



中国科学院高能物理研究所  
Institute of High Energy Physics  
Chinese Academy of Sciences



IHEP MeV Mission Workshop (Science and Instruments)  
**Preparing Next-Generation Astrophysics in the MeV Window**

# Discovery of MeV emission lines from GRBs

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(on behalf of GECAM team & many collaborators)  
State Key Laboratory of Particle Astrophysics, Institute of High Energy Physics  
2025-09-16



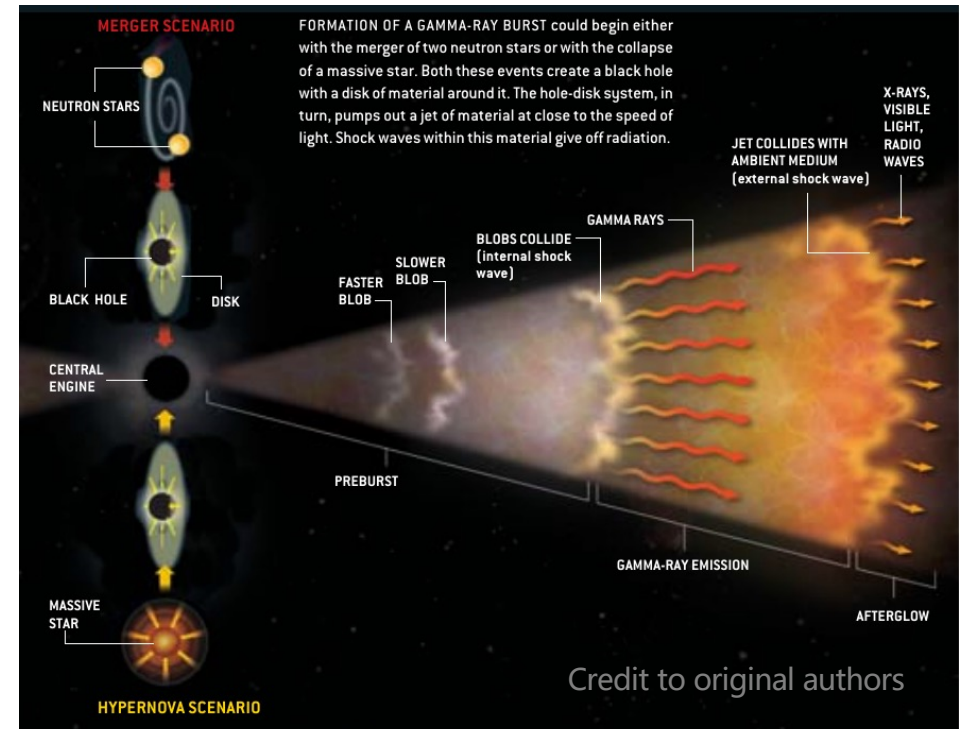
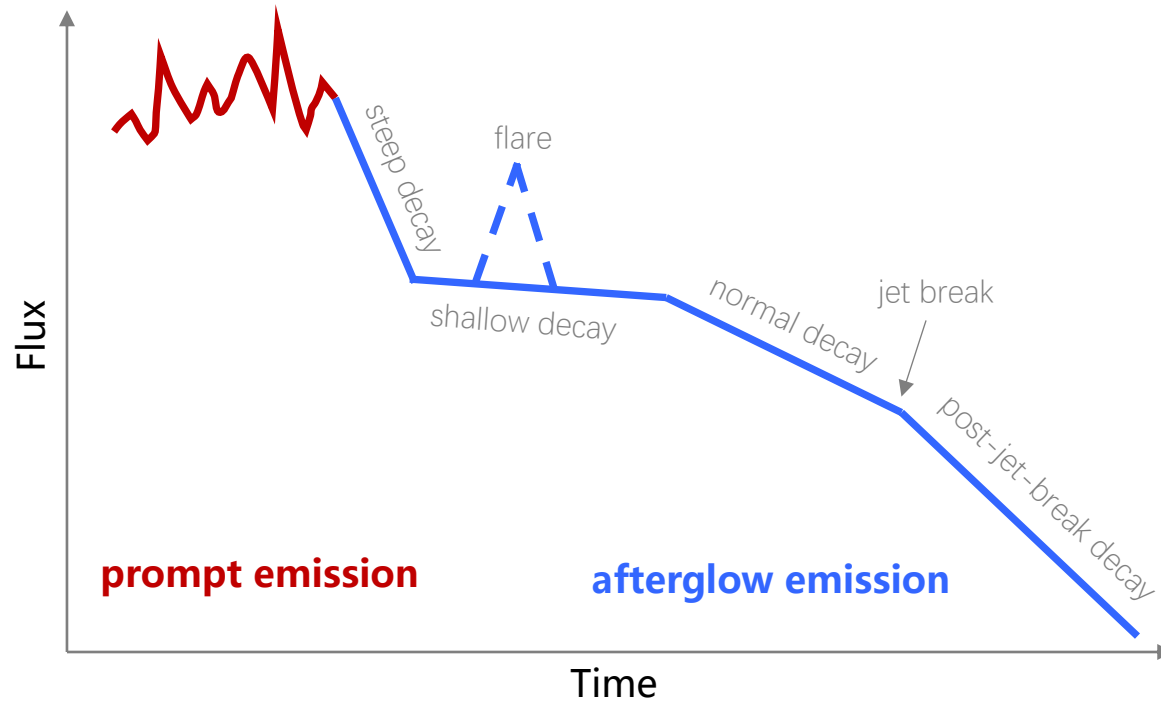
# Outline

- **GRB spectral line search**
- **GECAM & GRB 221009A**
- **MeV line in GRB 221009A**
- **Possible MeV line in other GRBs**
- **Plausible interpretations**



Credit: GECAM team, IHEP/CAS

# Gamma-Ray Burst (GRB)



## Key Questions

**Progenitor:** single star/binary merger

**Central engine:** BH/NS/others?

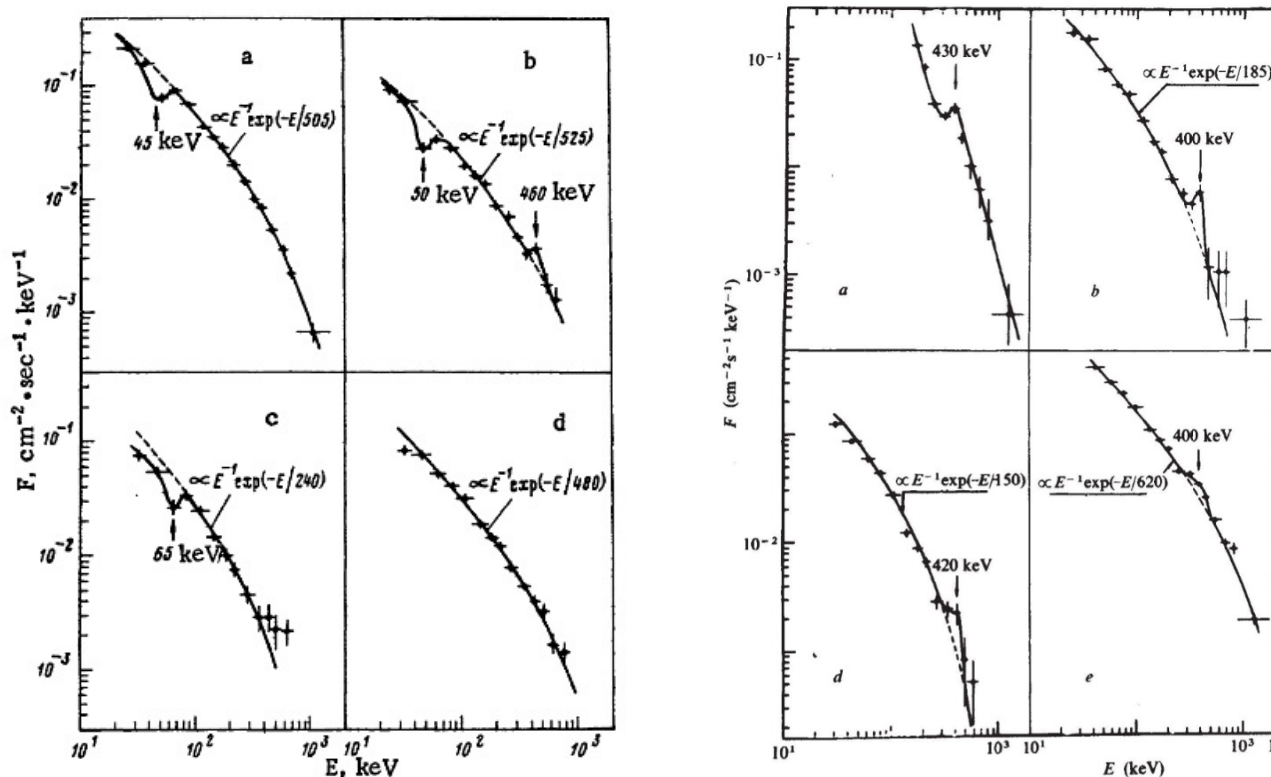
**Jet:** composition, geometry, speed, emission

**Multi-messenger:** GW, HEN, Supernova/Kilonova

**Heavy elements, fundamental physics, cosmology**

# History of Gamma-Ray Burst Spectral Line Search

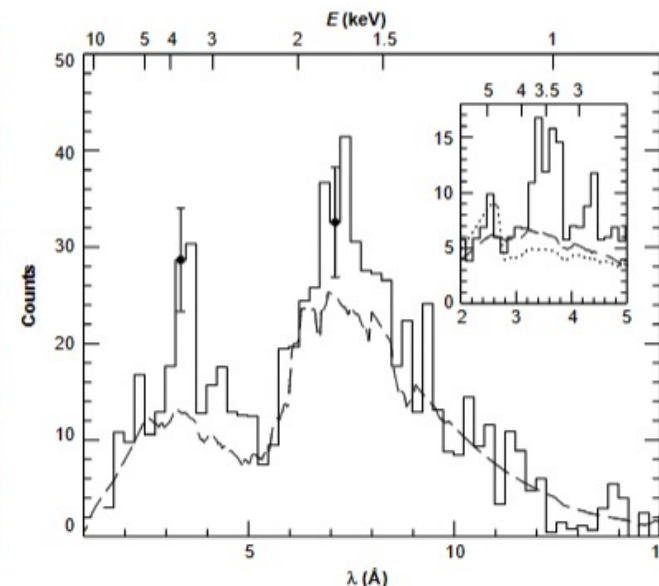
*Nature* Vol. 290 2 April 1981



## Prompt Emission

Mazets, E., et al. *Nature* 290, 378–382 (1981)

Fig. 1. The x-ray afterglow spectrum of GRB991216 obtained with the Chandra high-energy gratings [High Energy (HE) and Medium Energy (ME)] summed together. The background is negligible. The exposure time of the observation was 9700 s. For improved statistics, the grating spectrum has a bin size of 0.25 Å, including about 10 resolution elements of the ME and 20 of the HE. The dashed line represents the best-fit power law on the 0th order ACIS-S spectrum. The peak (i.e., 2 bins) around 3.5 Å ( $E = 3.5$  keV) is detected with a 7-σ confidence.



