



天关卫星时代的X射线天文学暑期学校

伽马射线暴和快速X射线暂现源

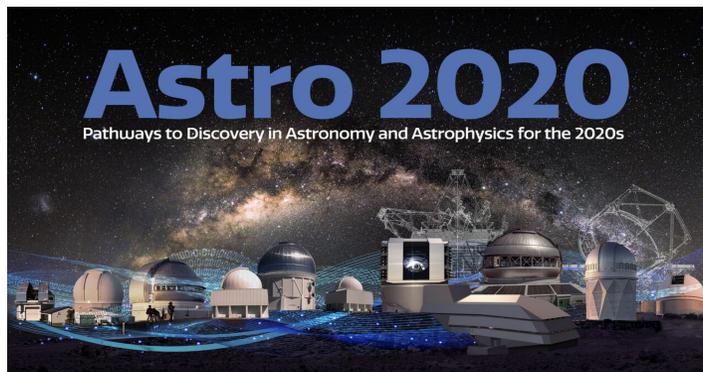
吴雪峰

中国科学院紫金山天文台

2025年8月20日

天文学研究已从**刻画静态宇宙**发展到**认识动态宇宙**的新阶段。**时域天文学**主要研究宇宙中各类天体的**短时标演化规律**，并**发现和探索各类新天体、新现象和新物理!**

未来10-20年，**时域天文学**将持续引领国际天文学，成为**“金矿”型的重大前沿科学领域!**



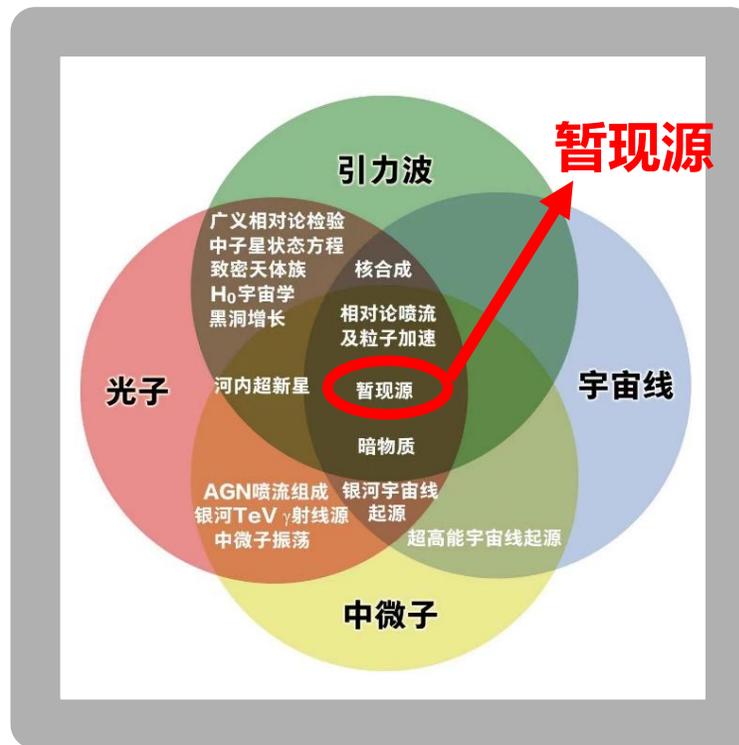
科学主题1：恒星和世界的联系
优先方向：探索宜居系外行星



科学主题2：多信使和新物理
优先方向：动态宇宙的新窗口



科学主题3：宇宙生态系统
优先方向：探寻星系演化的驱动力



Astro2020建议的现代天文观测手段及科学目标，**暂现源处于核心位置**

Science News Reports on the Top Mysteries



Dark Energy



Dark Matter



Missing Baryons



Exploding Stars



Reionization



Cosmic Rays



Planetary Diversity



Hot Solar Corona

爆炸恒星：
2012年
《Science》
8大天文学之谜之一

- **伽马射线暴：**四次被Science杂志评为当年度世界十大科技成就之一，2011年度邵逸夫天文学奖
- **引力波事件：**2017年度诺贝尔物理学奖，2016、2017年度Science杂志世界十大科技突破之首
- **河外快速X射线暂现源：**新的机遇



目 录



1. 研究背景介绍

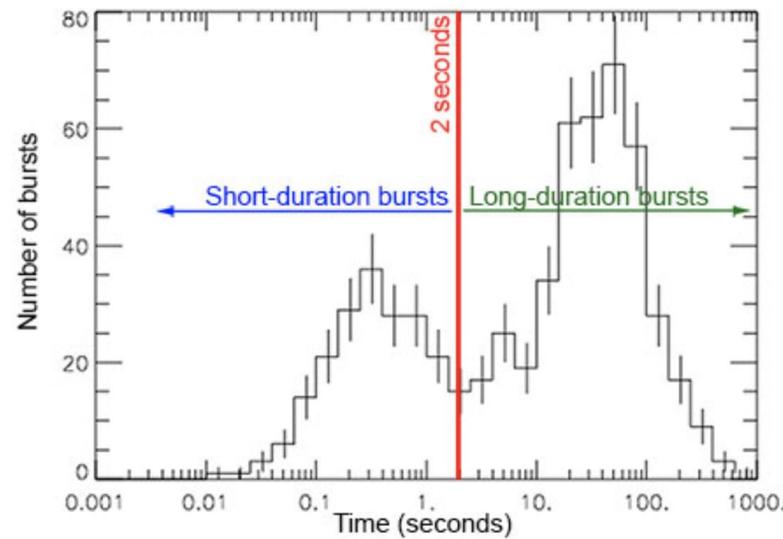
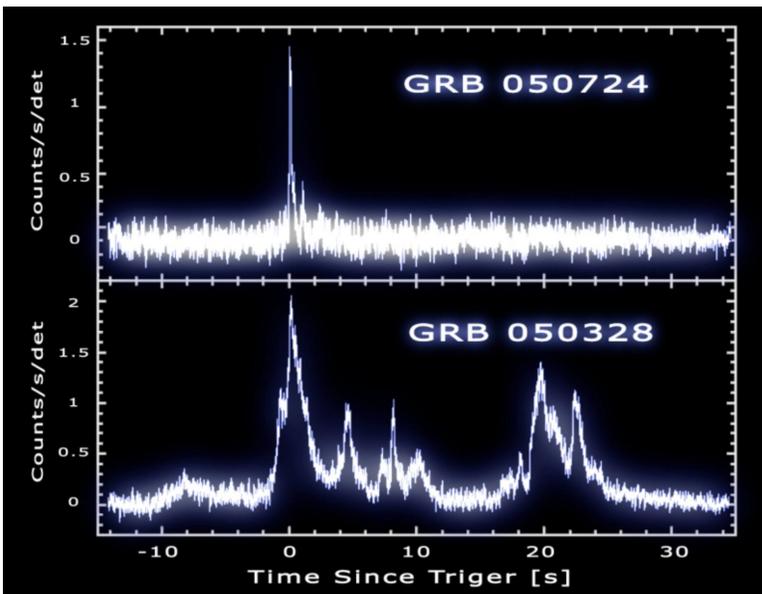
- 伽马射线暴
- 快速河外X射线暂现源

2. EP时代的观测与理论进展

- EP源观测性质
- EP源理论模型

3. EP时代的机遇展望

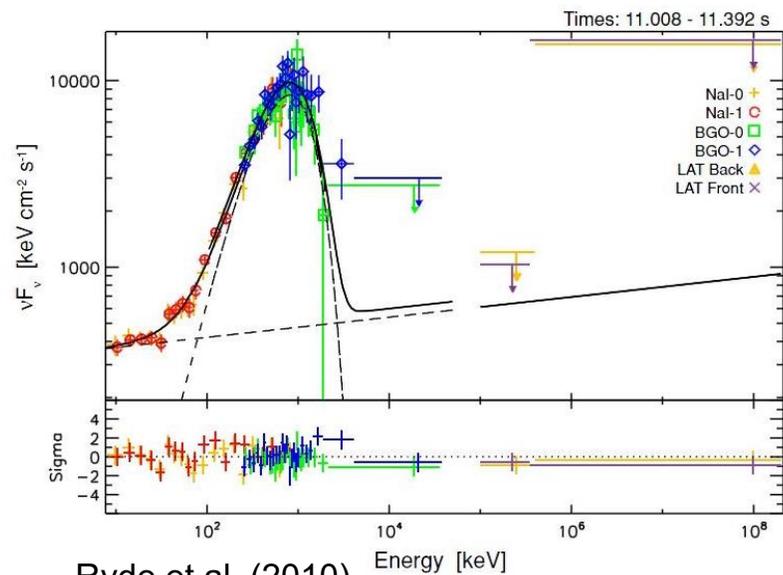
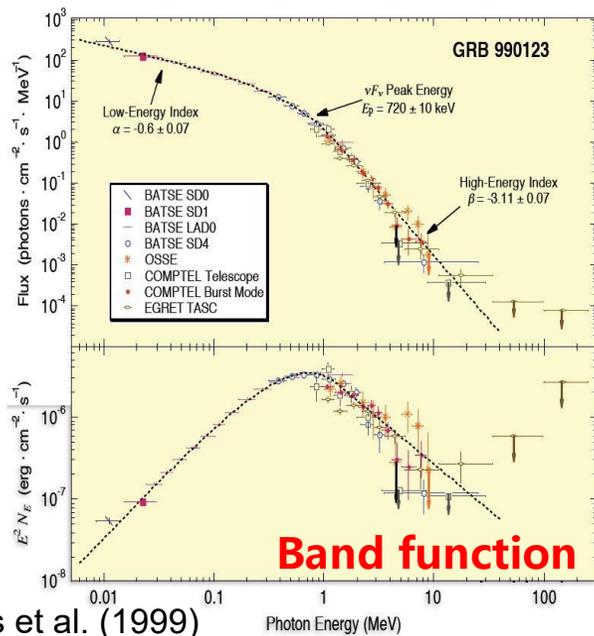
4. 总结



传统观测定义：
宇宙中伽马射线或硬X射线爆发现象

时变特征：

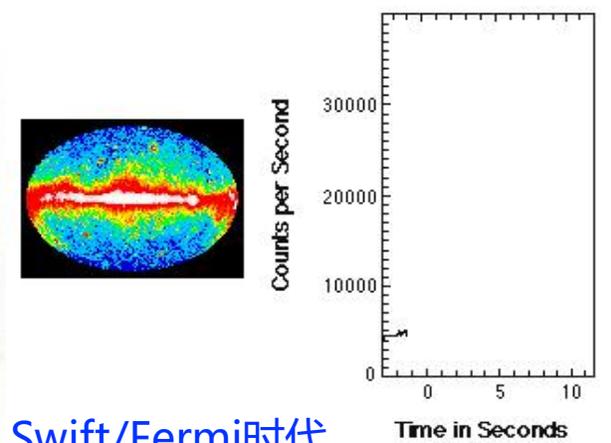
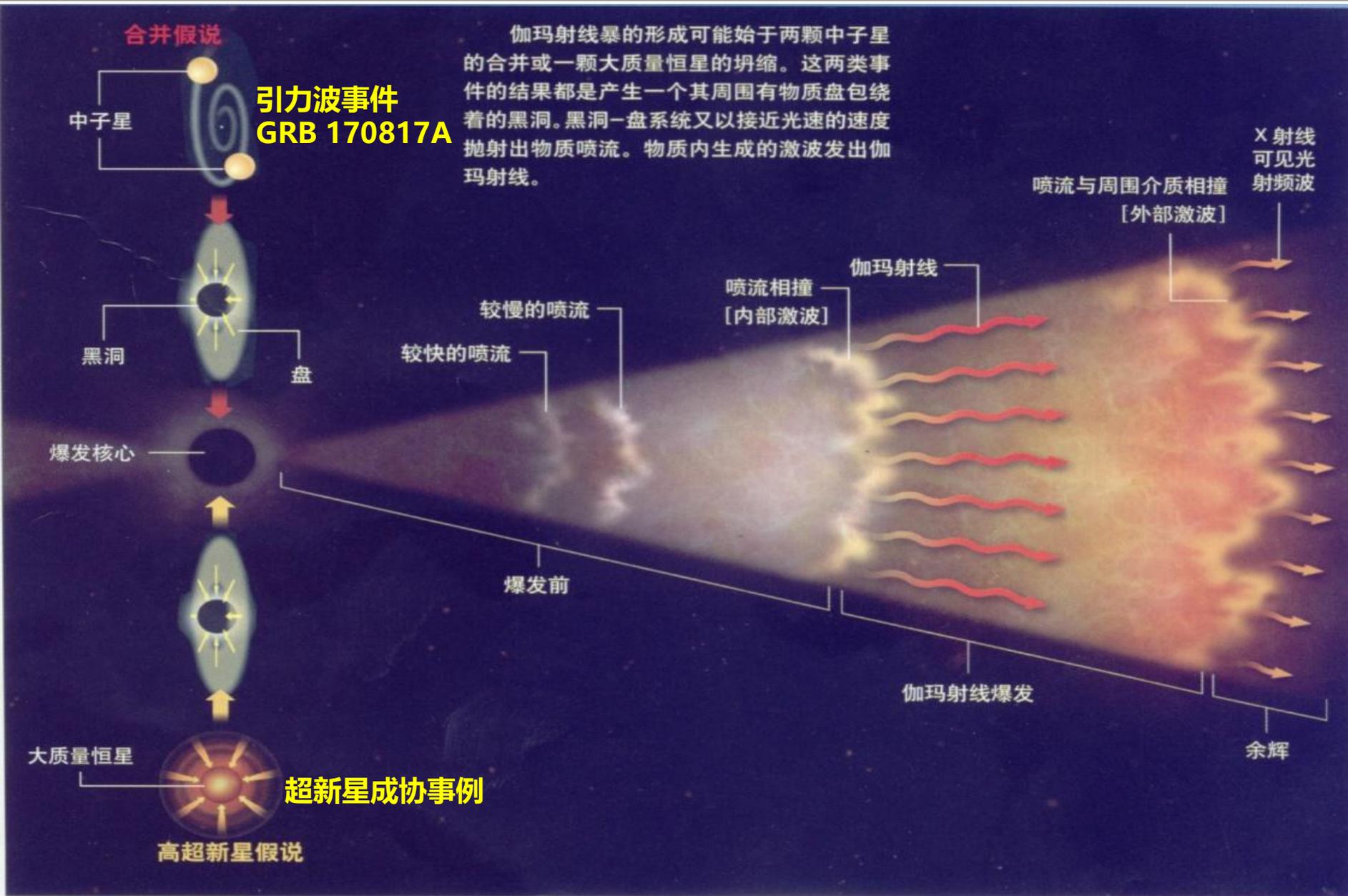
- 多样性
 - 光滑单峰/复杂多峰
- 唯像分类
 - 长/短(时标)爆发



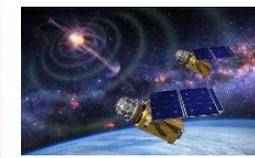
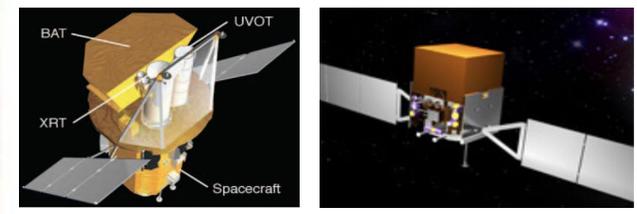
能谱特征：

- 大部分呈现非热谱
- 少数呈现热谱
- 少数有高能辐射成分

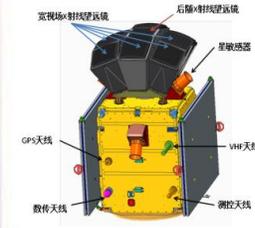
伽马暴基本物理图像



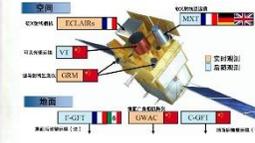
Swift/Fermi时代



GECAM



EP



SVOM

中国时代

- **发现余辉**: 1997年BeppoSAX卫星等发现长时间的多波段余辉, 并测量红移, 证实**最剧烈恒星爆发**现象;
- **长暴起源**: GRB030329/SN2003dh的成协观测表明**长暴 (>2秒)**起源于大质量恒星塌缩;
- **早期余辉**: 2005年Swift卫星发现早期余辉平台和耀发;
- **短暴起源**: **GW170817**及其电磁对应体揭示**短暴**起源于双中子星并合, 标志多信使天文学的新时代。



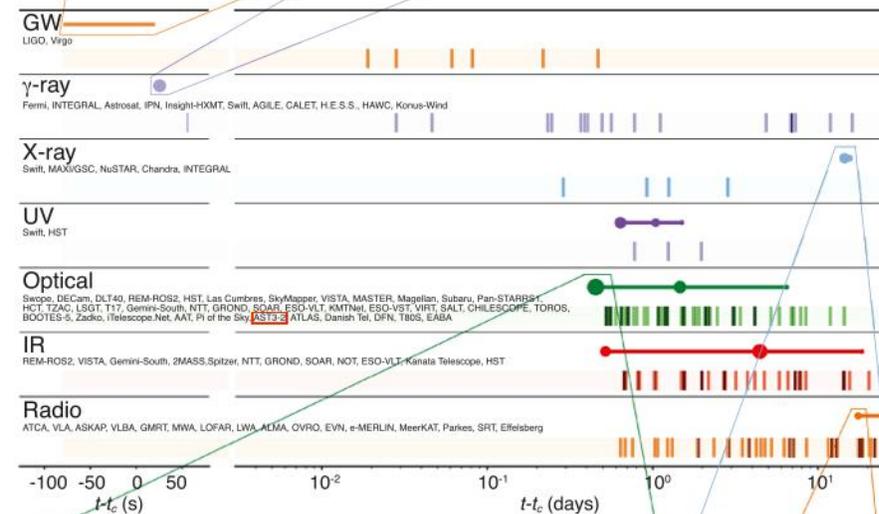
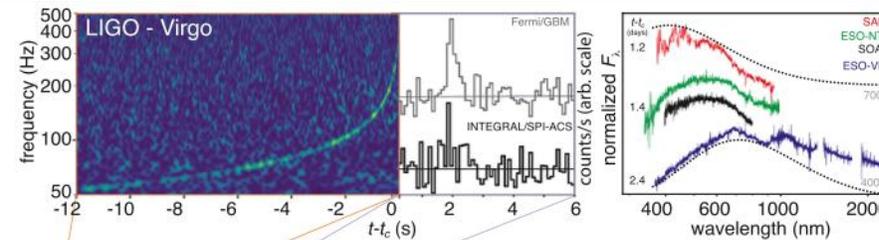
相关重大科学问题:

- 相对论喷流的基本性质与动力学 (产生、传播)
- 早期宇宙恒星形成历史、宇宙再电离历史
- 基本物理—量子引力理论验证
- 星系际磁场
- 哈勃常数危机
- 中子星物态
- 宇宙超铁元素起源

伽马暴	红移	宇宙年龄
今日	$z = 0$	137 亿年
050904	$z = 6.3$	9 亿年
080913	$z = 6.7$	8 亿年
090423	$z = 8.2$	6 亿年
090429B	$z = 9.4$	5 亿年



伽马暴研究里程碑一：双中子星并合



THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20

<https://doi.org/10.3847/2041-8213/aa91c9>

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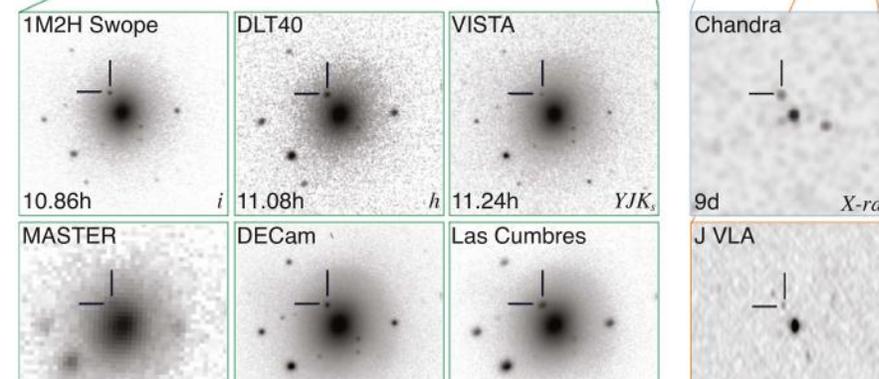
OPEN ACCESS



Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The IM2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, CaltechNRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT (See the end matter for the full list of authors.)

