A bright electron-positron annihilation line in the BOAT GRB221009A

报告人：张镇

ZZ*, H. Lin*, Z. Li*, S.–L. Xiong* et al., **ApJL**, 2405.12977

S.–X. Yi*, **ZZ***, et al., **MNRAS**, 2409.08485

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Discoveries of γ-ray lines in GRB 221009A

❑ M. E. Ravasio et at. 2023, 2024

12 MeV ↘ 6 MeV

M.E. Ravasio et al. (2023) arXiv

[astro-ph.HE] 28 Mar 2023

A bright megaelectronvolt emission line in γ-ray burst GRB 221009A

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RESEARCH ARTICLE | GAMMA-RAY BURSTS

A mega–electron volt emission line in the spectrum of a gamma-ray burst

MARIA EDVIGE RAVASIO, OM SHARAN SALAFIA, GOR OGANESYAN, ALESSIO MEI, GIANCARLO GHIRLANDA, STEFANO ASCENZI, BISWAJIT BANERJEE, SAMANTA MACERA, MARICA BRANCHESI, [...], AND GABRIELE GHISELLINI +6 authors Authors Info & Affiliations

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M.E. Ravasio et al. (2024)

❑ Y. Q. Zhang et at. 2024

37 MeV ↘ 6 MeV

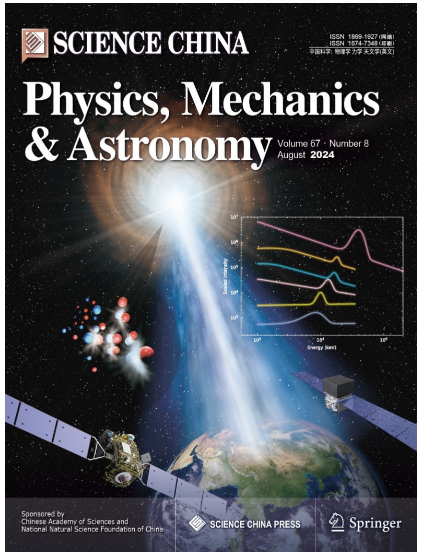
Power-law evolution of line energy and flux

SCIENCE CHINA
Physics, Mechanics & Astronomy
CrossMark
• Article •
August 2024 Vol. 67 No. 8: 289511
https://doi.org/10.1007/s11433-023-2381-0

Y.-Q. Zhang et al. (2024)

Observation of spectral lines in the exceptional GRB 221009A

Yan-Qiu Zhang[1,2], Shao-Lin Xiong[1*], Ji-Rong Mao[3,4,5*], Shuang-Nan Zhang[1*], Wang-Chen Xue[1,2], Chao Zheng[1,2], Jia-Cong Liu[1,2], Zhen Zhang[1], Xi-Lu Wang[1], Ming-Yu Ge[1], Shu-Xu Yi[1], Li-Ming Song[1], Zheng-Hua An[1], Ce Cai[6], Xin-Qiao Li[1], Wen-Xi Peng[1], Wen-Jun Tan[1,2], Chen-Wei Wang[1,2], Xiang-Yang Wen[1], Yue Wang[1,2], Shuo Xiao[7], Fan Zhang[1], Peng Zhang[1,8], and Shi-Jie Zheng[1]



Highest-energy γ-ray line firmly detected in the universe!

伽马暴观测研究里程碑！我国科学家发现宇宙迄今最高能量伽马谱线

央视新闻客户端 | 2024–07–25 11:25:14 浏览量639931

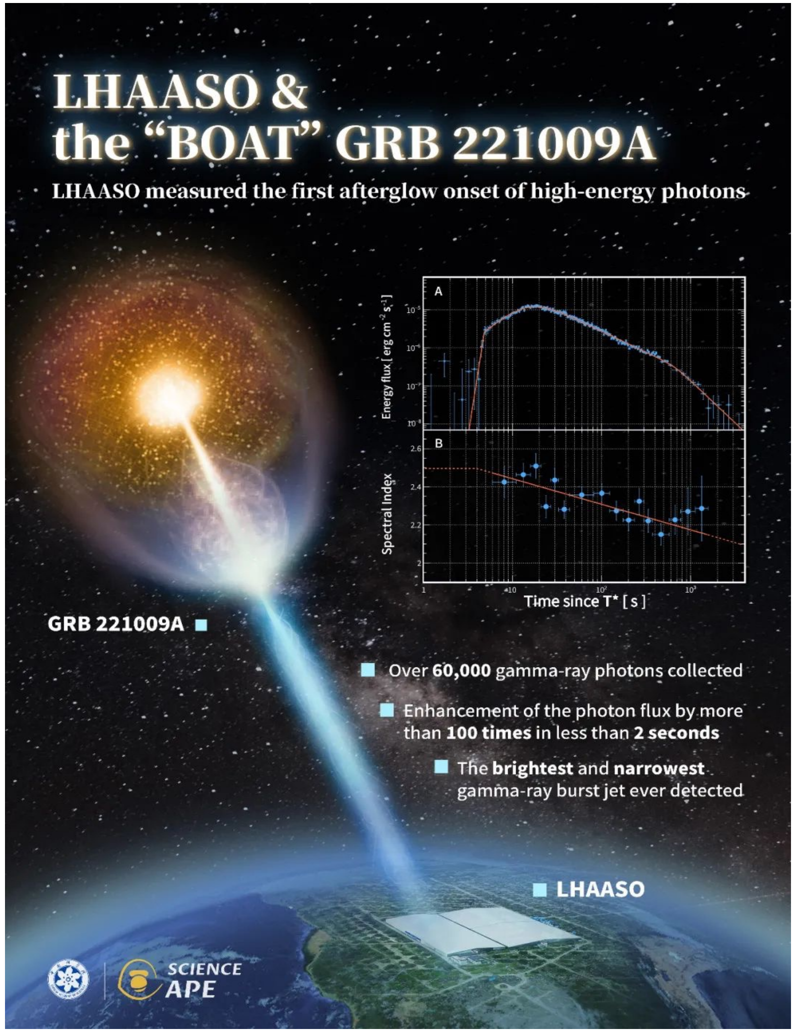
记者今天（25日）从中国科学院高能物理研究所获悉，近日，该所牵头的科研团队，通过分析极目空间望远镜和费米卫星的联合观测数据，在伽马暴中发现能量高达**37兆电子伏特的伽马射线谱线**，且谱线的能量和光度均以幂律形式演化，**这是迄今观测到的宇宙天体产生的能量最高、证据最确凿的谱线**。这些发现为破解伽马暴及相对论性喷流产生之谜**提供了全新的重要线索，是伽马暴观测研究的里程碑**。相关研究成果7月25日以封面论文形式在《中国科学：物理学 力学 天文学》（英文版）期刊正式发表。

Brightest-of-all-time (BOAT) GRB 221009A

- ❑ GECAM-C/HXMT/Fermi-GBM:
  main burst (keV-MeV-sub GeV)
  - this burst is so bright that the Fermi–GBM detector suffered significant data loss and pile–up effect during the bright part of the burst, making reliable data analysis very difficult. (HXMT & GECAM 2024)
  - Fortunately, GECAM–C did not experience such problems thanks to its dedicated design of the instrument; thus, the GECAM–C data was used to correct the Fermi/GBM data. (Y.-Q. Zhang et al. 2024)
- ❑ **LHAASO: TeV afterglow**
- ❑ MeV lines: **the biggest surprise in the prompt GRB spectra in at least a decade**

--- 第三届南京伽马射线暴国际会议

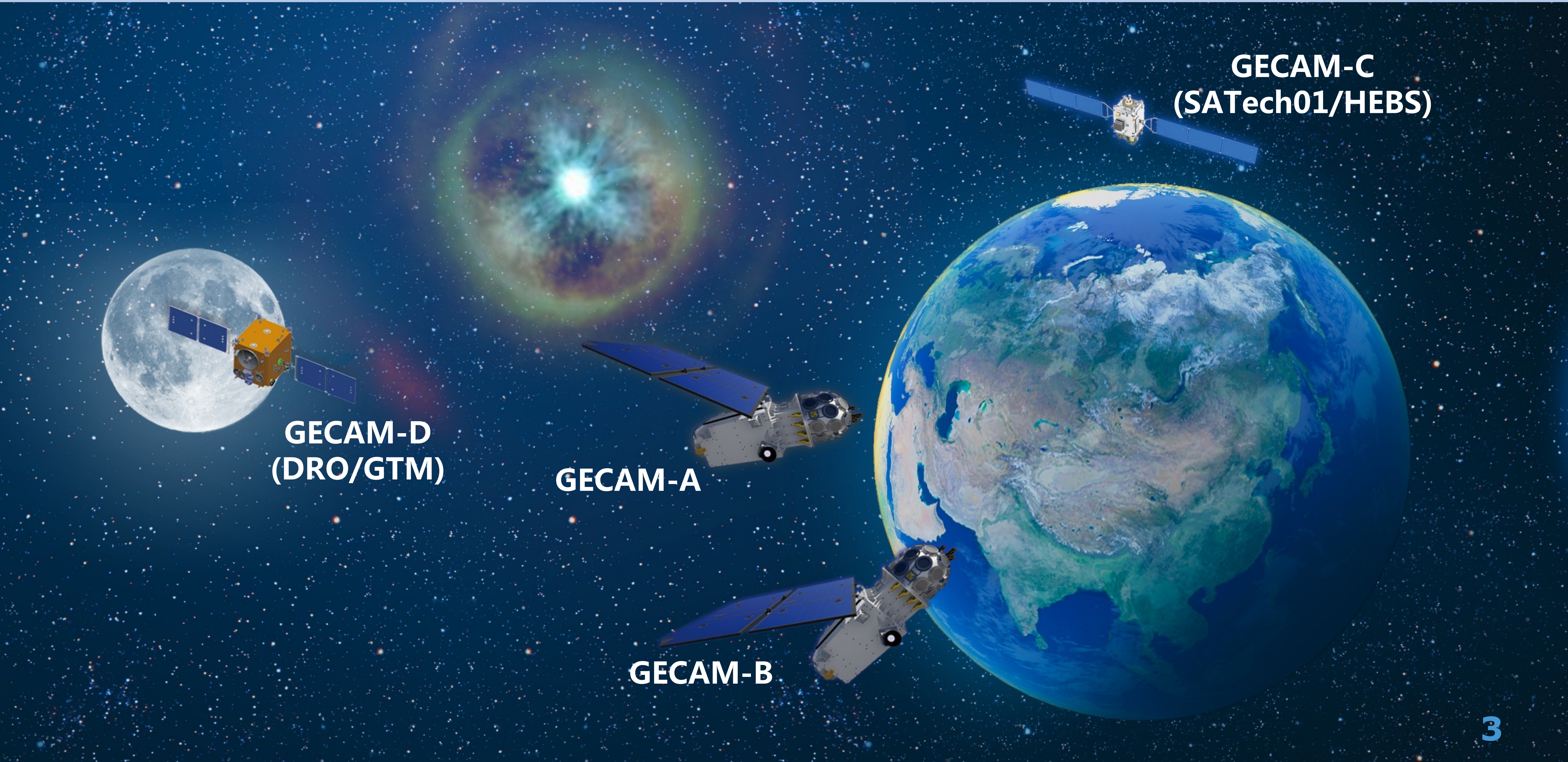
中国十大科学进展 (2023年)



