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. (2024), **ApJL**, 2405.12977

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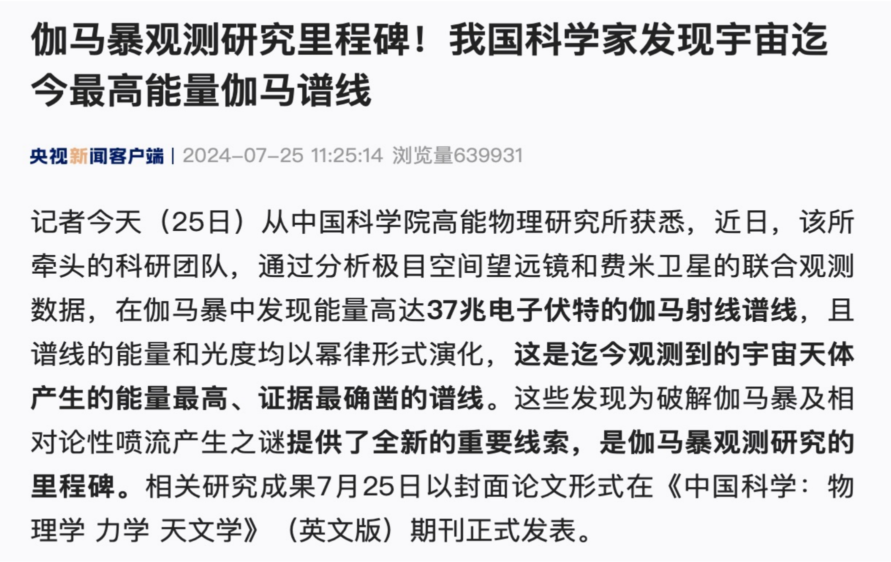
Discovery of γ-ray lines

- ❑ by **GECAM** Group: **the highest-energy γ-ray line detected in the universe!**

央视、新华社等先后报道：



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

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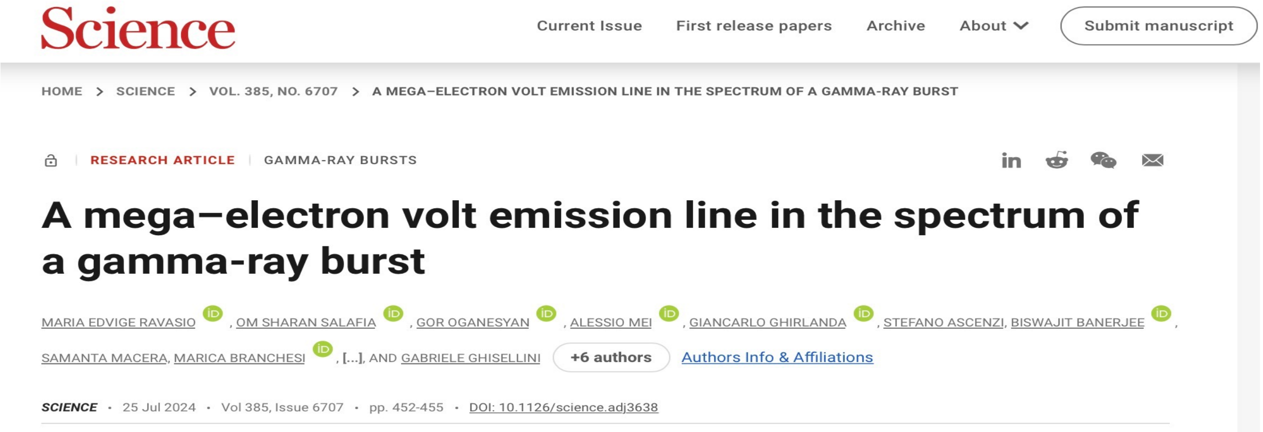
记者今天（25日）从中国科学院高能物理研究所获悉，近日，该所牵头的科研团队，通过分析极目空间望远镜和费米卫星的联合观测数据，在伽马暴中发现能量高达**37兆电子伏特的伽马射线谱线**，且谱线的能量和光度均以幂律形式演化，**这是迄今观测到的宇宙天体产生的能量最高、证据最确凿的谱线**。这些发现为破解伽马暴及相对论性喷流产生之谜**提供了全新的重要线索，是伽马暴观测研究的里程碑**。相关研究成果7月25日以封面论文形式在《中国科学：物理学 力学 天文学》（英文版）期刊正式发表。

- ❑



Science

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RESEARCH ARTICLE | GAMMA-RAY BURSTS

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

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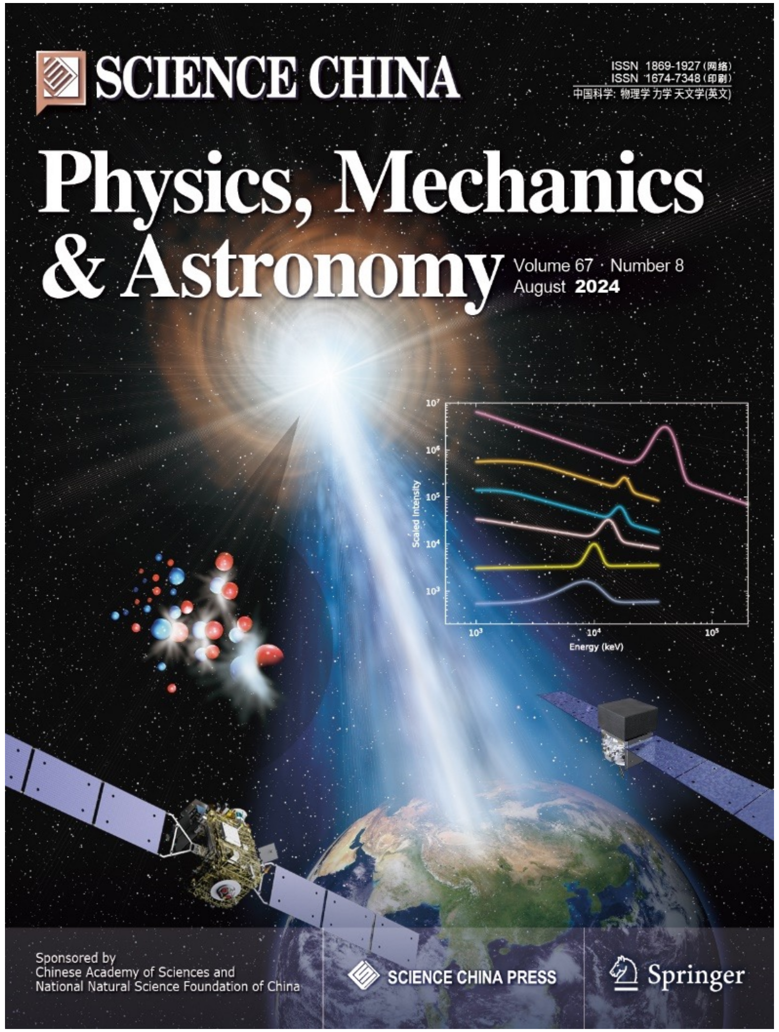
Ravasio et al. (2024)



GECAM Collaboration* Y.-Q. Zhang et al. (2024)

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

☐ GECAM-C/HXMT/Fermi-GBM:
main burst (keV-MeV-sub GeV)