历史性的超过
3000合署作者
文章

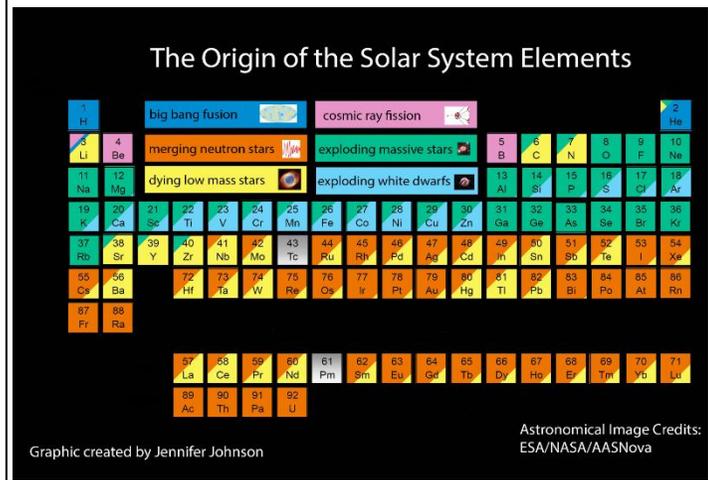
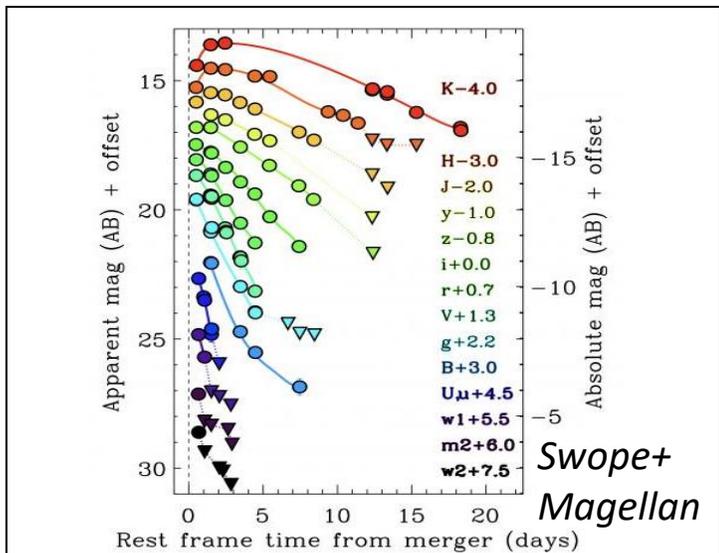


Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

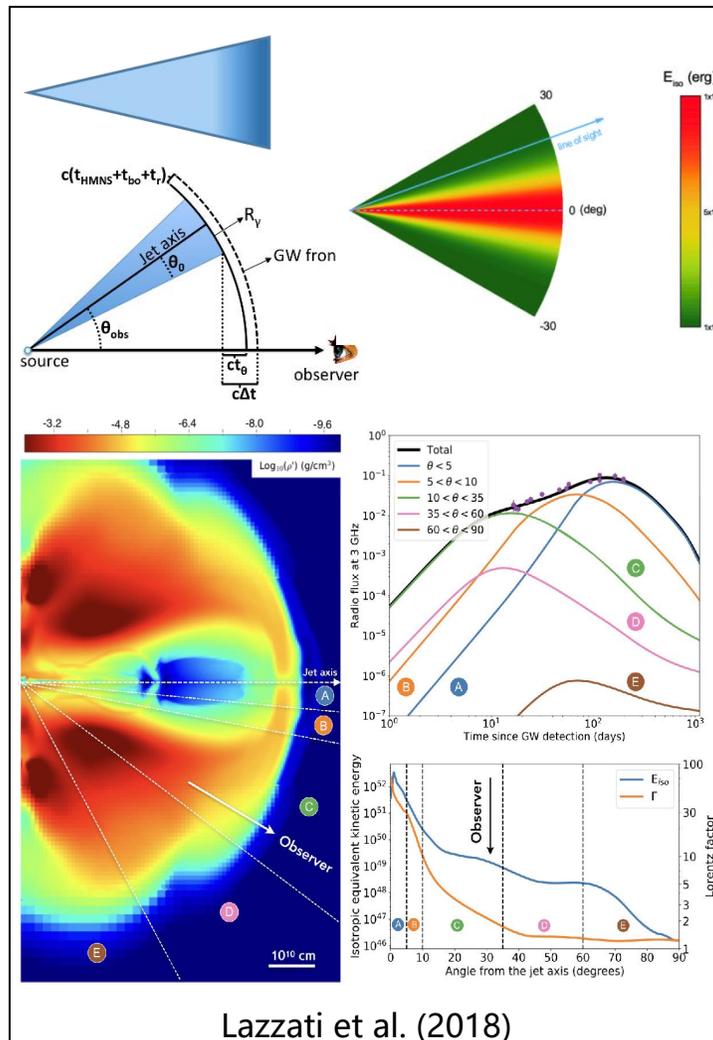
2017年被《科学》杂志评为年度世界十大科学突破之首

最经典的并合短伽马暴GRB 170817A启发：

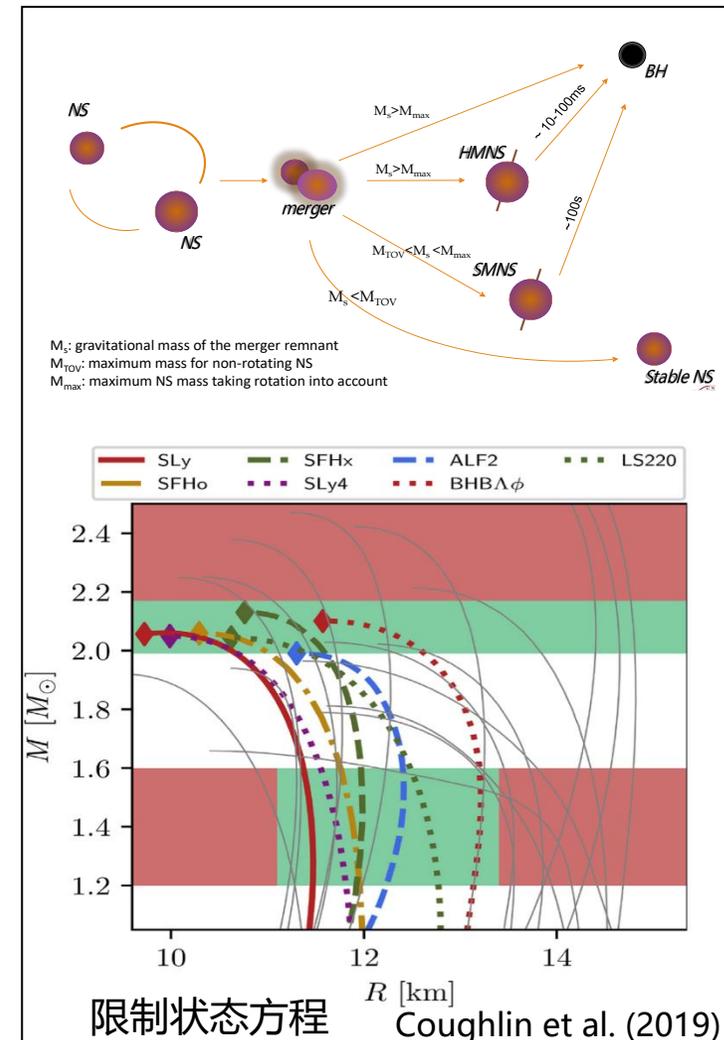
(1) 并合过程产生超铁元素



(2) 喷流是结构化的

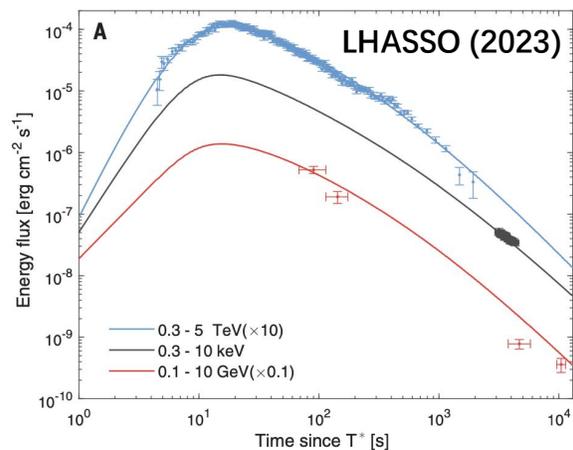


(3) 揭示致密星物理

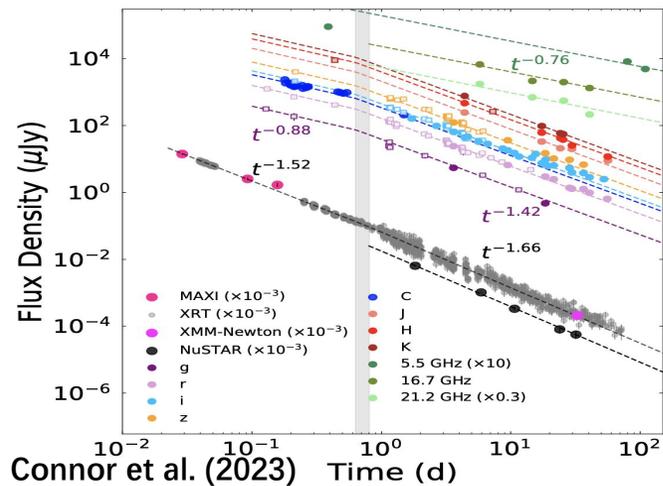


伽马暴研究里程碑二：史上最亮伽马暴

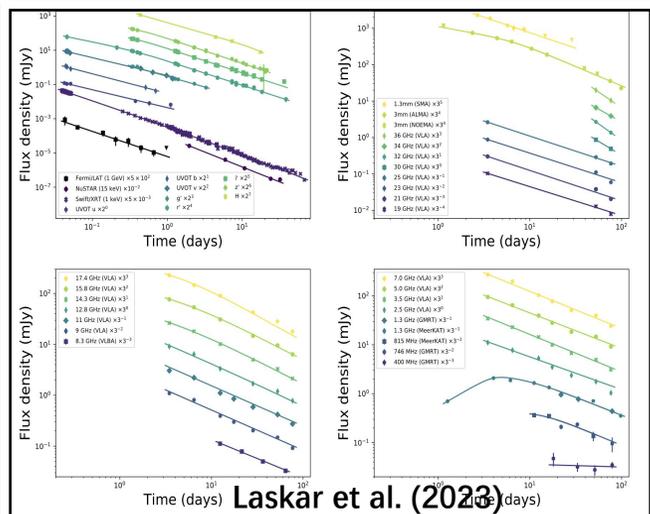
瞬时阶段TeV辐射



中晚期X射线/光学辐射



晚期射电辐射

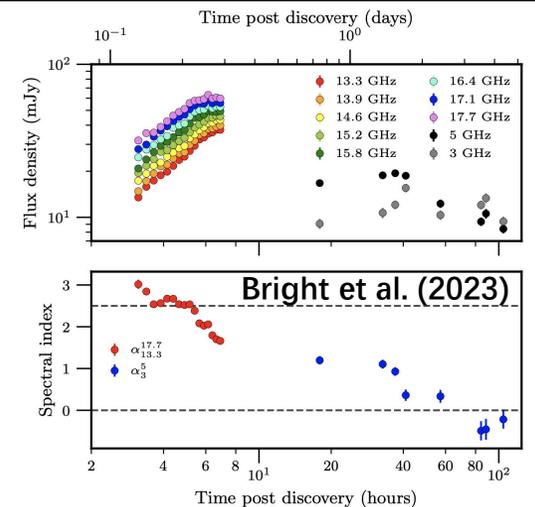


GRB 221009A包含了几乎所有GRB已知电磁信号特征元素:

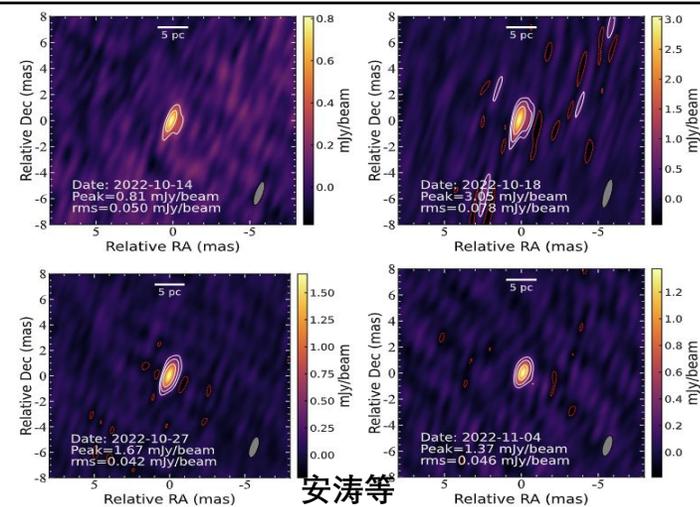
瞬时MeV发射线

瞬时-余辉 TeV到射电光变演化

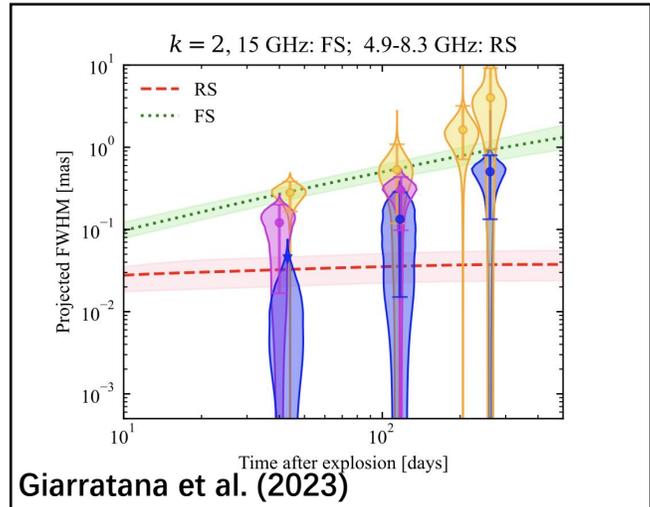
极早期射电辐射



中期射电图像



晚期射电图像



射电VLBI成像

Jet break?

超新星辐射

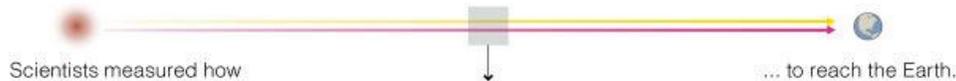
但其完整图像是什么?

安涛等

Giarratana et al. (2023)

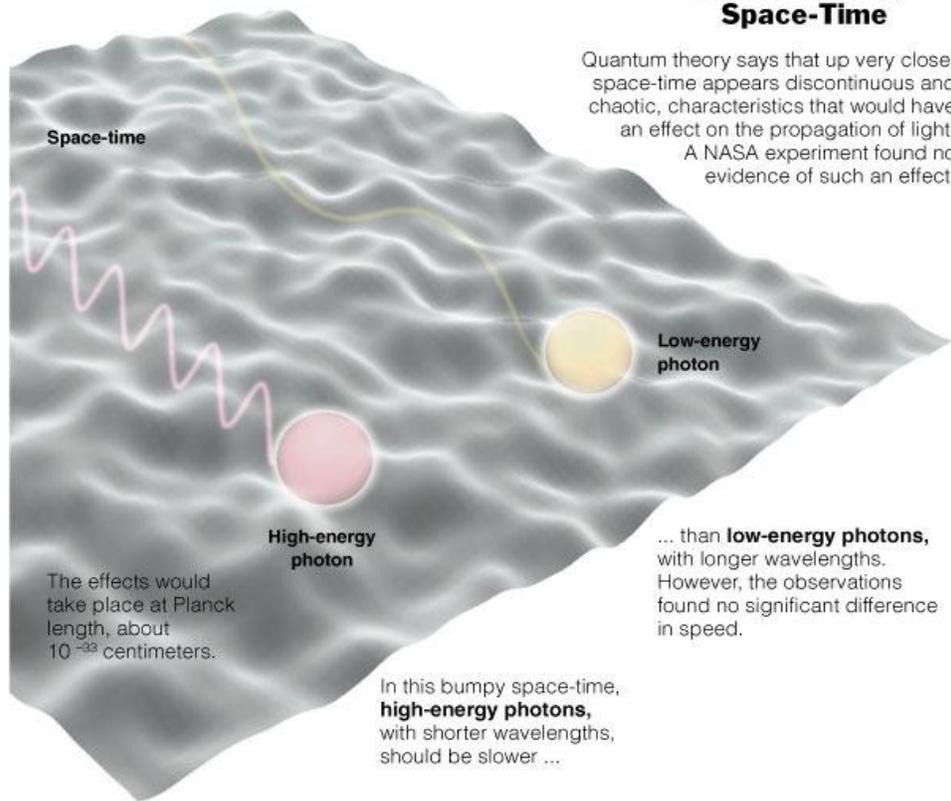
普朗克尺度下时空呈“泡沫”化

THE EXPERIMENT



A Sprint Across Bumpy Space-Time

Quantum theory says that up very close, space-time appears discontinuous and chaotic, characteristics that would have an effect on the propagation of light. A NASA experiment found no evidence of such an effect.



Source: Nature

THE NEW YORK TIMES

$$E^2 - p^2 c^2 \simeq \pm p^2 c^2 \left(\frac{pc}{\xi E_{\text{Pl}}} \right)^n$$

对于光子，如果洛伦兹不变性破缺存在，则此项不为零

普朗克长度： $l_{\text{Pl}} = \sqrt{G\hbar/c^3} \simeq 1.62 \times 10^{-35} \text{ m}$

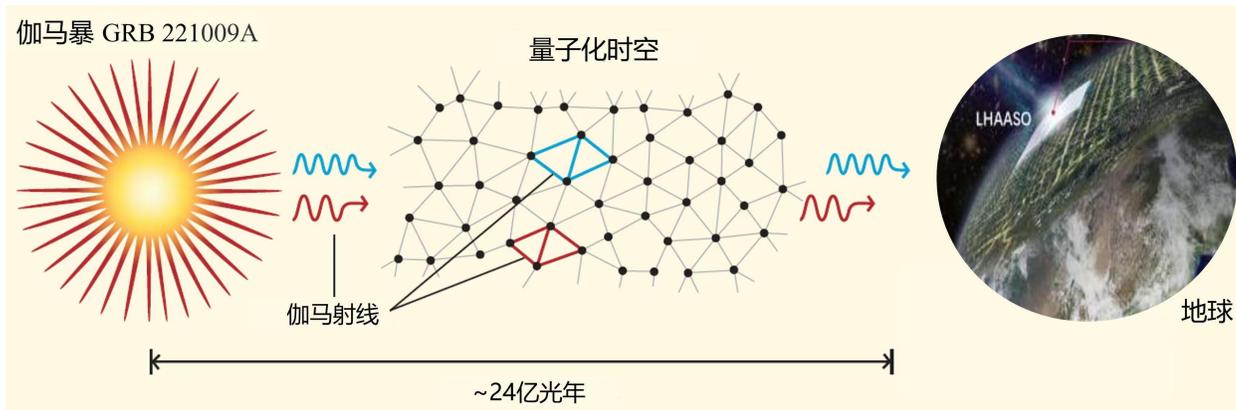
普朗克能量： $E_{\text{Pl}} = \sqrt{\hbar c^5/G} \simeq 1.22 \times 10^{19} \text{ GeV}$

不同频率/偏振态光子：

□ 真空色散效应

□ 真空双折射效应

检验洛伦兹不变性的理想天体:



伽马射线暴



极端物理特征

- ① 宇宙学距离
- ② 短时标
- ③ 高能量

男子100米



马拉松



VS

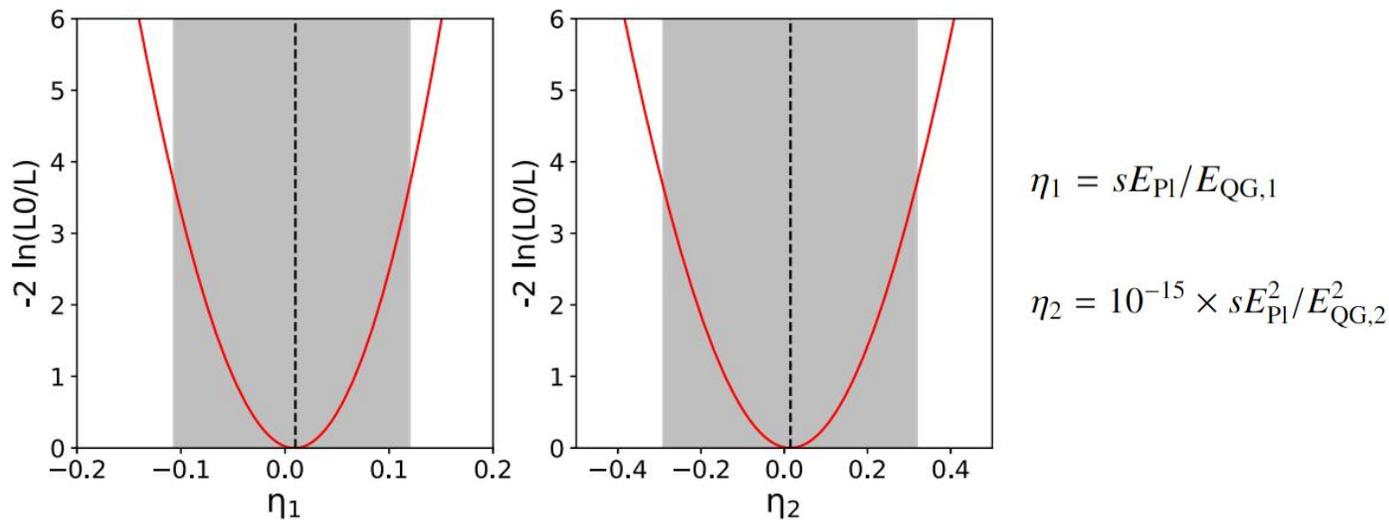
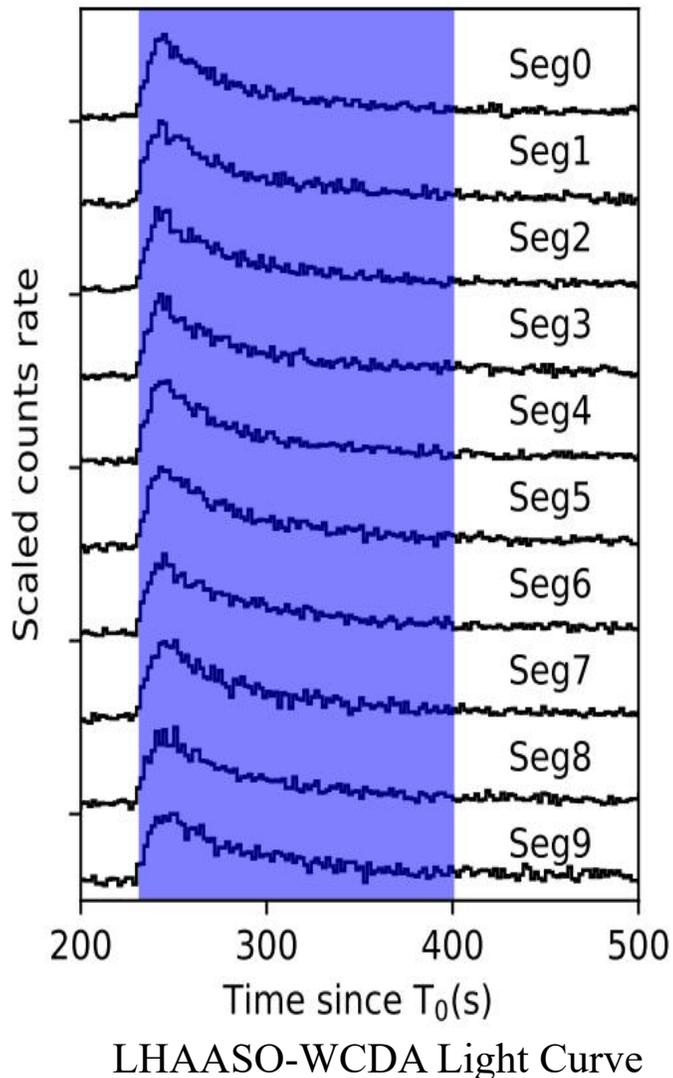


TABLE I. Values for the best fits (BF) and the 95% lower (LL) and upper (UL) limits, provided for the dimensionless LIV parameter η_n using both the CCF and ML methods. Additionally, the 95% confidence level (CL) lower limits on the quantum gravity (QG) energy scale E_{QG} for the linear ($n = 1$) and quadratic ($n = 2$) cases are listed^a.