## Afterglow

Piro, L., et al. *Science*, (2000)

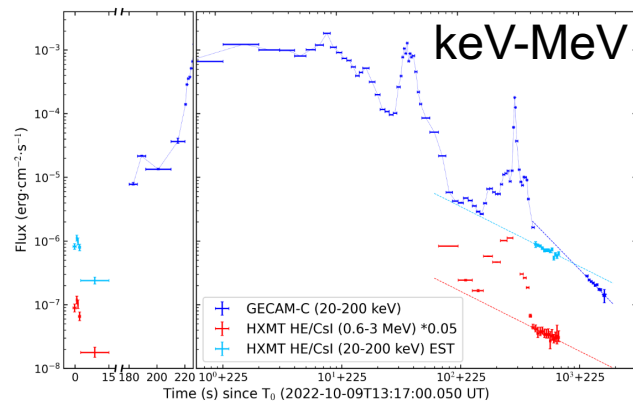
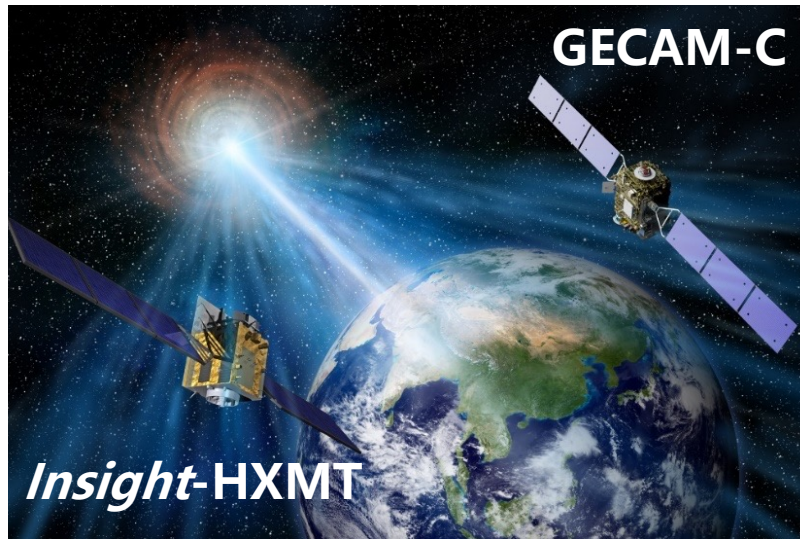
None of these results has been firmly confirmed!



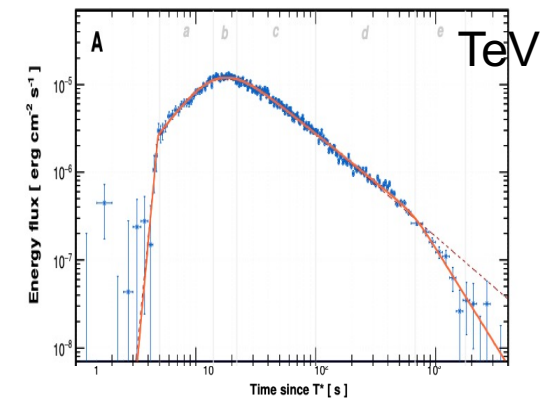
# GRB 221009A: Brightest GRB

One per thousands of years. Many observations & discoveries

Great opportunity for spectral line search



An et al., 2023



LHAASO collaboration. 2023

# GECAM

Gravitational wave high-energy Electromagnetic Counterpart All-sky Monitor

## ● GECAM Instruments

- GECAM-A: Dec. 10, 2020 **Operation**
- GECAM-B: Dec. 10, 2020 **Operation**
- GECAM-C (HEBS): Jul. 27, 2022-Feb. 22, 2025
- GECAM-D (DRO/GTM ): Mar. 13, 2024 **Operation**

## ● GECAM science: High energy transients

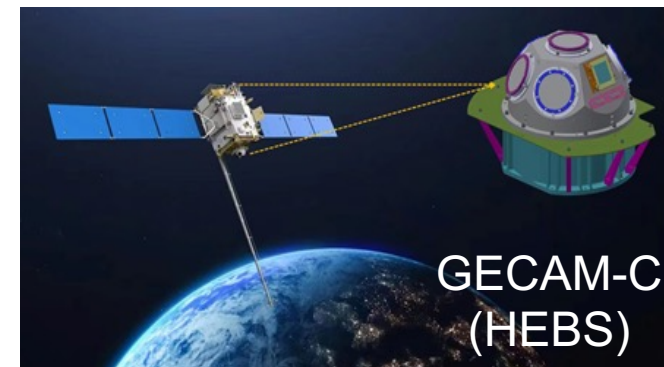
- GRB, SGR, high energy transients associated with GW/FRB
- Solar Flares, Terrestrial Gamma-ray Flashes & new type of events

## ● GECAM characteristics

- **FOV:** ~100% all-sky
- **Energy band:** 6 keV – 5 MeV
- **Sensitivity:** ~1E-8 erg/cm<sup>2</sup>/s
- **Localization:** ~2 deg (1- $\sigma$  stat., 1E-5 erg/cm<sup>2</sup>)



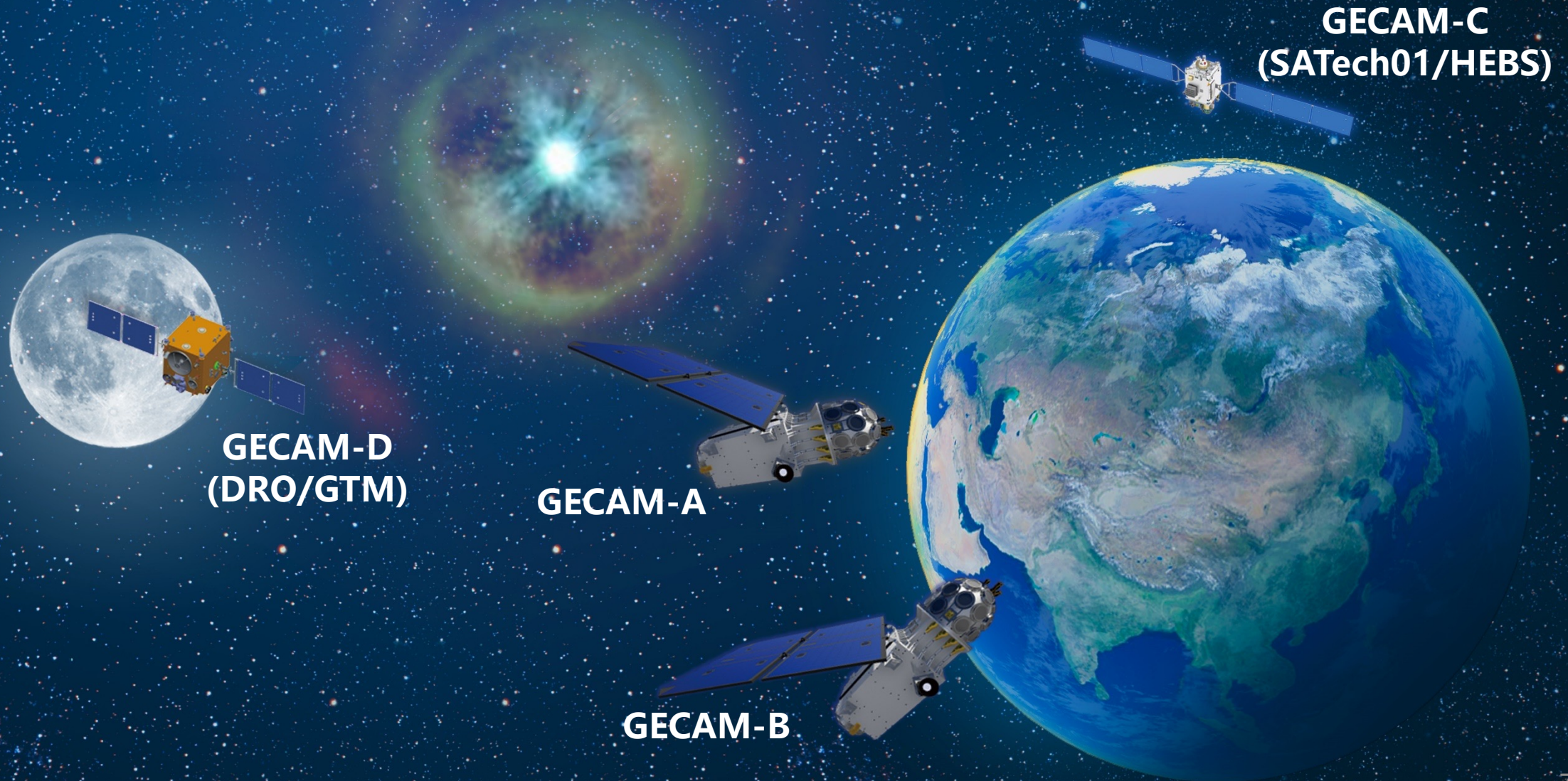
GECAM-A/B launched from Xichang Satellite Launch Center (XSLC) on Dec. 10, 2020