LHAASO Collaboration* *Science* 380 (2023) 6652

GECAM

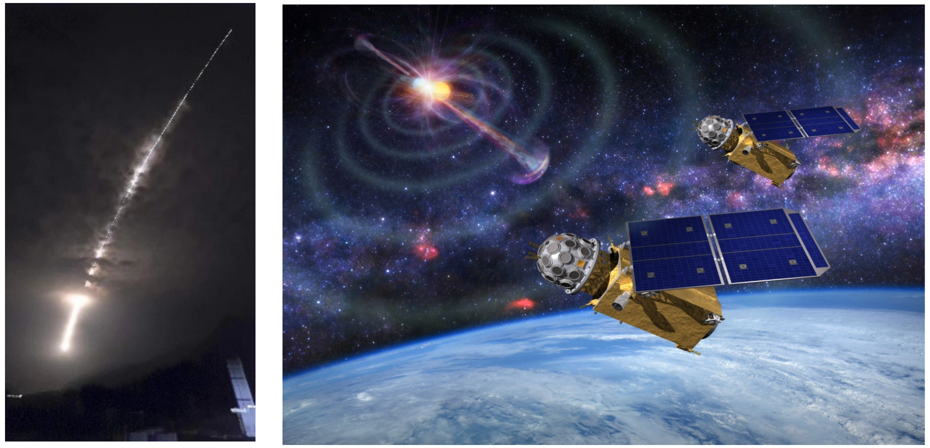
Gravitational wave high-energy Electromagnetic Counterpart All-sky Monitor



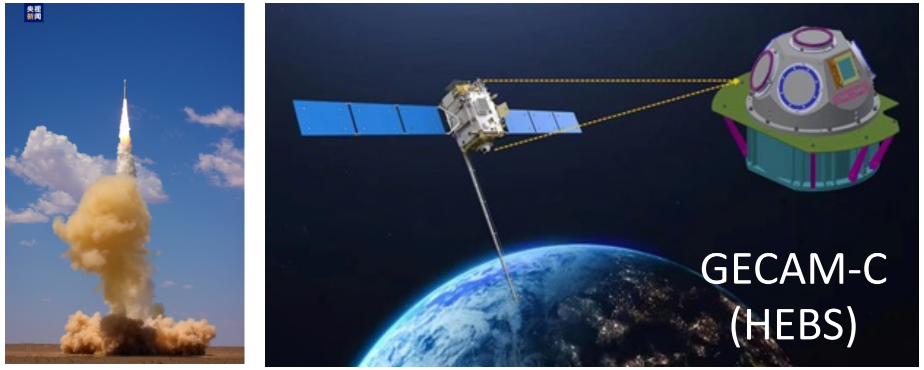
GECAM

Gravitational wave high-energy Electromagnetic Counterpart All-sky Monitor

- **GECAM twins → GECAM series**
  - GECAM-A: Dec. 10, 2020 **Few observation**
  - GECAM-B: Dec. 10, 2020 **Operation**
  - HEBS (GECAM-C): Jul. 27, 2022 **Operation**
  - DRO/GTM (GECAM-D): Mar. 13, 2024 **Commissioning**
- **GECAM detected many transients**
  - GRBs, SGRs, especially those associated with FRBs
  - Solar Flares, Terrestrial Gamma-ray Flashes & new type of events
- **Characteristics of GECAM series**
  - **FOV :** ~ 100% all-sky
  - **Energy band :** 6 keV – 5 MeV
  - **Sensitivity :** ~ 1E-8 erg/cm^2/s
  - **Localization :** ~2 deg (1-σ stat., 1E-5 erg/cm^2)



GECAM-A/B launched from the Xichang Satellite Launch Center (XSLC)