Method	CCF			ML (MINOS)			ML (Calibrated)	
	η^{LL}	η^{BF}	η^{UL}	η^{LL}	η^{BF}	η^{UL}	η^{LL}	η^{UL}
η_1	-0.18	0.06	0.20	-0.11	0.003	0.12	-0.12	0.11
η_2	-0.47	0.25	0.66	-0.31	0.01	0.32	-0.30	0.29
$E_{\text{QG},1}$ [10^{20} GeV]	Superluminal		Subluminal	Superluminal		Subluminal	Superluminal	Subluminal
$E_{\text{QG},2}$ [10^{11} GeV]	0.7		0.6	1.1		1.0	1.0	1.1
	5.6		4.7	7.0		6.9	7.0	7.2

**给出了迄今为止二阶量子引力能标的最严格限制，
将之前的最好限制结果提高了5-7倍**

LHAASO Collaboration (项光漫、魏俊杰、姚志国、吴雪峰 共同通讯) et al. 2024, *PRL*, 133, 071501

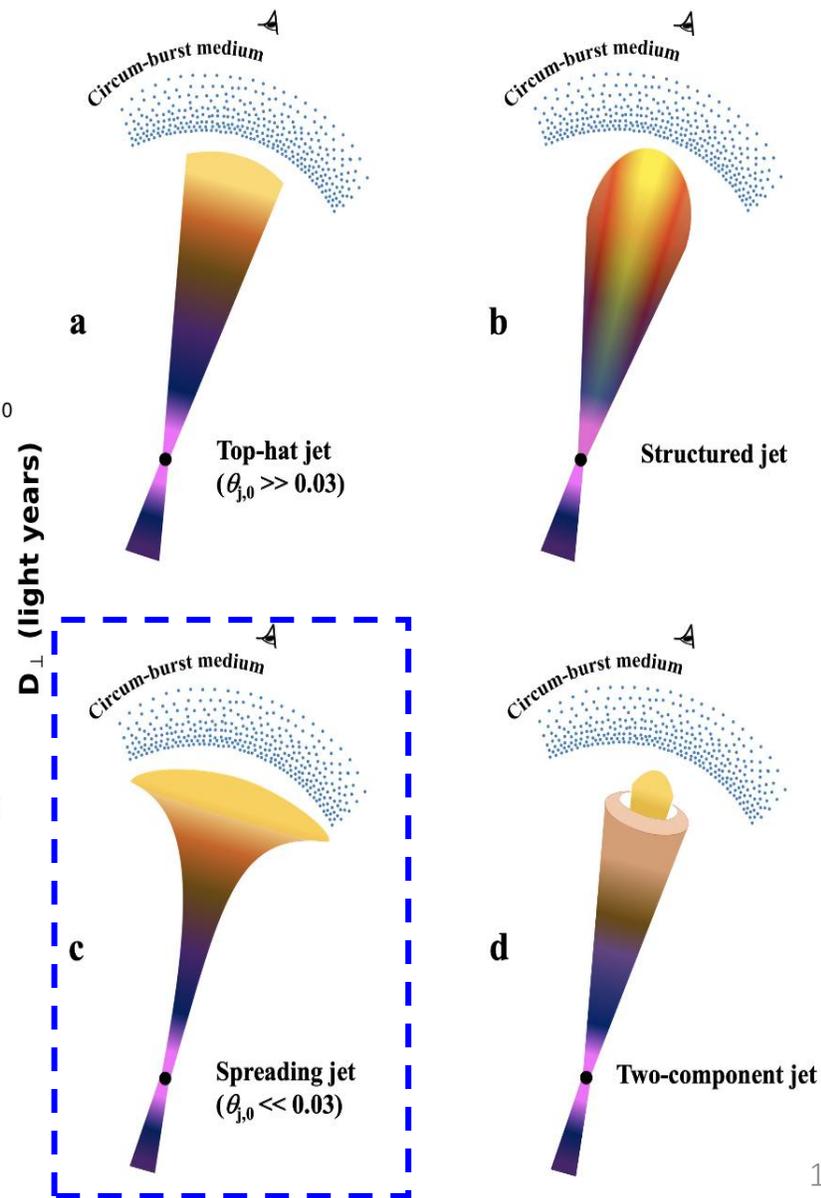
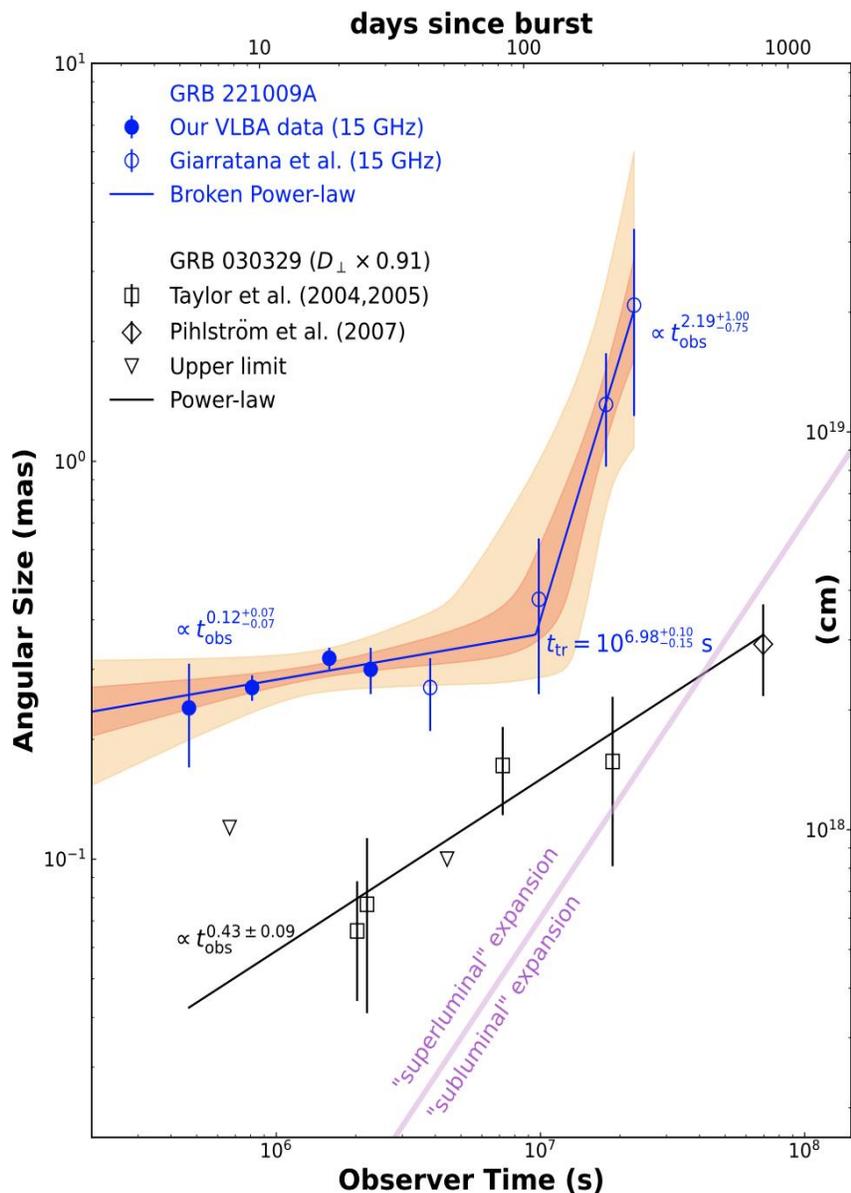
被美国物理学会Physics网站特别报道 (约1-2%的PRL论文被选为Featured in Physics, 这一类别仅适用于被认为特别具有开创性或
对更广泛的物理学界特别感兴趣的论文)

GRB 221009A的特殊/稀缺性:

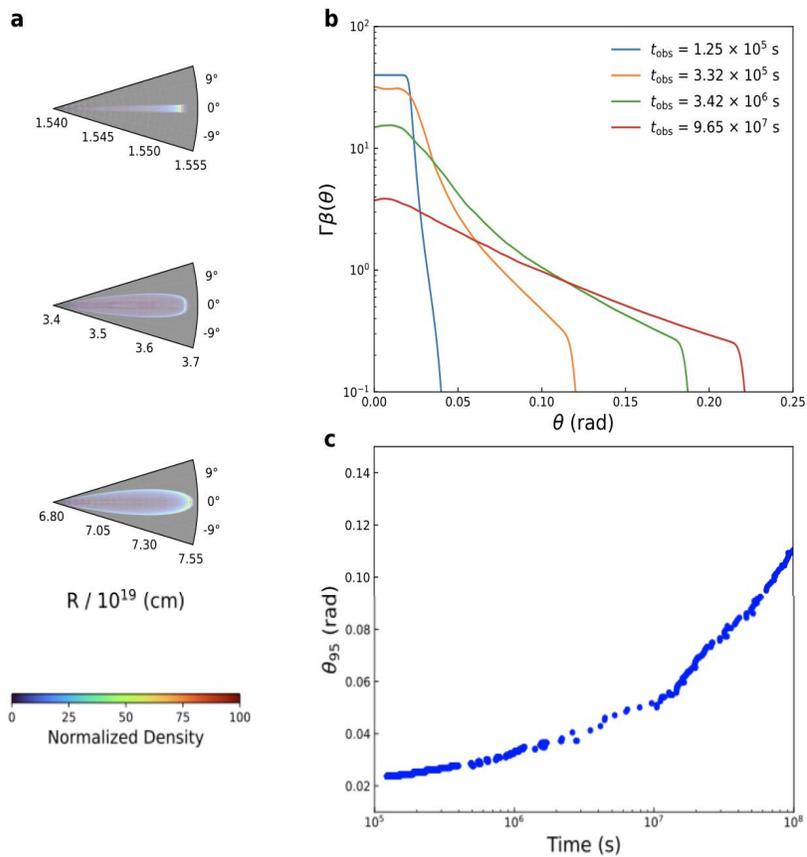
- ❑ 爆发源距离非常近
- ❑ 完美正轴观测
- ❑ 喷流初始张角极窄

VLBI成像揭示尺寸演化:

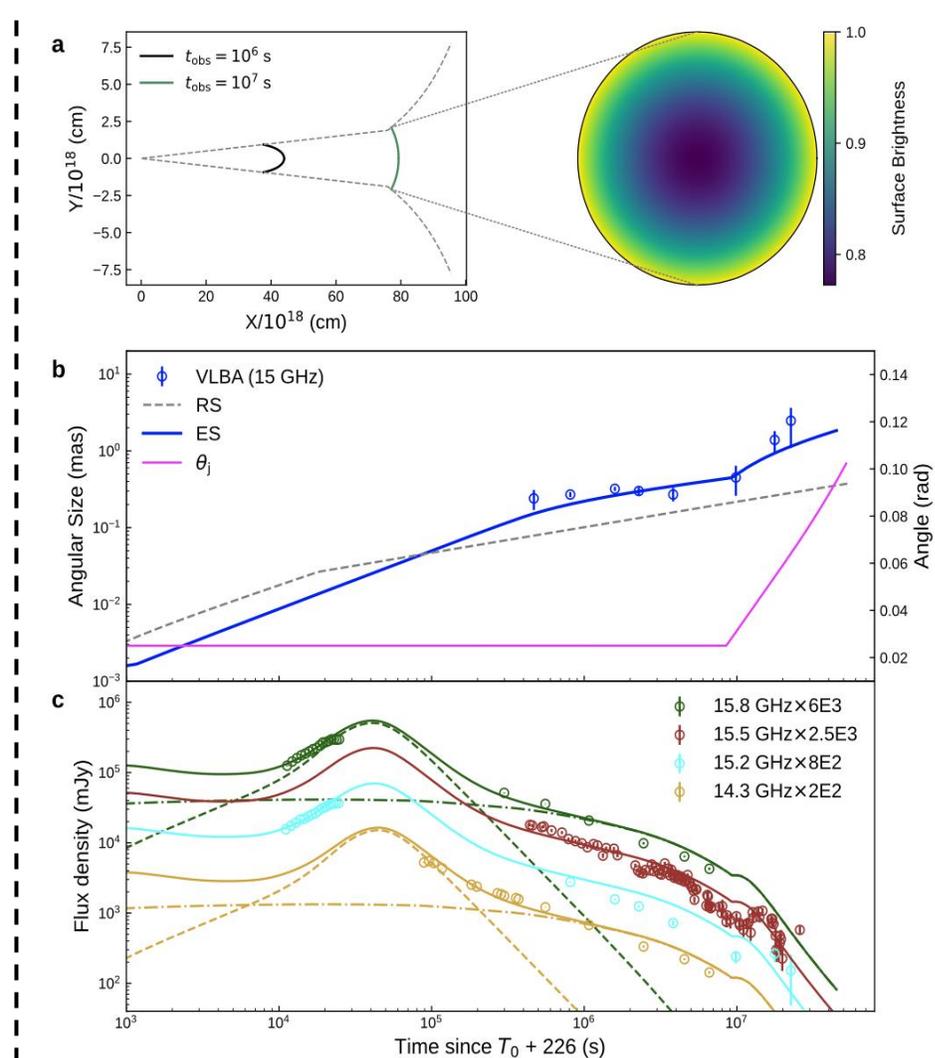
- 早期缓慢增长阶段
 - > 支持晚期暴周环境为均匀介质
 - 对现有模型提出挑战
 - 与JWST的观测一致
- 晚期快速膨胀阶段
 - > 证认了理论上预言的极窄喷流
 - 侧向膨胀现象



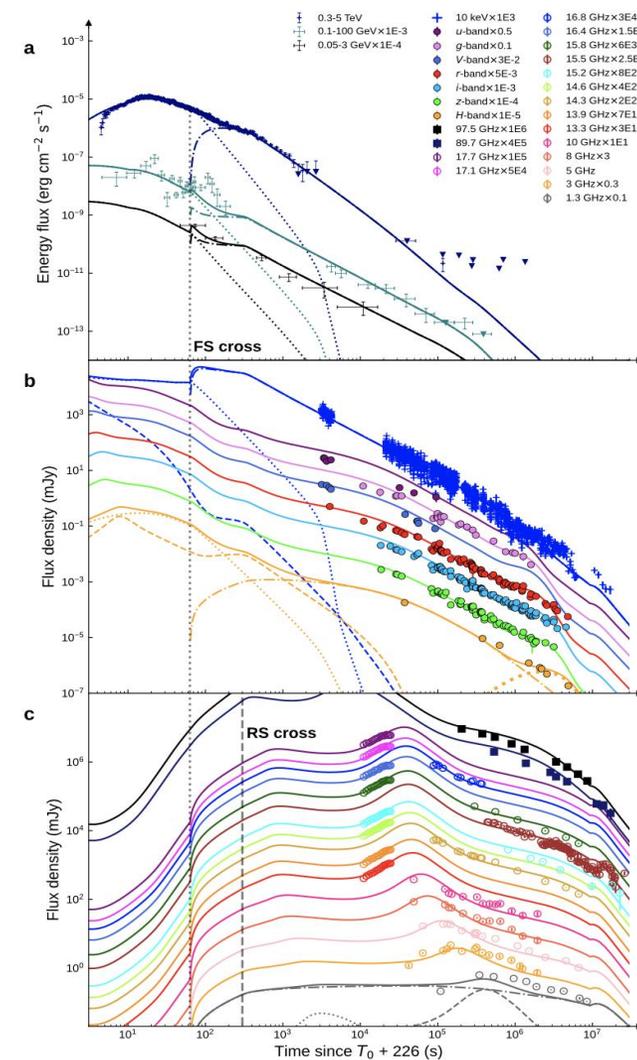
严格流体模拟证认



尺寸演化建模



多波段辐射建模



定义：分钟到小时量级的短标X射线闪耀现象

快速发展的新兴前沿！

取自戴子高教授报告

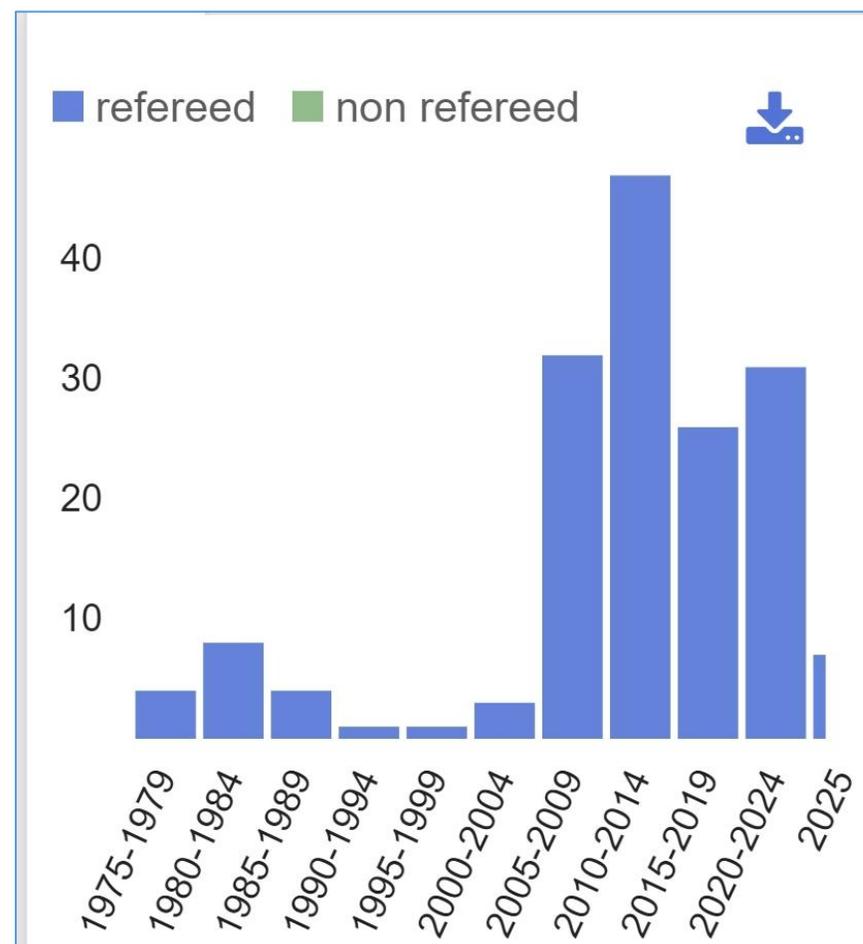
title:(fast x-ray transients)

Your search returned **164** results

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- 1 2025ApJ...982L..47V 2025/04 cited: 18
The Einstein Probe Transient EP240414a: Linking Fast X-Ray Transients, Gamma-Ray Bursts, and Luminous Fast Blue Optical Transients
van Dalen, Joyce N. D.; Levan, Andrew J.; Jonker, Peter G. *and 30 more*
- 2 2025A&A...696A.167M 2025/04
4XMM J181330.1-175110: A new supergiant fast X-ray transient
Marelli, M.; Sidoli, L.; Polletta, M. *and 3 more*
- 3 2025ApJ...981...48B 2025/03 cited: 12
The Radio Counterpart to the Fast X-Ray Transient EP240414a
Bright, Joe S.; Carotenuto, Francesco; Fender, Rob *and 10 more*
- 4 2025MNRAS.537..931D 2025/02 cited: 5
Representation learning for time-domain high-energy astrophysics: Discovery of extragalactic fast X-ray transient XRT 200515
Dillmann, Steven; Martínez-Galarza, Juan Rafael; Soria, Roberto *and 2 more*



THE ASTROPHYSICAL JOURNAL, 206:L139-L142, 1976 June 15
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A FAST TRANSIENT SOURCE OF HARD X-RAYS AT HIGH GALACTIC LATITUDE

S. RAPPAPORT,* J. BUFF, G. CLARK, W. H. G. LEWIN, T. MATILSKY, AND J. MCCLINTOCK

Department of Physics and Center for Space Research, Massachusetts Institute of Technology

Received 1976 January 27; revised 1976 March 15

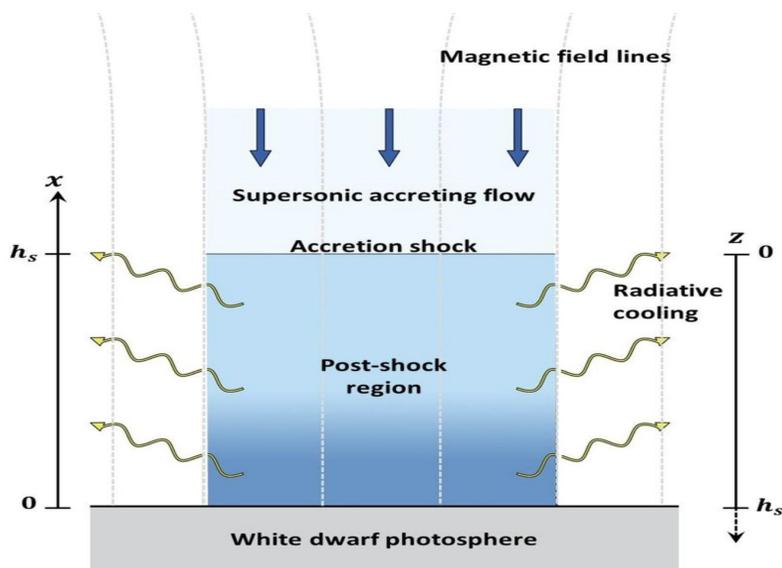
ABSTRACT

An extremely short-lived transient X-ray source has been detected with the SAS-3 satellite at a high galactic latitude ($b^{\text{II}} \approx -51^\circ$). The source, designated MX 2346-65, had a duration of between 45 s and 2200 s, and had a very hard spectrum. This source had not been detected in previous sky surveys and was not seen again by SAS-3 in 7 days of further periodic observations. Possible explanations of this type of event are discussed.