GECAM-C onboard SATech-01 launched from Jiuquan Satellite Launch Center on Jul. 27, 2022



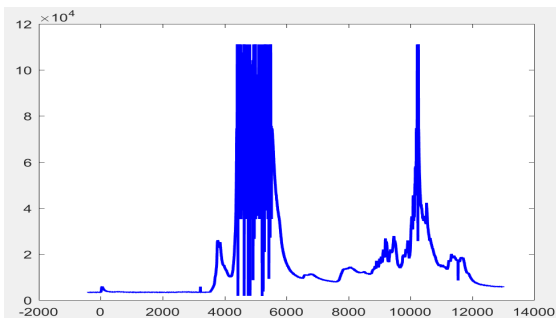
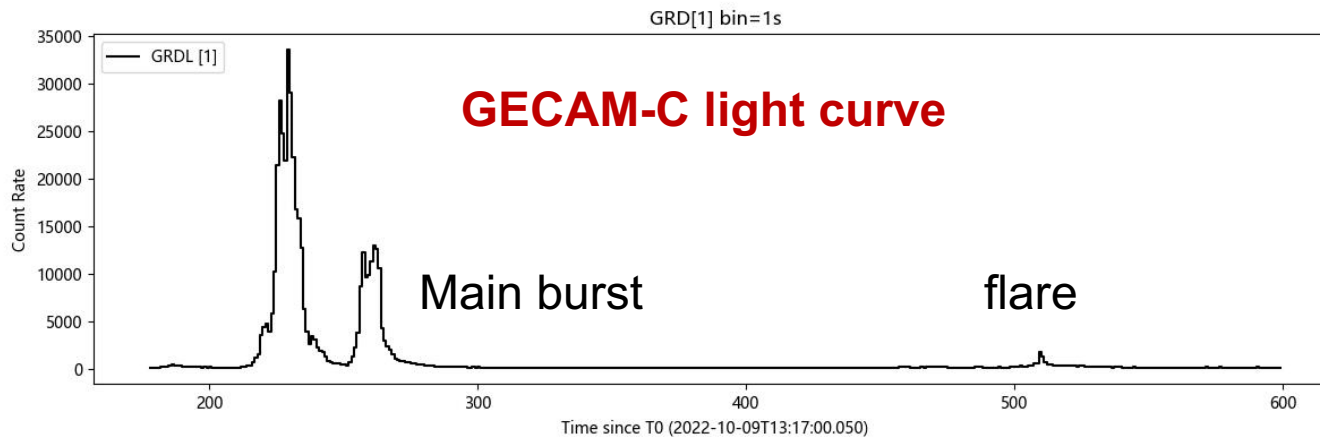
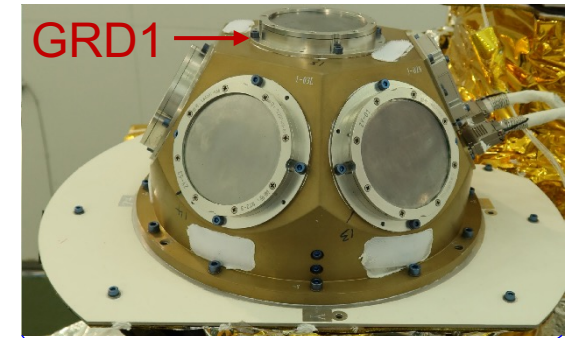
# GECAM Constellation



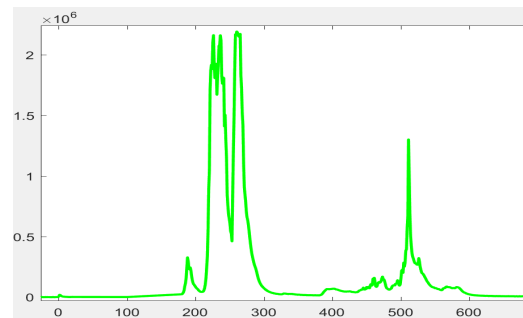


# GECAM-C observation of GRB 221009A

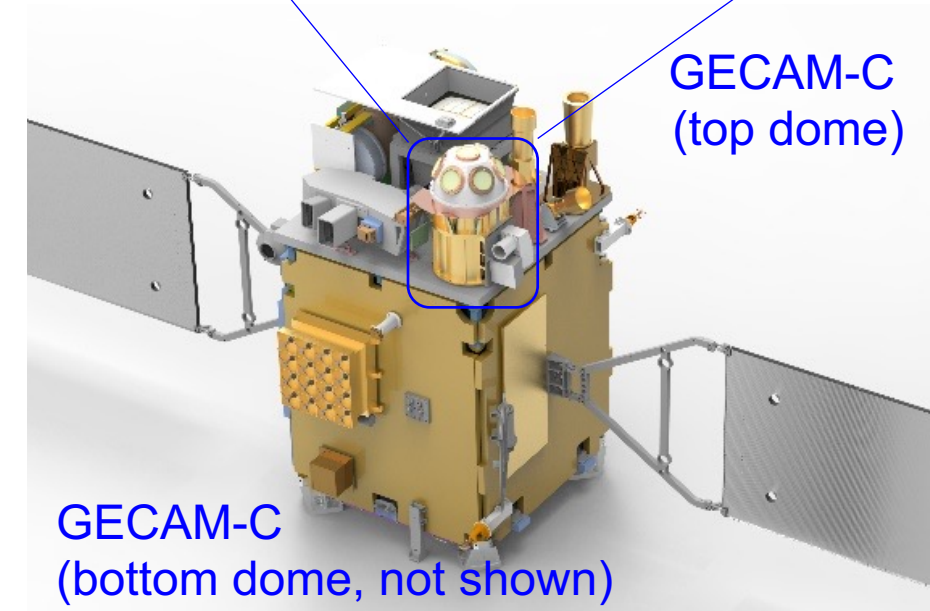
- This GRB arrived **~2 months** after the launch of GECAM-C and when the in-flight operation of GECAM-C was optimized
- GECAM-C provided the **uniquely accurate and high temporal and spectral resolution** measurement of the main burst part



**Fermi/GBM**



**INTEGRAL/SPI-ACS**



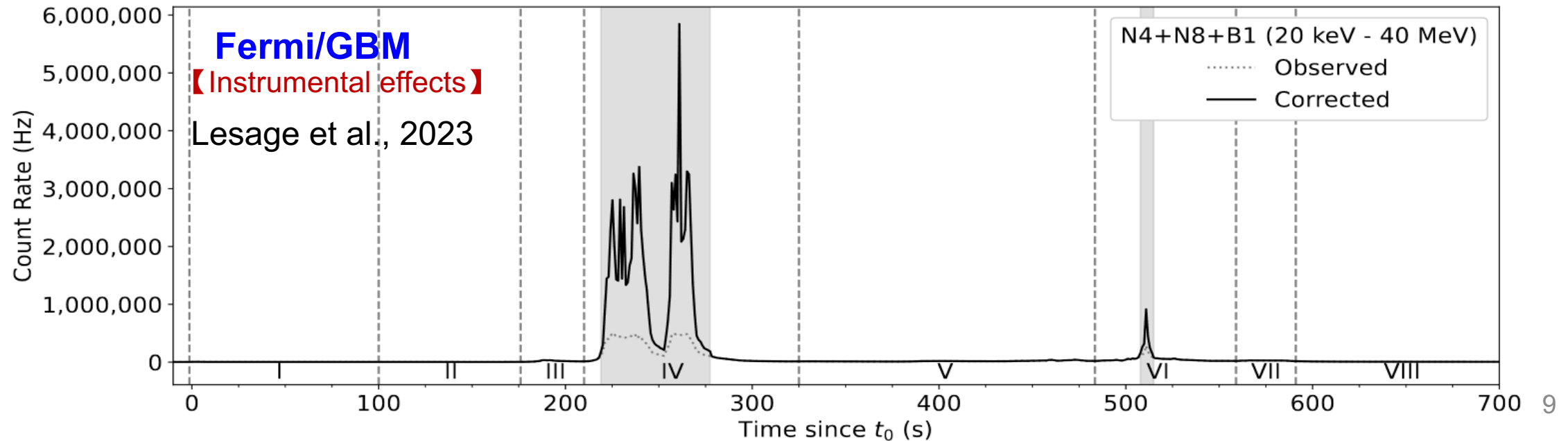
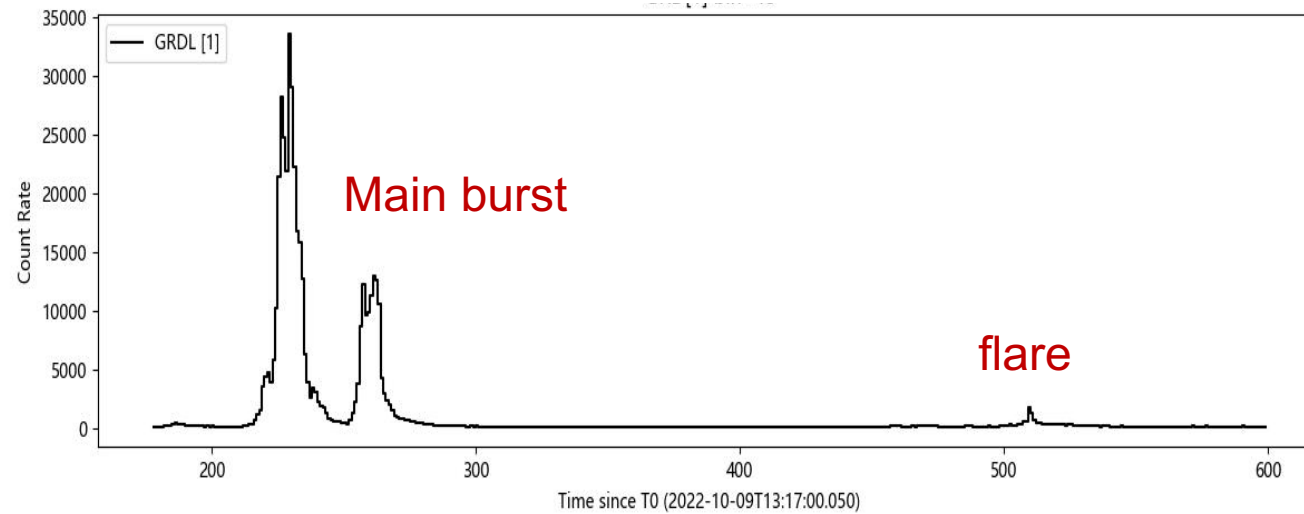
SATech-01 satellite  
(2022/7/27-2025/2/22)