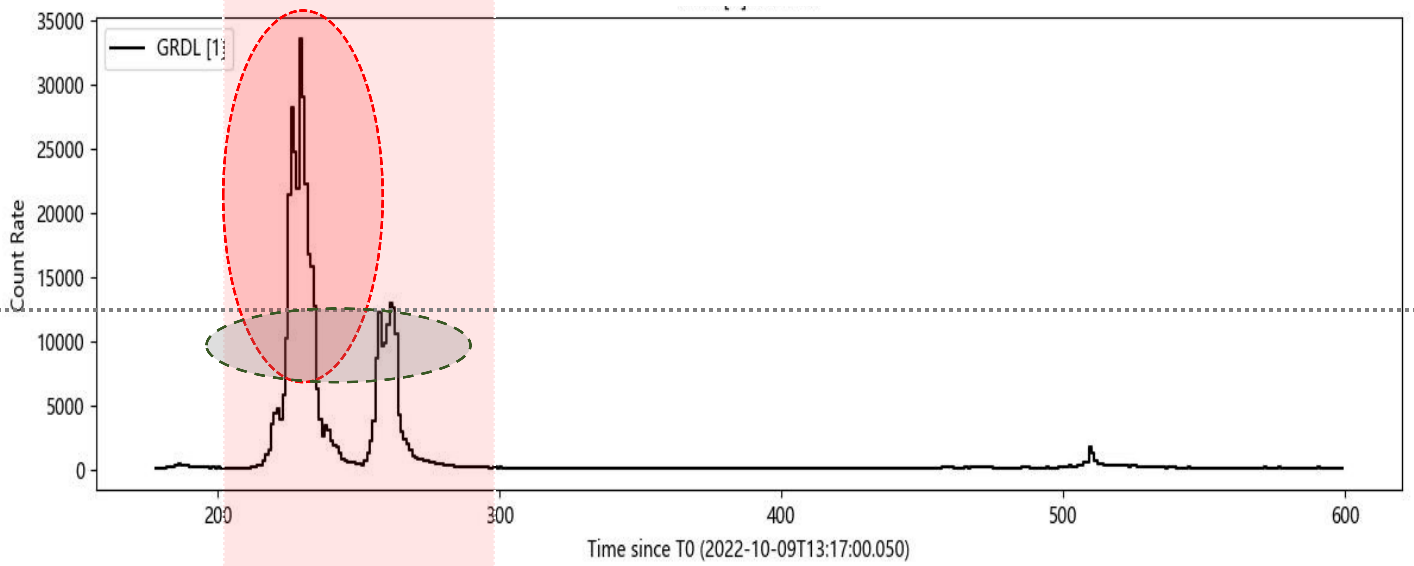


GECAM-C onboard SATech-01 launched from the Jiuquan Satellite Launch Center

Light Curve: GECAM vs. Fermi/GBM

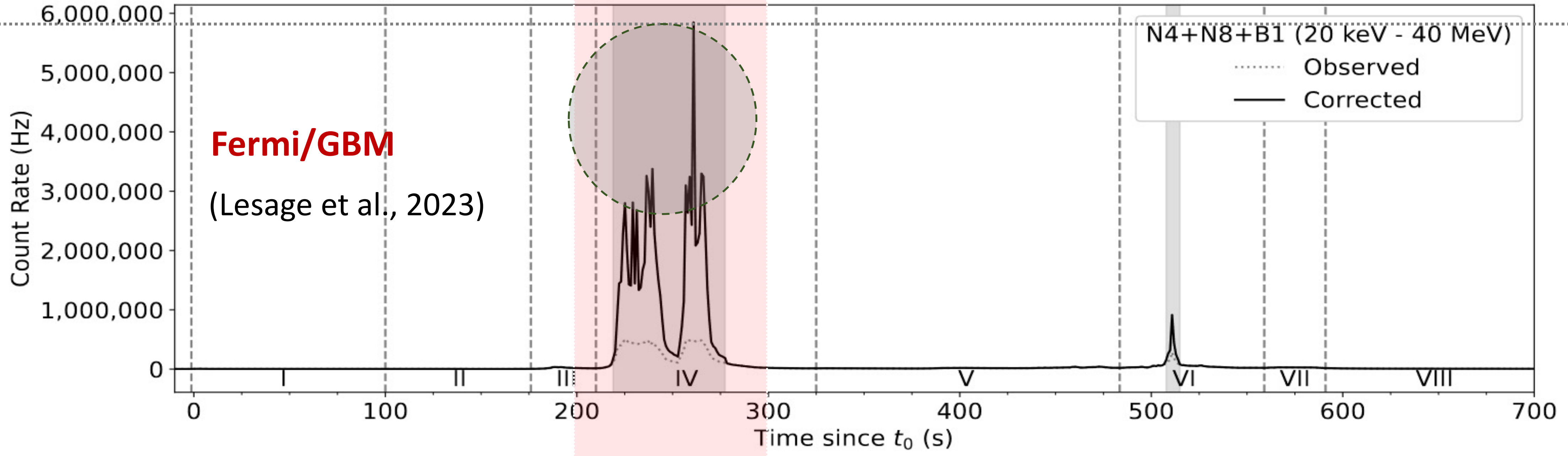
GECAM-C

No instrumental effects

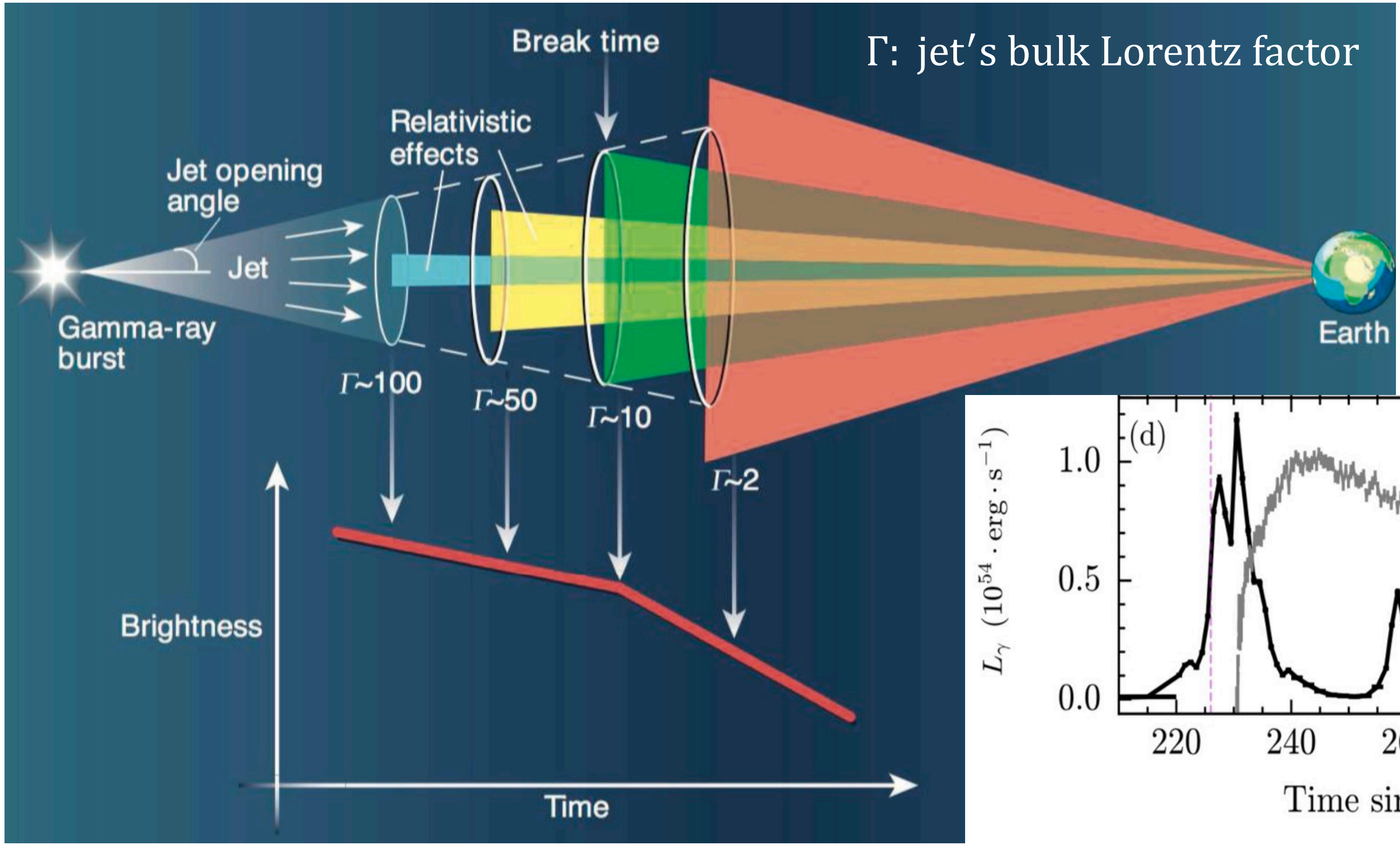


Fermi/GBM

(Lesage et al., 2023)



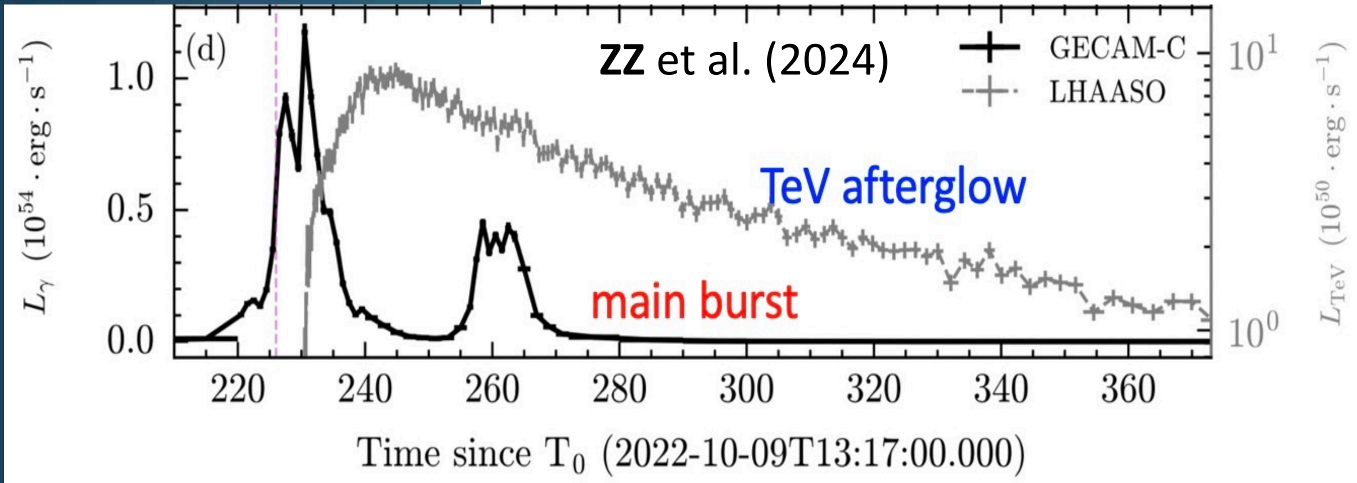
The global picture of γ-bursts (GRBs)



Jet structure:

→ **imprints** on main burst

$$\epsilon^*(\theta) = \frac{\mathrm{d}E_{\mathrm{line}}}{\mathrm{d}\Omega} = \begin{cases} \epsilon_0^* \left(\frac{\theta}{\theta_{\mathrm{jet}}}\right)^{-\alpha}, & \theta \leq \theta_{\mathrm{jet}}, \\ 0, & \theta > \theta_{\mathrm{jet}}, \end{cases}$$



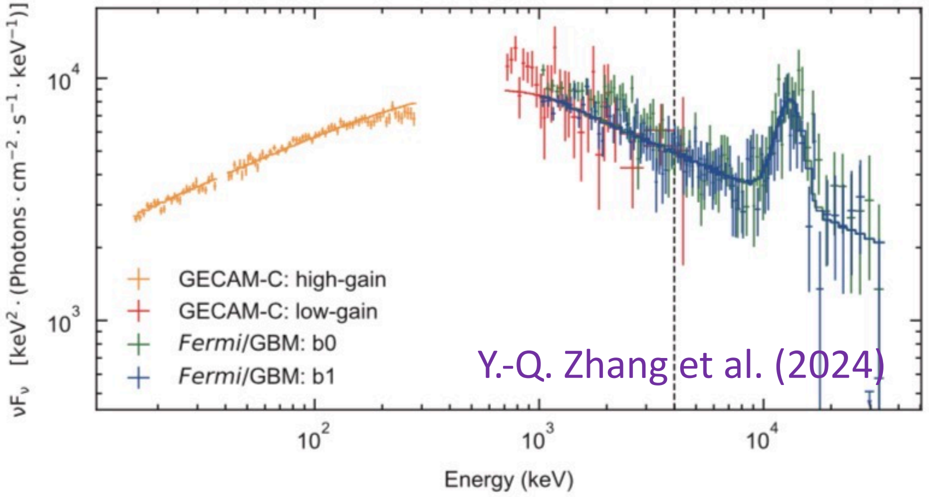
Synchrotron radiation (SR) Inverse Compton (IC) scattering

relativistic jet ⇒ e.g., internal shocks → main burst external shocks → TeV afterglow

数据分析

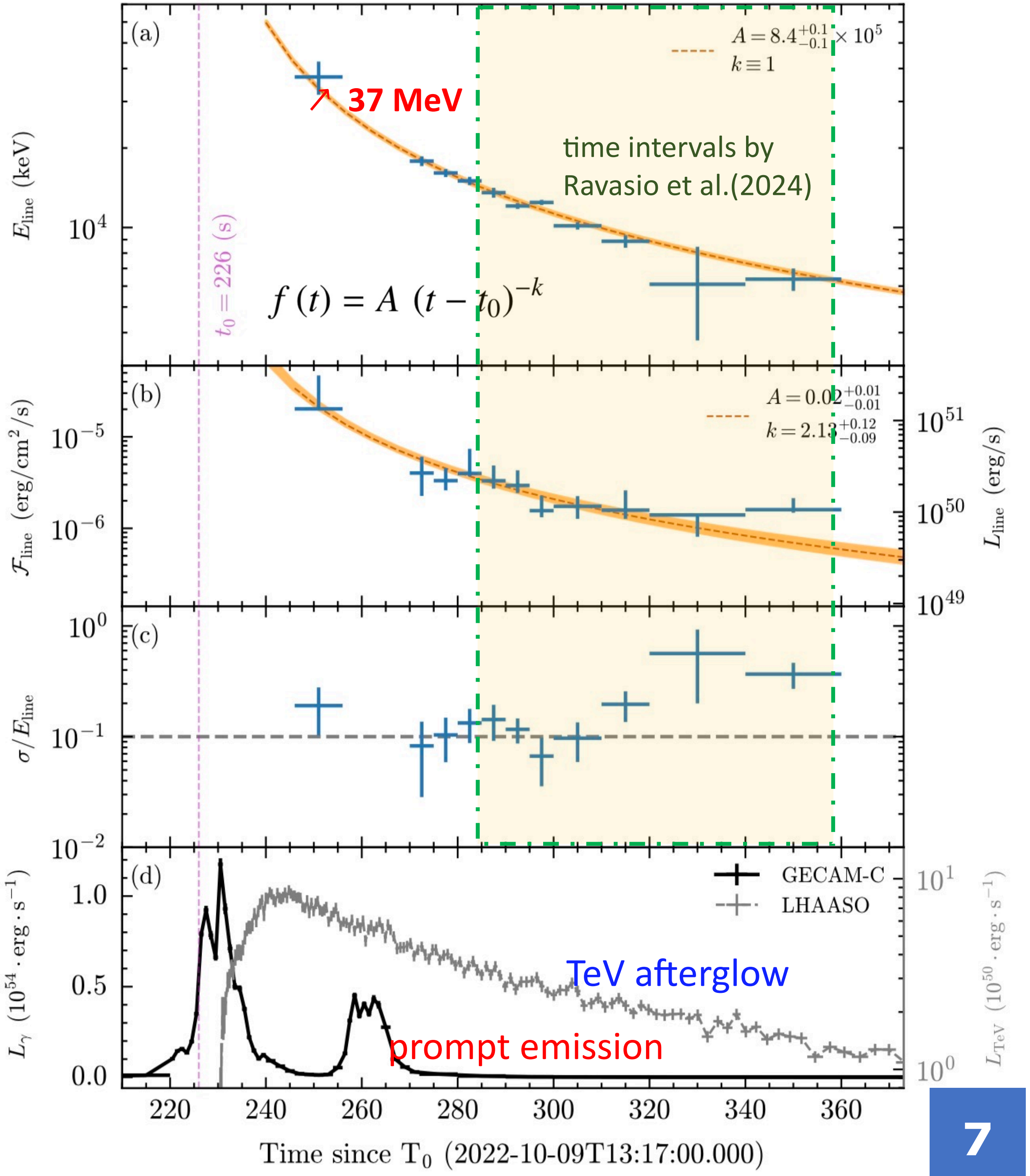
Y.-Q. Zhang et al. (2024);
ZZ et al. (2024)