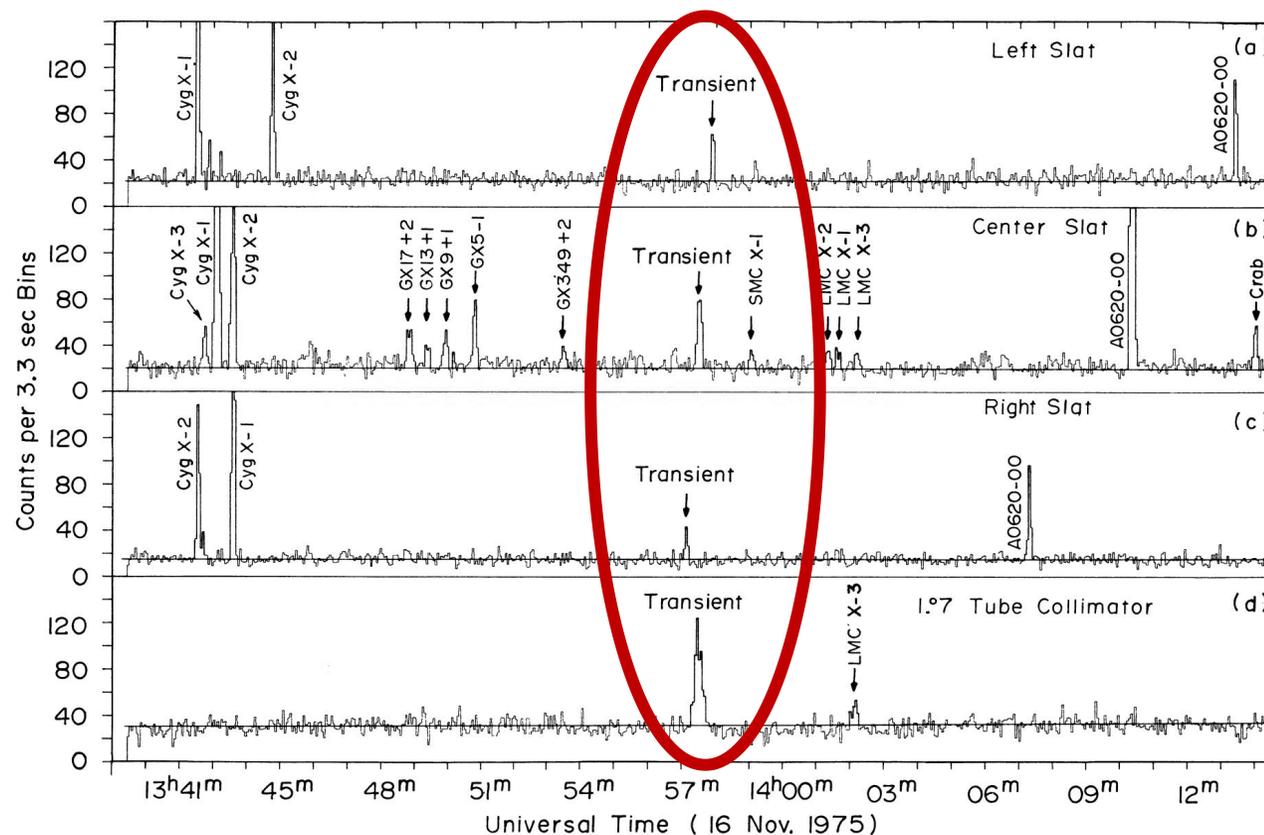
Subject heading: X-rays variable

物理解释：白矮星的吸积-吸积物质的引力

能在白矮星表面形成的驻激波处被热化



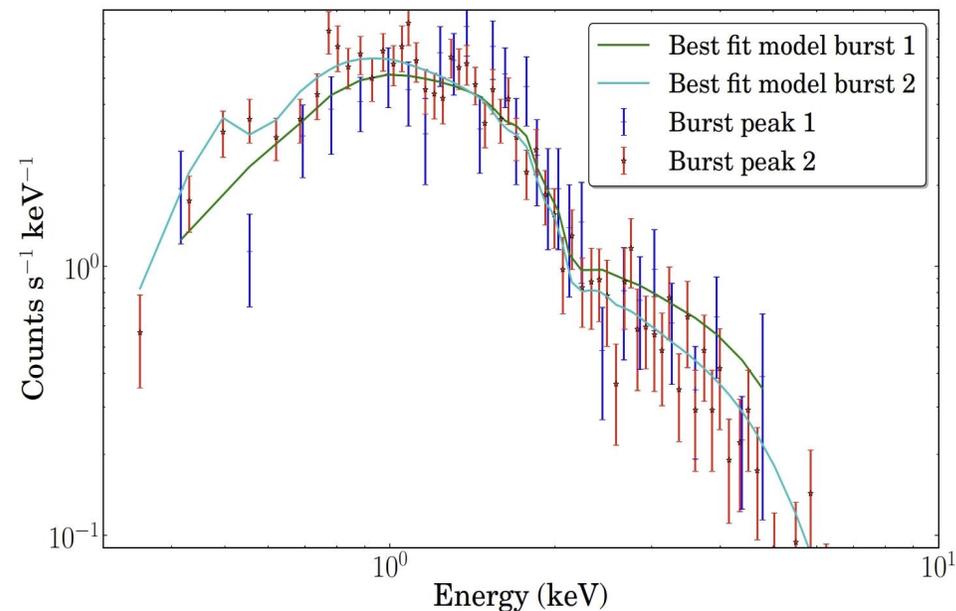
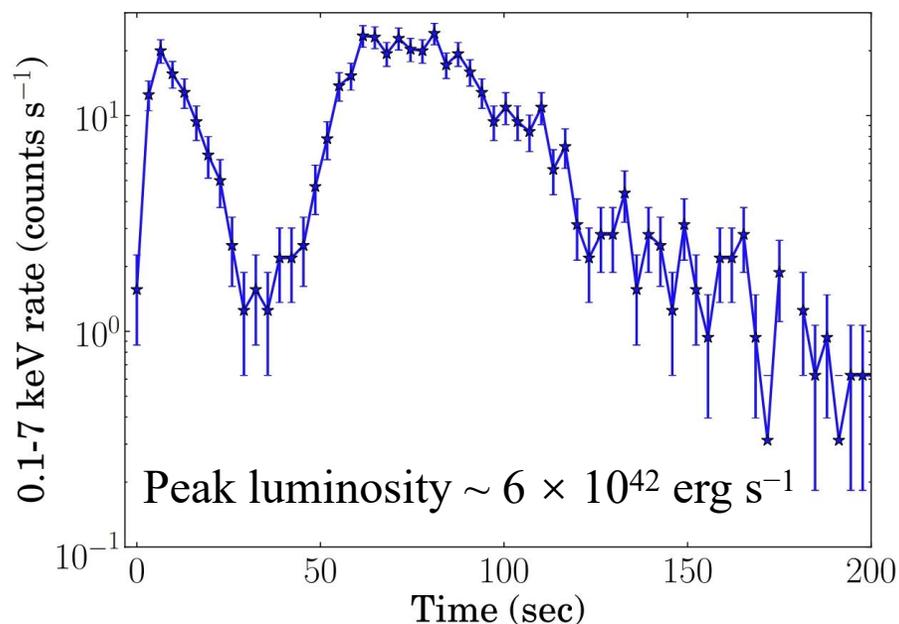
1975年11月16日，SAS-3卫星探测到一个名为MX 2346-65的**硬X射线快速暂现源**



快速软X射线暂现源

DISCOVERY OF A NEW KIND OF EXPLOSIVE X-RAY TRANSIENT NEAR M86

P. G. JONKER^{1,2,3}, A. GLENNIE⁴, M. HEIDA^{1,2}, T. MACCARONE⁵, S. HODGKIN⁶, G. NELEMANS^{2,7},
J. C. A. MILLER-JONES⁸, M. A. P. TORRES¹, AND R. FENDER⁴



物理解释： 中等质量黑洞对白矮星的潮汐瓦解事件。
其他可能情景包括：中子星吸积小行星，或偏轴伽马暴。

取自戴子高教授报告

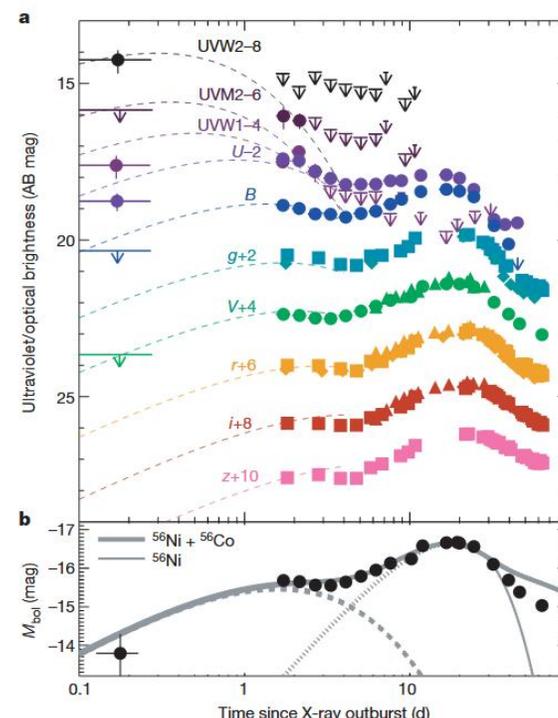
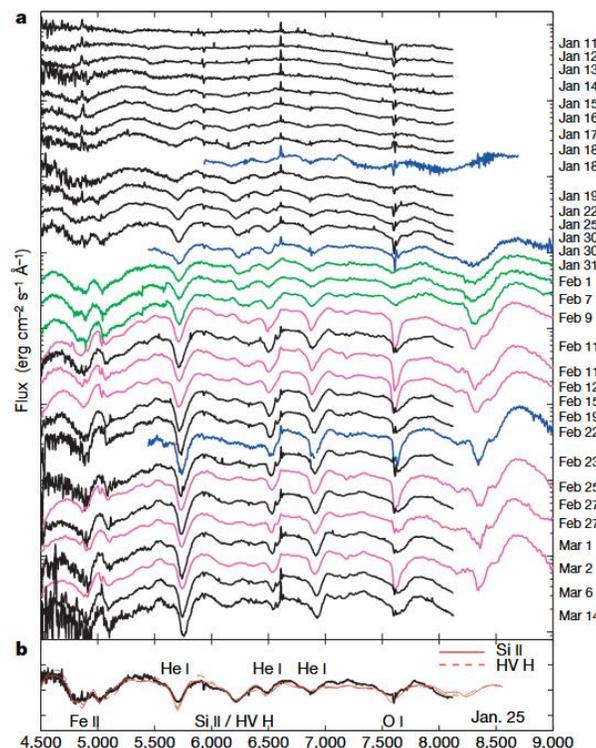
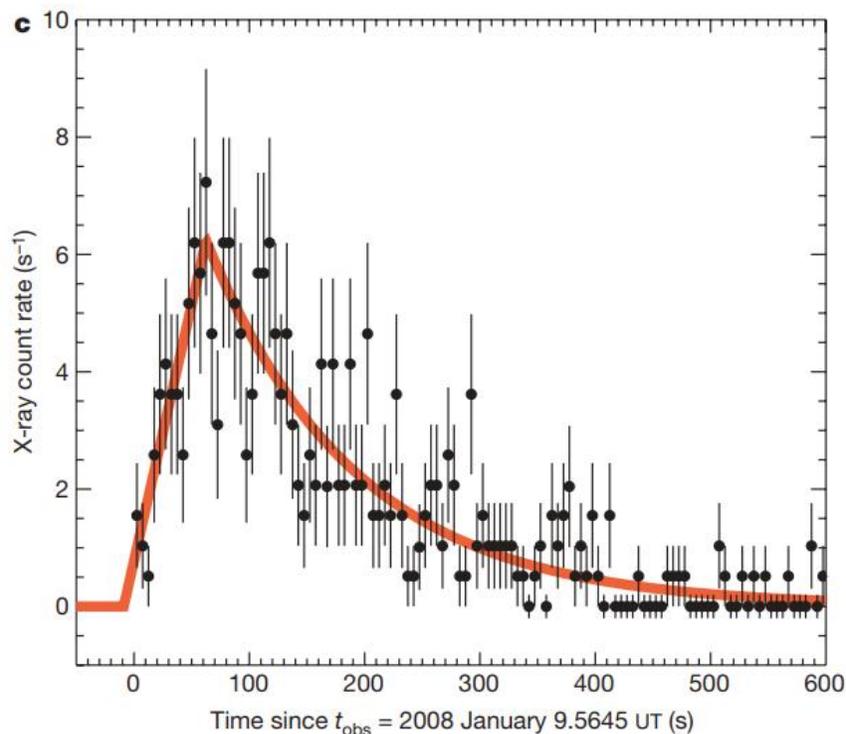
An extremely luminous X-ray outburst at the birth of a supernova

XRO 080109/ SN 2008D

物理解释：超新星激波突破

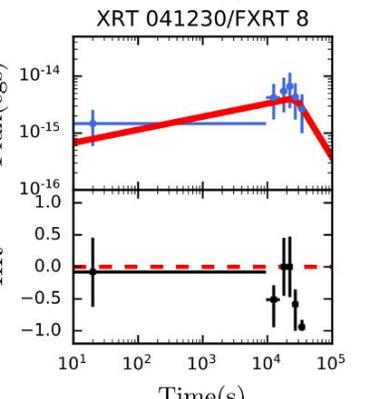
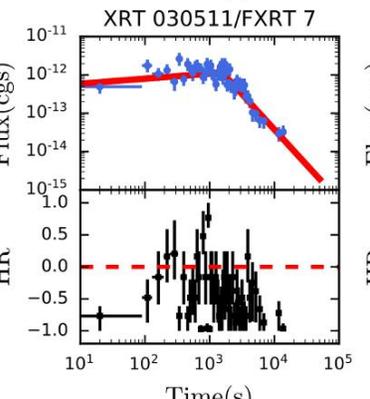
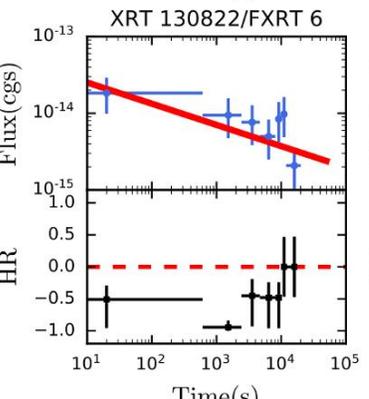
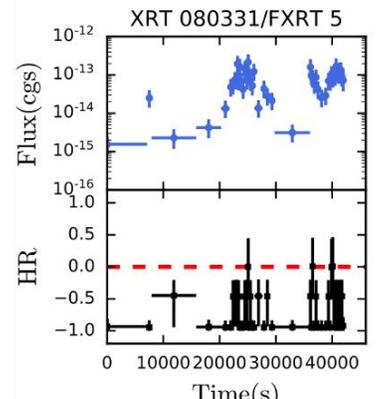
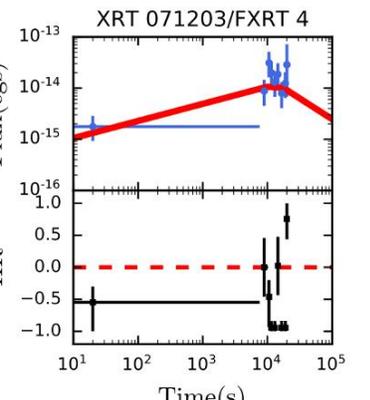
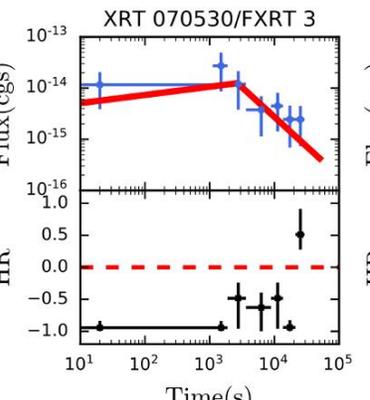
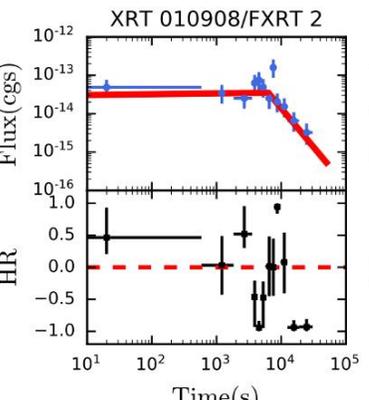
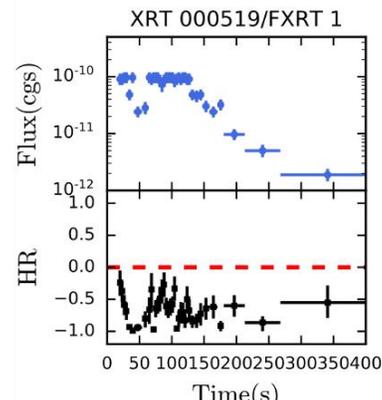
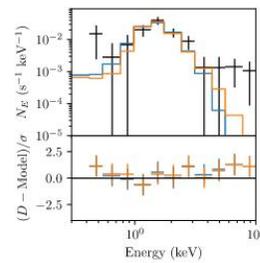
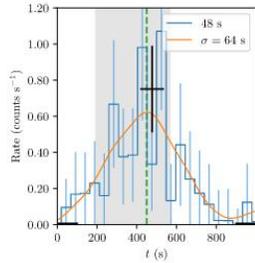
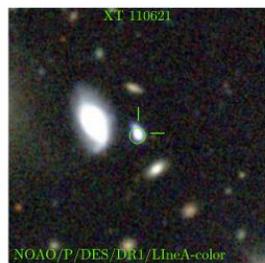
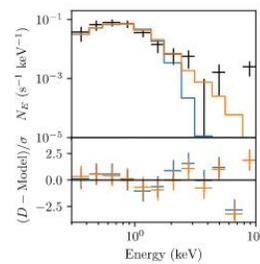
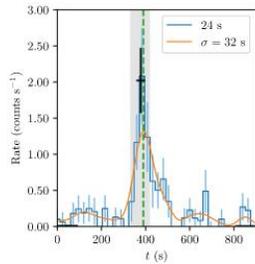
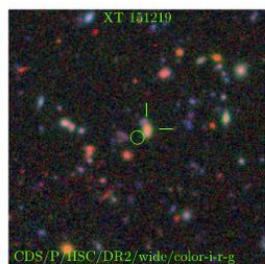
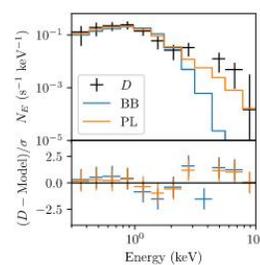
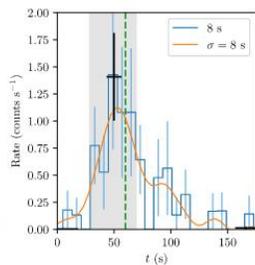
A. M. Soderberg^{1,2}, E. Berger^{1,2}, K. L. Page³, P. Schady⁴, J. Parrent⁵, D. Pooley⁶, X.-Y. Wang⁷, E. O. Ofek⁸, A. Cucchiara⁹, A. Rau⁸, E. Waxman¹⁰, J. D. Simon⁸, D. C.-J. Bock¹¹, P. A. Milne¹², M. J. Page⁴, J. C. Barentine¹³, S. D. Barthelmy¹⁴, A. P. Beardmore³, M. F. Bietenholz^{15,16}, P. Brown⁹, A. Burrows¹, D. N. Burrows⁹, G. Byrngelson¹⁷, S. B. Cenko¹⁸, P. Chandra¹⁹, J. R. Cummings²⁰, D. B. Fox⁹, A. Gal-Yam¹⁰, N. Gehrels²⁰, S. Immler²⁰, M. Kasliwal⁸, A. K. H. Kong²¹, H. A. Krimm^{20,22}, S. R. Kulkarni⁸, T. J. MacCarone²³, P. Mészáros⁹, E. Nakar²⁴, P. T. O'Brien³, R. A. Overzier²⁵, M. de Pasquale⁴, J. Racusin⁹, N. Rea²⁶ & D. G. York²⁷

$$t_{\text{bo}} \simeq 1200 \left(\frac{T_{\text{obs}}}{0.1 \text{ keV}} \right)^{-4/7} \left(\frac{E_{\text{th}}}{10^{50} \text{ erg}} \right)^{3/7} \left(\frac{\kappa}{\tau} \right)^{2/7} \text{ s.}$$



在卫星历史数据中搜索到~30例, 起源未知

(可能解释: XRB/ULX/SGR/AXP/SBO/LL-GRB/off-axis GRB/TDE...)



