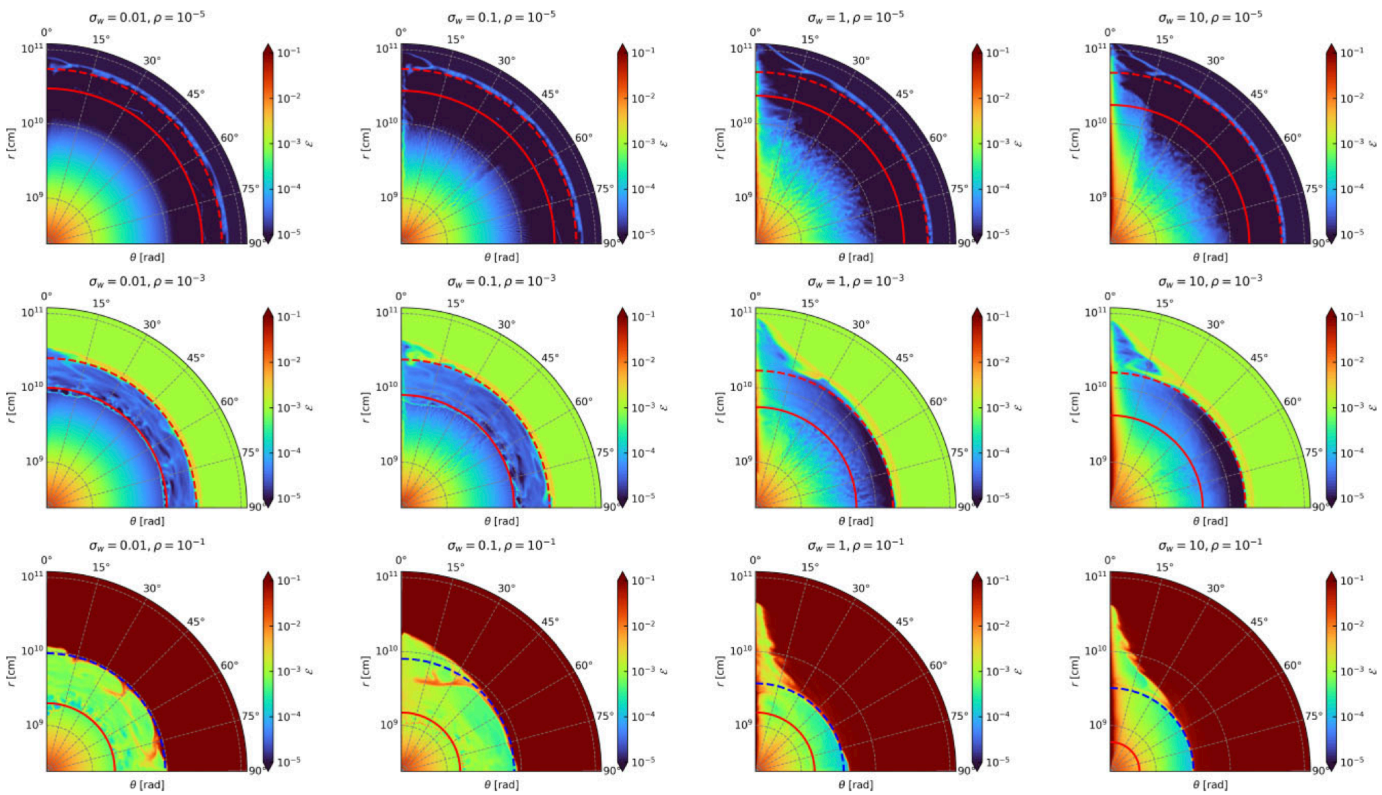

$L_{sd} = 10^{47}$ erg s$^{-1}$

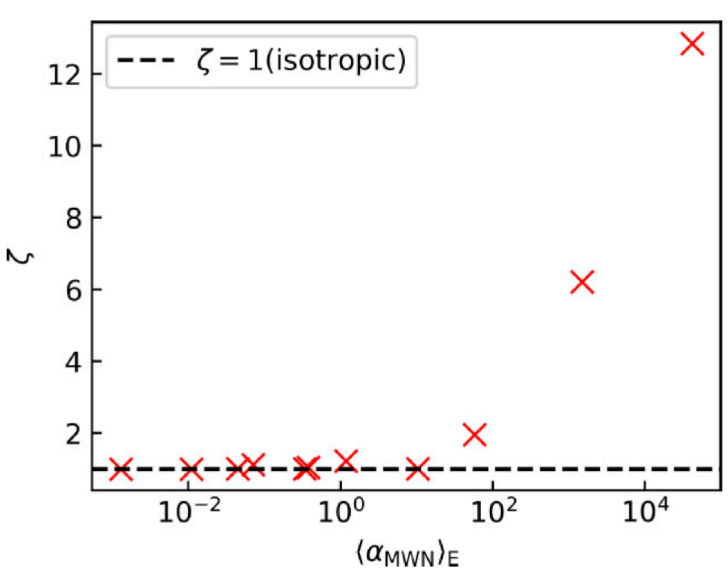



$L_{sd} = 10^{45}$ erg s$^{-1}$

Ai, Gao & Zhang, 2024, arXiv:2405.00638

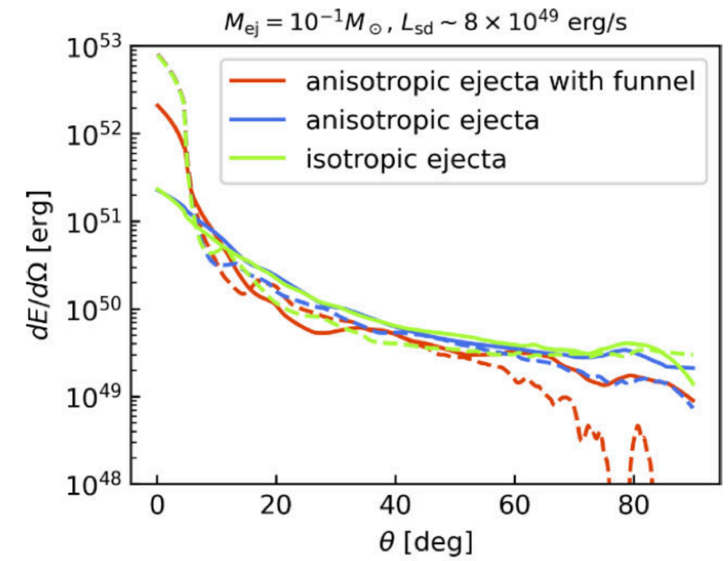