- Gaussian lines: *non-blackbody*
- non-thermal continuum



发射线的主要观测特征：

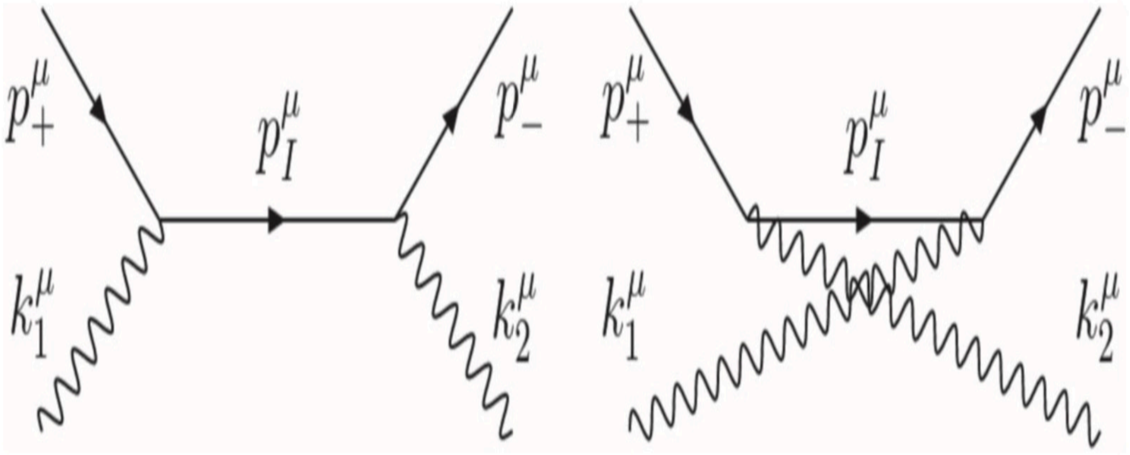
Q1: line energy: $E_{\rm line} \propto (t - t_0)^{-1}$
Q2: line luminosity: $L_{\rm line} \propto (t - t_0)^{-2.1}$
Q3: extremely bright: $L_{\rm line,0} \gtrsim 10^{51-52}$ erg/s
Q4: narrow line width: $\sigma / E_{\rm line} \sim 0.1$



Creation, annihilation, and decouping of $e^{\pm}$ pairs

no assumptions on $e^{\pm}$ pairs' particle physics origin

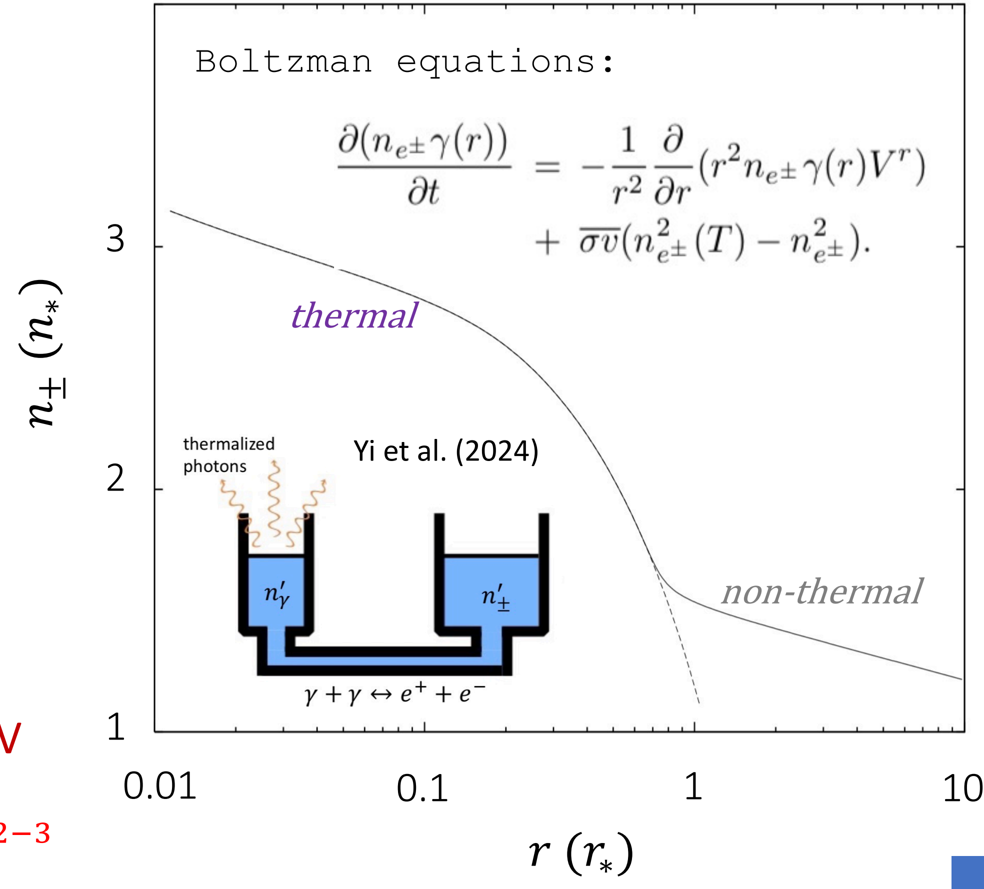
$$\gamma + \gamma \leftrightarrow e^{+} + e^{-}$$



- **Super-QED interactions** in ultra-strong magnetic fields (Kostenko & Thompson 2018, 2019)
- **Pair annihilation lines** @ $E'_{\rm line} \sim m_e c^2 \sim 0.511$ MeV $\ll$ 37 MeV

Ultra-relativitistic effect → $E_{\rm line} \sim \delta_D\, E'_{\rm line}$, $\delta_D = \frac{1}{\Gamma(1-\beta\cos\theta)} \sim 10^{2-3}$

- **decoupling** of $e^{\pm}$ pairs from jet plasma (Ruffini et al. 1999, 2000, 2001)
- Yi et al. (2024): **storyline & multi-band signals**



类似于暗物质的宇宙学退耦

Q1: Line energy power-law decay index -1

High-Latitude Emission (HLE)

An expanding sphere (i.e. a jet with opening angle $\theta_{\rm jet}$) that moves at $\beta = \frac{v}{c} \sim 1$ and produce line emission from r to $r + \Delta r$

- Equal arrival time surface (EATS):

$$\frac{1}{1+z}(t - t_0) = (1 - \beta\cos\theta)\,\frac{r}{\beta c}$$

- HLE effect:

$$\delta_D = \frac{r}{\Gamma}\frac{1+z}{\beta c}(t-t_0)^{-1} \overset{\Gamma \gg 1}{\propto} (t - t_0)^{-1}$$

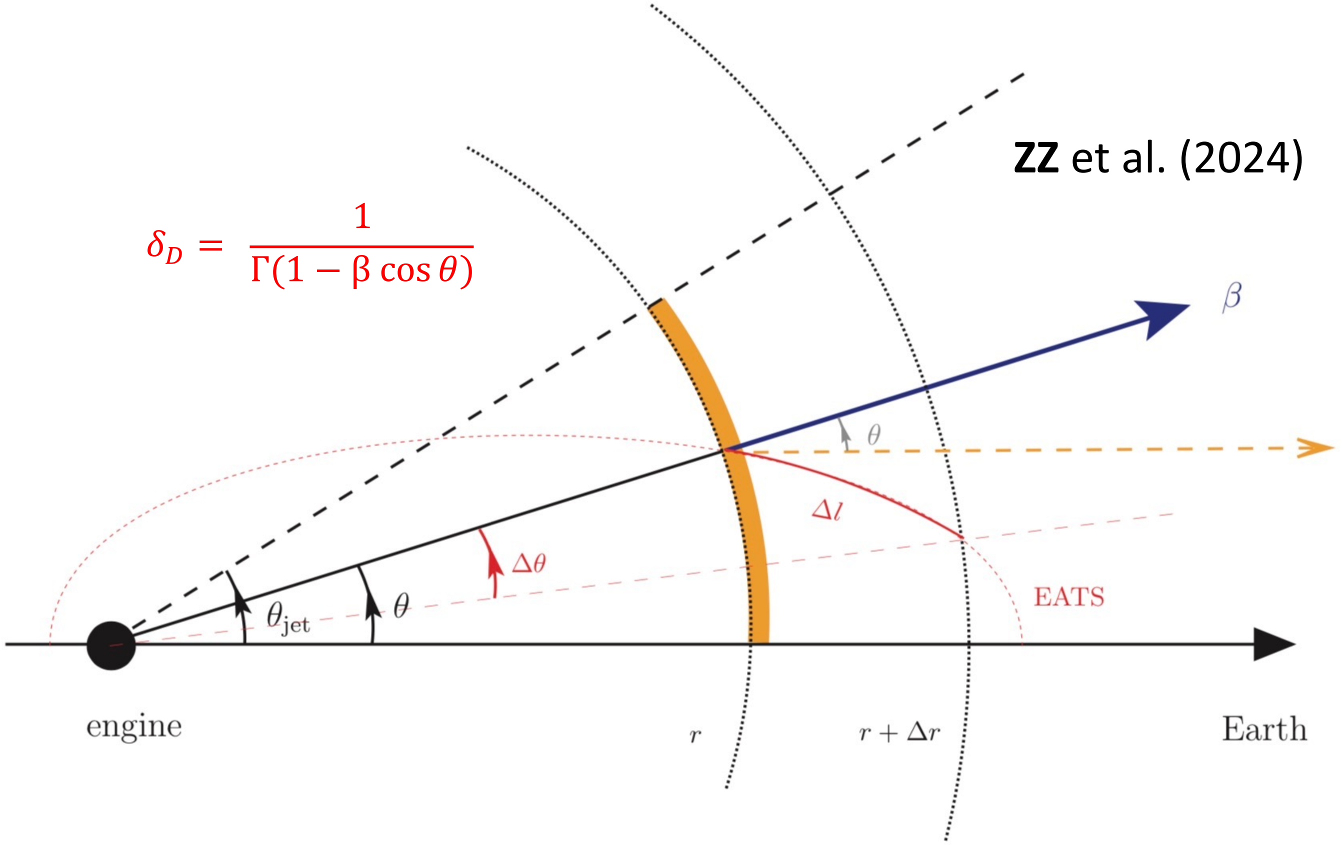
$$\rightarrow E_{\rm line} \sim \delta_D\, E'_{\rm line} \propto (t - t_0)^{-1}$$

$$f(t) = A\,(t - t_0)^{-k}$$

k = 1

ZZ et al. (2024)

$$\delta_D = \frac{1}{\Gamma(1 - \beta\cos\theta)}$$



Observation: $t'_{\rm dyn} = \frac{r}{\Gamma c} = A/E'_{\rm line}$ $\overset{\Gamma \gg 1}{\Rightarrow}$ $\Gamma \sim r$ cons. $\Rightarrow$ No θ-structure in Γ