XMM-Newton

Alp et al. 2020

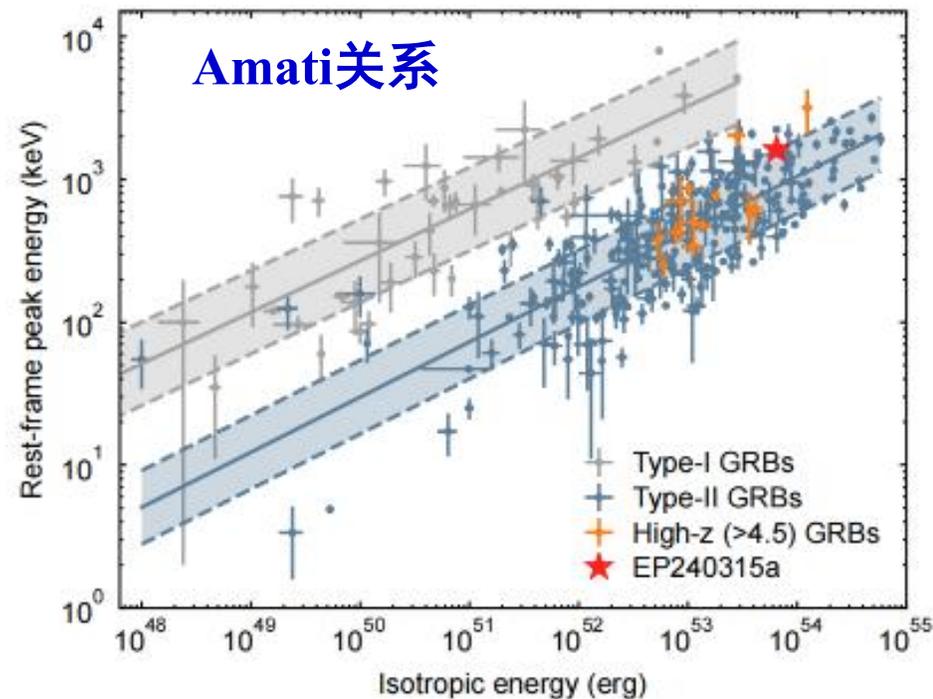
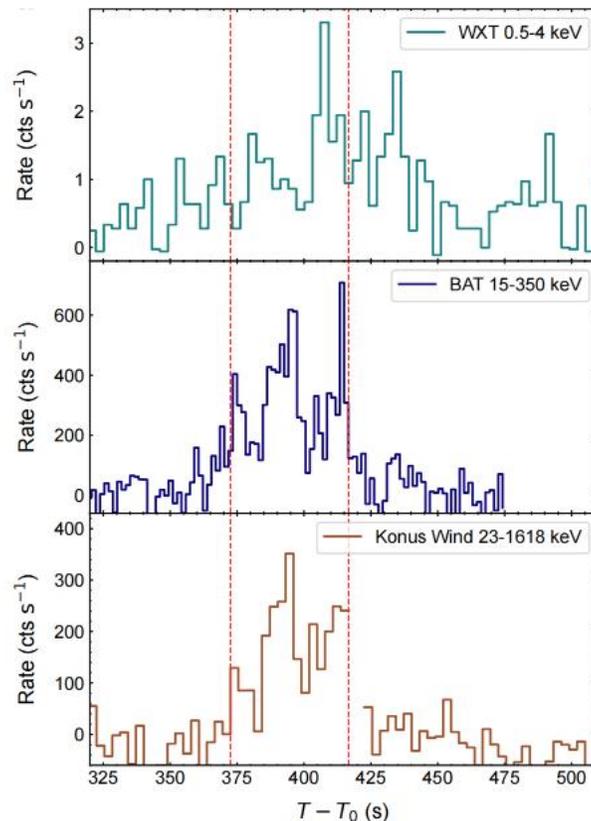
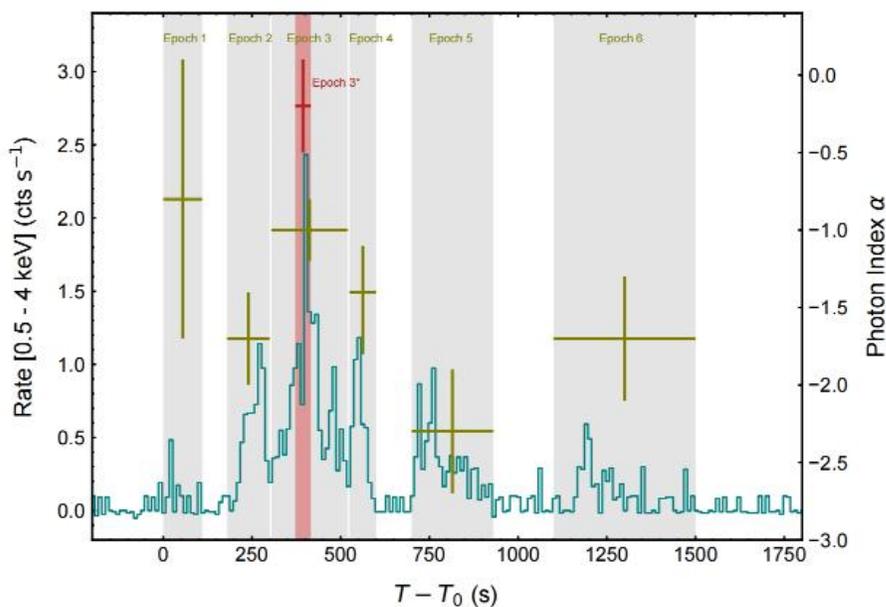
Chandra

Quirola-Vasquez et al. 2022

EP240315a: 与GRB成协，EP第一个具有光学和射电对应体探测事件

红移: 4.859

$$T_{90,X} = 1034 \text{ s} \quad T_{90,\gamma} \sim 38 - 41 \text{ s}$$

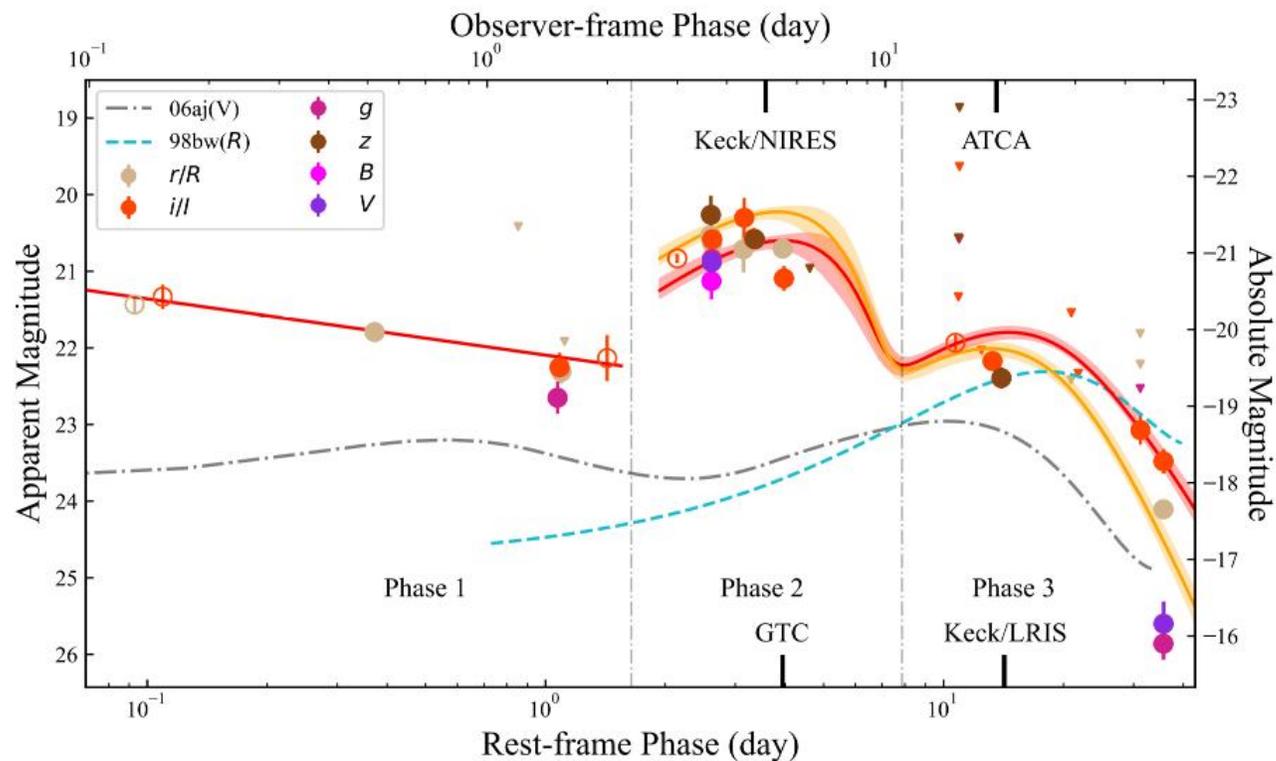
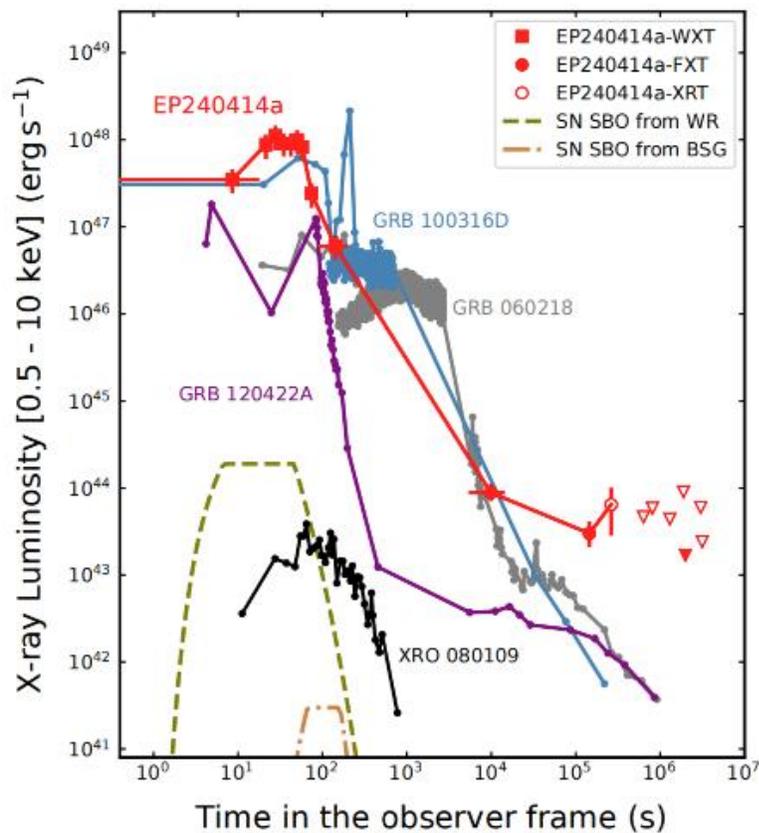


伽马射线对应体：**GRB 240315C**
X射线早于伽马射线

脉冲轮廓相似

位于高红移伽马暴的高能端

EP240414a: EP第一个与宽线Ic型超新星成协的事件



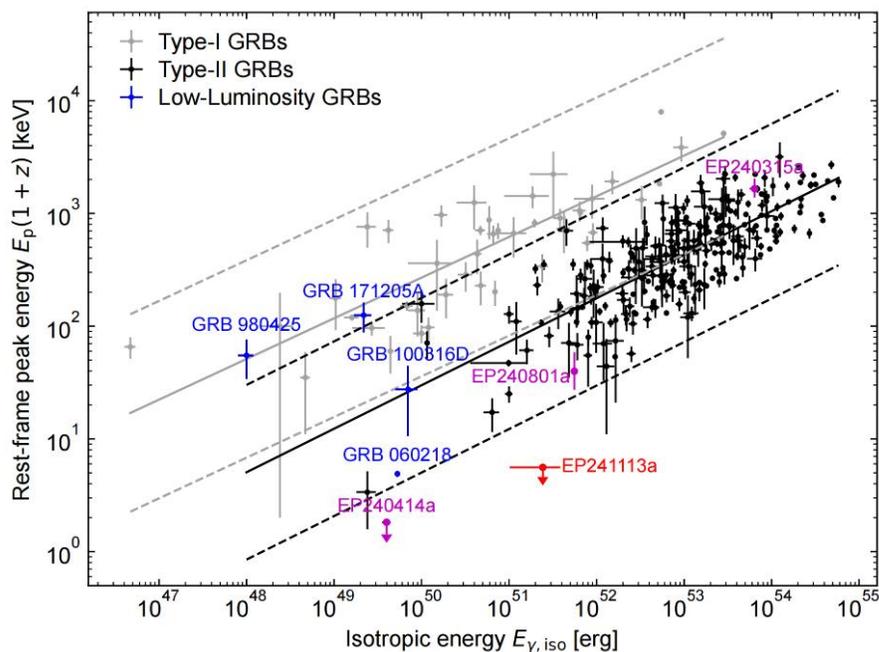
Sun et al. 2025, Nature Astronomy, 9, 1073

- (1) X射线光度位于低光度伽马暴的范围
- (2) 快速下降 + 平台 + 再增亮

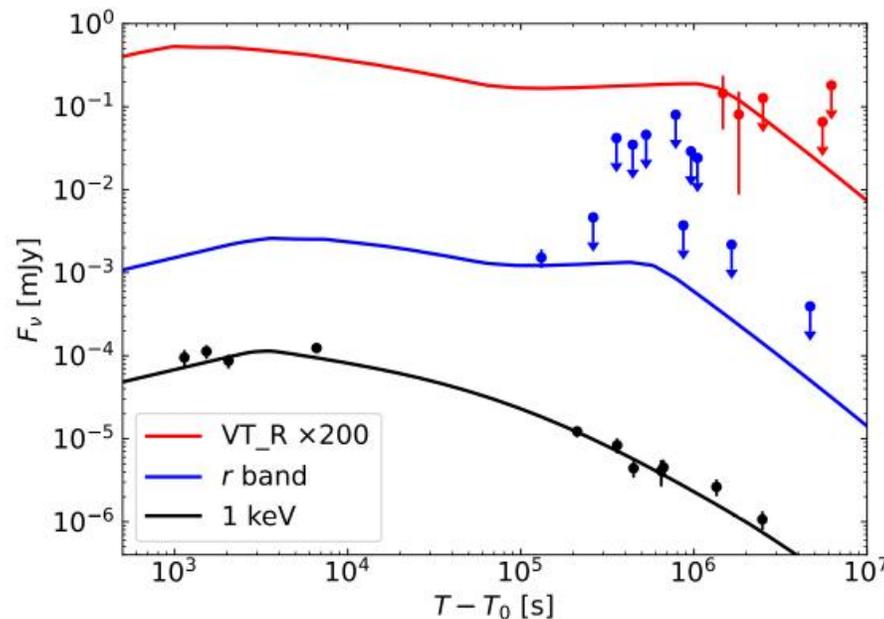
宽线Ic型超新星SN 2024gsa: 三个阶段演化

EP时代：实时触发的大样本

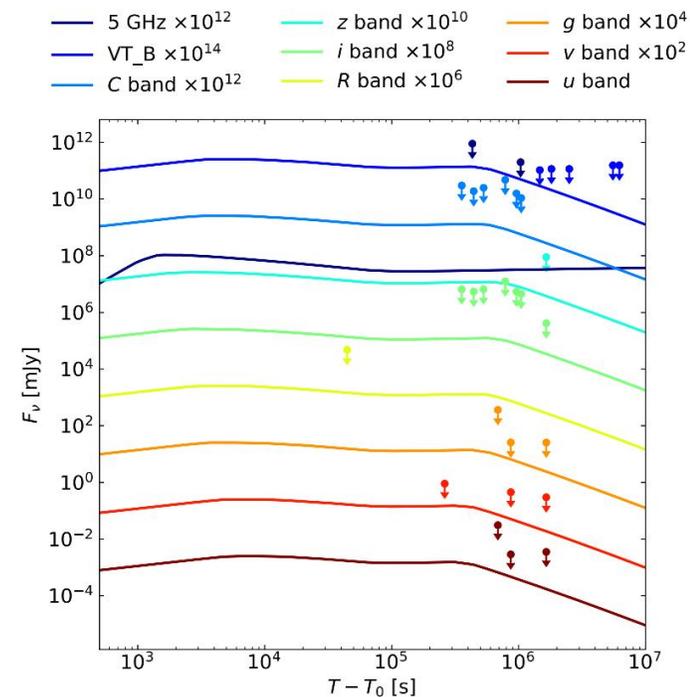
EP241113a：脏火球事件的原型？



位于Amati关系的 3σ 区域外



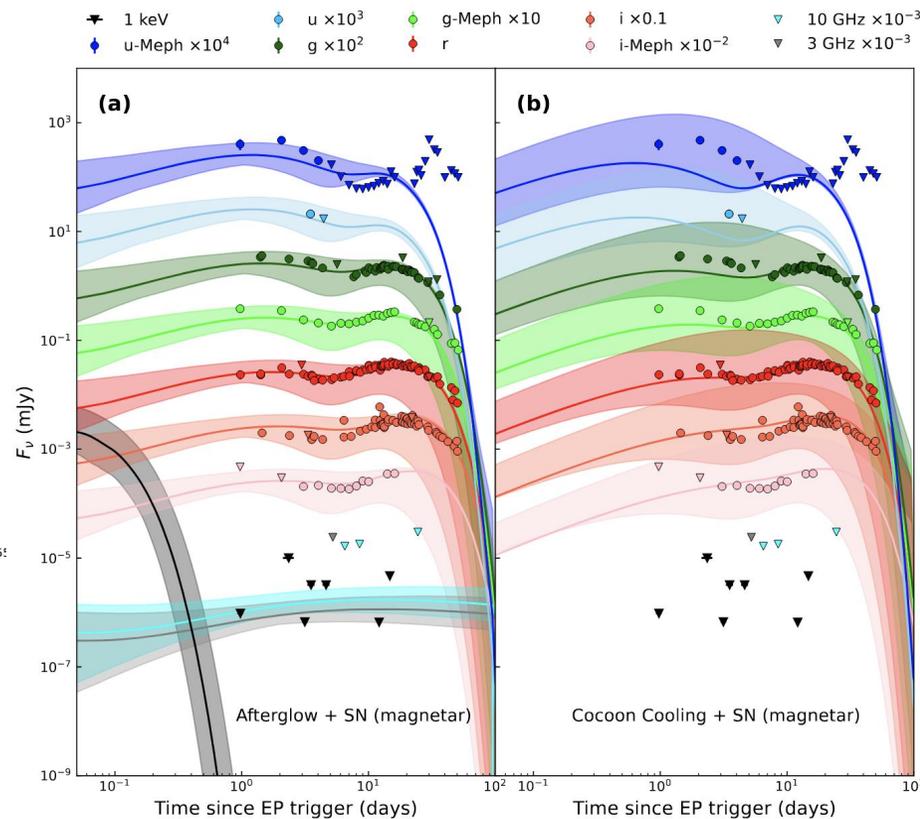
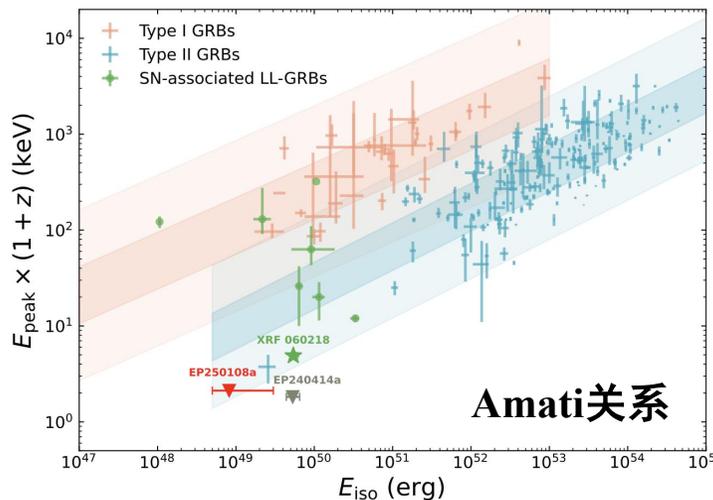
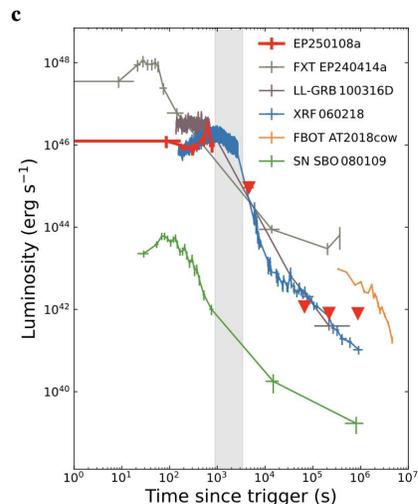
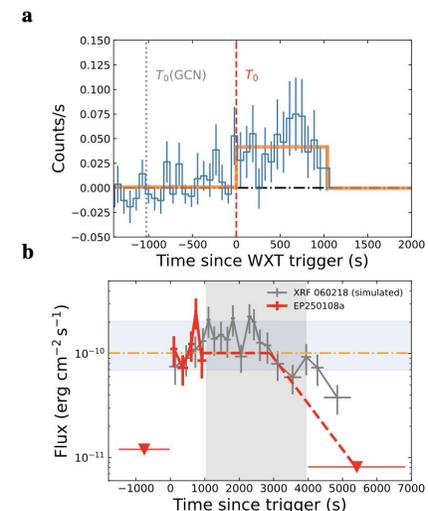
物理解释：星风环境中的慢速喷流



$$E_k \simeq 6.9 \times 10^{52} \text{ erg}$$

$$\Gamma \simeq 20$$

EP250108a：与超新星成协的软X射线暂现源



- 相比EP240414a能量更低—弱喷流
- 余辉流量限制表明激波洛伦兹因子小于20
- 超新星光变拟合表明抛射物或受到中心引擎的持续供能

$$\Gamma_0 \leq 20 \left(\frac{F_{\nu, \text{peak}}}{0.03 \text{ mJy}} \right) \left(\frac{f_e}{0.1} \right)^{-2/3} \left(\frac{A_*}{10^{-2}} \right)^{-1} \left(\frac{\epsilon_B}{10^{-3}} \right)^{-1/3}$$



EP引领的快速X射线暂现源研究进展

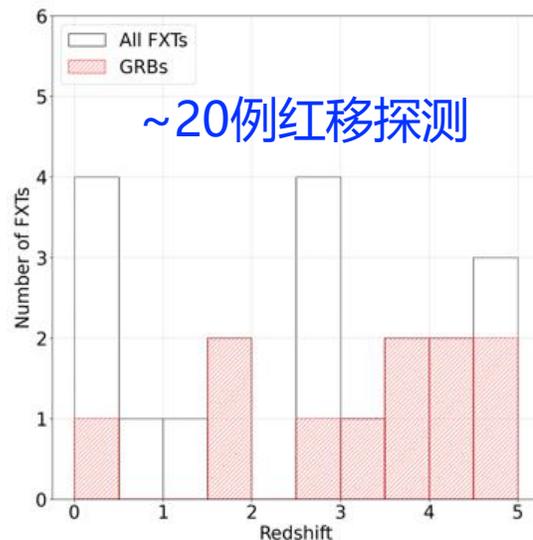
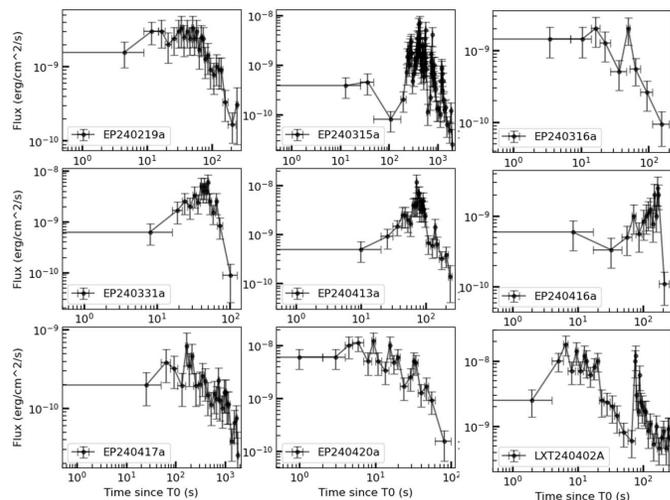


取自戴子高教授报告

Name	redshift	$T_{90,X}$	E_{peak}	E_{iso}	Gamma-ray counterpart	Optical counterpart	X-ray counterpart	Radio counterpart	Model
EP240219a	No	129 s	257 keV	No	GRB 240219A	No	No	No	X-ray-rich GRB
EP240315a	4.859	1034 s	283 keV	6.4×10^{53} erg	GRB 240315C	Yes	Yes	Yes	GRB afterglow
EP240408a	No	83.8 ks (duration)	No	No	No	No	Yes	No	A new type of transients with intermediate timescales
EP240414a	0.401	155 s	<1.3 keV	5.3×10^{49} erg	No	SN 2024gsa (SN Ic-BL)	Yes	Yes	Off-axis jet-cocoon, on-axis weakened jet, etc.
EP240801a	1.673	148 s	14.9 keV	5.6×10^{51} erg	Yes	Yes	Yes	No	Two-component jet, FS-RS, FS with energy injection
EP241021a	0.75	100 s	<100 keV	5.1×10^{49} erg	No	Yes	Yes	Yes	Refreshed shock (Wu, Yu, Y.-W. + 2025), TDE
EP241113a	1.53	204 s	<2.2 keV	1.4×10^{51} erg	No	Yes	Yes	No	Dirty fireball or refreshed shock
EP250108a	0.176	960 s	$\lesssim 1.8$ keV	$\lesssim 10^{49}$ erg	No	SN 2025kg (SN Ic-BL)	No	No	Slow jet + SN or Cocoon Cooling + SN