# GECAM vs. Fermi/GBM

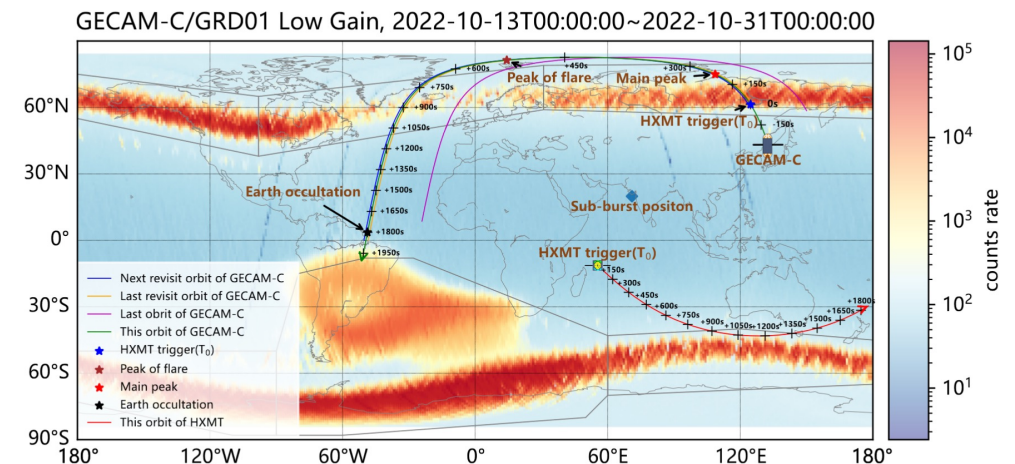
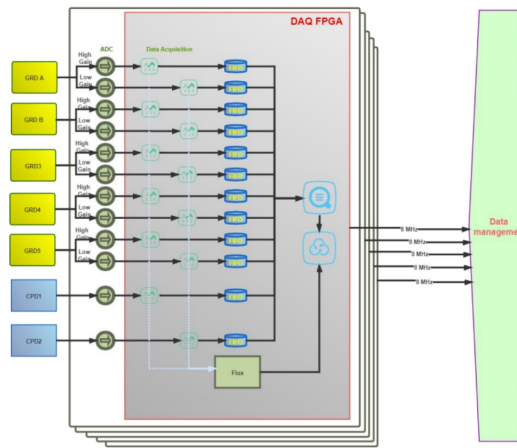
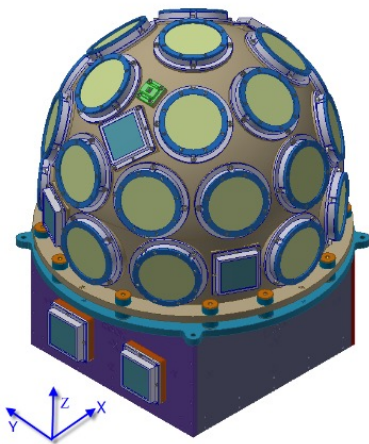
**GECAM-C**

【No instrumental effects】



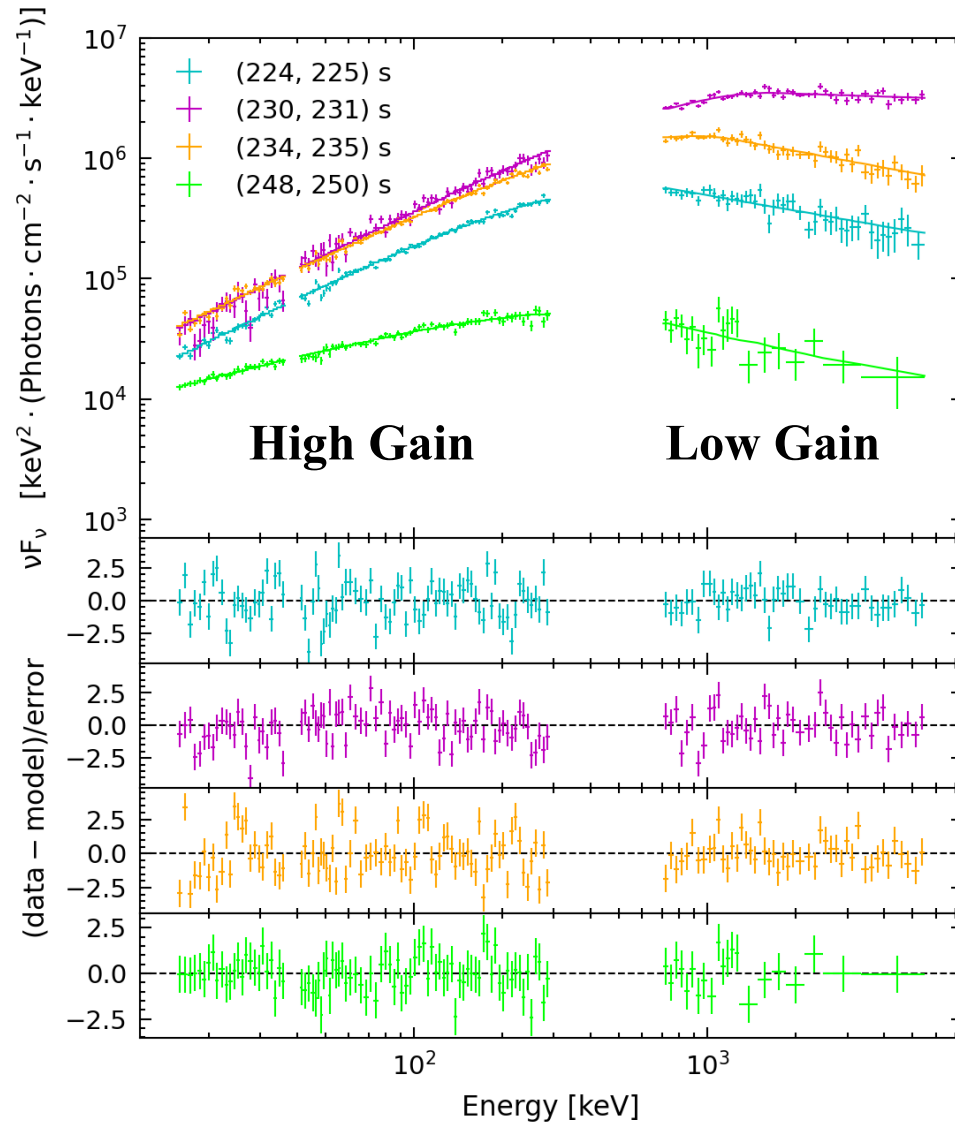
# Why GECAM-C?

- **Design:** GECAM is dedicated for detecting bright burst
  - **Instrument design:** novel designs on detector and readout electronics, lessons learned from previous missions
  - **Observation mode:** turn off all but one detector during the high latitude region for catching the bright burst
- **Fortune:** GRB 221009A was just on the right time and location
  - GECAM-C was in the high latitude region but with low background
    - the novel observation mode was executed → eliminate the data saturation
    - the main burst is not contaminated by the background
  - Not occulted by the Earth

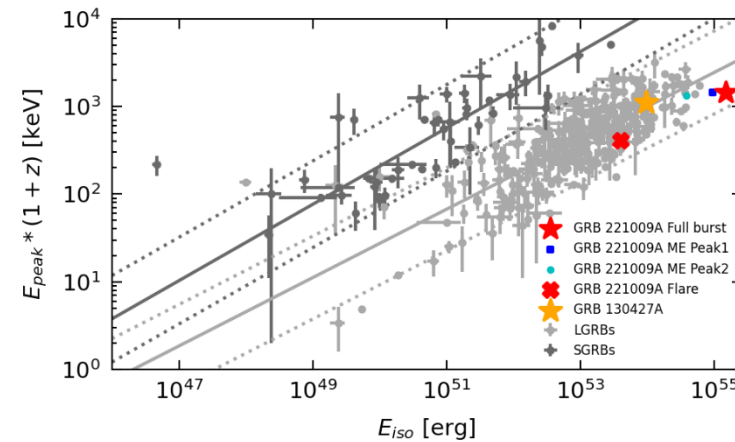
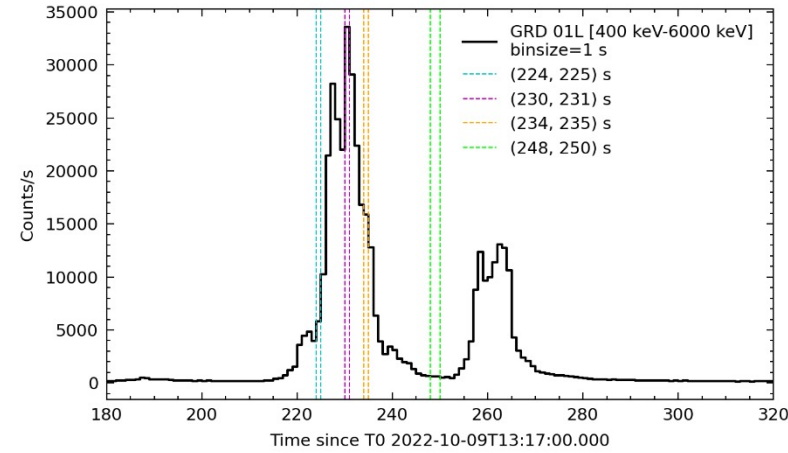