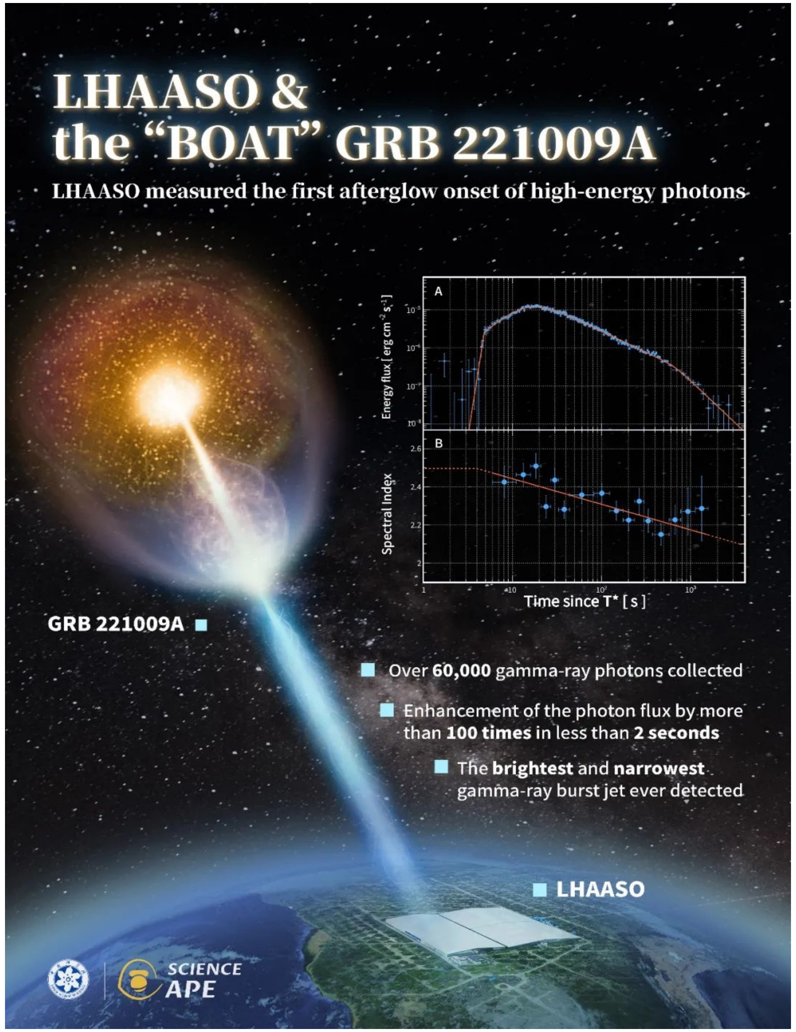
- this burst is so bright that the Fermi−GBM detector suffered significant data loss and pile−up effect during the bright part of the burst, making reliable data analysis very difficult. (HXMT & GECAM 2024)
- Fortunately, GECAM−C did not experience such problems thanks to its dedicated design of the instrument; thus, the GECAM−C data was used to correct the Fermi/GBM data. (Y.-Q. Zhang et al. 2024)

☐ **LAHHSO: TeV afterglow**

☐ MeV lines: **the biggest surprise in the prompt GRB spectra in at least a decade**

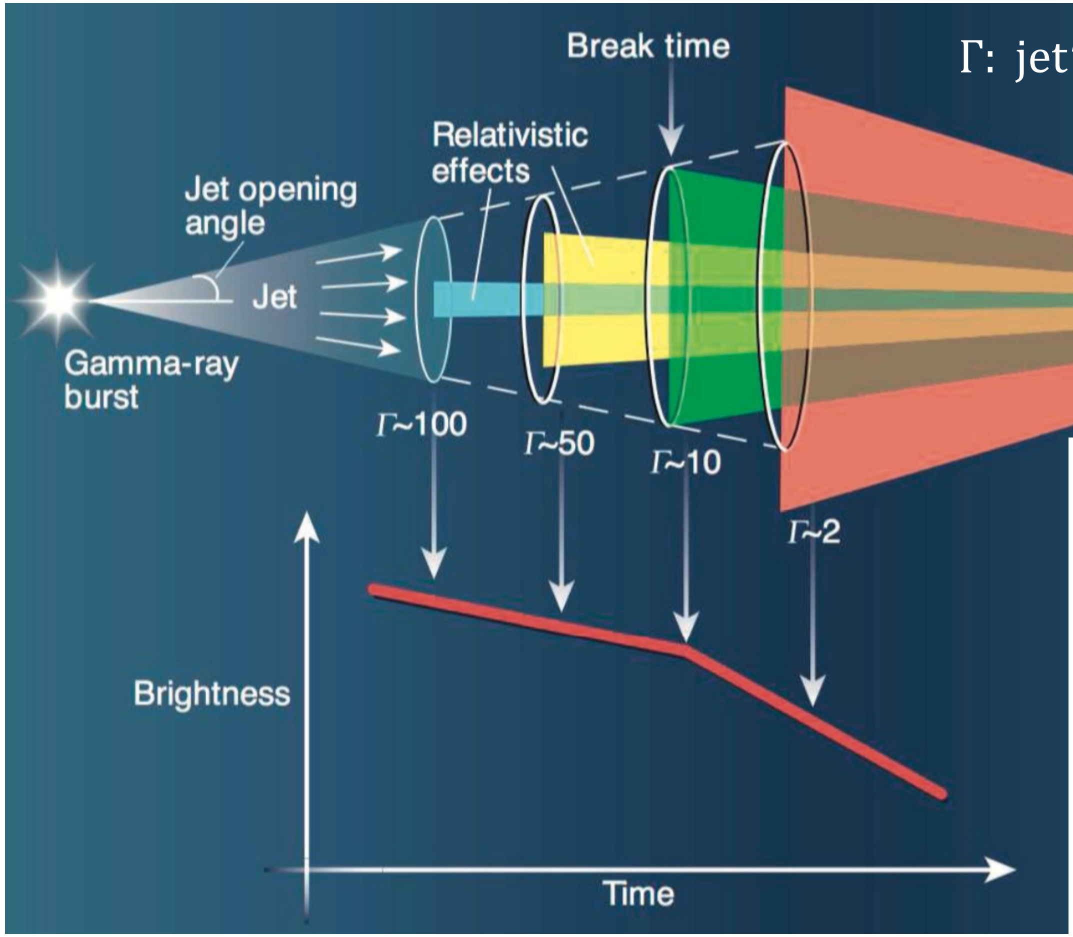
--- 某国际会议上

中国十大科学进展 (2023年)



LHAASO Collaboration* *Science* 380 (2023) 6652

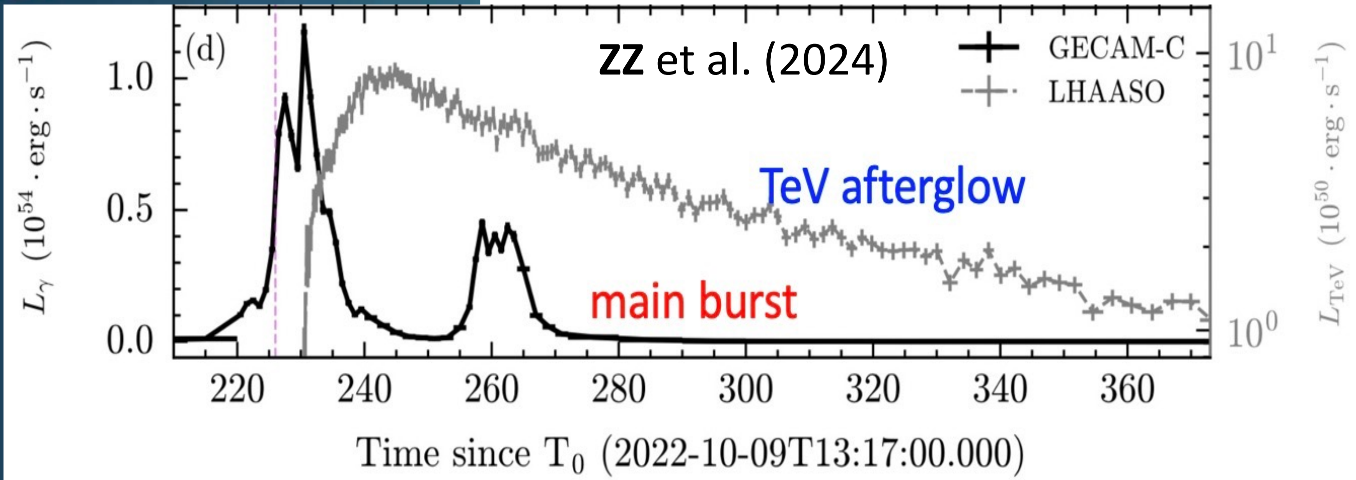
The global picture of γ-bursts (GRBs)



Jet structure:

→ **imprints** on main burst

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



Synchrotron radiation (SR) Inverse Compton (IC) scattering

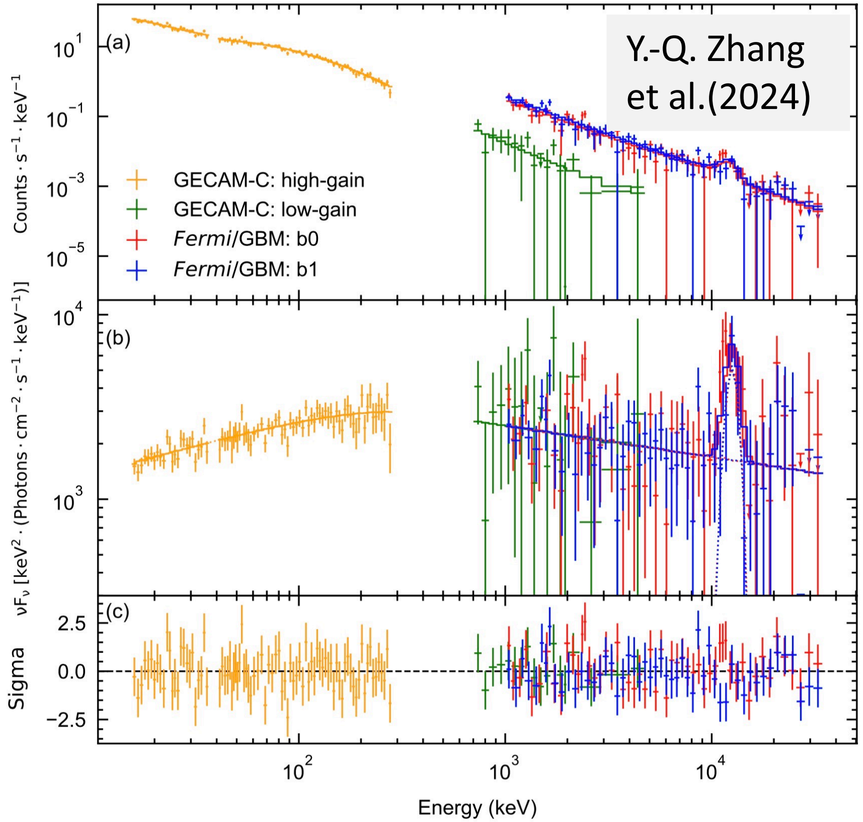
relativistic jet ⇒ e.g., internal shocks → main burst external shocks → TeV afterglow

数据分析

ZZ et al. (2024)

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

⇒ γ-rays from *optically thin* plasma

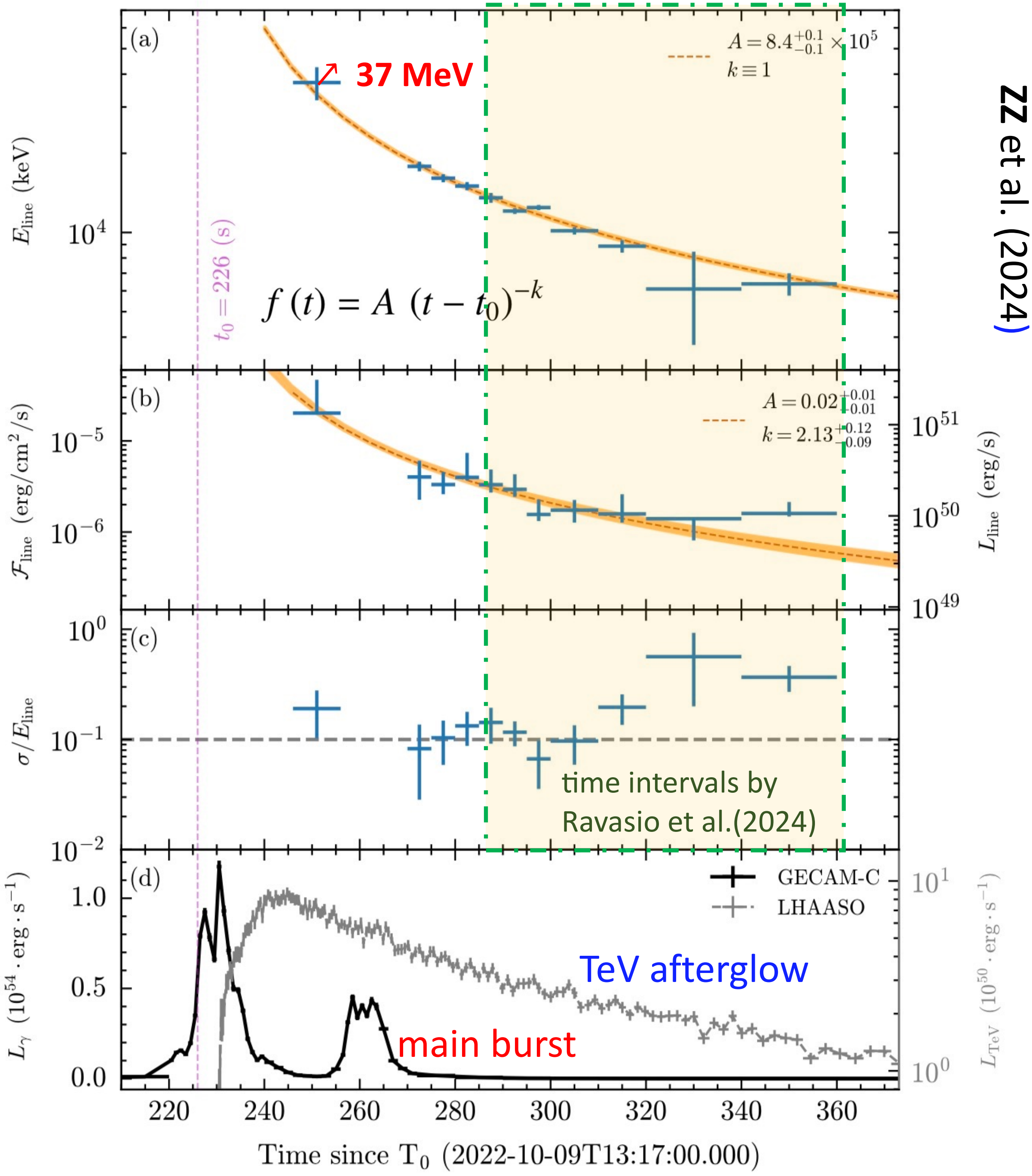


Y.-Q. Zhang et al.(2024)

✓ line central energy: $E_{\mathrm{line}} \propto (t - t_0)^{-1}$

✓ high line luminosity: $L_{\mathrm{line}} \propto (t - t_0)^{-2.1}$

✓ narrow line width: $\sigma / E_{\mathrm{line}} \sim 0.1$



37 MeV

time intervals by Ravasio et al.(2024)