EP已探测高显著性快速X射线暂现源约**100例** (2024年1月至今) — 孙惠提供

- 约三分之一 (36例) 有与之成协的伽马暴探测
- 另有约三分之一 (30例) 虽有伽马射线覆盖, 但无探测



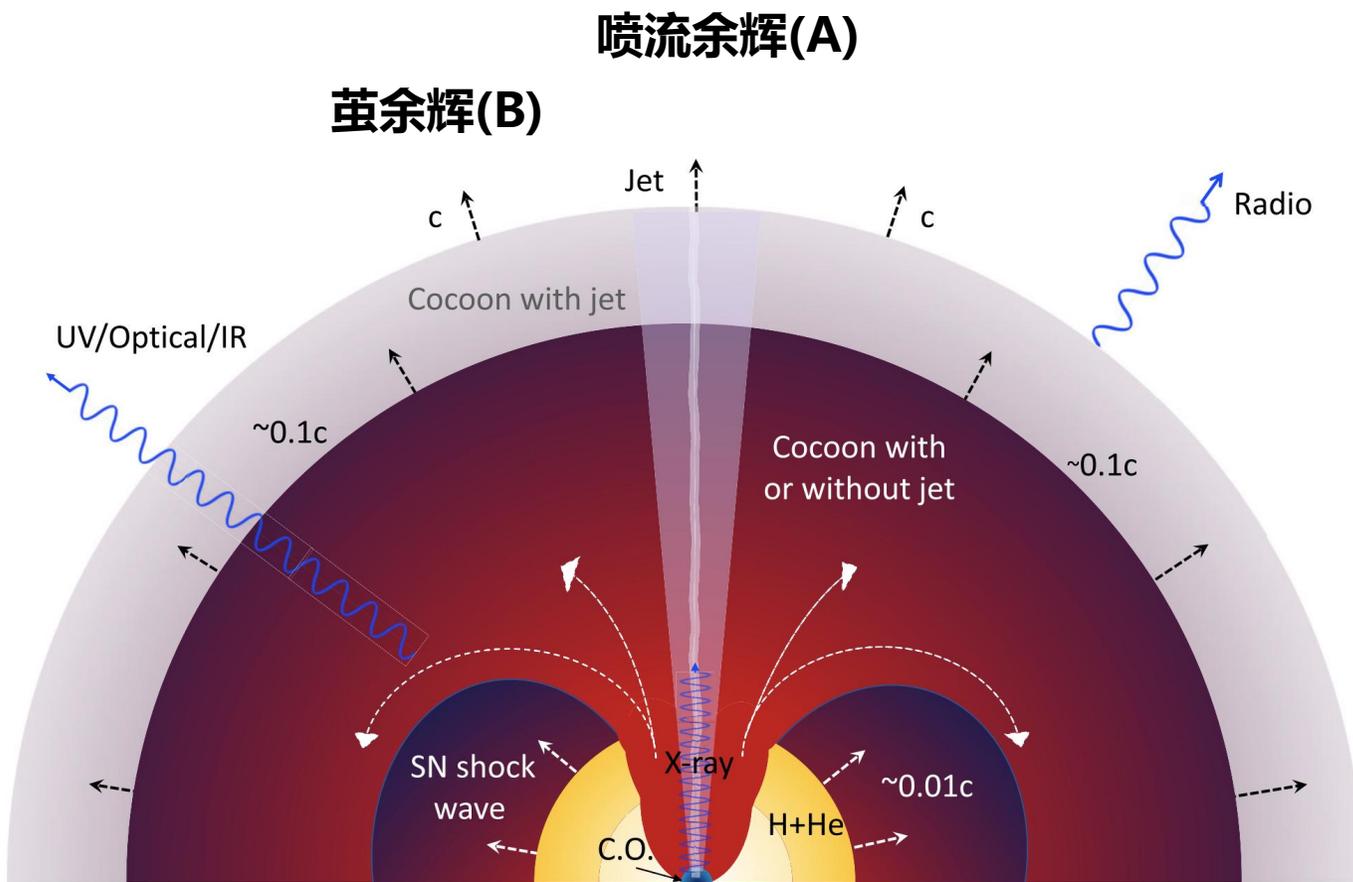
FXRTs一些可能的起源:

- ✓ X射线闪或高红移伽马暴 Soderberg et al. 2004
- ✓ 中心磁陀星活动 Dai et al. 2006
- ✓ 脏火球 Huang, Dai & Lu 2002
- ✓ 喷流-茧系统 Bromberg et al. 2011
- ✓ 伽马暴中的激波能量注入 Dai & Lu 1998
- ✓ 偏轴伽马暴 Huang, Gou, Dai & Lu 2000
- ✓ 双成分喷流 Huang, Wu, Dai et al. 2004

所有的这些模型都已经在伽马暴领域广泛讨论过 (例如, 长暴和短暴) !

但观测源与模型的一一对应依然存在挑战!

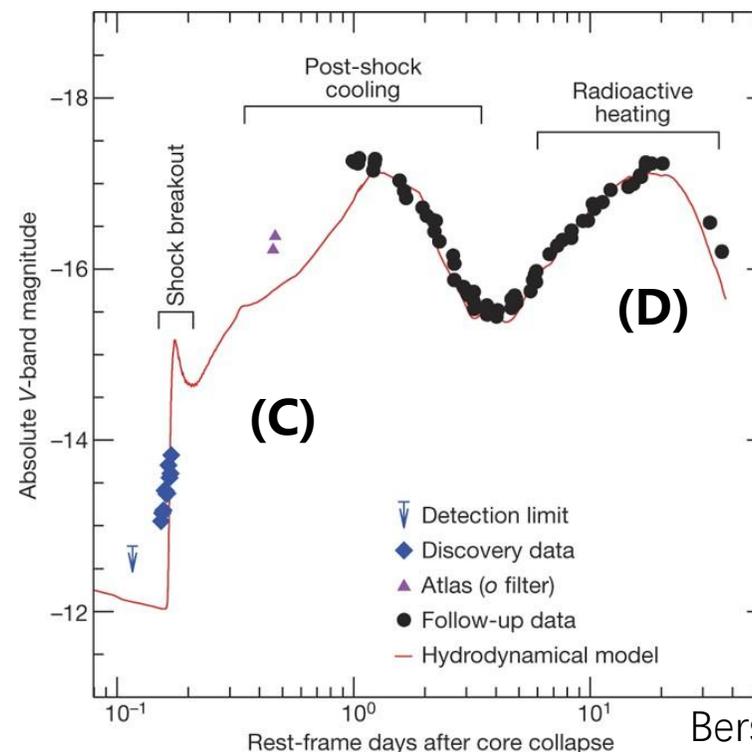
取自戴子高教授报告



Gottlieb et al. (2022)

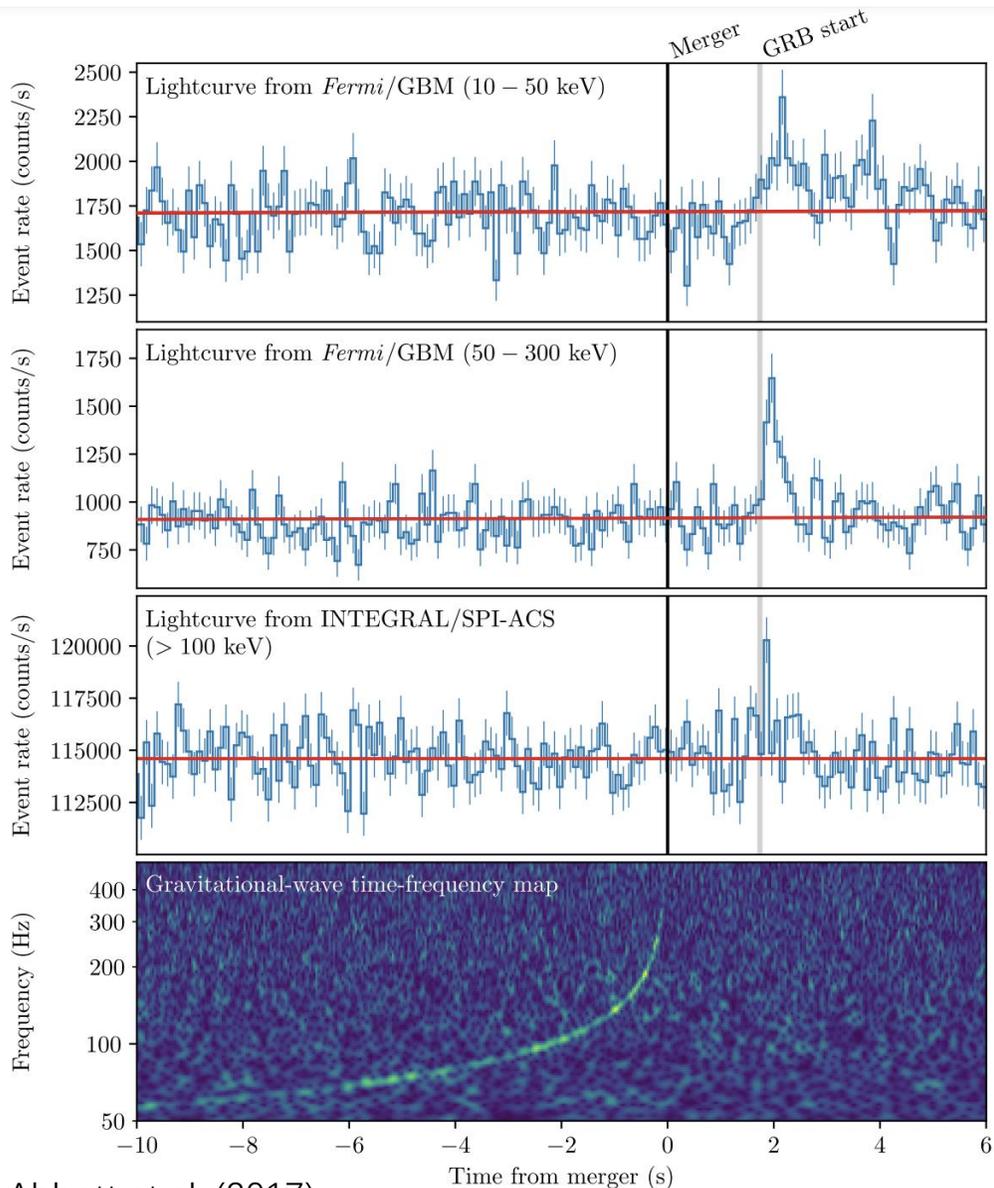
EP及后随观测或是多辐射成分叠加组合:

- 极端/中等相对论性喷流 (A)
- 中等相对论性茧物质 (B)
- 超新星激波突破 (X射线) + 冷却 (C)
- 超新星辐射 (D)
- 中心引擎持续活动?

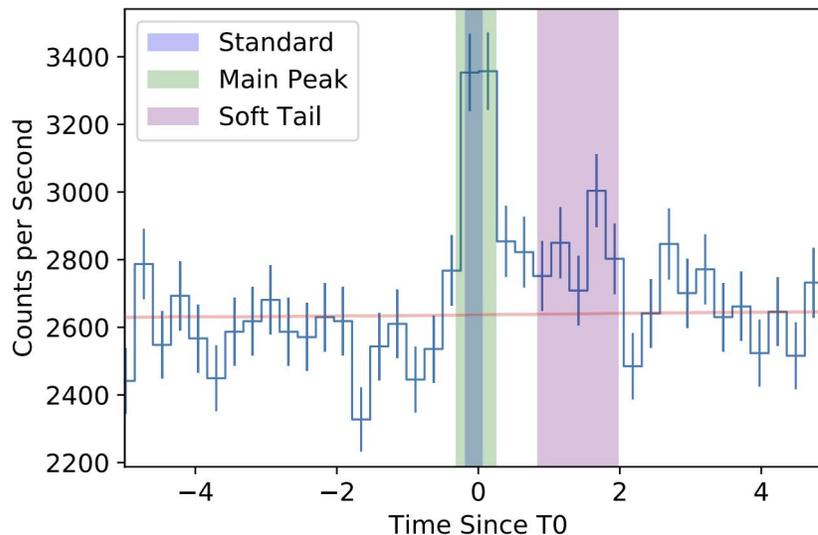


SN2016gkg

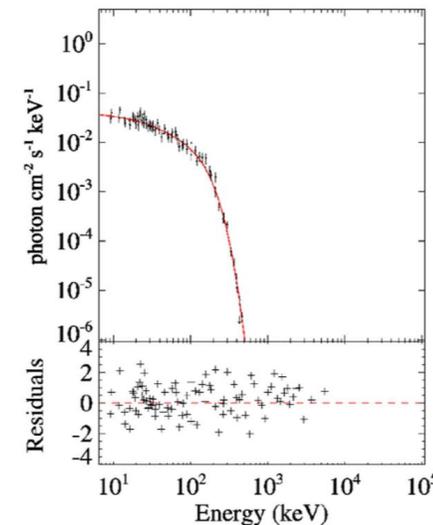
GRB 170817A的启发



Abbott et al. (2017)



Goldstein et al. (2017)



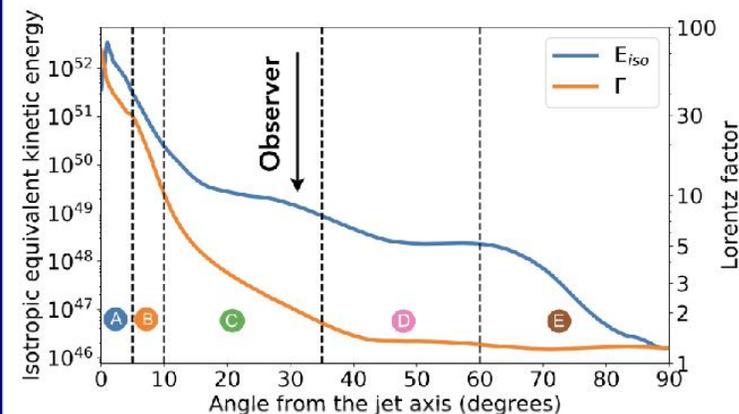
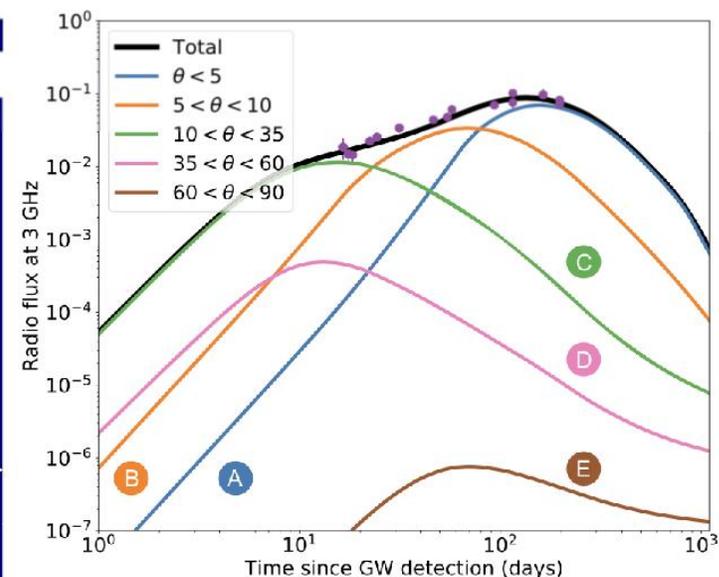
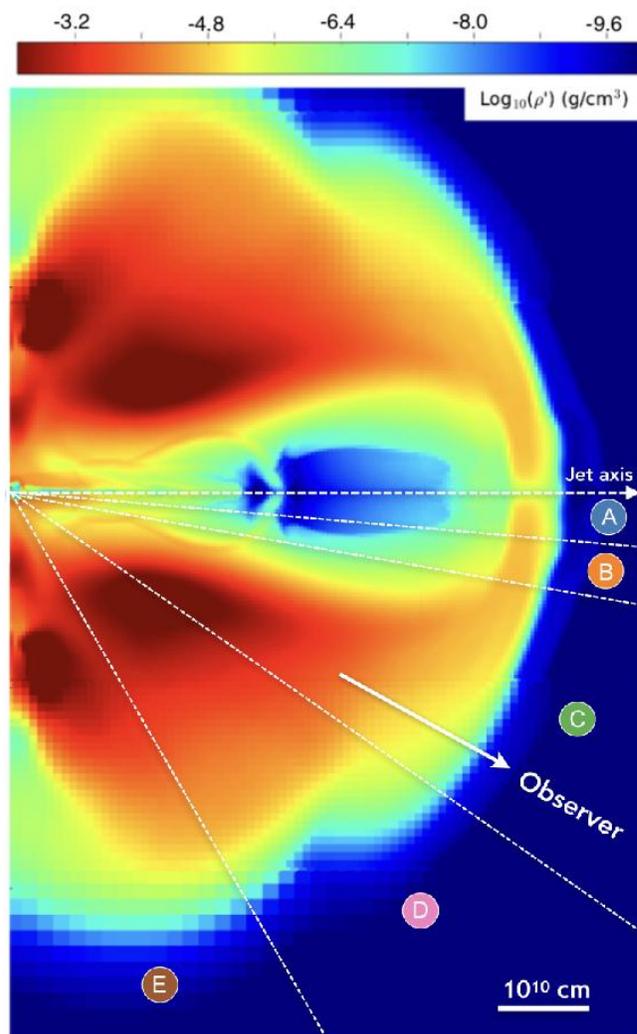
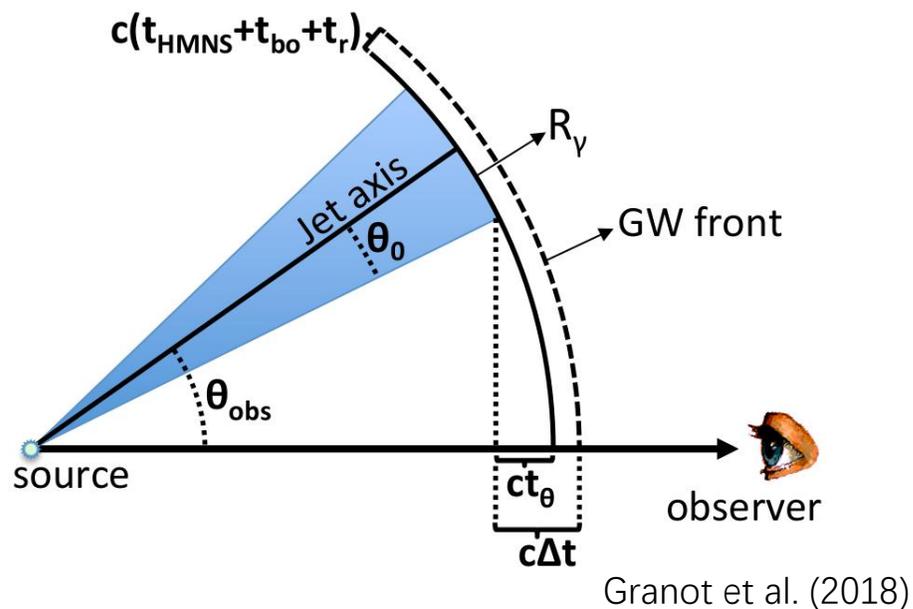
Goldstein et al. (2017)

Table 1 Properties of GRB 170817A

Total spanning duration (s)	~2.05
Spectral peak energy (first peak) E_p (keV)	149.1 ^{+229.4} _{-24.2} 谱能量稍低
Total fluence (erg cm^{-2})	$2.24^{+3.51}_{-0.53} \times 10^{-7}$
Spectral lag (25-50 keV vs. 50-100 keV)	0.03 ± 0.05 s
Redshift z	~0.009
Luminosity distance D_L (Mpc)	39.472
Total isotropic energy E_{iso} (erg)	$4.17^{+6.54}_{-0.99} \times 10^{46}$ 总能量显著偏低
Peak luminosity L_{iso} (erg s^{-1})	$1.6^{+2.5}_{-0.4} \times 10^{47}$

Zhang et al. (2018)

晚期余辉的演化规律支持结构化喷流

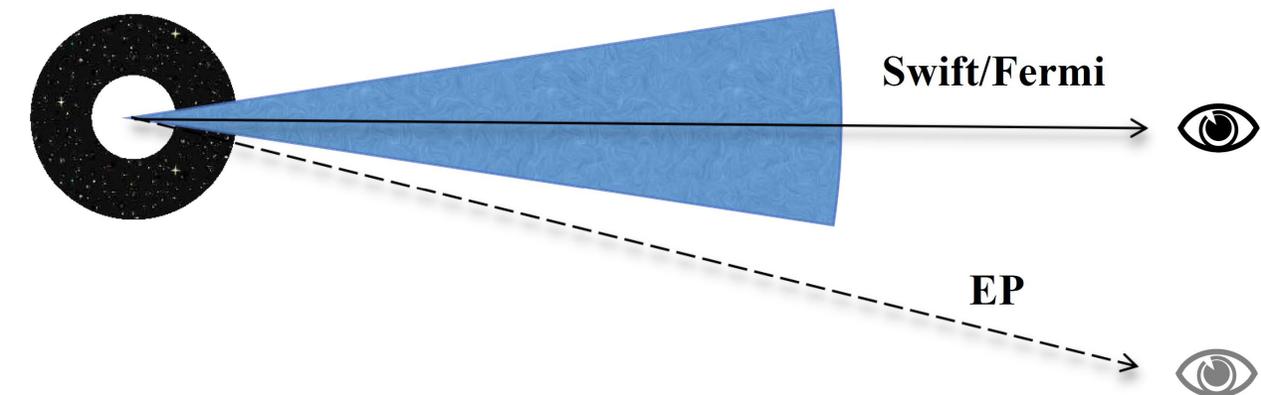


Lazzati et al. (2018 PRL)

$$\frac{E_p(\theta_{\text{obs}})}{E_p(0)} \equiv a \approx \begin{cases} 1 & \theta_{\text{obs}} < \theta_0, \\ \frac{1}{1+(\Gamma\Delta\theta)^2} \sim (\Gamma\Delta\theta)^{-2} & \theta_{\text{obs}} > \theta_0, \end{cases}$$

$$\frac{E_{\gamma,\text{iso}}(\theta_{\text{obs}})}{E_{\gamma,\text{iso}}(0)} \approx \begin{cases} 1 & \theta_{\text{obs}} < \theta_0, \\ a^2 \sim (\Gamma\Delta\theta)^{-4} & 1 < \frac{\theta_{\text{obs}}}{\theta_0} < 2, \\ \frac{(\Gamma\theta_0)^2}{(\Gamma\Delta\theta)^6} \sim \frac{(\Gamma\theta_0)^2}{(\Gamma\theta_{\text{obs}})^6} & \theta_{\text{obs}} > 2\theta_0, \end{cases}$$

谱峰值能量与总能量的关联性
排除了均匀喷流这一假设!