Q2: Line Flux evolution

- Line flux $\mathcal{F}_{\rm line}$ evolves as:

$$\mathcal{F} = \frac{c}{2 d_L^2} \frac{\delta_D^3 \, \epsilon^*}{r \Gamma}$$

谱线辐射的角度依赖：

$$\epsilon^*(\theta) = \frac{dE_{\rm line}}{d\Omega}$$

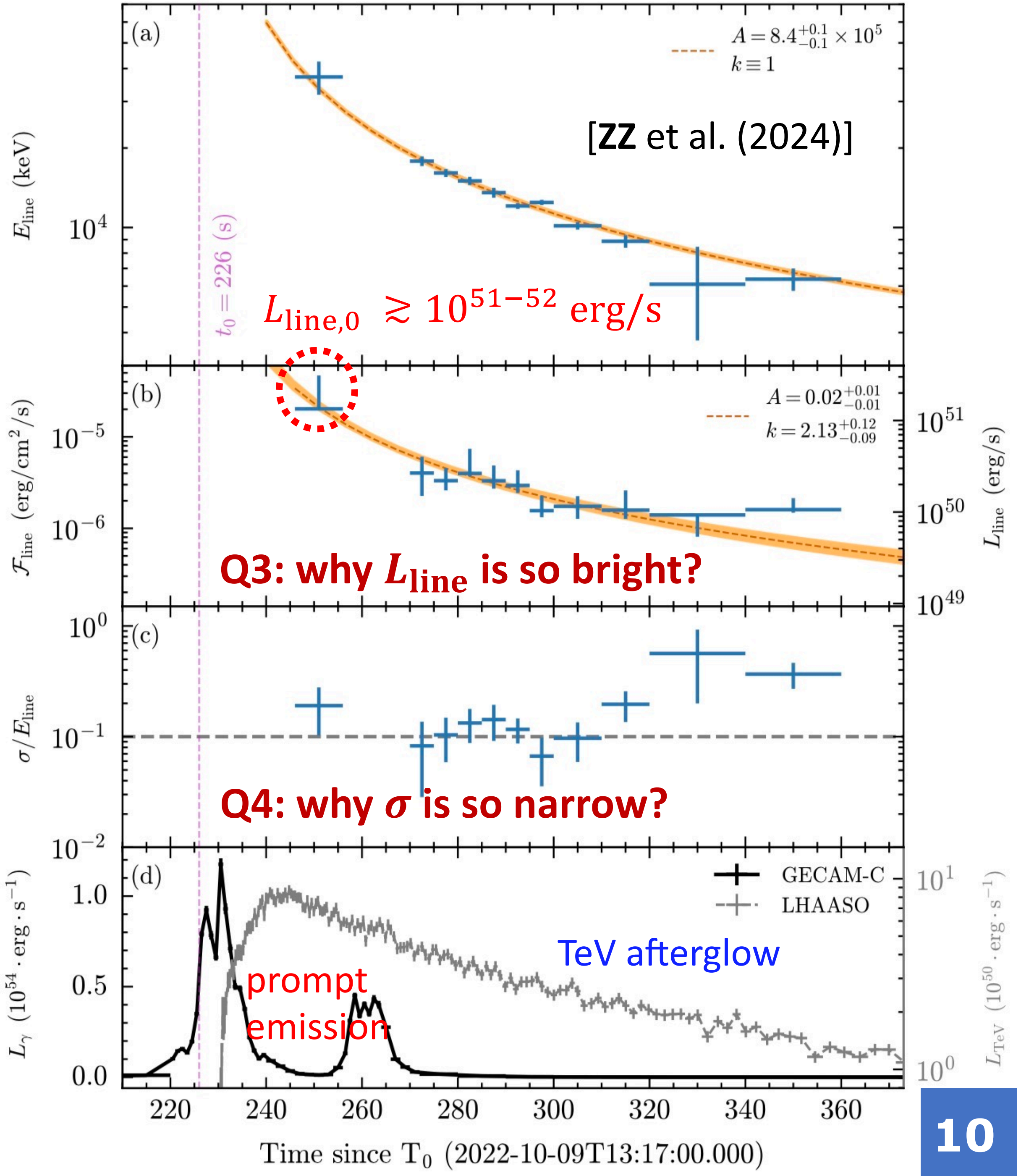
$$\epsilon^* \propto \theta^{2a} \rightarrow \propto (t - t_0)^{-3+a}$$

Data Fitting → $a \sim 0.9$

线辐射：与结构化喷流有差异

- Two key problems: Q3 & Q4
- Q4 is a big chanllenge !

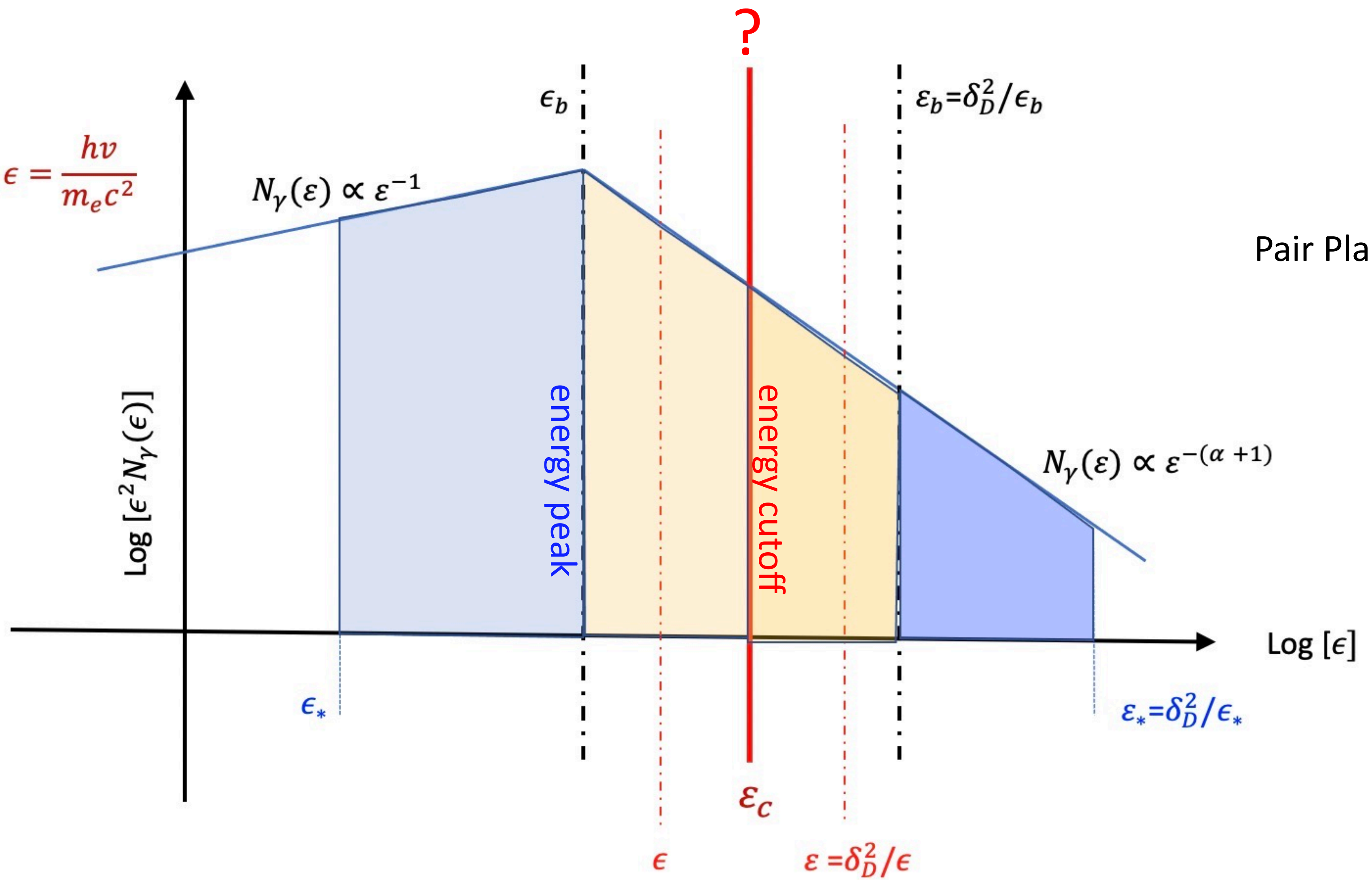
ignored in the literature



Q3: Why the MeV line is so bright ?

- GRB spectra

Z.Li 2010; **ZZ** et al. (2024)



$$f_\pm = \frac{\int_{\epsilon_c} \frac{dN_\gamma}{dTd\epsilon} d\epsilon}{\int \frac{dN_\gamma}{dTd\epsilon} d\epsilon} \leftarrow L_\epsilon/\epsilon \equiv \frac{dN_\gamma}{dTd\epsilon}$$

Pair Plasma: $$\frac{dN_\pm}{dT} \approx \int_{\epsilon_c} \frac{dN_\gamma}{dTd\epsilon} d\epsilon$$

$$L_{\text{ann}} \approx \delta_D m_e c^2 \frac{dN_\pm}{dT} \approx \delta_D f_\pm \frac{L_{\text{peak}}}{\epsilon_{\text{peak}}}$$

(Li 2010) $\Downarrow$ $\varepsilon_c \sim$ 1-100 GeV ?

Line luminosity:

? $L_{\text{line}} \gtrsim 10^{50-51}$ erg/s

Pair production optical depth $\tau_{\gamma\gamma} \Rightarrow \varepsilon_c$

$$\frac{dN_\pm}{dt'dN_\gamma(\epsilon_1')} \approx \frac{c}{2}\int(1-\mu')\frac{d\Omega'}{4\pi}\int\frac{dN_\gamma}{dV'd\epsilon_2'}\sigma_{\gamma\gamma}\,d\epsilon_2'$$

(Svensson, R. 1987, MNRAS, 227, 403)

$$= (\eta_\alpha/2)\,c\sigma_T(1/\epsilon_1')\left.\frac{dN_\gamma}{dV'd\epsilon_2'}\right|_{\epsilon_2'=1/\epsilon_1'}$$

$$\approx \frac{(\eta_\alpha/2)\,\sigma_T}{4\pi R^2}(\delta_D^2/\epsilon_1)\left.\frac{dN_\gamma}{dt'd\epsilon_2}\right|_{\epsilon_2=\delta_D^2/\epsilon_1}$$

(1)

$$\tau_{\gamma\gamma}(\epsilon_1) = \frac{dN_\pm}{dN_\gamma(\epsilon_1)} \approx \frac{(\eta_\alpha/2)\,\sigma_T}{4\pi R^2}(\delta_D^2/\epsilon_1)\left.\frac{dN_\gamma}{d\epsilon_2}\right|_{\epsilon_2=\delta_D^2/\epsilon_1}$$

$$= \frac{(\alpha\eta_\alpha/2)\,\sigma_T\,N_{>\delta_D^2/\epsilon_1}}{4\pi R^2} \approx \frac{(11/180)\,\sigma_T\,N_{>\delta_D^2/\epsilon_1}}{4\pi R^2}$$

$$dN_\gamma/d\epsilon \propto L_\epsilon/\epsilon \propto \epsilon^{-(\alpha+1)}$$

$$\alpha \approx p/2 \approx 1,\ \eta_\alpha/2 = 11/180$$

(2) $N_{>\delta_D^2/\epsilon} \approx (\delta_D^2/\epsilon)^{-\alpha}\,\delta N_\gamma$

δN_γ: photon number above the spectral peak;

$\delta E_\gamma = \delta N_\gamma\, \delta_D\, m_e\, c^2$;

(3)

$$\epsilon|_{\tau_{\gamma\gamma}=1} = \frac{\Gamma^2}{\epsilon_p}\left[\frac{4\pi r^2\epsilon_p m_e c^2}{(\alpha\eta_\alpha/2)\sigma_T\delta E_\gamma}\right]^{1/\alpha}$$

$$= 6300\left(\frac{r}{10^{16}\ \mathrm{cm}}\right)^{2/\alpha}\left(\frac{\Gamma}{500}\right)^2\left(\frac{\delta E_\gamma}{10^{54}\ \mathrm{erg}}\right)^{-1/\alpha}$$

$$\Longrightarrow \varepsilon_c \sim \max(\varepsilon|_{\tau_{\gamma\gamma}=1}, \delta_D)$$ at $\alpha = 1$)

ZZ, H.Lin, Z.Li, S.Xiong et al. (2024); Z. Li 2010

$L_{\rm line} \gg 10^{51}$ erg/s is required!