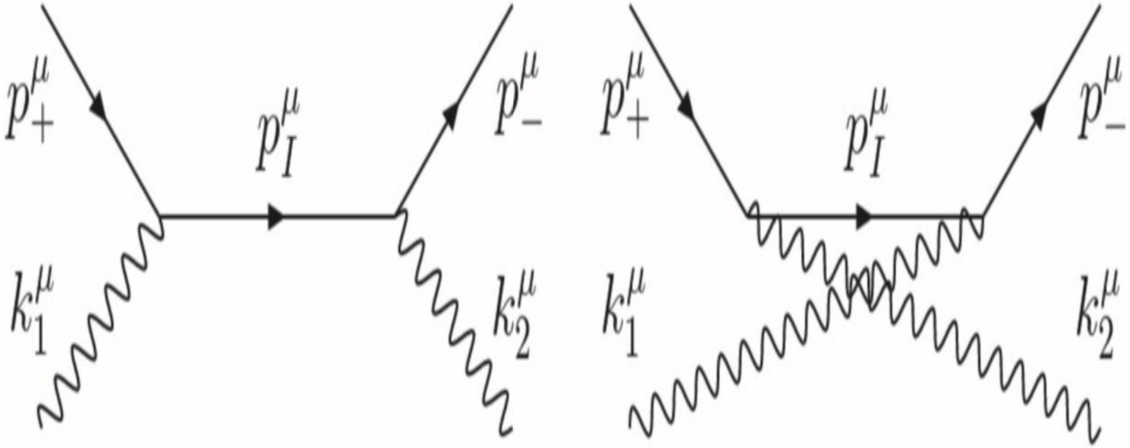
TeV afterglow

main burst

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

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

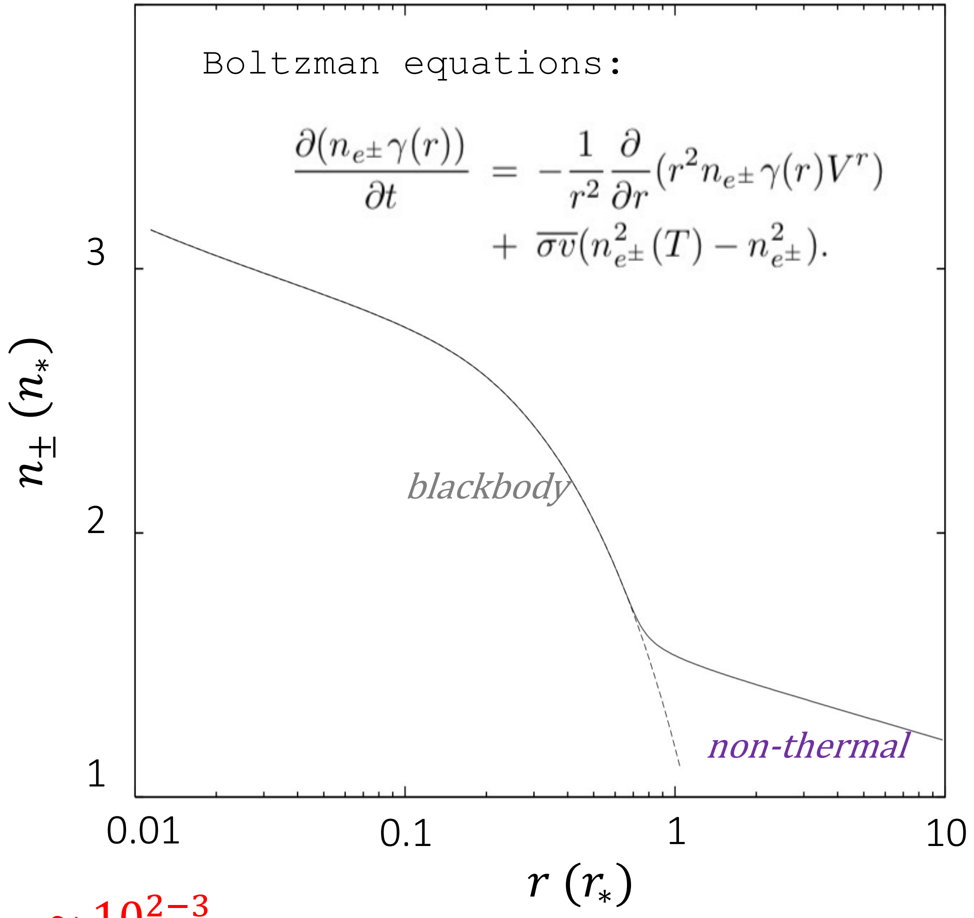
$$\boxed{\gamma+\gamma \leftrightarrow e^{+}+e^{-}}$$



- **Super-QED interactions** in ultra-strong magnetic fields (Kostenko & Thompson 2018, 2019)
- **Pair annihilation lines @** $E'_{\rm line} \sim 2m_e c^2 \sim 1$ 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 **pair plasma** (Ruffini et al. 1999, 2000, 2001)



类似于暗物质的宇宙学退耦

Model and Assumption

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):

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

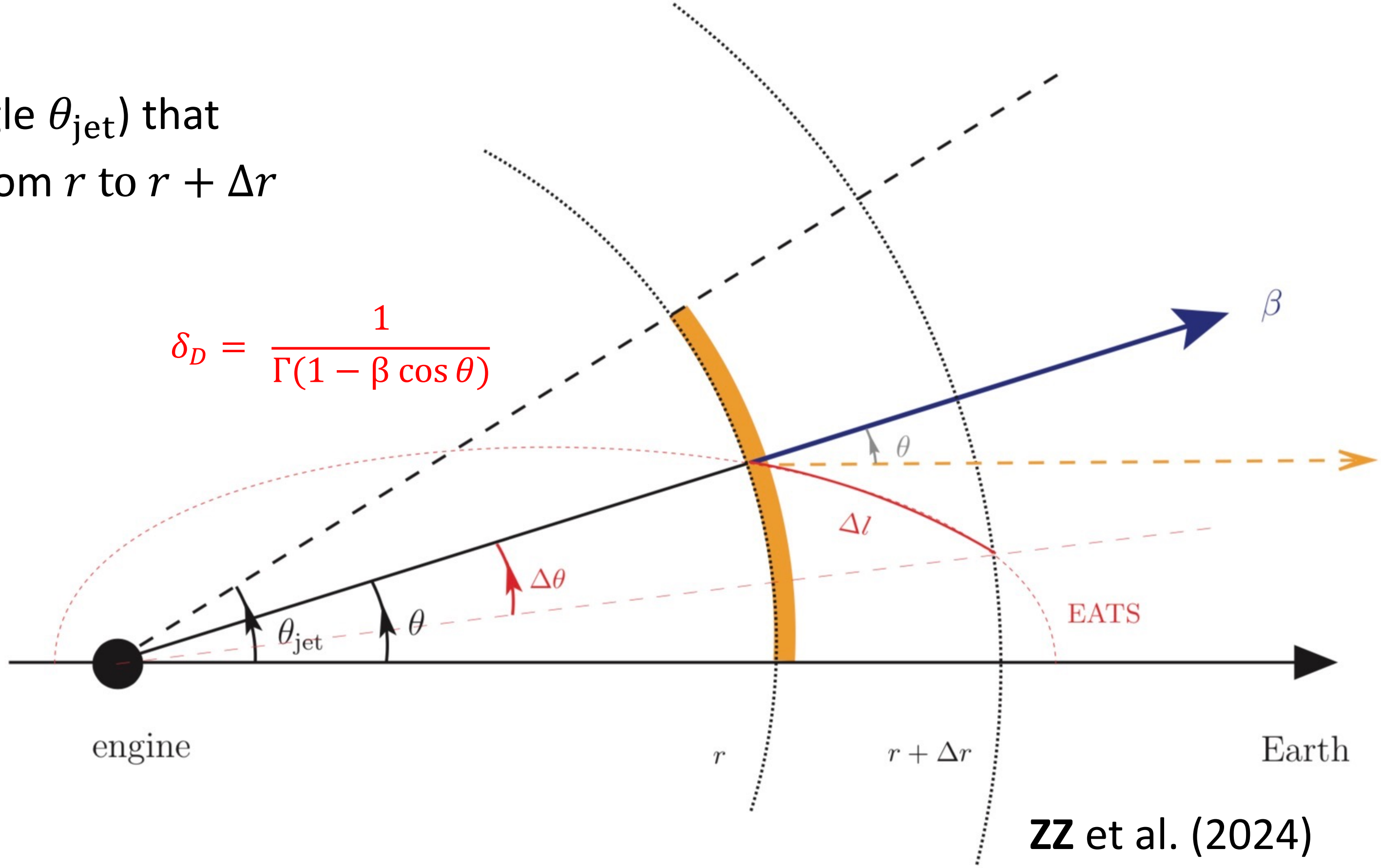
- *High-latitude curvature* effect:

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

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

- Line flux evolves as:

$$\mathcal{F} = \frac{c}{2d_{\rm L}^2}\frac{\delta_D^3\,\epsilon^*}{r\,\Gamma} \xrightarrow{\boxed{\epsilon^* \propto \theta^{2a}}} \propto (t-t_0)^{-3+a}$$



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

ZZ et al. (2024)

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

- Line central energy:

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

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

  $\epsilon^* \propto \theta^{2a}$

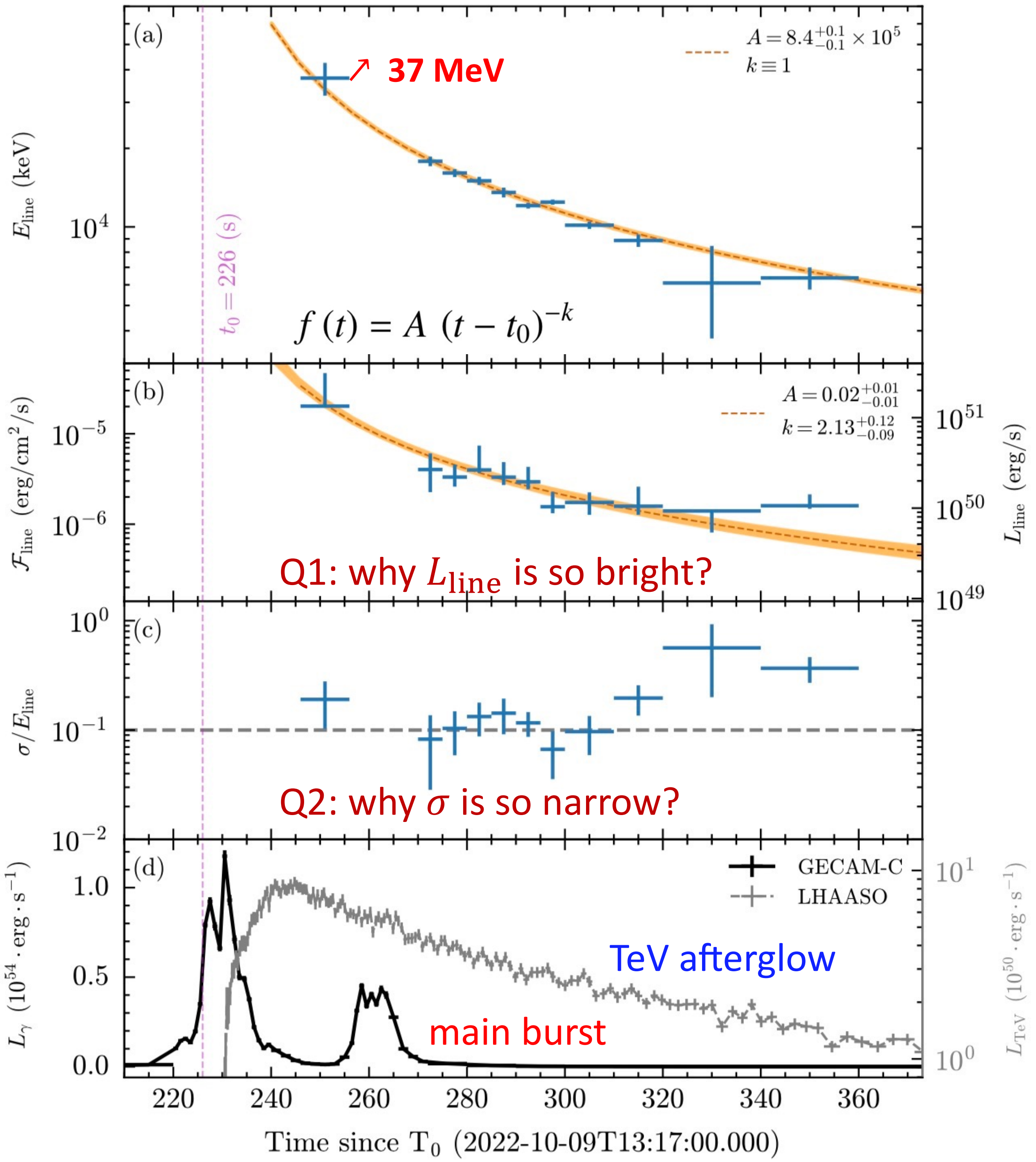
  $\Rightarrow\quad \mathcal{F}_{\rm line} \ \propto\ (t - t_0)^{-3+a}$