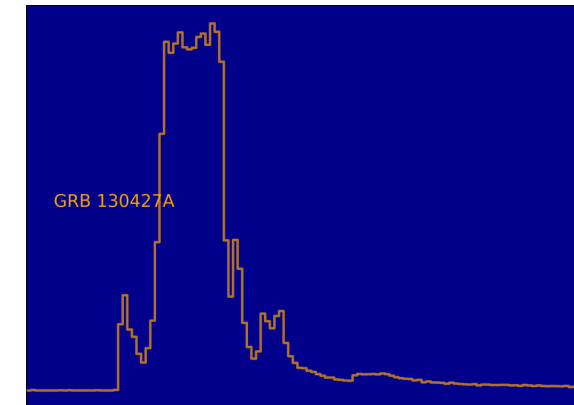
# GECAM-C accurate measurement of spectrum



Z.-H. An et al., 2023

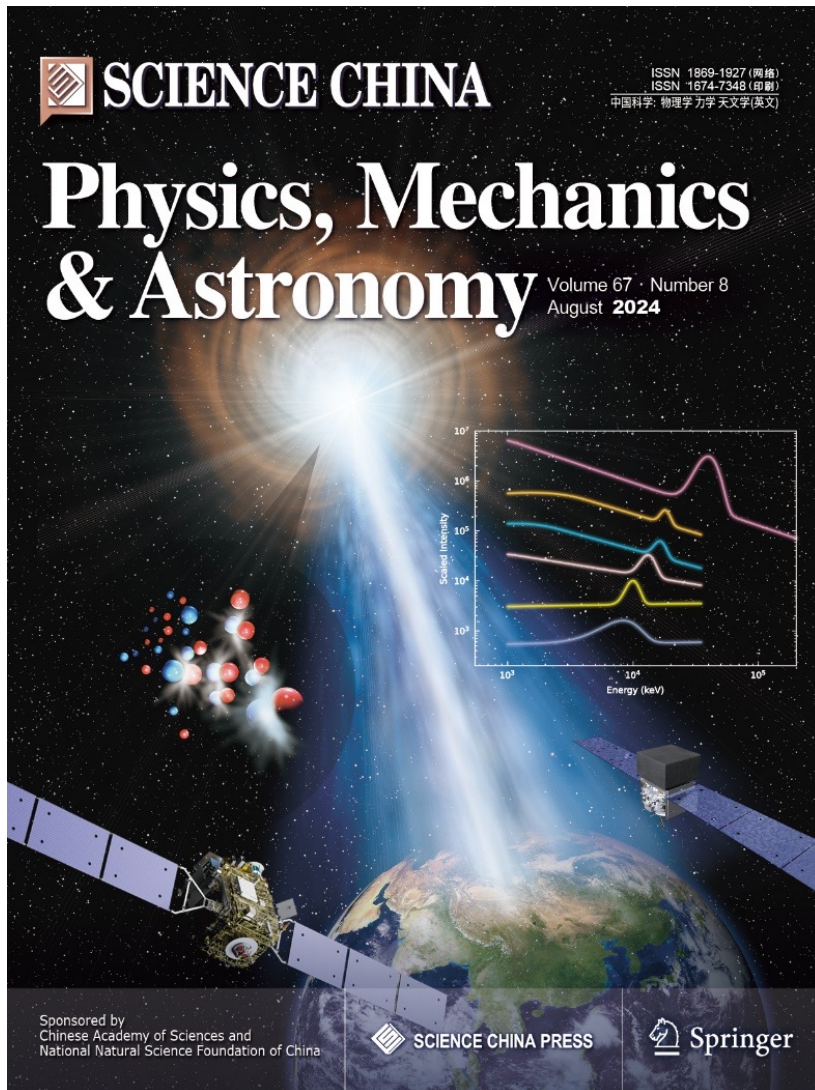


$E_{iso} \sim 1.5 \times 10^{55}$  erg  
Set new record of GRBs!



Credit: Y.Q. Zhang

# MeV emission line in GRB 221009A



SCIENCE CHINA  
Physics, Mechanics & Astronomy



• Article •

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<https://doi.org/10.1007/s11433-023-2381-0>

## Observation of spectral lines in the exceptional GRB 221009A

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Chao Zheng<sup>1,2</sup>, Jia-Cong Liu<sup>1,2</sup>, Zhen Zhang<sup>1</sup>, Xi-Lu Wang<sup>1</sup>, Ming-Yu Ge<sup>1</sup>, Shu-Xu Yi<sup>1</sup>,  
Li-Ming Song<sup>1</sup>, Zheng-Hua An<sup>1</sup>, Ce Cai<sup>6</sup>, Xin-Qiao Li<sup>1</sup>, Wen-Xi Peng<sup>1</sup>, Wen-Jun Tan<sup>1,2</sup>,  
Chen-Wei Wang<sup>1,2</sup>, Xiang-Yang Wen<sup>1</sup>, Yue Wang<sup>1,2</sup>, Shuo Xiao<sup>7</sup>, Fan Zhang<sup>1</sup>,  
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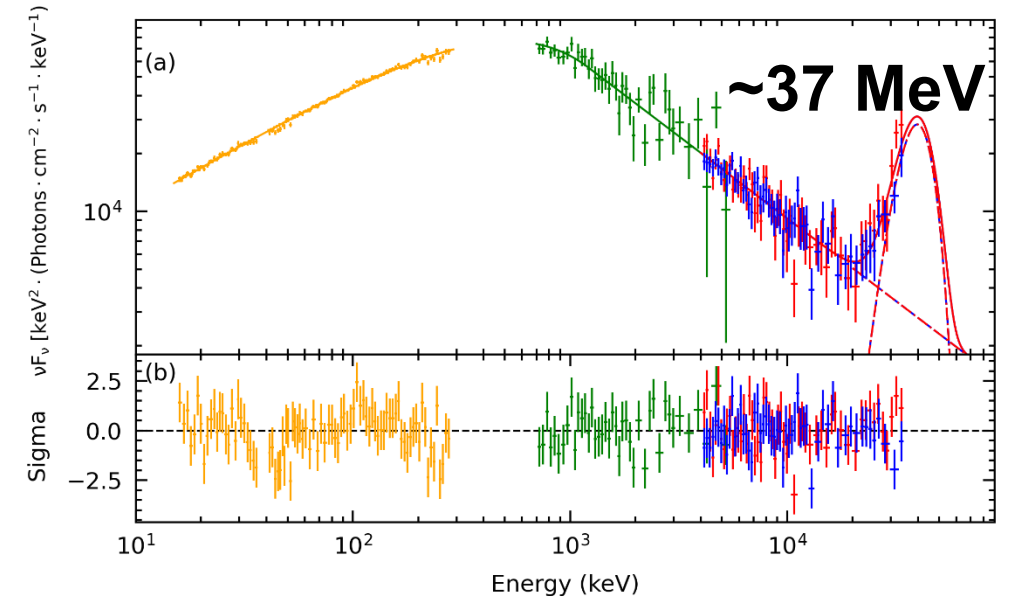
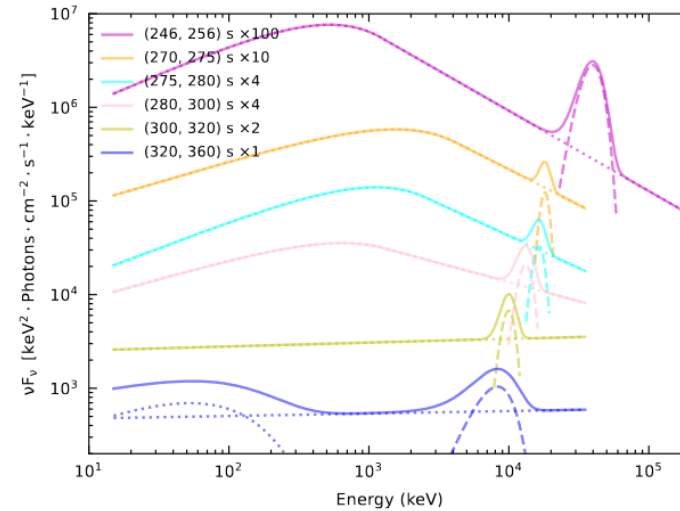
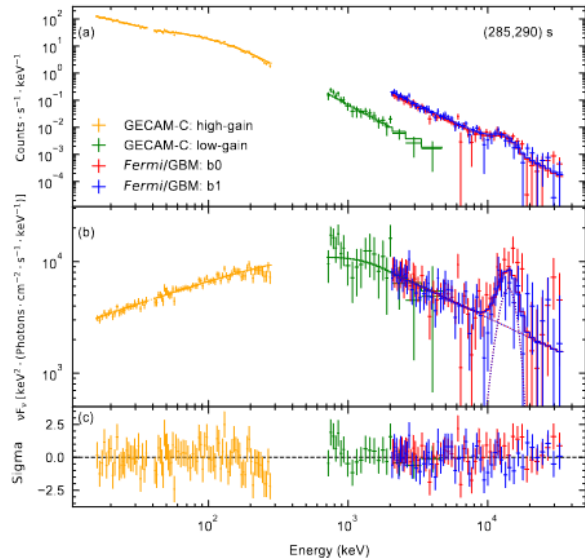
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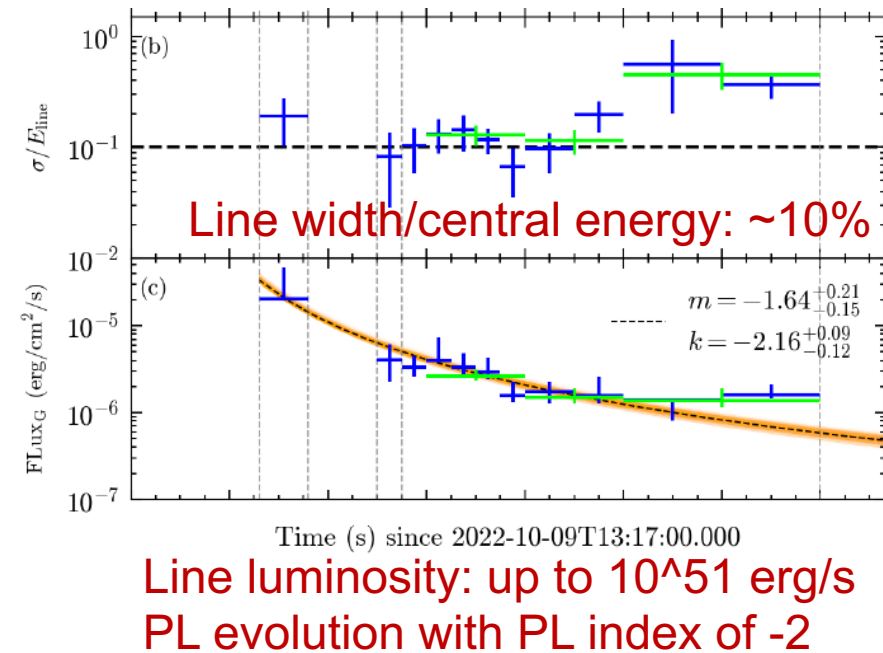
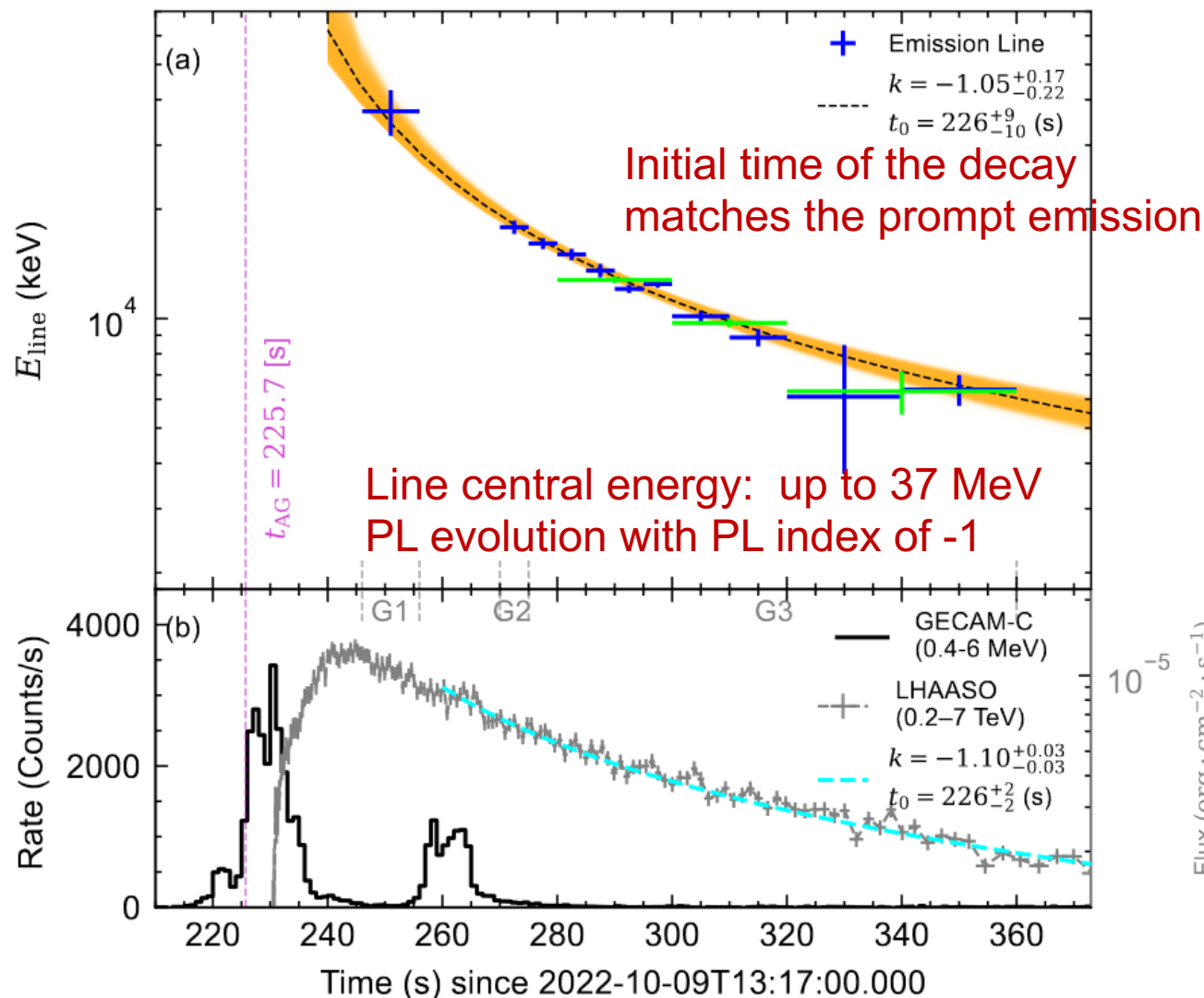