- δN_γ: photon number above the spectral peak;
- $\delta E_\gamma = \delta N_\gamma\, \delta_D\, m_e\, c^2$

$$\frac{L_\epsilon}{\epsilon} \propto N_\gamma(\varepsilon) \propto \varepsilon^{-(\alpha+1)}$$

$$\frac{dN_\pm}{dT} \approx \int_{\epsilon_c} \frac{dN_\gamma}{dTd\epsilon} d\epsilon = \int_{\epsilon_c} \frac{L_\epsilon/\epsilon}{m_e c^2} d\epsilon \approx \frac{\int_{\epsilon_c} \epsilon^{-(\alpha+1)} d\epsilon}{\int_{\epsilon_p} \epsilon^{-(\alpha+1)} d\epsilon} \dot{N}_\gamma \sim \epsilon_c^{-\alpha} \dot{N}_\gamma \Leftarrow \dot{N}_\gamma \approx L_\gamma/(\epsilon_p m_e c^2)$$

ZZ et al. (2024)

$\Downarrow$

$$L_{\rm ann} \approx \delta_D m_e c^2 \frac{dN_\pm}{dT}$$

$\epsilon_c \approx \Gamma$, $L_{\rm line} \sim L_\gamma$.

$\epsilon_c > \Gamma$, $L_{\rm line} = 7.9 \times 10^{52} {\rm erg\ s^{-1}} \left(\frac{L_\gamma}{10^{54} {\rm erg\ s^{-1}}}\right) \left(\frac{r}{10^{16}\,{\rm cm}}\right)^{-2} \left(\frac{\Gamma}{500}\right)^{-(2\alpha-1)} \left(\frac{\delta E_\gamma}{10^{54}\,{\rm erg}}\right)$;

$\gtrsim 10^{52}$ erg/s

$\gg 10^{51}$ erg/s

1

When $\Gamma = \epsilon|_{\tau_{\gamma\gamma}=1}$, we have

$$r_\Gamma = 0.28 \times 10^{16} {\rm cm} \left(\frac{\Gamma}{500}\right)^{-\alpha/2} \left(\frac{\delta E_\gamma}{10^{54}\,{\rm erg}}\right)^{1/2}$$

Q4: Why the MeV line is so narrow ?

❖ Narrow line width:

$\sigma/E_{\rm line} \sim 0.1 \longrightarrow e^{\pm}$ velocity: $\beta'_e \lesssim 0.1$

mostly ignored in the literature

A. Plasma's thermal motion
B. Jet's bulk motion

限制性很强，显著增加了物理的理解难度

a). Constraint on thermal motion:

- Cooling mechanisms:
  - Synchrotron radiation: $U'_B = L_B/4\pi r^2\Gamma^2 c$
  - Inverse Compton (IC) scattering: $U'_\gamma = L_\gamma/4\pi r^2\Gamma^2 c$
- Background magnetic field:

$$B = \sqrt{8\pi\left(\frac{L_\gamma}{4\pi r^2\,\Gamma^2\,c}\right)\left(\frac{\epsilon_B}{\epsilon_e}\right)} = \sqrt{8\pi\left(\frac{L_B}{4\pi r^2\,\Gamma^2\,c}\right)}$$

$$\sim 1.6\times10^3\,{\rm G}\left(\frac{L_B}{10^{54}\,{\rm erg\,s^{-1}}}\right)^{\frac{1}{2}}\left(\frac{r}{10^{16}\,{\rm cm}}\right)^{-1}\left(\frac{\Gamma}{500}\right)^{-1}$$

Fast cooling mechanisms

- Cooling equation → Energy-lose rate: $U' = U'_B + U'_\gamma$

$$\frac{d\gamma'_e}{dt'} = -\frac{4}{3}\frac{\gamma'^2_e\beta'^2_e\sigma_T c U'}{m_e c^2} = -\frac{\gamma'^2_e\beta'^2_e}{2\tau}$$

[see **ZZ** et al. (2024)]

- Timescale for Cooling of $e^\pm$ pairs: $\tau = 3\pi r^2\Gamma^2 m_e c^2/2\sigma_T L_{em}$

$$\beta'^2_e = 4\,e^{-t'/\tau}\left(2 + e^{-t'/\tau}\right)^{-2}$$

$\Downarrow$ cooling of $e^\pm$ pairs to NR

$$\beta'_e = 0.1 \;\rightarrow\; t' = t'_{NR} = 4.6\,\tau$$

Q4: Why the MeV line is so narrow?

b). Constraint on bulk motion

- Variations over EATS:

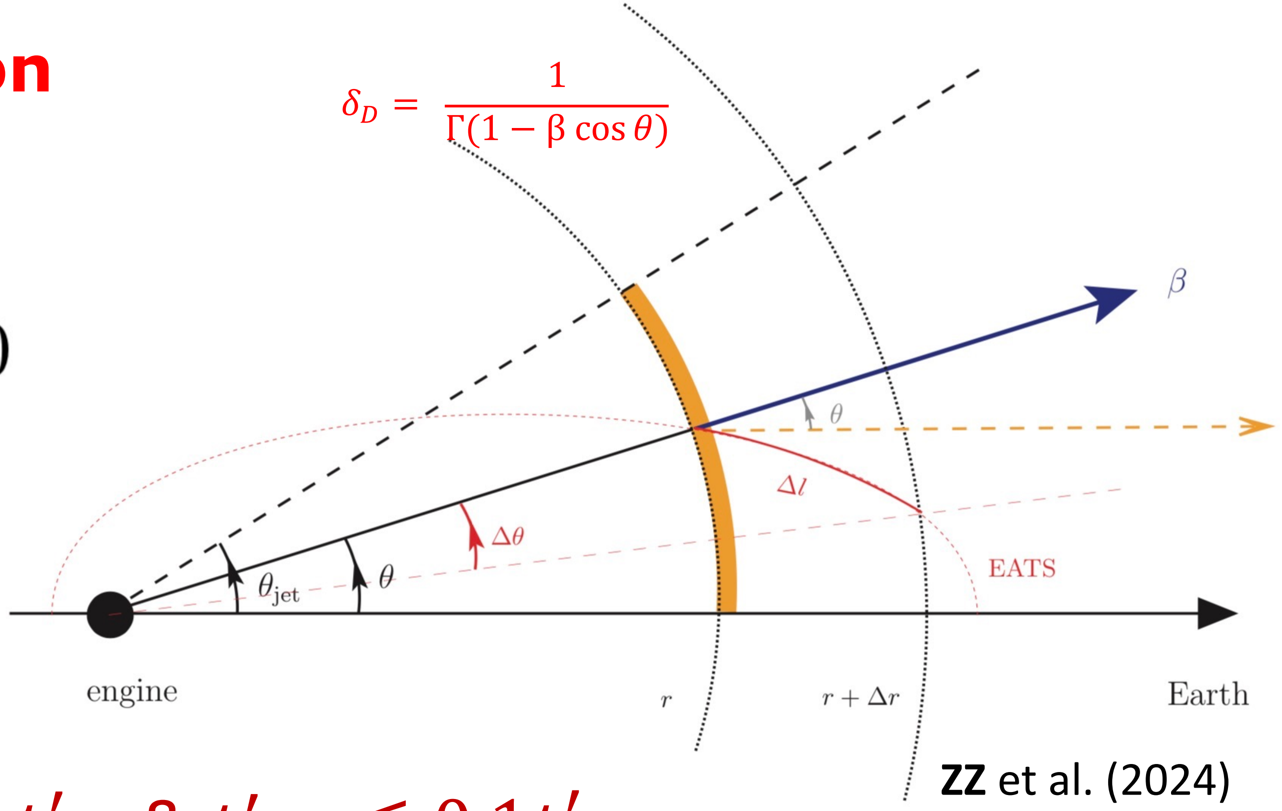
$$\Delta(1-\beta\cos\theta)r + (1-\beta\cos\theta)\Delta r = 0$$

- Narrow line width of $\sim 10\%$

$$\frac{\Delta r}{r} = \frac{\Delta\delta_D}{\delta_D} \lesssim 0.1$$

Independent of line's origins!

$\Rightarrow$ The HLE approximation holds well! (also see Yi et al. 2024)



ZZ et al. (2024)

- Fast **cooling** & **annihilation** timescales: $t'_{\rm NR}$ & $t'_{\rm ann} \lesssim 0.1 t'_{\rm dyn}$

2

✓ The line central energy evolving as t^{-1} $\Rightarrow$ $t'_{\rm dyn} = \frac{r}{\Gamma c} = A/m_e c^2 = 1.64\times10^3\ s$

$\Longrightarrow$ **further constraints** on $e^{\pm}$ pair's **creation**, **cooling**, and **annihilation**

Further constraints

○ $t'_{\rm NR} = 4.6\,\tau \lesssim 0.1 t'_{\rm dyn}$ => fast **cooling** mechanism:

3

$$r \lesssim \sigma_{\rm T} L_{\rm em}/69\pi\Gamma^3 m_e c^3 \implies r \lesssim 10^{16}{\rm cm}\left(\frac{\Gamma}{500}\right)^{-3}\left(\frac{L_{\rm em}}{10^{55}{\rm erg\ s^{-1}}}\right)$$

fast cooling of $e^{\pm}$ pairs to NR

○ $t'_{\rm ann} \lesssim 0.1 t'_{\rm dyn}$ => fast **annihilation** of $e^{\pm}$ pairs :

- Cross section of annihilation: $\sigma_{e^+e^-} = \frac{3}{8}\,\sigma_T\,\beta_e'^{-1}$
- Timescale for pair annihilation: $t'_{\rm ann} \simeq \frac{1}{n'_{\pm}\sigma_{e^+e^-}\beta'_e c} = \frac{8}{3}\frac{1}{\sigma_T n'_{\pm} c} \lesssim 0.1 t'_{\rm dyn}$

How to estimate the number density $n'_{\pm}$ of $e^{\pm}$ pairs ?