  $\rightarrow\ a \sim 0.9$

- Line width: $\sigma/E_{\rm line} \sim 0.1$

  $\Rightarrow$ non-relativistic

  (**NR**, comoving frame)



↗ 37 MeV

Q1: why $L_{\rm line}$ is so bright?

Q2: why σ is so narrow?

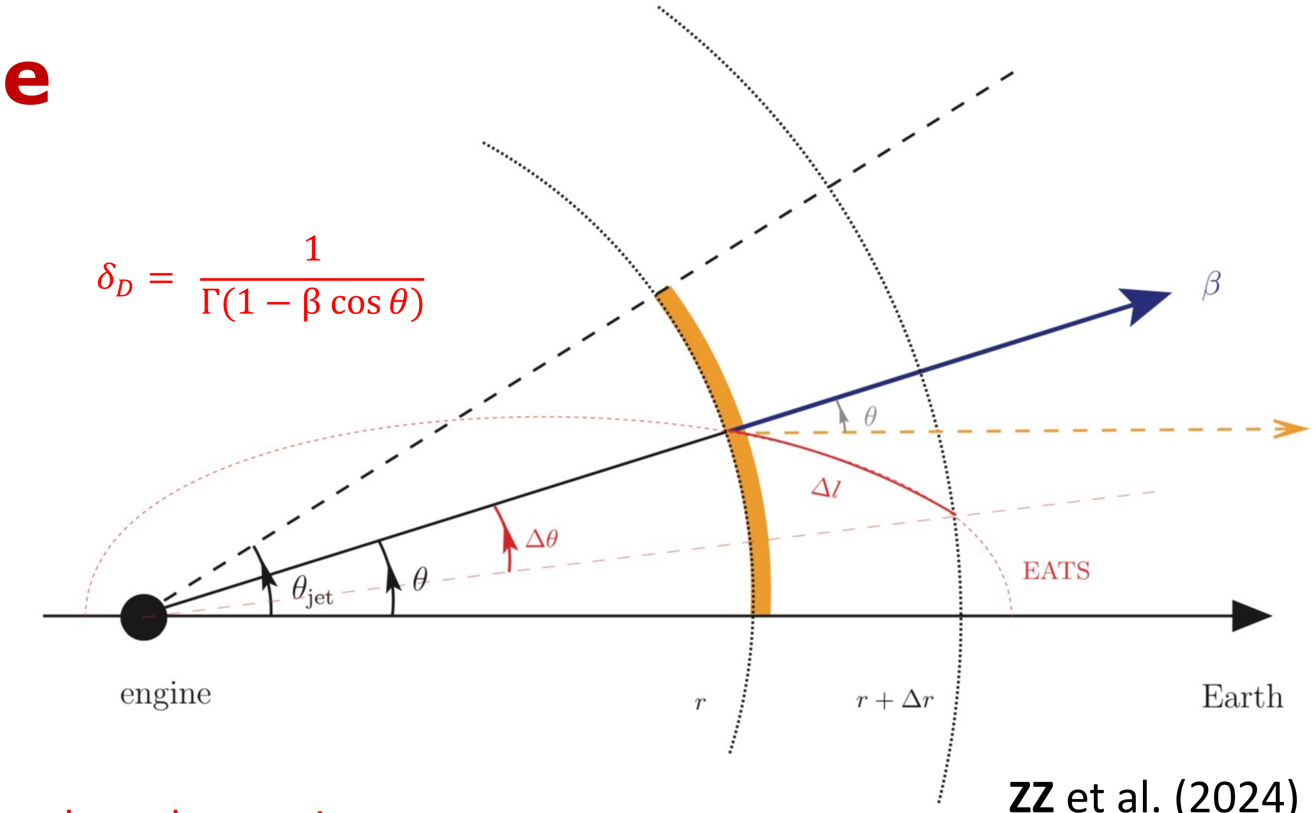
TeV afterglow

main burst

Jet’s half-opening angle

○ Line central energy:

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



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

ZZ et al. (2024)

The power-law decay lasts for ≳ 135 s. Thus,

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

$\approx 0.8^{\rm o}$ consistent with TeV afterglow observation

- Our direct, independent measurement!

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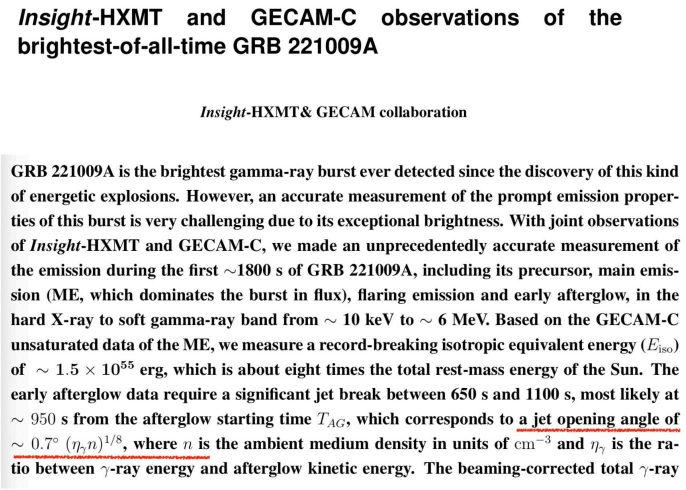
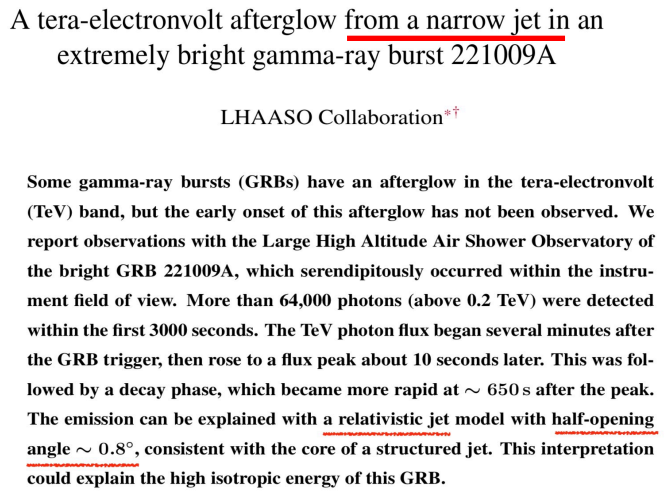
NSR, … … , 2303.01203



***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 ∼ $0.7^\circ\ (\eta_\gamma n)^{1/8}$, where n is the ambient medium density in units of $\rm cm^{-3}$ 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