# Reveal the full picture of MeV emission line

- We started the **spectral analysis** and **line search** of GRB 221009A immediately after the GECAM-C detection
- We did joint spectral analysis with **GECAM-C** and **Fermi/GBM** data, and GECAM-C provided a benchmark for the **bright part** of this burst where Fermi/GBM suffered issues, allowing us to **explore the line features for whole burst**
- We **independently found spectral excess features** and did comprehensive background, instrumental effects and cross calibration studies to ensure reliable analysis of the continuum thus reliable identification of the emission line
- We identified a series of emission lines from **37 MeV to 6 MeV**, whose energy and flux evolve in **power-law decay** as function of time, revealing **crucial feature** and **solid evidence for the GRB origin of these lines**



# Discovery of power-law decay of the MeV lines



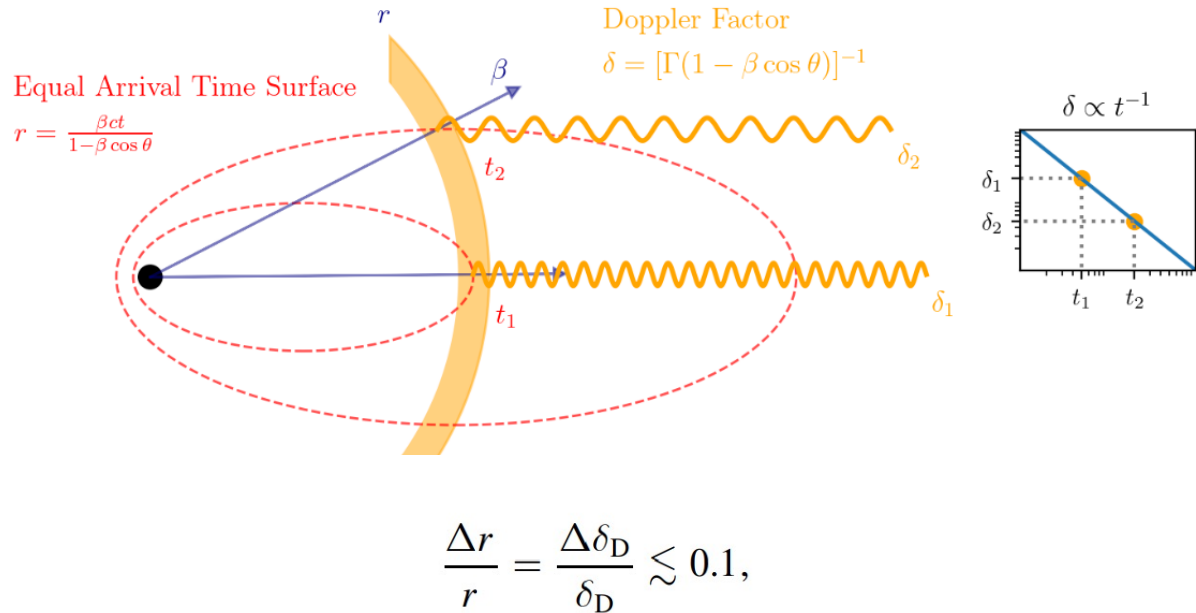
## Preliminary Interpretations

- Doppler boosted  $e^\pm$  pair annihilation 511 keV is the most natural and probable scenario
- Line energy PL index of -1 supports the high latitude effect but the HLE of a uniform jet is disfavored by the line flux PL index of -2
- Jet dynamics is possible, then an unusual  $\Gamma \sim t^{-1}$