Number density of NR $e^{\pm}$ pairs $n'_{\pm} = ?$

If the spatial distribution of NR pairs is **clumpy** with volume filling factor $f_v < 1$, then

$$n'_{\pm} = f_{\rm v}^{-1}\langle n'_{\pm}\rangle$$

- Here, $f_v < 1$ may arise from magnetic connection, shocks, baryonic interaction, and NP mechanisms**?**

- **Balance** between **formation** and **annihilation of** $e^{\pm}$ pairs:

formation rate density $=$ annihilation rate density

$$\dot{N}_{\gamma}|_{>\epsilon_c}/4\pi r^2 c\Gamma t'_{\rm dyn} \simeq (\epsilon_c/\epsilon_p)^{-\alpha} L_{\gamma}/4\pi r^3 m_e c^2 \epsilon_p \iff \langle n'_{\pm}\rangle/t'_{\rm ann} \simeq (3/8)\langle n'_{\pm}\rangle n'_{\pm}\sigma_T c$$

↑ observation (for $\dot{N}_{\gamma}|_{>\epsilon_c}$)

(spatially averaged) (spatially averaged)

$$\Rightarrow \quad n'_{\pm} = f_{\rm v}^{-1/2}[(8/3)(\epsilon_c/\epsilon_p)^{-\alpha} L_{\gamma}/4\pi r^3 m_e c^3 \sigma_T \epsilon_p]^{1/2}$$

$n'_\pm$ & $t'_{\rm ann}$

$$n'_\pm = f_{\rm v}^{-1/2}[(8/3)(\epsilon_c/\epsilon_p)^{-\alpha} L_\gamma/4\pi r^3 m_e c^3 \sigma_T \epsilon_p]^{1/2}$$

$\Downarrow$ $\varepsilon_c \sim \max(\varepsilon|_{\tau_{\gamma\gamma=1}}, \delta_D)$

- $t'_{\rm ann} \simeq \frac{8}{3}\frac{1}{\sigma_T n'_\pm c} \lesssim 0.1 t'_{\rm dyn}$:

$\Downarrow$

4

$$r \lesssim 10^{15}\,{\rm cm} \times \min\left[0.065\, f_{\rm v}^{-1}\left(\frac{\Gamma}{500}\right)^{-(\alpha+2)}\left(\frac{L_\gamma}{10^{54}\,{\rm erg\,s^{-1}}}\right), 0.80\, f_{\rm v}^{-1/3}\left(\frac{\Gamma}{500}\right)^{-(2\alpha+2)/3}\left(\frac{\delta E_\gamma}{10^{54}\,{\rm erg}}\right)^{1/3}\left(\frac{L_\gamma}{10^{54}\,{\rm erg\,s^{-1}}}\right)^{1/3}\right]$$

Optical depth problem

❖ Q3: large $L_{\rm line}$ → high $n'_{\pm}$↑ → large $\tau_{\rm es}$ ↑→ blackbody ⇏ Q4: narrow Gaussian line

- Generally, the Thompson optical depth of a GRB jet for a photon:

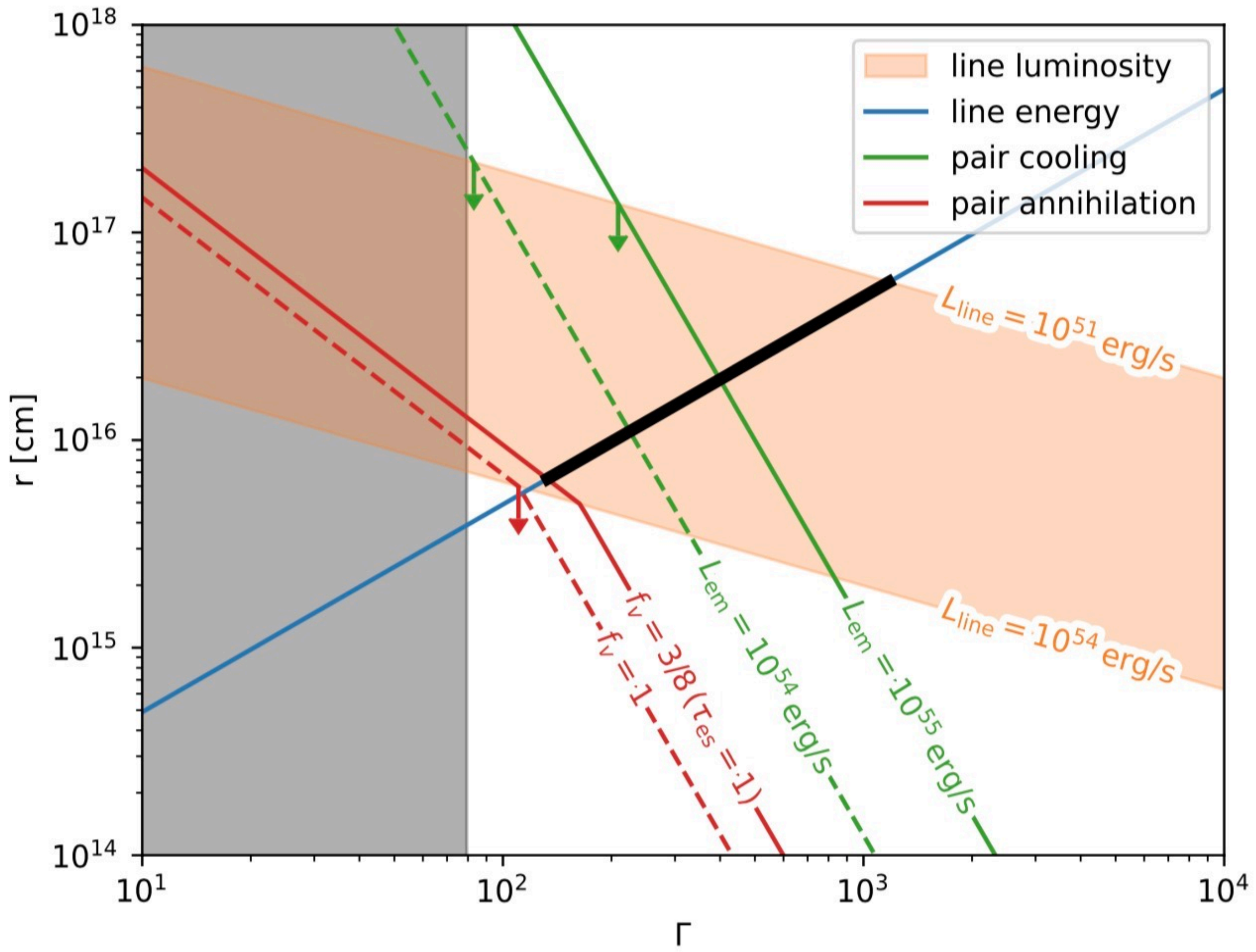
$$\tau_{\rm es} = \langle n'_{\pm} \rangle \sigma_T \, r/\Gamma = \frac{8}{3} f_v \frac{t'_{\rm dyn}}{t'_{\rm ann}} \sim \frac{80}{3} f_v$$

- Traditionally, $f_v = 1 \rightarrow \tau_{\rm es} \gg 1$ (always). If so, any spectral line should appear as *blackbody* emission, inconsistent with observations. [That's why we introduce $f_v < 1$]

- As fast pair annihilation occurs, it reduces the time that a photon can interact with pairs to $0.1\, t'_{\rm dyn}$. Thus, the Thompson optical depth of the line emission

$$\tau_{\rm es} = 0.1 \langle n'_{\pm} \rangle \sigma_T \, r/\Gamma = \frac{8}{30} f_v \frac{t'_{\rm dyn}}{t'_{\rm ann}} \sim \frac{8}{3} f_v$$

- If $\tau_{\rm es} = 1$, $f_v < \frac{3}{8}$ ⇒ the presence of a slightly clumpy region;
- The MeV line is able to freely escape from the pair plasma.



→ directly restrict the physics of GRB jets with observations, leaving a large parameter space available.

1) 粗黑线(Q1): $E_{line} \propto t^{-1}$

2) 灰色阴影: ~ 37 MeV

3) 褐色阴影(Q3): $L_{line,0} \gtrsim 10^{51-52}$ erg/s

4) 红(虚)线(Q3↔Q4): $\tau_{es} = 1$?

5) 绿(虚)线(Q4): $\sigma / E_{line} \sim 0.1$

→ High-latitude emission from a bright $e^{\pm}$ annihilation line!

--- partially confirmed by Pe'er & Zhang; Yi et al. 2024

Dynamic mechanism / TeV afterglow origin ⁉

Jet's bulk Lorentz factor: $\Gamma \propto (t - t_0)^{-k}$ Medium density: $n \propto r^{-s}$

If $s \in [0,\ 3)$, $k = (3 - s)/(8 - 2s) < 3/8$

If $s \gtrsim 3$, n will decrease steeply with r and the shock even speeds up with r

✓ $k \approx 1$ → large density bumps in the medium in front of shocks ⇒ modify THs of GRBs

✓ Γ decreases to ~ 10 within $t_{\rm dur} \sim 100$s, in contradiction with TeV afterglow data ($\Gamma \sim 440 \nearrow 700$)

At the deceleration radius (LHAASO 2024),

$$r_{\rm dec} \sim 10^{17}\ {\rm cm}(E_{\rm k}/10^{55}\ {\rm erg})^{1/3}(\Gamma_0/440)^{-2/3}(n/1\ {\rm cm}^3)^{-2/3}$$

✓ → The born pairs are unable to reach a NR state because the luminosity $L_{\rm TeV}$ of the external shock emission is too low

Atomic line / Nuclear line ⁉

- keV-scale atomic line of heavy element

E. Ravasio et al.(2024) Wei et al.(2024)

  - $E_{\mathrm{line}} \sim 8 - 10\ \mathrm{MeV} \rightarrow \Gamma \sim$ 800-1700

Y.Q. Zhang et al.(2024)

  - If $E_{\mathrm{line}} \sim 37\ \mathrm{MeV}$, $\Gamma \gg 700$, in contradiction with TeV afterglow data

$(\Gamma \sim 440 \nearrow 700)$

- nuclear decay line

  - line central energy: $E_d \sim 0.1 - 3\ \mathrm{MeV}$
  - mean lifetime (τ_d): $t_{\mathrm{dur}} \sim 135$ s, i.e., $\tau_d \gtrsim \Gamma t_{\mathrm{dur}} \gtrsim 10^3 - 10^4 \mathrm{s}$
  - total mass of radioisotope (M_{iso}):

Hadronic Processes：
How to cool baryons to NR?

$$L_{\mathrm{line}} = \Gamma^2 f_d E_d M_{\mathrm{iso}} / (\tau_d A_{\mathrm{iso}} m_b) \sim 10^{51} \mathrm{erg\ s^{-1}} \Longrightarrow M_{\mathrm{iso}} \gtrsim A_{\mathrm{iso}} f_d^{-1} M_{\odot}$$

branching ratio of nuclear line: $f_d < 1$

A traditional core collapse supernova: $\lesssim 0.1 M_{\odot}$ $^{56}\mathrm{Ni}$ with $\tau_d \sim 10^6 s$