偏轴观测伽马暴的瞬时辐射特性

➤ 弱爆发能量 + 典型谱峰值能量

$$\frac{E_p(\theta_{\text{obs}})}{E_p(0)} \equiv a \approx \begin{cases} 1 & \theta_{\text{obs}} < \theta_0, \\ \frac{1}{1+(\Gamma\Delta\theta)^2} \sim (\Gamma\Delta\theta)^{-2} & \theta_{\text{obs}} > \theta_0, \end{cases}$$

$$\frac{E_{\gamma,\text{iso}}(\theta_{\text{obs}})}{E_{\gamma,\text{iso}}(0)} \approx \begin{cases} 1 & \theta_{\text{obs}} < \theta_0, \\ a^2 \sim (\Gamma\Delta\theta)^{-4} & 1 < \frac{\theta_{\text{obs}}}{\theta_0} < 2, \\ \frac{(\Gamma\theta_0)^2}{(\Gamma\Delta\theta)^6} \sim \frac{(\Gamma\theta_0)^2}{(\Gamma\theta_{\text{obs}})^6} & \theta_{\text{obs}} > 2\theta_0, \end{cases}$$

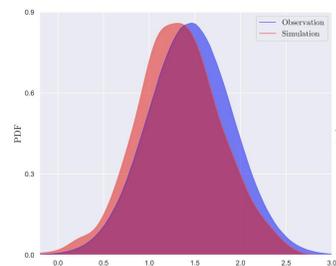
“正轴”暴的物理参数分布范围

$\Gamma, \gamma'_m, N'_{\text{inj}}, B'_0, R_0, t_{\text{off}},$ and z .

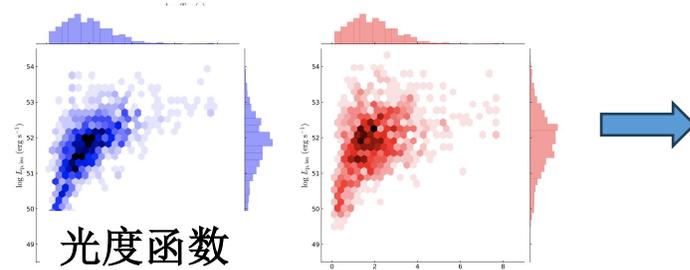
➤ 瞬时辐射持续时间更长

$$\Delta t_{\text{obs}} \approx (1+z)\Gamma(1-\beta\cos\bar{\theta})\Delta t'$$

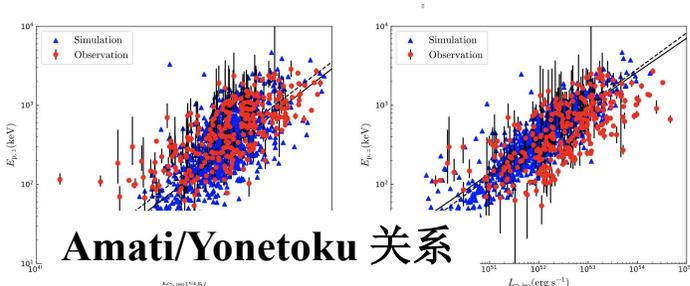
$$\frac{t_{\text{obs}}(\bar{\theta}_{\text{off}})}{t_{\text{obs}}(\bar{\theta}_{\text{on}})} = \frac{1-\beta\cos\bar{\theta}_{\text{off}}}{1-\beta\cos\bar{\theta}_{\text{on}}} \approx 8 \quad \theta_c \cong 2.5^\circ \theta_V \cong 5^\circ$$



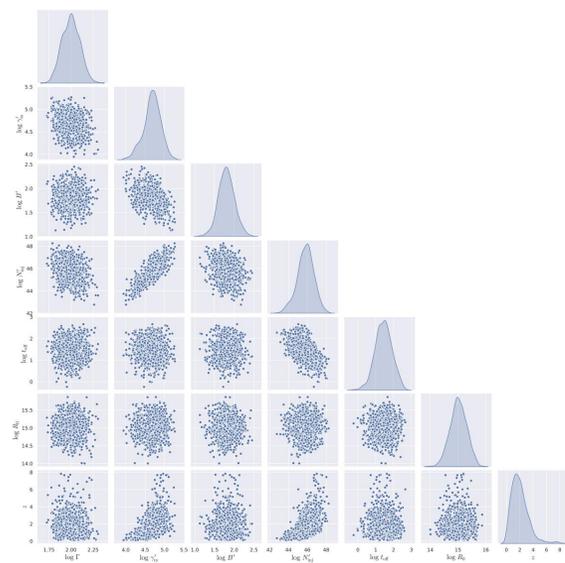
持续时间



光度函数

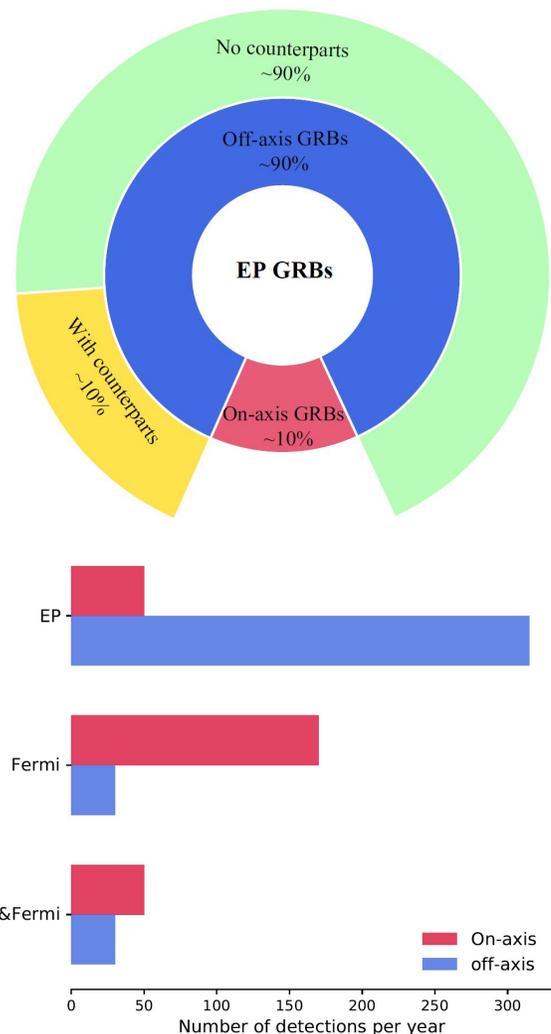


Amati/Yonetoku 关系

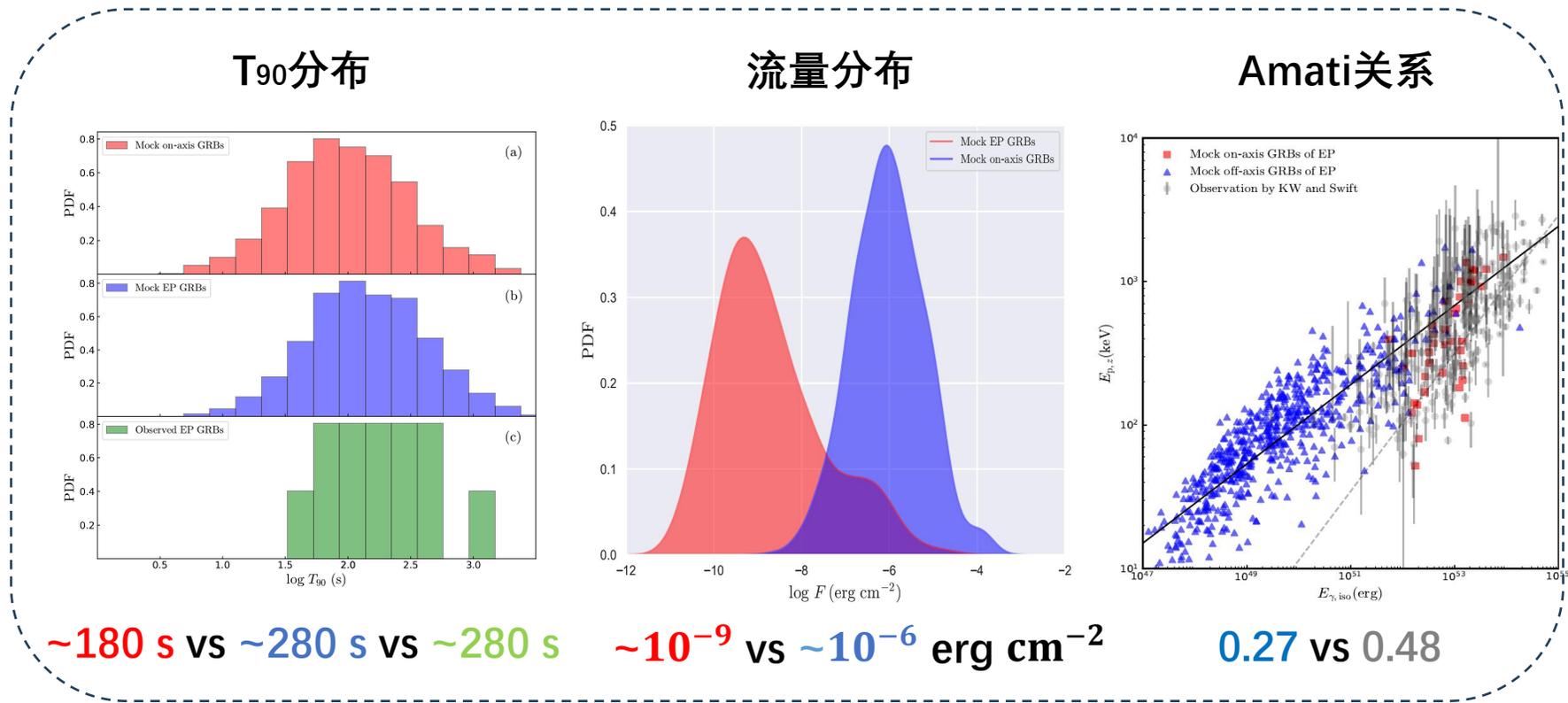


高浩轩、耿金军、梁泽方、孙惠、许帆、吴雪峰、黄永锋、戴子高、袁为民, 2025, ApJ, 986, 106

EP伽马暴理论预测样本



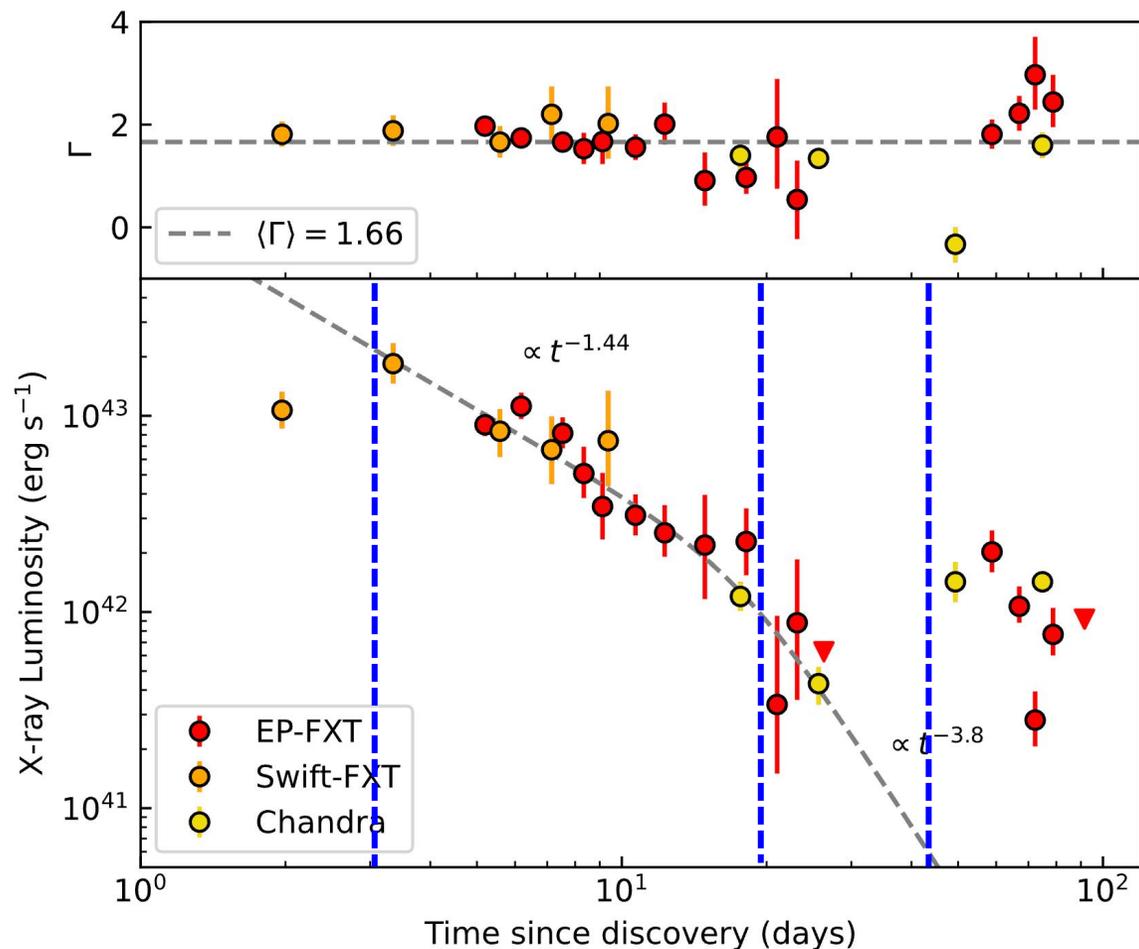
EP伽马暴理论预测样本性质



➤ EP-WXT的大视场性能使其在捕捉高红移暴、内禀弱喷流、偏轴观测喷流方面具有显著优势

➤ 理想模式下，每年约有30例偏轴暴发可被EP与Fermi联合探测到

快蓝暂现源AT2024wpp的X射线光变



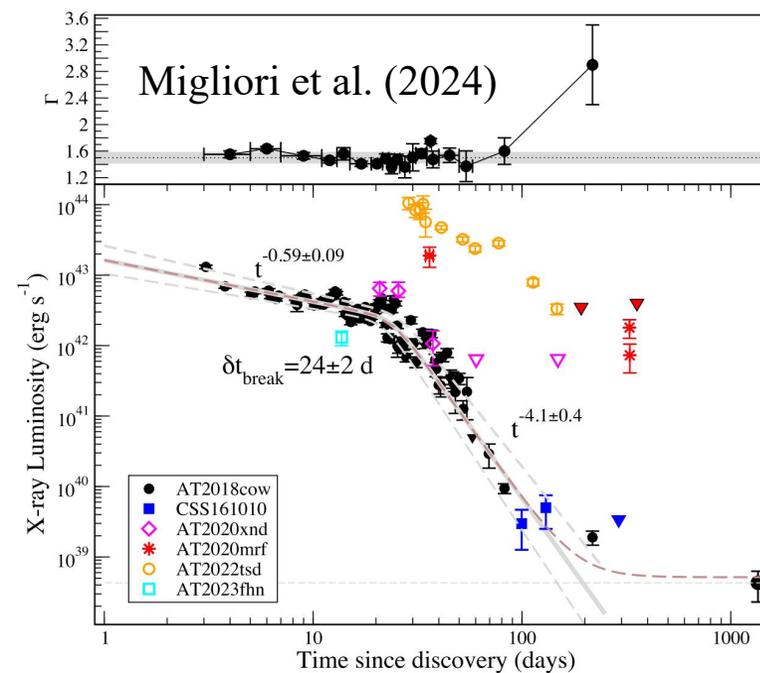
阶段 I
上升

阶段 II
缓降

阶段 III
陡降

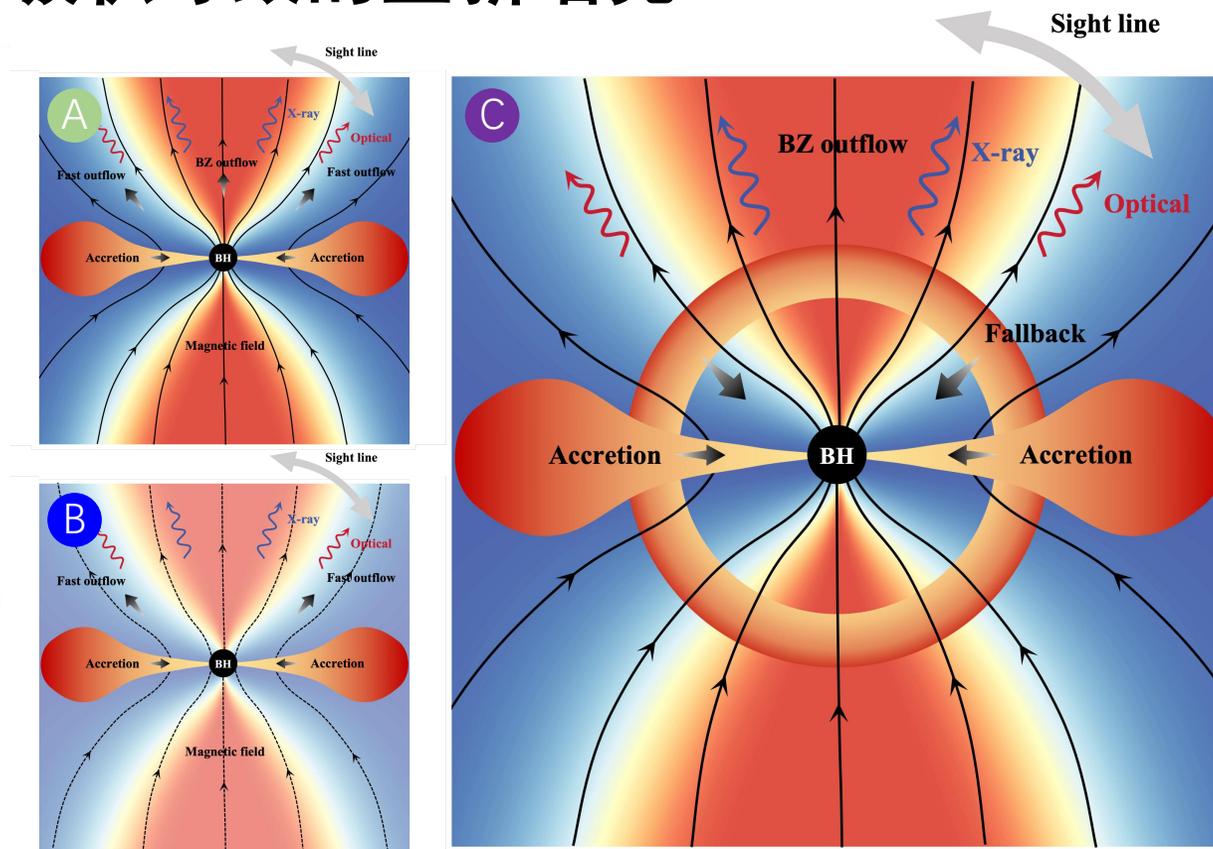
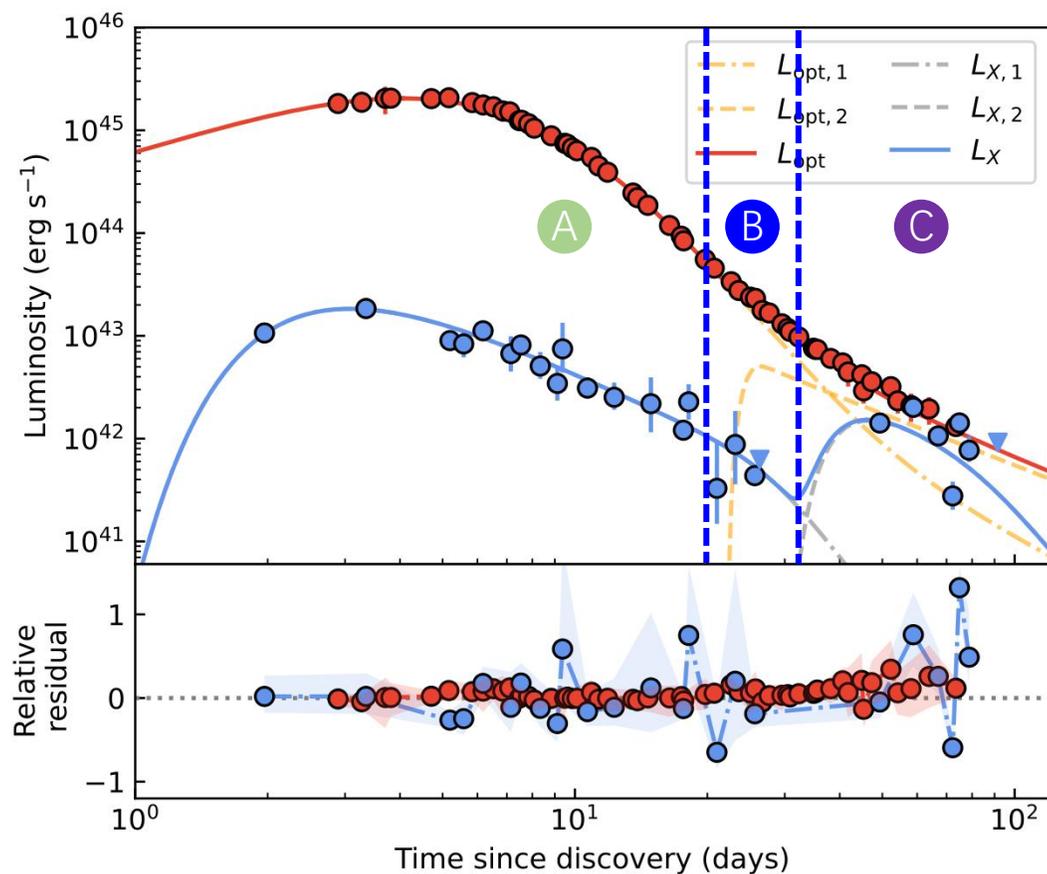
阶段 IV
增亮