# Anisotropic energy injection in engine-fed kilonova

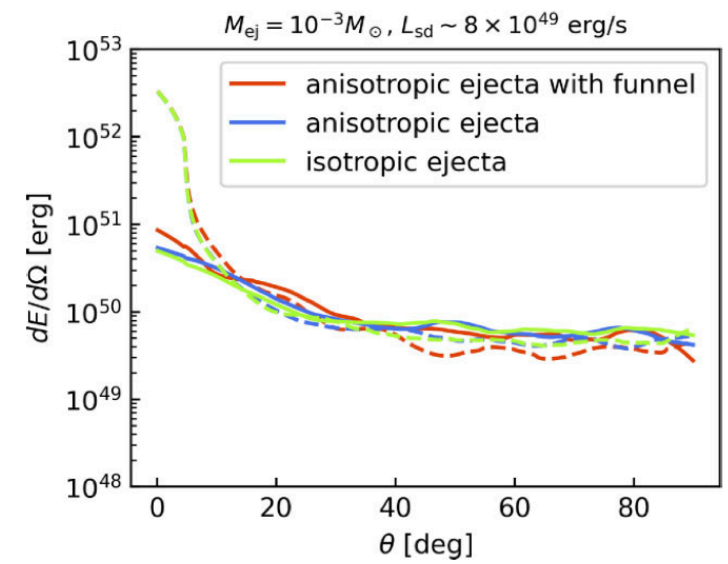





$$\langle \alpha_{\rm MWN} \rangle_{\rm E} = \frac{\int \alpha \mathcal{E} {\rm d}V}{\int \mathcal{E} {\rm d}V}$$