Summary and Conclusions

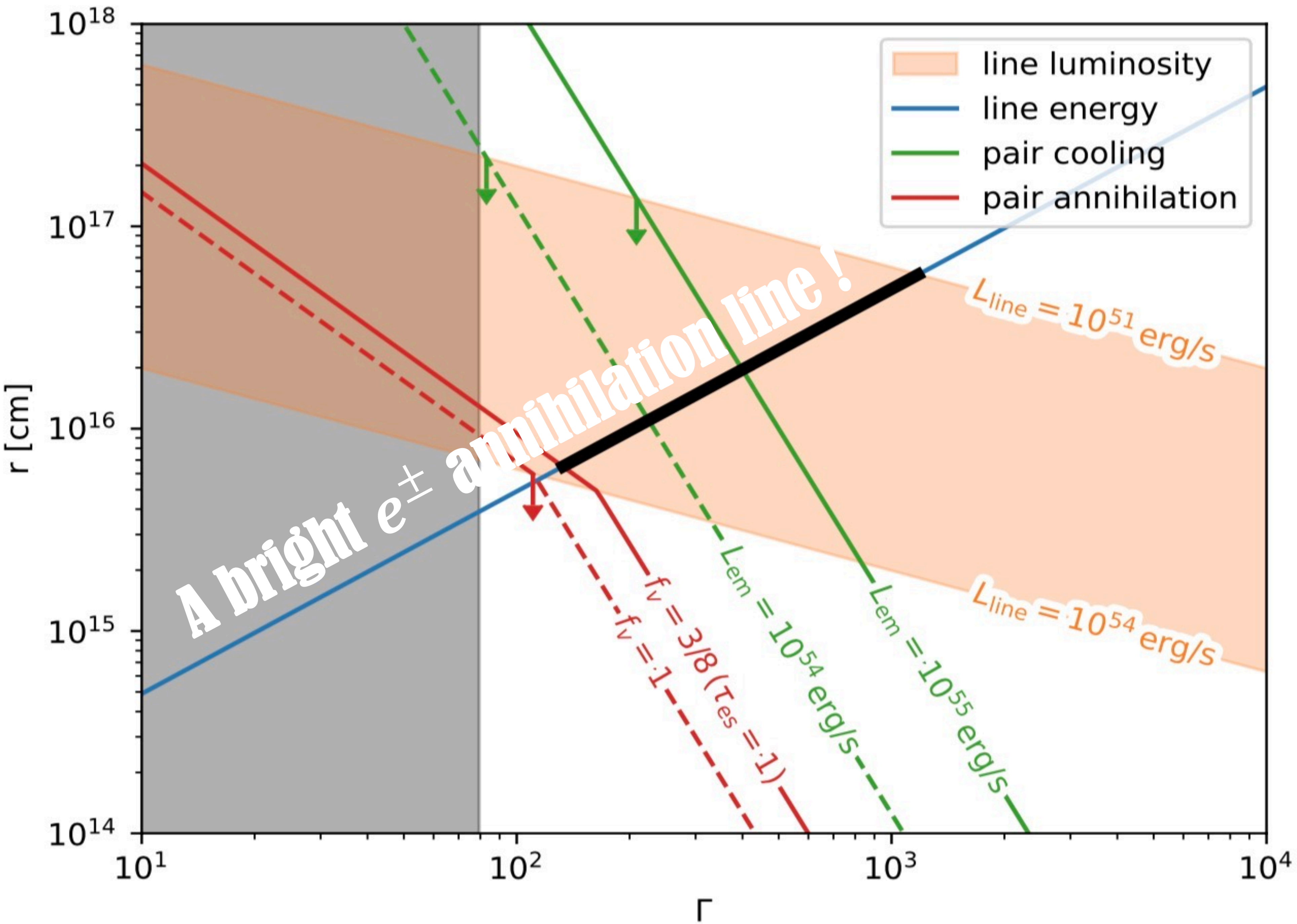
❖ Global Picture [see Yi et al. 2024 for details] :

large amount of prompt photons -> formation of $e^{\pm}$ pairs -> two-photon annihilation -> balance before decoupling -> fast cooling -> annihilation line -> broadening factors -> escaping emission line from jet plasma

○ Restricted the jet physics & emission mechanisms with observations, leaving a large parameter space available for the origin and mechanism of $e^{\pm}$ annihilation line

1) $\theta_{\rm jet} \gtrsim 0.8^{\rm o}$ [new method; direct measurement]
2) $r \gtrsim 10^{16}$cm & Γ ($\sim r$ const.) $\gtrsim$ 120 [also see Yi et al. 2024]
3) $L_{\rm line} \propto t^{-2.1} \rightarrow$ angle dependence of line, as high-latitude emission ($E_{\rm line} \propto t^{-1}$)
4) $\Gamma \gtrsim 400$ (TeV afterglow) $\rightarrow$ a magnetic-energy dominated jet

➢ The γ-ray line can be naturally attributed to the high-latitude emission from the electron-positron annihilation line, basically excluding other origins such as atomic and nuclear lines, in consideration of conditions within GRB jets.



天文学上首次探测到正负电子湮灭线！

Thank you

BACKUP

Jet's half-opening angle

- Narrow line width of ~ 10% → $\frac{\Delta r}{r} = \frac{\Delta \delta_D}{\delta_D} \lesssim 0.1$

  ⇒ **The HLE approximation holds well!**

- Line central energy:

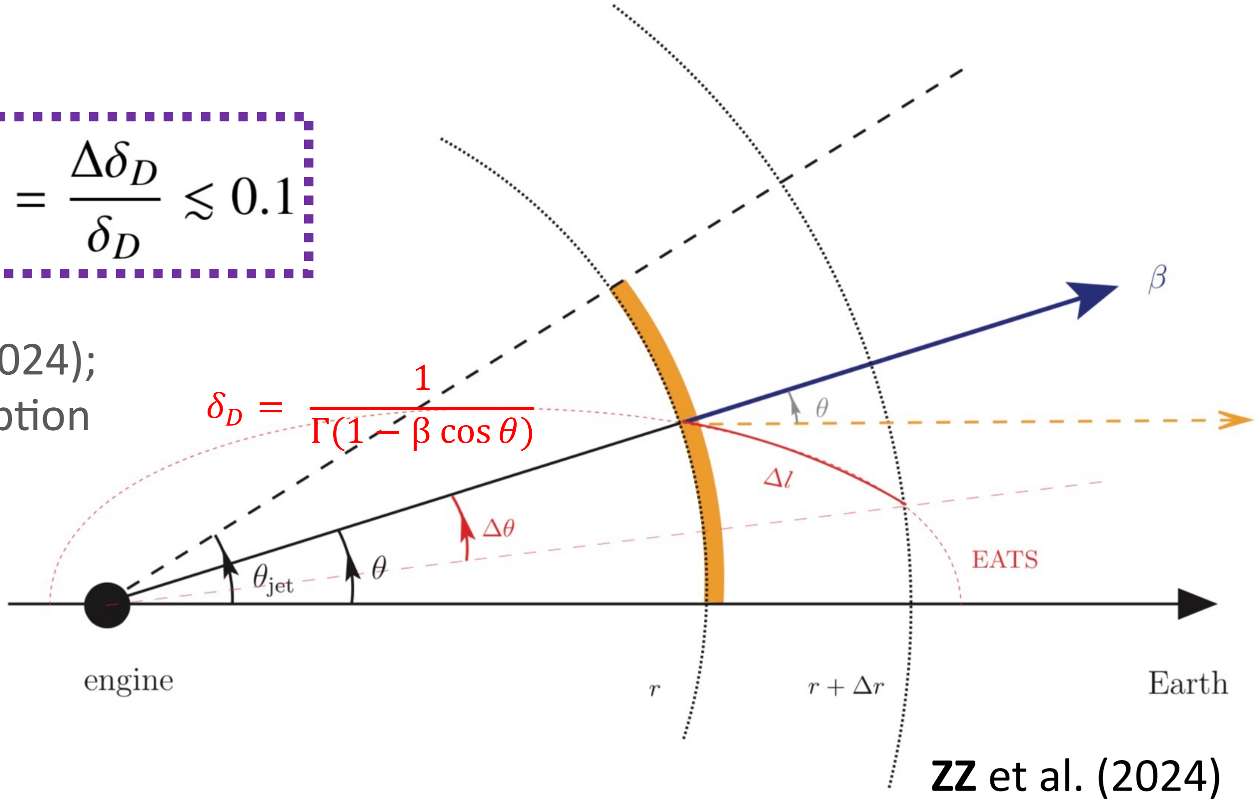
  also see Yi et al. (2024);
  no HLE-like assumption

  → $E_{\rm line} \sim \delta_D \, E'_{\rm line} \propto (t - t_0)^{-1}$

The power-law decay lasts for ≳ 135 s

$$\Rightarrow \quad \theta_{\rm jet} \gtrsim 0.017 \ {\rm rad} \left(\frac{\Gamma}{500}\right)^{-1/2}$$

≈ 0.8° consistent with TeV afterglow observation



$$\delta_D = \frac{1}{\Gamma(1 - \beta \cos\theta)}$$

ZZ et al. (2024)

- **Direct, independent** measurement !
- **New** method !!

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NSR, … … , 2303.01203

***Insight*-HXMT and GECAM-C observations of the brightest-of-all-time GRB 221009A**

Insight-HXMT& GECAM collaboration

GRB 221009A is the brightest gamma-ray burst ever detected since the discovery of this kind of energetic explosions. However, an accurate measurement of the prompt emission properties of this burst is very challenging due to its exceptional brightness. With joint observations of *Insight*-HXMT and GECAM-C, we made an unprecedentedly accurate measurement of the emission during the first ~1800 s of GRB 221009A, including its precursor, main emission (ME, which dominates the burst in flux), flaring emission and early afterglow, in the hard X-ray to soft gamma-ray band from ~ 10 keV to ~ 6 MeV. Based on the GECAM-C unsaturated data of the ME, we measure a record-breaking isotropic equivalent energy ($E_{\rm iso}$) of ~ 1.5×10^{55} erg, which is about eight times the total rest-mass energy of the Sun. The early afterglow data require a significant jet break between 650 s and 1100 s, most likely at ~ 950 s from the afterglow starting time T_{AG}, which corresponds to a jet opening angle of ~ 0.7° $(\eta_\gamma n)^{1/8}$, where n is the ambient medium density in units of cm^{-3} and η_γ is the ratio between γ-ray energy and afterglow kinetic energy. The beaming-corrected total γ-ray

A tera-electronvolt afterglow from a narrow jet in an extremely bright gamma-ray burst 221009A

LHAASO Collaboration*†

Some gamma-ray bursts (GRBs) have an afterglow in the tera-electronvolt (TeV) band, but the early onset of this afterglow has not been observed. We report observations with the Large High Altitude Air Shower Observatory of the bright GRB 221009A, which serendipitously occurred within the instrument field of view. More than 64,000 photons (above 0.2 TeV) were detected within the first 3000 seconds. The TeV photon flux began several minutes after the GRB trigger, then rose to a flux peak about 10 seconds later. This was followed by a decay phase, which became more rapid at ~ 650 s after the peak. The emission can be explained with a relativistic jet model with half-opening angle ~ 0.8°, consistent with the core of a structured jet. This interpretation could explain the high isotropic energy of this GRB.