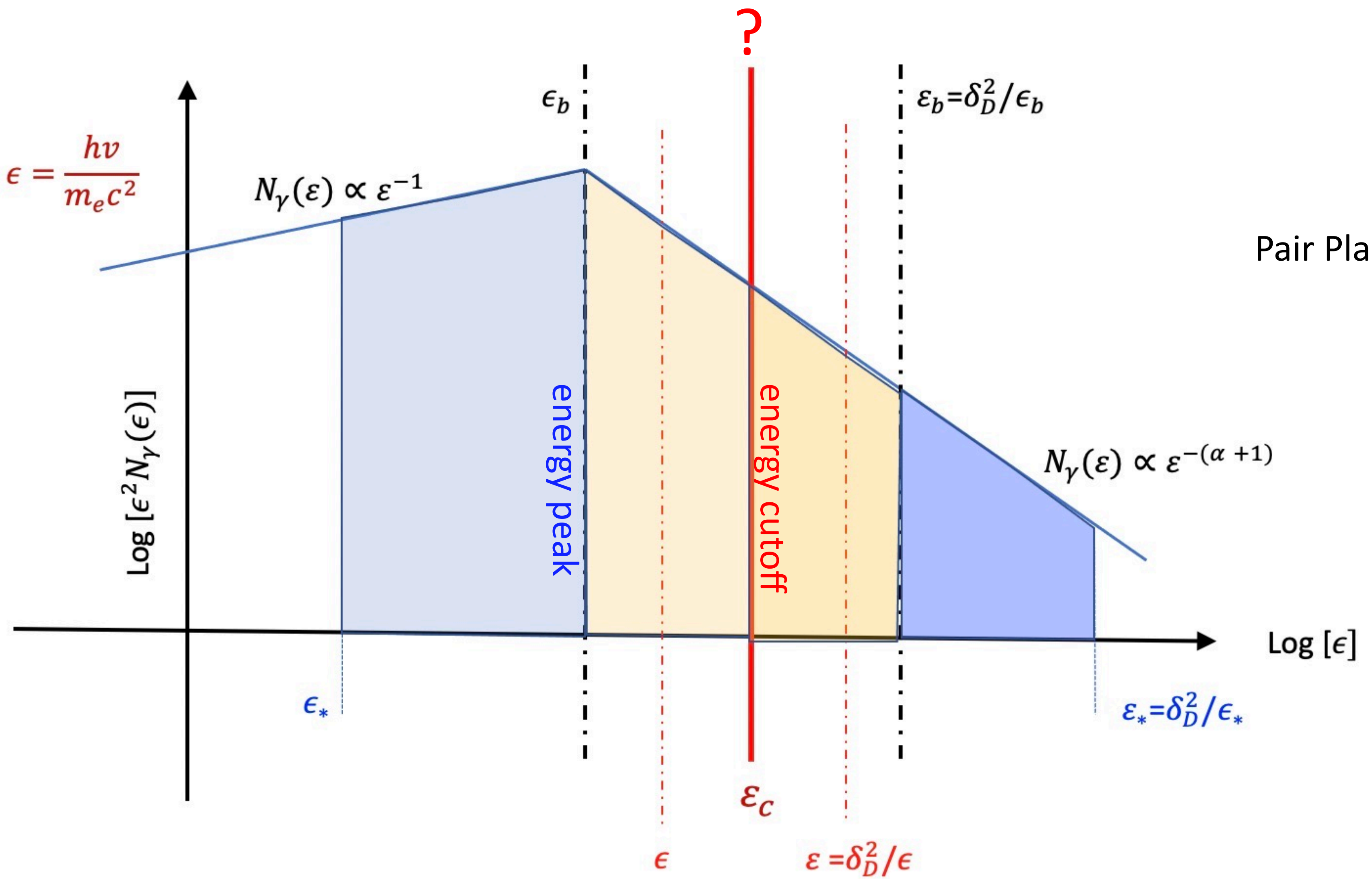
LHAASO Collaboration*†

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.

Why the MeV line is so bright ?

- GRB spectra

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



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

$$\downarrow \qquad \downarrow$$

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

$$\Downarrow$$

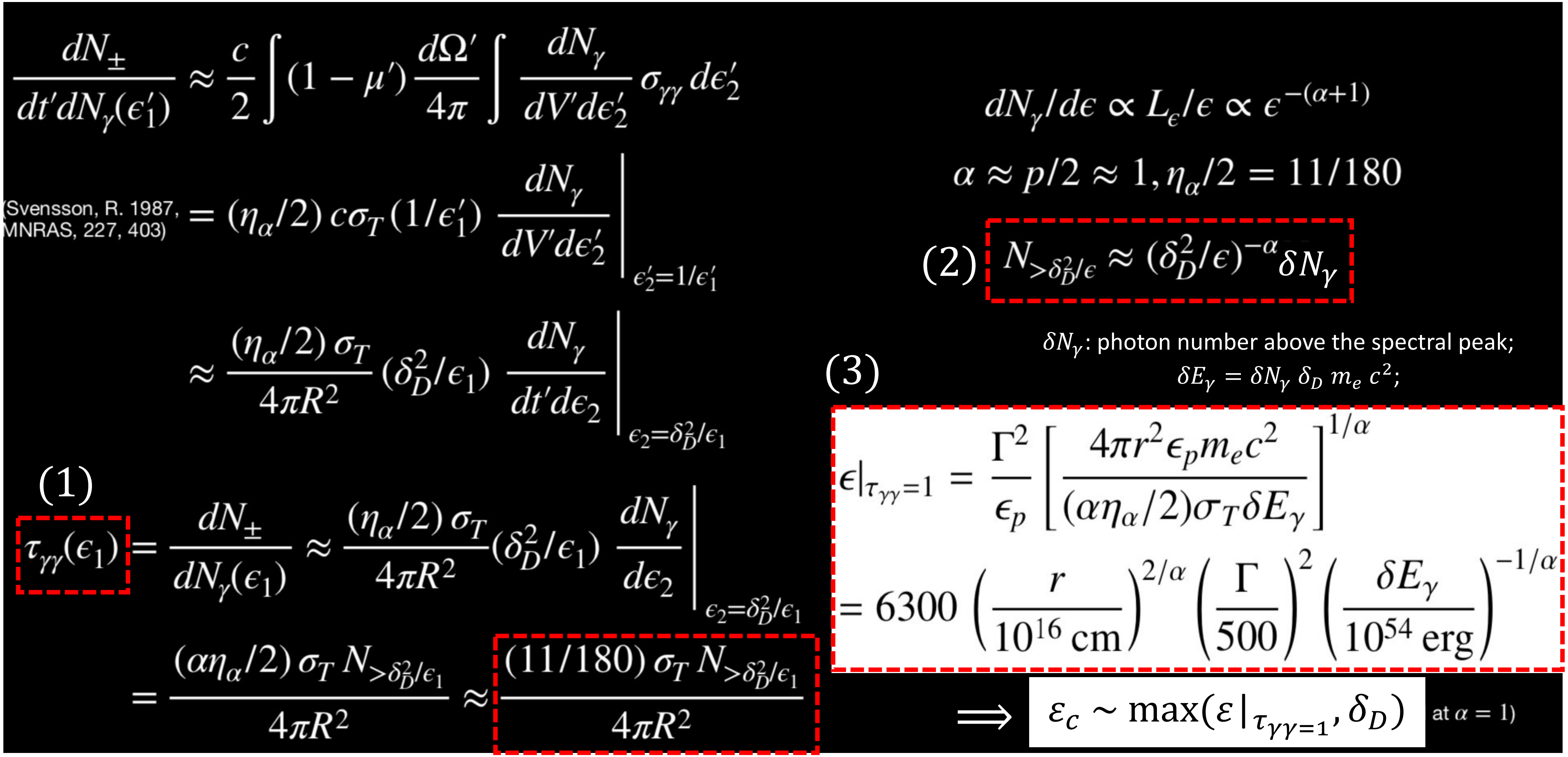
$$L_{\rm ann} \approx \delta_D m_e c^2 \frac{dN_\pm}{dT} \approx \delta_D f_\pm \frac{L_{\rm peak}}{\epsilon_{\rm peak}}$$

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

Line luminosity:

? $L_{\rm line} \sim 10^{50} - 10^{51}$ 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)

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

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

(1)

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

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

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

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

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

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

(3)

$$\boxed{\begin{aligned}\epsilon|_{\tau_{\gamma\gamma}=1} &= \frac{\Gamma^2}{\epsilon_p}\left[\frac{4\pi r^2\epsilon_p m_e c^2}{(\alpha\eta_\alpha/2)\sigma_T\delta E_\gamma}\right]^{1/\alpha}\\ &= 6300\left(\frac{r}{10^{16}\,\mathrm{cm}}\right)^{2/\alpha}\left(\frac{\Gamma}{500}\right)^2\left(\frac{\delta E_\gamma}{10^{54}\,\mathrm{erg}}\right)^{-1/\alpha}\end{aligned}}$$

$\Longrightarrow$ $\boxed{\varepsilon_c \sim \max(\varepsilon|_{\tau_{\gamma\gamma}=1}, \delta_D)}$ 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;
- $\delta E_\gamma = \delta N_\gamma\, \delta_D\, m_e\, c^2$

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

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

ZZ et al. (2024)

$$\Downarrow$$

$$L_{\rm ann} \approx \delta_D m_e c^2 \frac{dN_\pm}{dT} \quad \begin{cases} \epsilon_c \approx \Gamma, & L_{\rm line} \sim L_\gamma. \\ \epsilon_c > \Gamma, & L_{\rm line} = 7.9 \times 10^{52} {\rm erg\ s}^{-1} \left(\frac{L_\gamma}{10^{54} {\rm erg\ s}^{-1}}\right) \left(\frac{r}{10^{16}\ {\rm cm}}\right)^{-2} \left(\frac{\Gamma}{500}\right)^{-(2\alpha-1)} \left(\frac{\delta E_\gamma}{10^{54}\ {\rm erg}}\right); \end{cases}$$

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

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

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

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

Why the MeV line is so narrow ?