$$\alpha = \frac{u_{\rm A}}{u_{\rm MWN}},$$

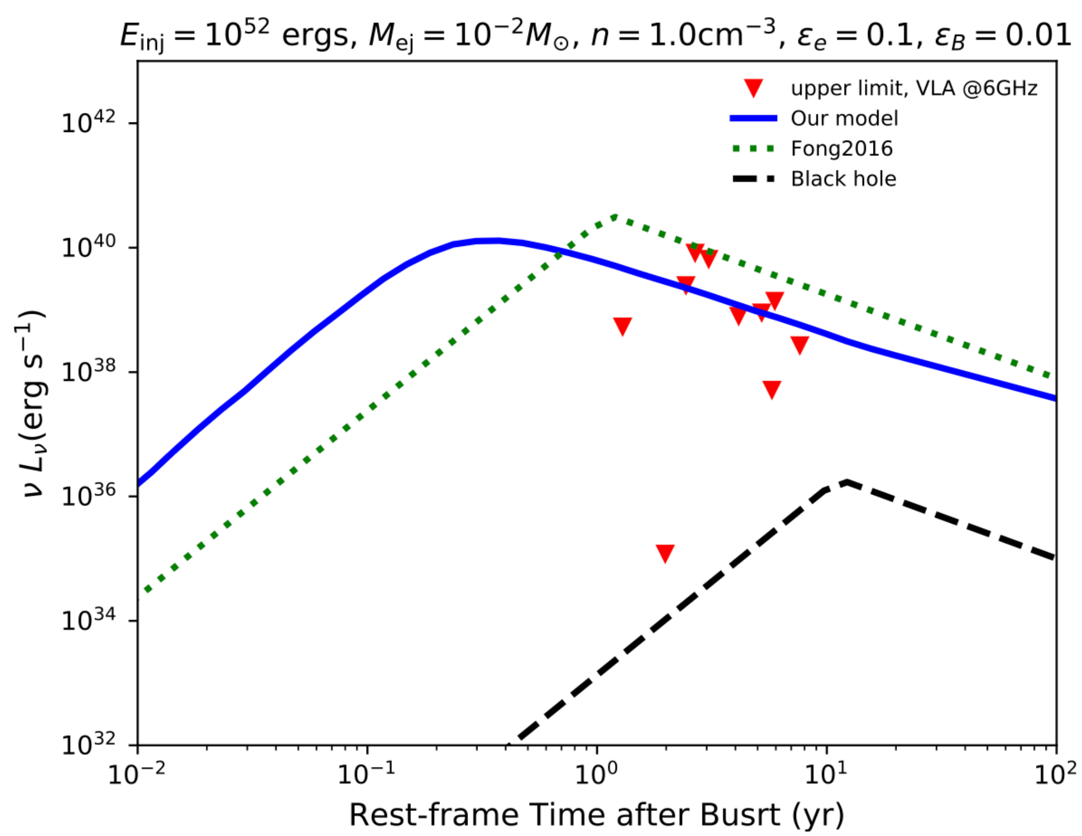


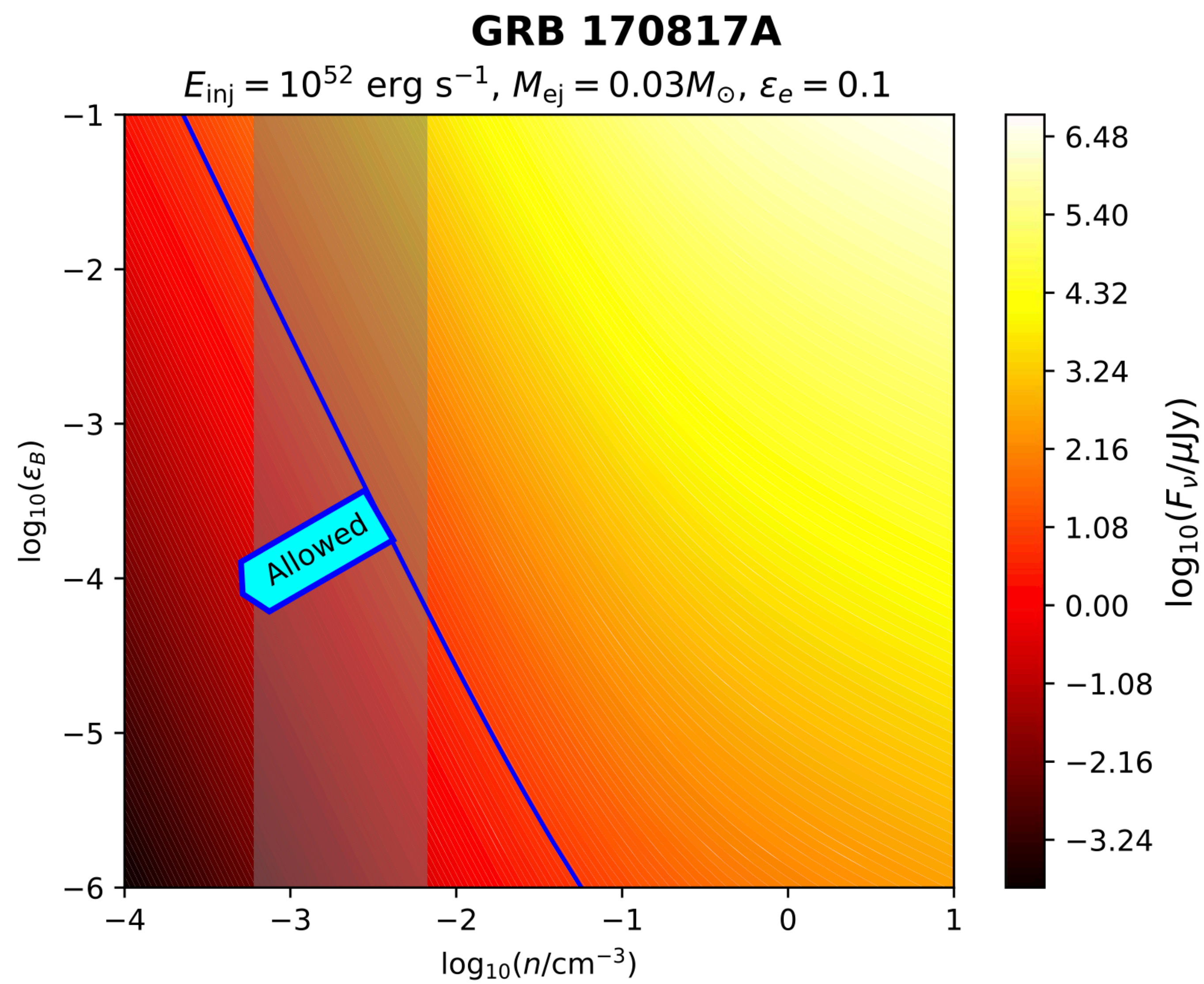




Energy injection is not isotropic!
Channeling energy to the jet axis direction
Effects of kilonova energy injection are smaller

Yihan Wang, Zhang & Zhu, 2024, MNRAS, 528, 3705

# Radio afterglow




Proper treatment of non-relativistic dynamics
Freedom of micro-physics parameters

—- A large kinetic energy up to 10^52 erg is still allowed

Liu, Gao & Zhang, 2020, ApJ, 890, 102

# What do we NOT know about GRBs?

# Known unknowns

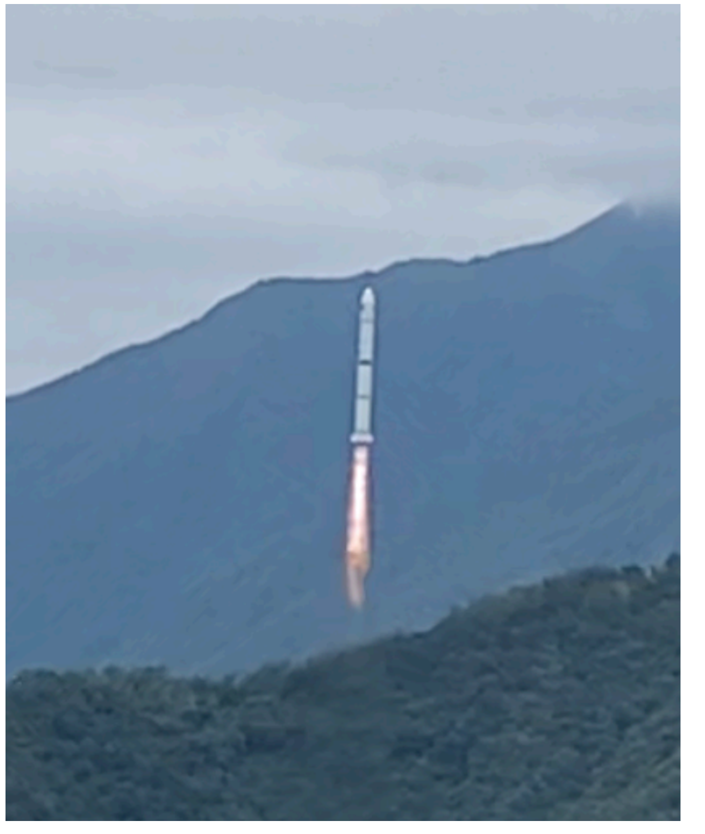
- **Massive star GRBs**
  - Are there multiple progenitor systems?
  - Single star or binary progenitor(s)?
- **Compact star GRBs**
  - Are there other progenitors besides NS-NS mergers?
    - BH-NS mergers?
    - BH-WD mergers?
    - NS-WD mergers?
- **Central engine**
  - Can NS-NS mergers with a long-lived magnetar engine power GRBs? (High-frequency GW detectors will tell eventually)
- **From how high redshift GRBs can be made (and detected)**
  - SVOM, Einstein Probe, Swift …
- **…**

# Unknown unknowns

- **???**
- **???**

# SVOM breakthroughs
## (See also Daigne's talk)

- GRB physical classification
- High-z GRBs
- Low-z GRBs and shock breakouts
- Multi-messenger counterparts
- A broad-band picture of GRB prompt emission for a large sample of GRBs (ECLAIRS, GRM, GWAC)
- A uniform sample of early optical afterglow & a systematic study of jet break (VT)
- …



# Summary

- We already know quite a bit about GRBs.
- Many open questions remain.
- Some known unknowns call for uncovering with new observations.
- There might be unknown unknowns to be discovered.

- SVOM will lead a new era of GRB studies!