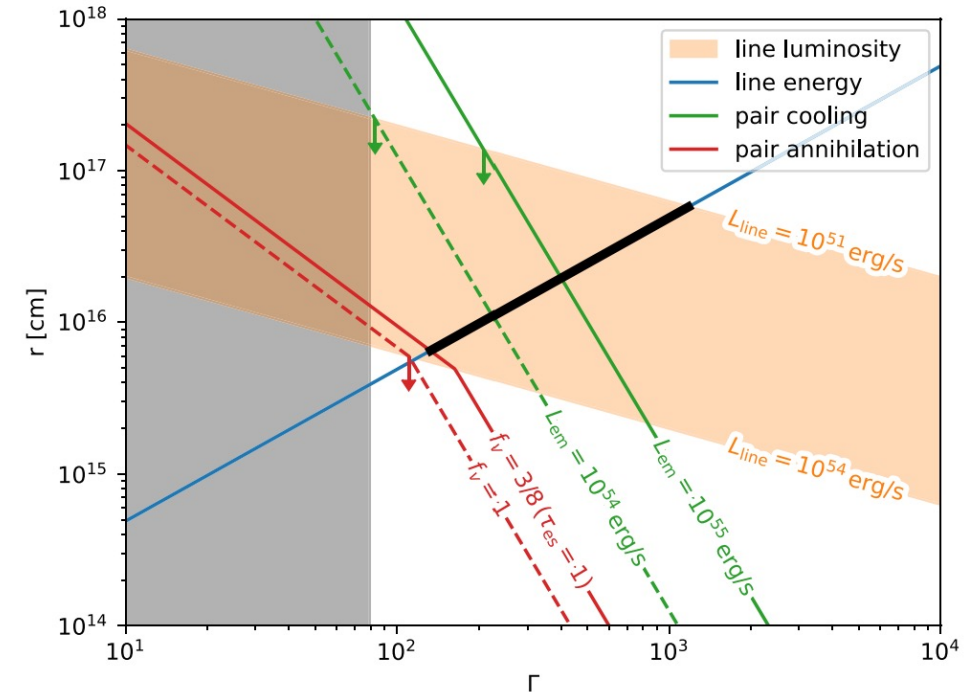


# Interpretation of the MeV line

attempted to explain **all observed features** of the line

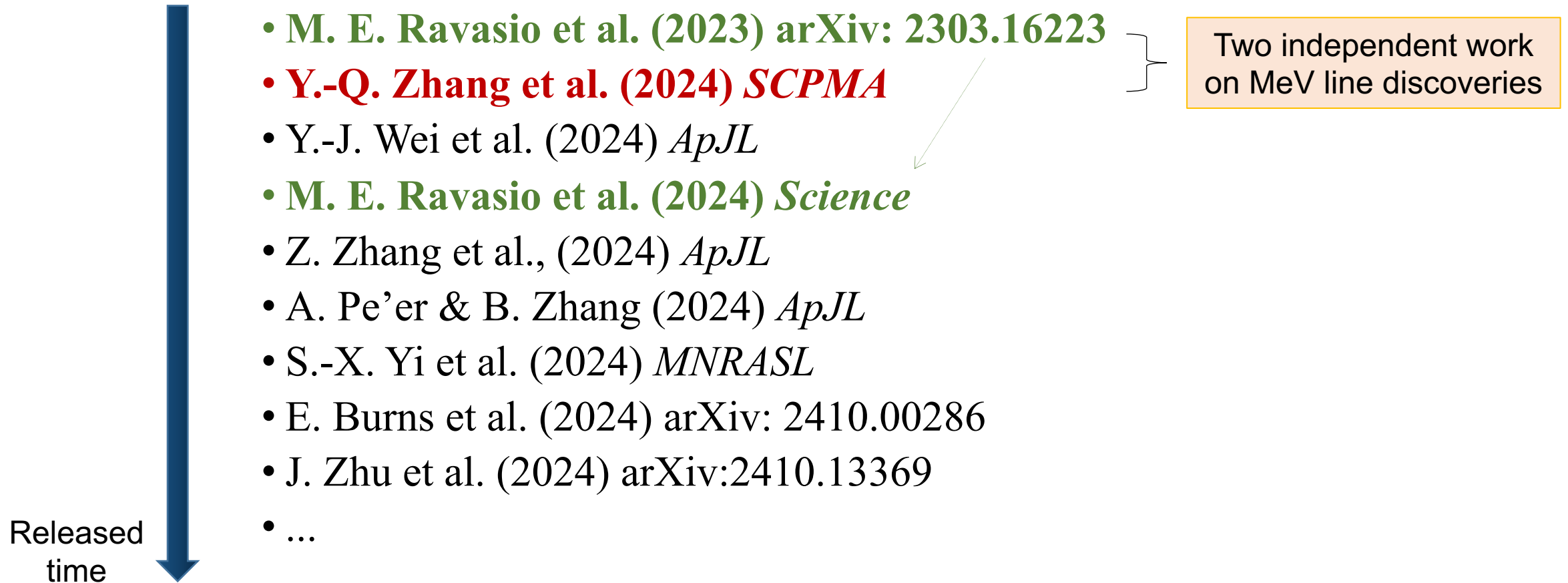


Pair annihilation 511 keV → Doppler effect boosted to MeV  
 High latitude effect → Line energy evolves as  $t^{-1}$



Constraints on the Lorentz factor and emission radius with line measurements

# Hot discussions/debates on the interpretation of the MeV line in GRB 221009A





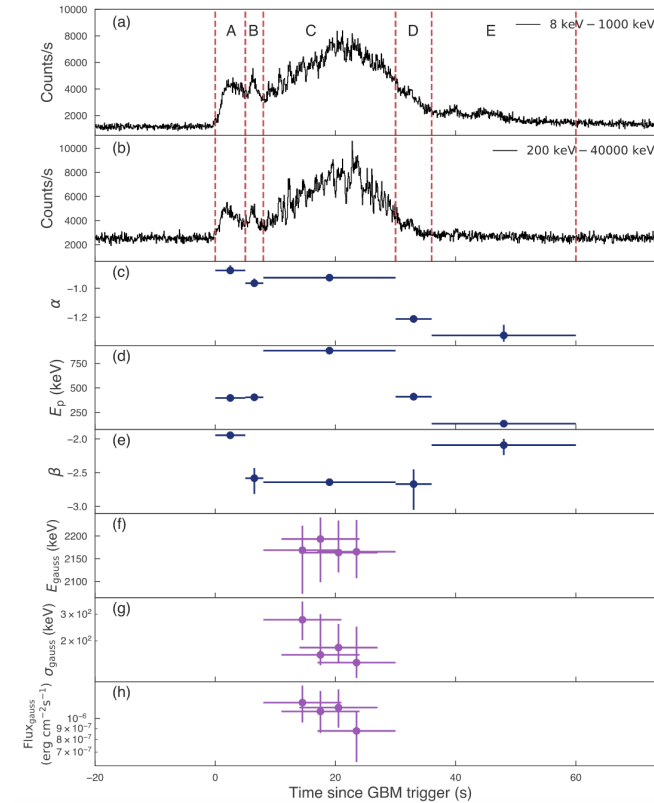
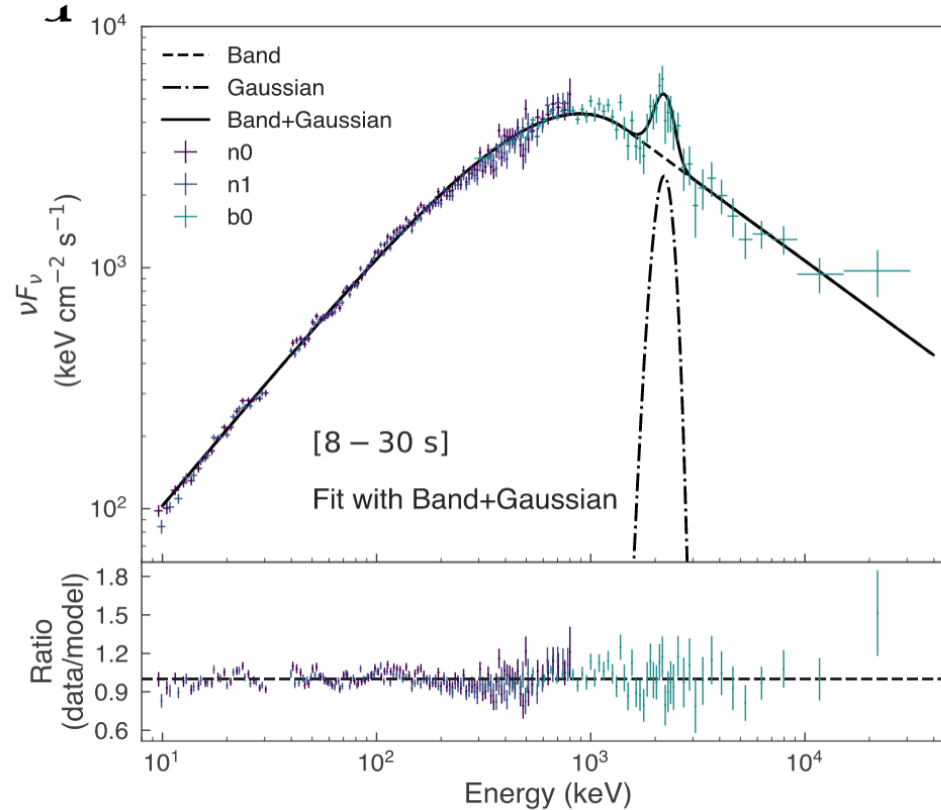
# GRB 221013A

L.-Y. Jiang et al., (2025) Nature Communications

**~2.2 MeV**

**No evidence of evolution**

**No redshift measurement**



- Interpretation in L.-Y. Jiang et al., (2025): de-excitation of excited electrons in the relativistic hydrogen-like high-atomic-number ions entrained in the GRB jet
- 2.2 MeV is a known line from instrumental effect of Fermi/GBM (Meegan et al. 2009 ApJ)
- Emission lines around 2.2. MeV are also found in other GRBs (T.-L. Liao et al. 2025 ApJ)