Constraint on thermal motion

- line width: $\sigma/E_{\mathrm{line}} \sim 0.1 \longrightarrow e^{\pm}$ velocity: $\beta_e' \lesssim 0.1$

- Background magnetic field:

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

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

- Cooling mechanisms:

Synchrotron radiation: $U_B' = L_B/4\pi r^2\Gamma^2 c$

Inverse Compton (IC) scattering: $U_\gamma' = L_\gamma/4\pi r^2\Gamma^2 c$

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: $\tau = 3\pi r^2\Gamma^2 m_e c^2/2\sigma_T L_{\rm em}$

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

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

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

Why the MeV line is so narrow?

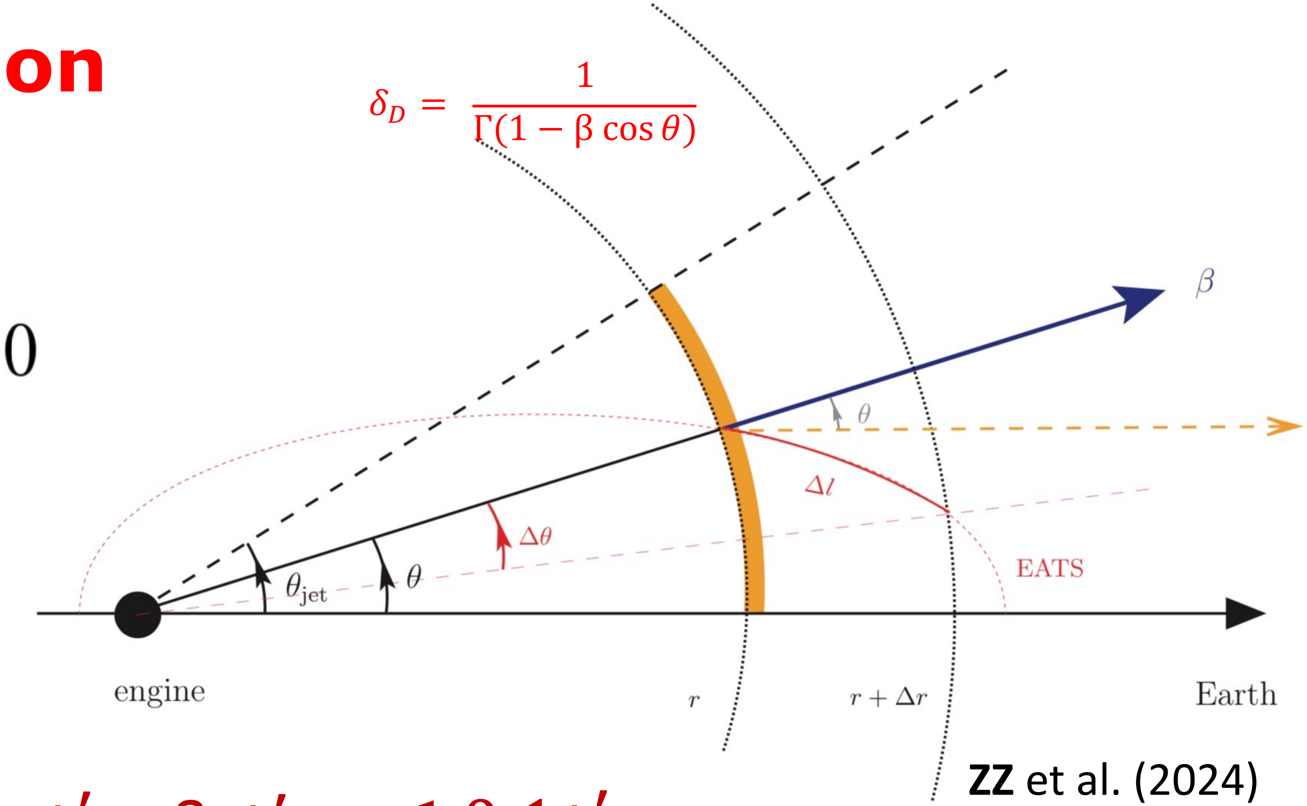
Constraint on bulk motion

- Variations over EATS:

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

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

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



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

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} ⇒ $\boxed{t'_{\rm dyn} = \frac{r}{\Gamma c} = A/m_e c^2 = 1.64\times 10^3\ s}$

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

Further constraints

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

3

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

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

○ $t'_{\mathrm{ann}} \lesssim 0.1 t'_{\mathrm{dyn}}$ => 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: $t'_{\mathrm{ann}} \simeq \frac{1}{n'_{\pm}\sigma_{e^+e^-}\beta'_e c} = \frac{8}{3}\frac{1}{\sigma_T \boxed{n'_{\pm}} c} \lesssim 0.1 t'_{\mathrm{dyn}}$

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

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

↑ observation

(spatially averaged)

(spatially averaged)

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

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

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

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

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

$\Downarrow$

4

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

Optical depth problem

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

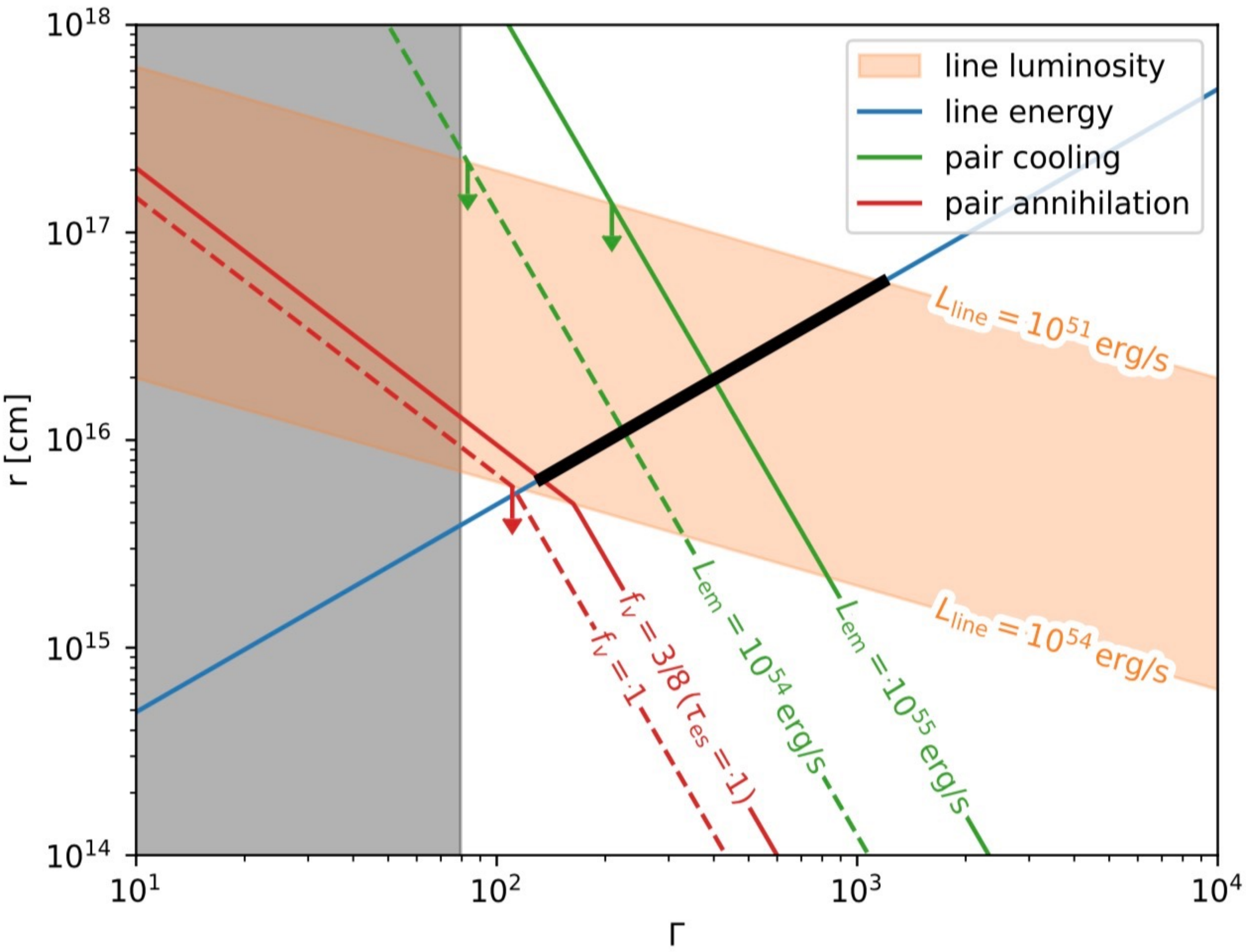
$$\tau_{\rm es} = \langle n'_{\pm} \rangle \, \sigma_T \, \mathrm{r}/\Gamma = \frac{8}{3} f_v \frac{t'_{\rm dyn}}{t'_{\rm ann}} \sim \frac{80}{3} f_v$$