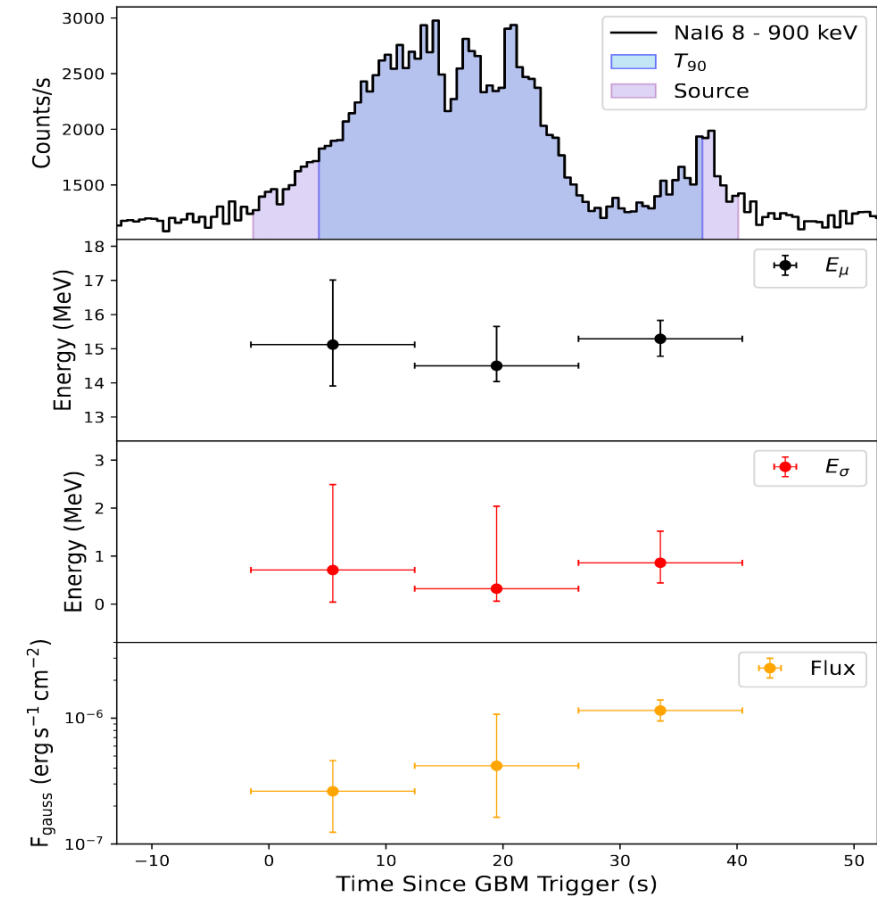
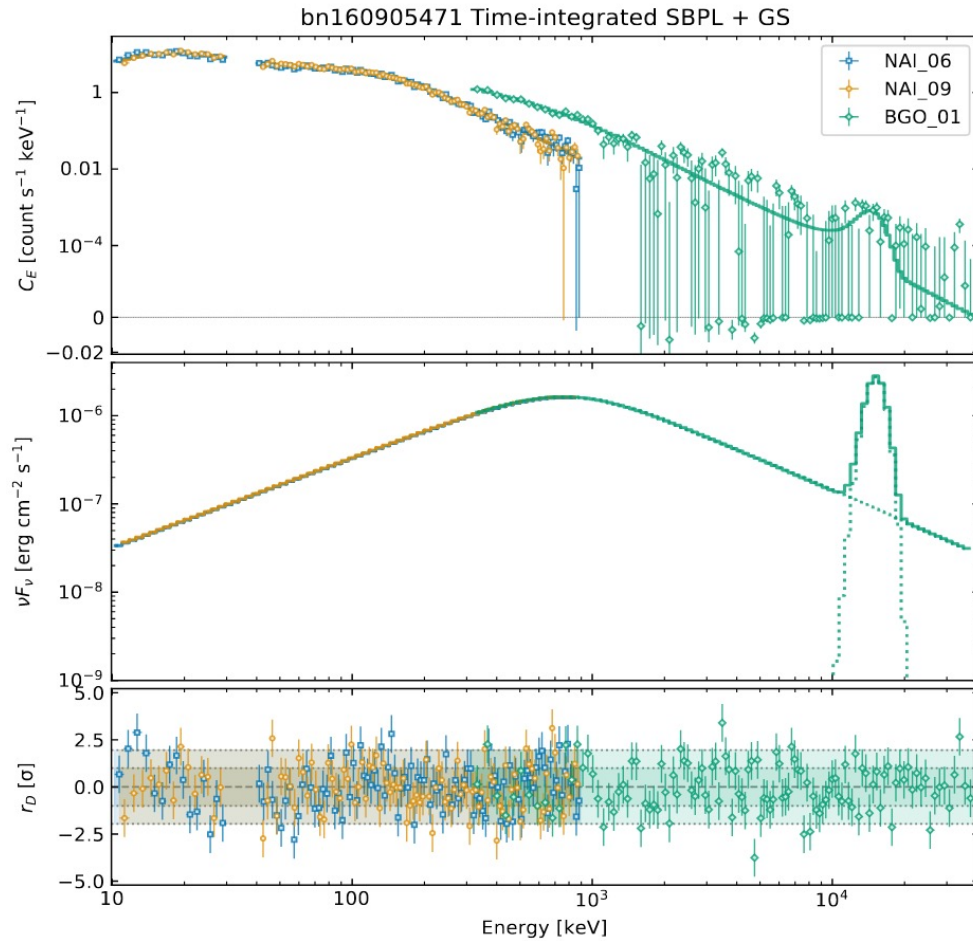
# GRB 160905A

T.-L. Liao et al. (2025) *ApJL*

~15 MeV ( $2.6 \sigma$ )

No evidence of evolution

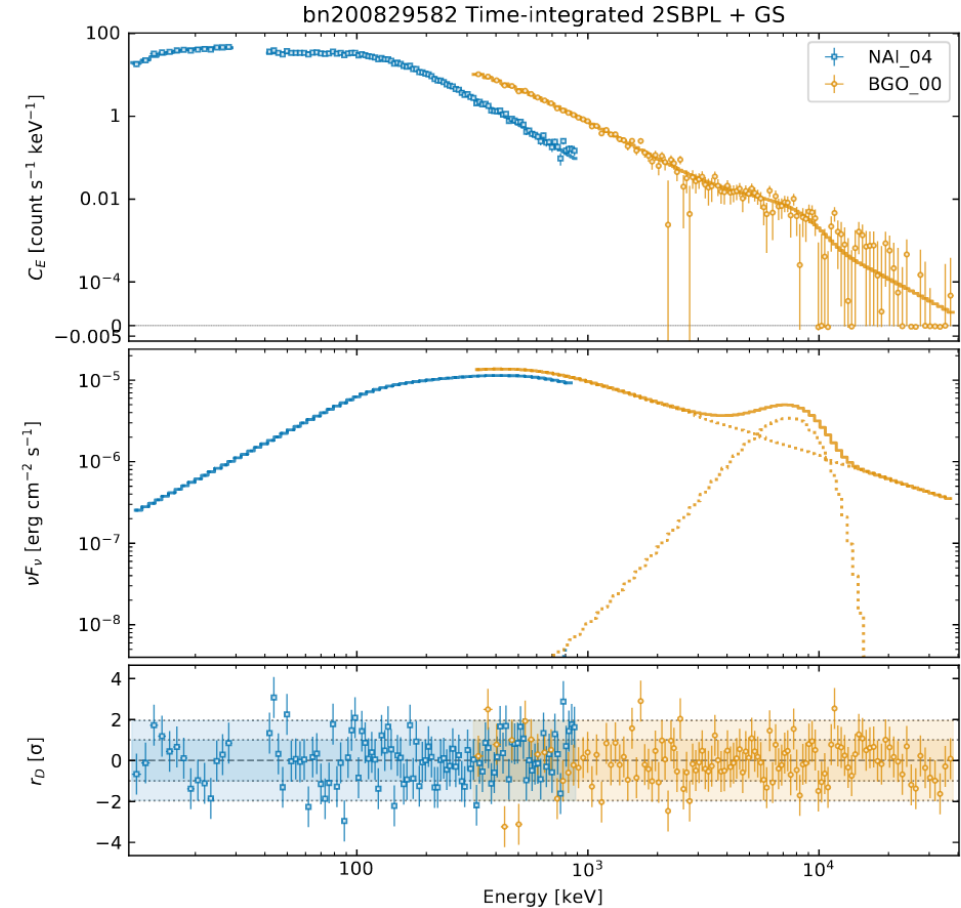
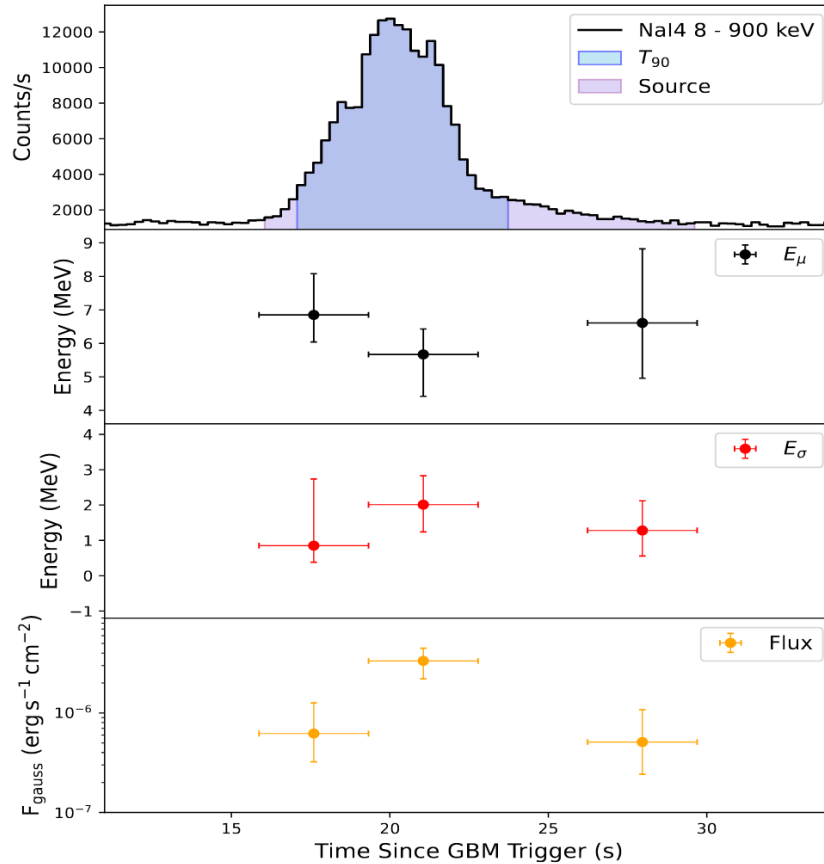
No redshift measurement





# GRB 200829A

T.-L. Liao et al. (2025) *ApJL*



- $\sim 6$  MeV ( $3.2 \sigma$ ), no evidence of evolution, unlike the case of GRB 221009A
- redshift  $z = 1.25 \rightarrow$  rest frame line energy  $\sim 13.5$  MeV, similar to that of GRB 221009A ( $z = 0.151$ )

# Summary

- **GECAM is composed of four monitors on different spacecrafts**
  - GECAM-A/B (2020 Dec.), GECAM-C (2022 July), GECAM-D (2024 March)
- **Dedicated designs make GECAM very powerful in observation of extremely bright GRBs, e.g. GRB 221009A, GRB 230307A**
  - Anti-data saturation, reduce pulse pileup, less systematics in detector response
- **Discoveries of MeV emission lines in GRB 221009A**
  - Brightest GRB ever, great opportunity to search for spectral line
  - GECAM-C accurate measurement without instrumental effects + Fermi/GBM
  - Reveal a striking power-law evolution of MeV lines from 37 MeV to 6 MeV
- **After this, several candidate MeV lines are reported in other GRBs**
- **Many theoretical models have been proposed to interpret these lines, and the debate is ongoing**

Thank you!



# backup