- Traditionally, $f_{\rm v} = 1 \rightarrow \tau_{\rm es} \gg 1$ (always). If so, any spectral line should appear as *blackbody* emission, inconsistent with observations. [That's why we introduce $f_v < 1$]
- If $\tau_{\rm es} = 1$, $f_v = \frac{3}{80} = 0.038 \Rightarrow$ **highly clumpy?**

- 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

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

- If $\tau_{\rm es} = 1$, $f_v < \frac{3}{8} \Rightarrow$ 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) r ≳ 10^{16}cm, Γ ≳130;
2) Line energy ∝ t^{-1}
3) → high-latitude effect;
4) Line flux ∝ $t^{-2.1}$ → angle dependence of line emission;
5) If $\Gamma \gtrsim 400$, a magnetic-energy dominated jet is required;
6) $t'_{\rm NR}$, $t'_{\rm ann} \lesssim 0.1 t'_{\rm dyn}$=164 s;
7) … …
8) $\tau_{\rm es} = 1$ → a slightly clumpy region with $f_v < 3/8$;

→ The MeV line can be naturally attributed to the High-latitude emission from annihilation of $e^{\pm}$ pairs!

（Pe’er & Zhang 2024 等重点引用）

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

- ✓ $k \approx 1$ → density bumps in the medium in front of the shock

✓ Γ decreases to 20 within $t_{\mathrm{dur}} \sim$ 100s, in contradiction with the TeV afterglow data

$(\Gamma \sim 440)$

At the deceleration radius (LHAASO 2024),

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

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

Atomic line / Nuclear line ⁉️

- keV-scale atomic line of heavy element

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

  - $E_{\rm line} \sim 8 - 10\ {\rm MeV} \rightarrow \Gamma \sim 800 - 10^3$ ⛈️

  $(\Gamma \sim 440 \nearrow 700$： 2404.03229)

  Y.Q. Zhang et al.(2024)

  - If $E_{\rm line} \sim 37\ {\rm MeV}$, $\boxed{\Gamma \gg 10^3}$, in contradiction with the TeV afterglow data

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

⛈️

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

branching ratio of nuclear line: $f_d < 1$

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

Summary and Conclusions

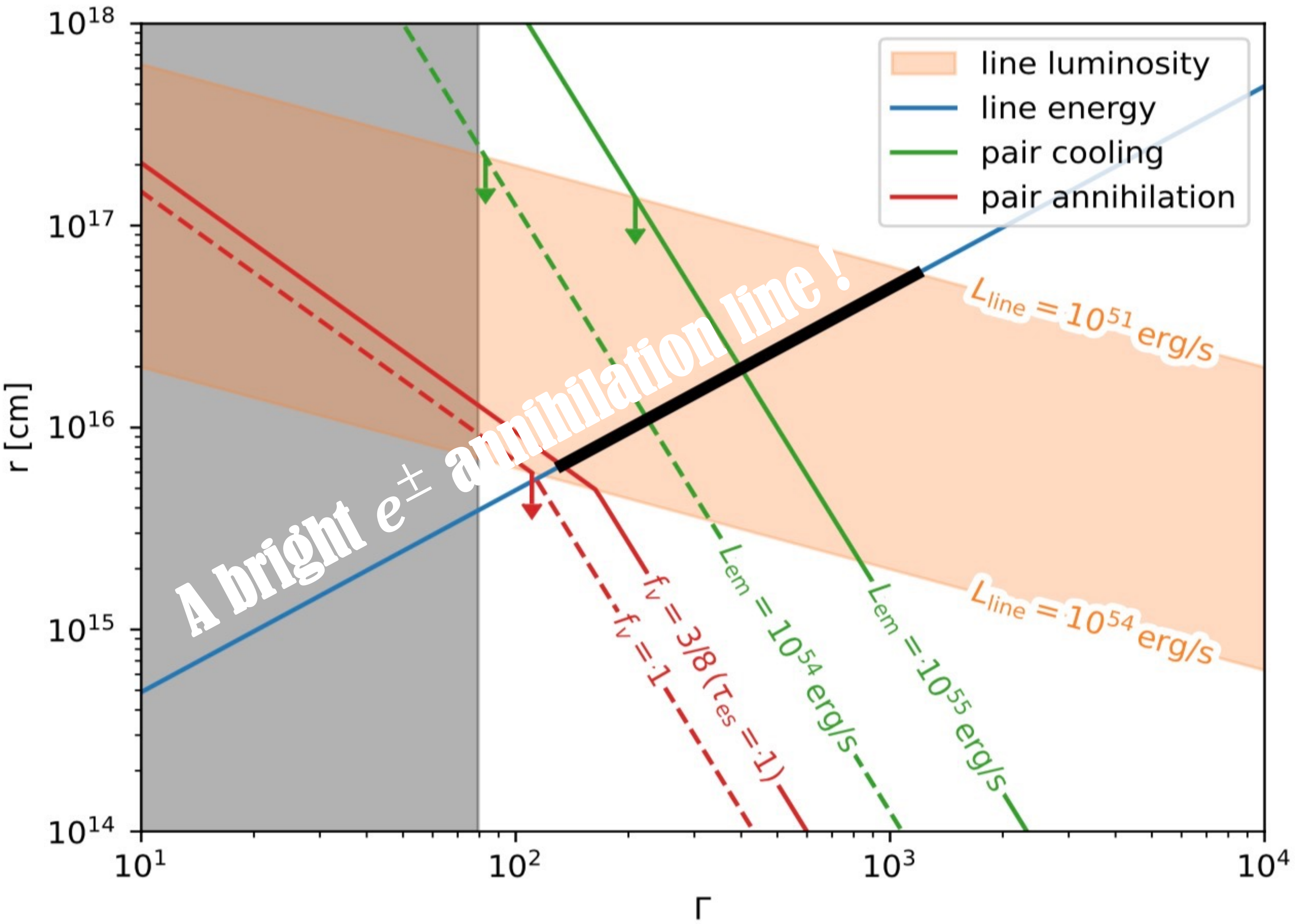
- Restricted the jet physics with observation, leaving a large parameter space available for the origin and mechanism of $e^{\pm}$ pair annihilation

- Solved problems on ~ 37 MeV, the high brightness, narrow width, and timing evolution of the MeV line, as well as those regarding creation, fast cooling and annihilation, balance between pair creation and annihilation, Thompson optical depth, the presence of clumpy regions with $\tau_{\mathrm{es}} = 1$ and $f_v < 3/8$, and relevant physical processes [mostly ignored in the literature]

1) $r \gtrsim 10^{16}$cm, $\Gamma \gtrsim 130$;
2) $L_{\mathrm{line}} \propto t^{-2.1}$ → angle dependence of line as *high-latitude* emission ($E_{\mathrm{line}} \propto t^{-1}$);
3) $\Gamma \gtrsim 400$ → a magnetic-energy dominated jet is required;

- Excluded other origins and mechanisms, such as the atomic line, nuclear line

Corollary. → The MeV line is indeed a bright $\boldsymbol{e^{\pm}}$ pair **annihilation line !**



A bright $e^{\pm}$ annihilation line !

天文学上首次探测到正负电子湮灭线！

Thank you