其他快蓝暂现源的X射线光变



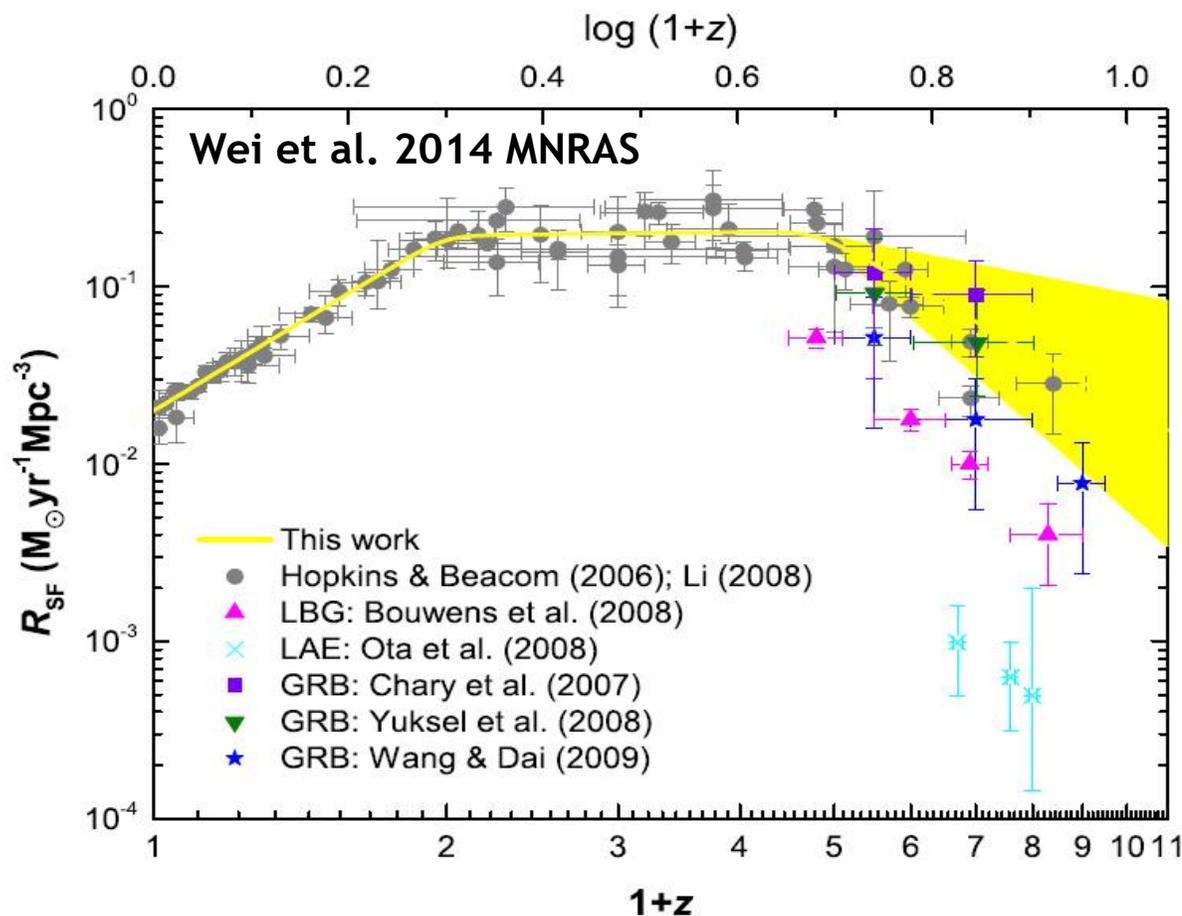
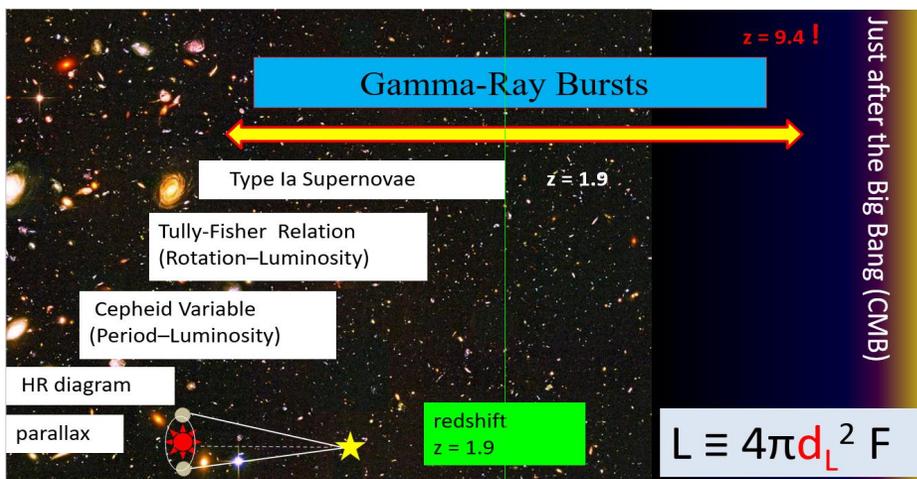
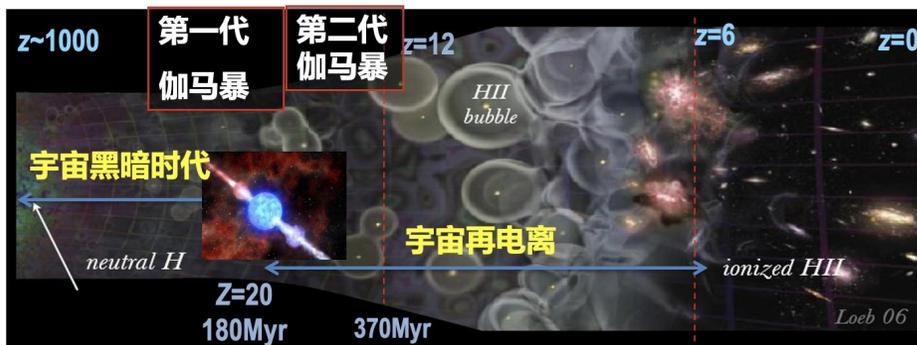
- 目前快蓝暂现源的观测样本较少，有很多新现象待发掘。EP-FXT的高灵敏度性能有助于揭示更多新的观测特征。
- 在AT2024wpp中发现X射线光度在陡降之后，发生了**重新增亮**。

AT2024wpp: 回落吸积导致的重新增亮?



- ✓ X射线辐射可能由BZ机制产生。
- ✓ 增亮阶段有产生outflow的迹象，可能是黑洞的回落吸积重新产生了喷流。

高红移伽马暴作为早期宇宙和第一代天体的探针



- ✓ 描绘宇宙再电离历史
- ✓ 延伸Ia型超新星哈勃图至更高红移处

- ✓ 示踪和限制早期宇宙的恒星形成历史

在过去二十年的运行中，Swift 卫星共探测到 **11** 例 $z>6$ 的伽马暴

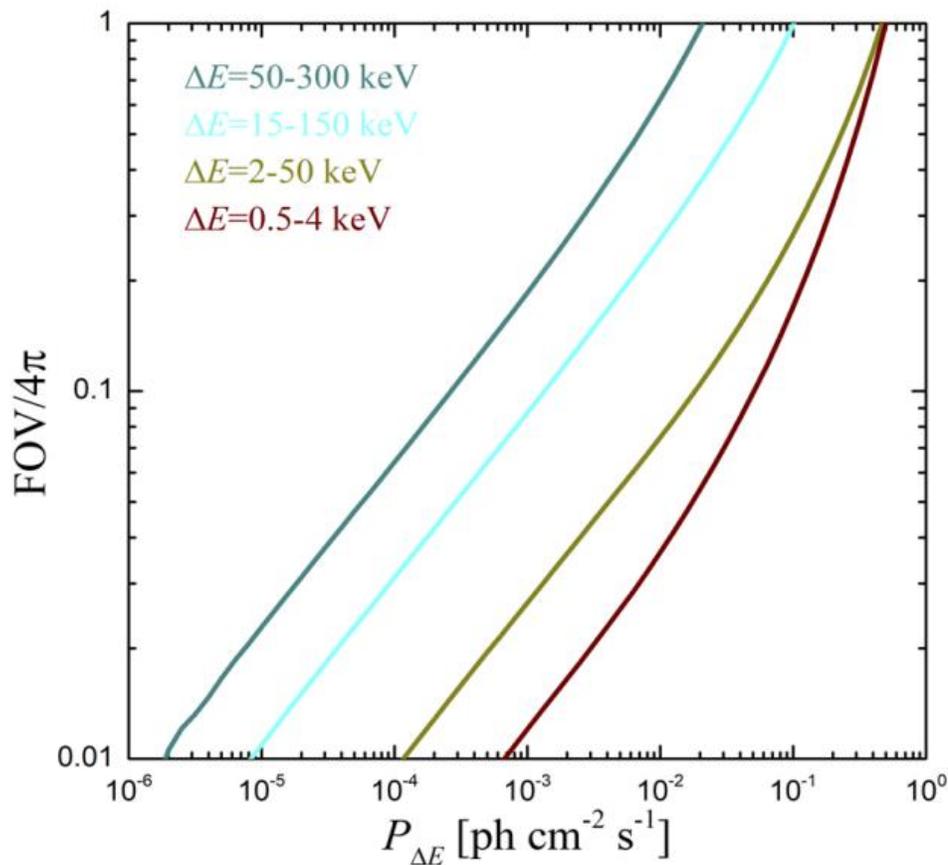
Status: **11** GRBs @ $z>6$ detected by Swift

光谱红移		测光红移	
GRB	z	GRB	z
050904	6.3	090429B	9.4
080913	6.7	100905A	7.9
090423	8.2	120521C	6.0
120923A	7.8		
130606A	5.9		
140515A	6.3		
210905A	6.3		
240218A	6.8		

高红移GRB探测极为稀少，这主要是由于：

- 现有探测器的灵敏度有限且观测能段相对较高
- 在零散的后随观测中，一些高红移GRB可能被遗漏了
 - 天气条件不好
 - 地面大口径光谱后随观测资源短缺

为了达到每年探测到10个 $z>8$ 伽马暴的目标，拥有不同观测能段的仪器所必备的最低灵敏度和视场



Swift/BAT
 视场: 1.4 sr
 能段: 15--150 keV
 灵敏度: 0.4 ph/s/cm²

- Swift卫星永远达不到每年探测到10个 $z>8$ 伽马暴的目标
- 为了达到该目标，Swift卫星至少需要比现有的灵敏度高出100倍！
- 与Swift卫星相同视场且观测能段是0.5--4 keV的X射线望远镜只需灵敏度为~0.06 ph/s/cm²就可以达到该目标

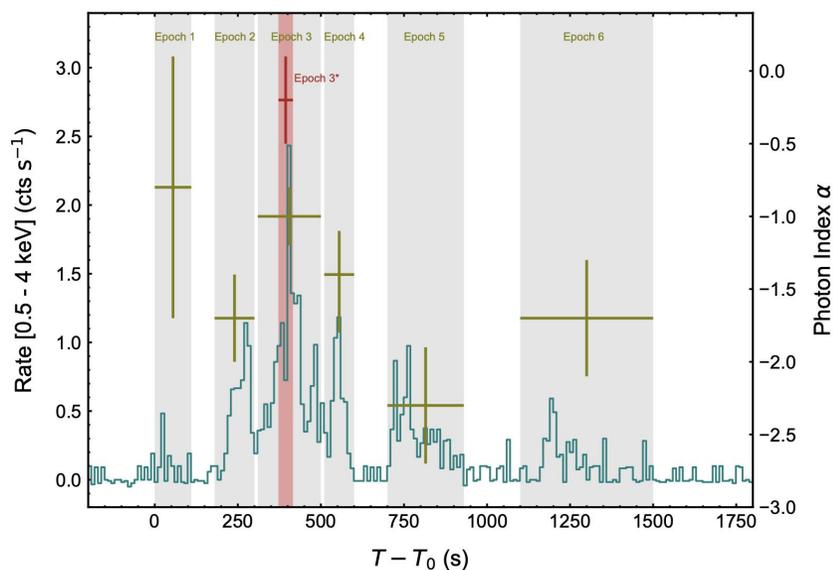
Ghirlanda et al. 2015; Salvaterra et al. 2015; Yuan et al. 2025

捕捉高红移伽马暴的最佳策略，是设计一台工作能段在**软X射线波段**且拥有**较高灵敏度**的观测设备

Table 2. The Properties of EP/WXT and SVOM/ECLAIRS

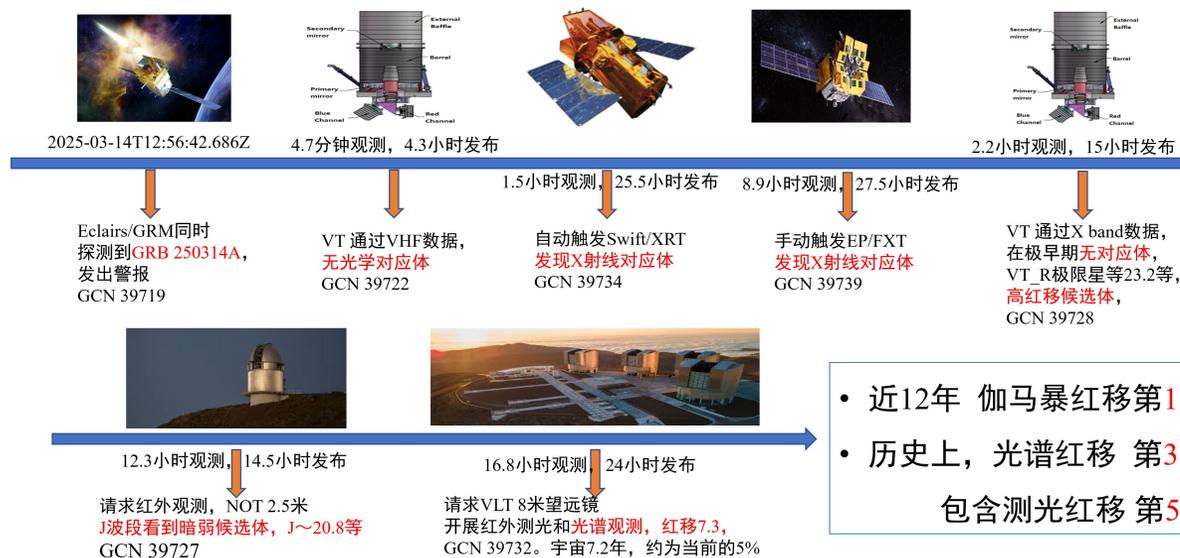
Mission	Energy band (keV)	Sensitivity (@10 s) ($\text{erg cm}^{-2} \text{s}^{-1}$)	Field of view (sr)	Duty cycle	References
EP/WXT	0.5–4	8.9×10^{-10}	1.1	67%	Yuan et al. (2025)
SVOM/ECLAIRS	4–150	7.2×10^{-8}	2.0	85%	Wei et al. (2016)

EP240315a @ $z=4.859$



Liu et al. 2025, Nature Astronomy 9, 564

连续24小时接力，探测并确认最红移伽马暴SVOM GRB 250314A: $z=7.3$



Cordier, Wei, Tanvir et al. 2025, arXiv: 2507.18783

➤ GRB爆发率:

$$\psi(z) \propto \psi_*(z)(1+z)^\delta$$

$$\psi_*(z) = (0.0157 + 0.118z) / [1 + (z/3.23)^{4.66}] \quad \delta = 1.7 \pm 0.5$$

➤ GRB光度函数:

$$\phi(L) \propto \begin{cases} \left(\frac{L}{L_b}\right)^{-\nu_1}; & L \leq L_b \\ \left(\frac{L}{L_b}\right)^{-\nu_2}; & L > L_b, \end{cases}$$

$$\nu_1 = 1.50^{+0.16}_{-0.32}, \nu_2 = 2.32^{+0.77}_{-0.32}, \text{ and } L_b = (3.8^{+6.3}_{-2.7}) \times 10^{52} \text{ erg s}^{-1}$$

The GRB LF is normalized to unity by integrating over the luminosity range $10^{47} \text{ erg s}^{-1}$ to $10^{55} \text{ erg s}^{-1}$

➤ 在特定能段下的GRB峰值流量:

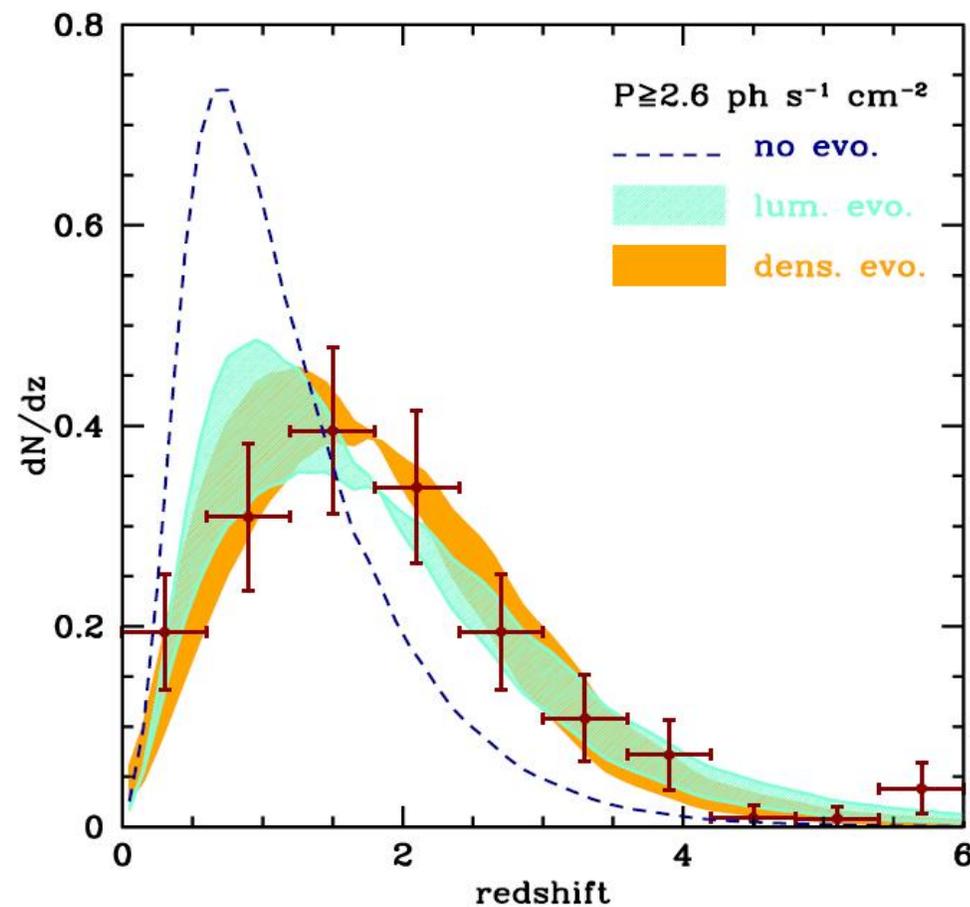
$$P_{\Delta E} = \frac{L}{4\pi d_L(z)^2} \frac{\int_{E_1}^{E_2} N(E) dE}{\int_{1 \text{ keV}/(1+z)}^{10^4 \text{ keV}/(1+z)} EN(E) dE}$$

➤ Band能谱:

$$\alpha = -1 \pm 0.2, \quad \beta = -2.3 \pm 0.2$$

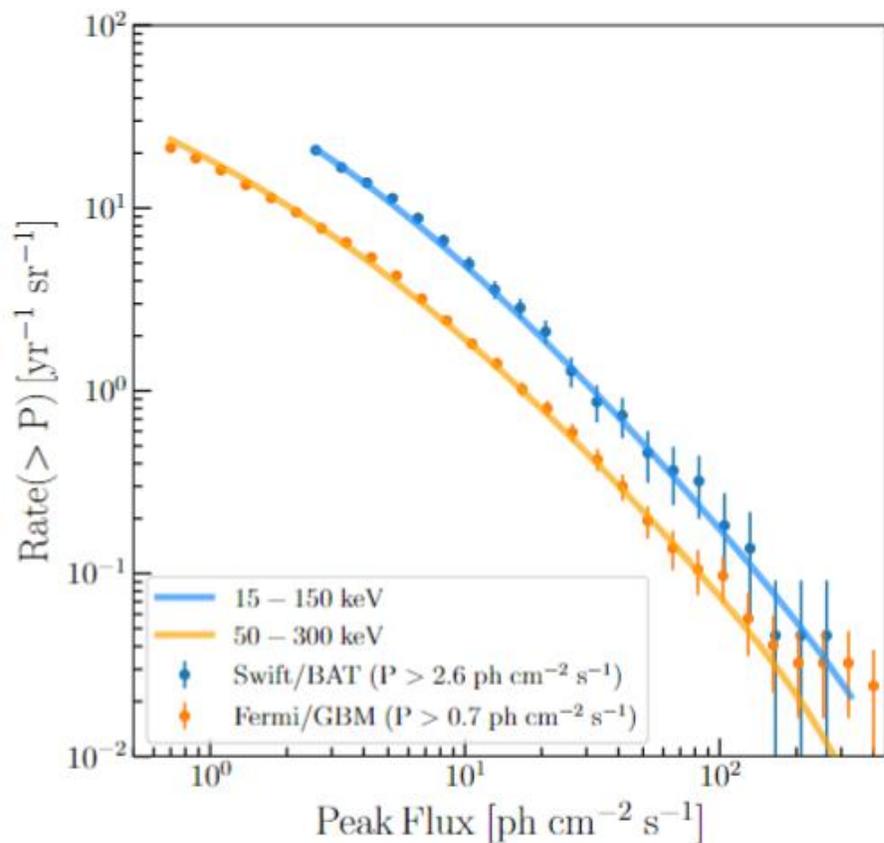
$$\log(E_p(1+z)) = -25.33 + 0.53 \log(L) \text{ with the scatter } \sigma_{\text{SC}} = 0.29$$

S12 模型



Salvaterra et al. 2012, ApJ, 749, 68

- 截至2024年12月，Swift 共探测到 **453** 个 $P \geq 2.6 \text{ ph cm}^{-2} \text{ s}^{-1}$ 的伽马暴
- 考虑Swift/BAT的视场(1.4 sr)，观测时间约20年和有效工作时间占比约78%，可以估算 Swift 对 $P \geq 2.6 \text{ ph cm}^{-2} \text{ s}^{-1}$ (15–150 keV) 的伽马暴的探测率约为 $\sim 21 \text{ events yr}^{-1} \text{ sr}^{-1}$
- 根据该探测率对模拟样本作相应的**归一化**



蓝点: 453 Swift/BAT GRBs with $P \geq 2.6 \text{ ph cm}^{-2} \text{ s}^{-1}$

黄点: 2637 Fermi/GBM GRBs with $P \geq 0.7 \text{ ph cm}^{-2} \text{ s}^{-1}$

模型预期的峰值流量分布与 Swift 和 Fermi 卫星的观测样本分布非常吻合，无需对模型参数做任何调整

魏俊杰、吴雪峰，2025, ApJL, 988, L71

基于S12 模型

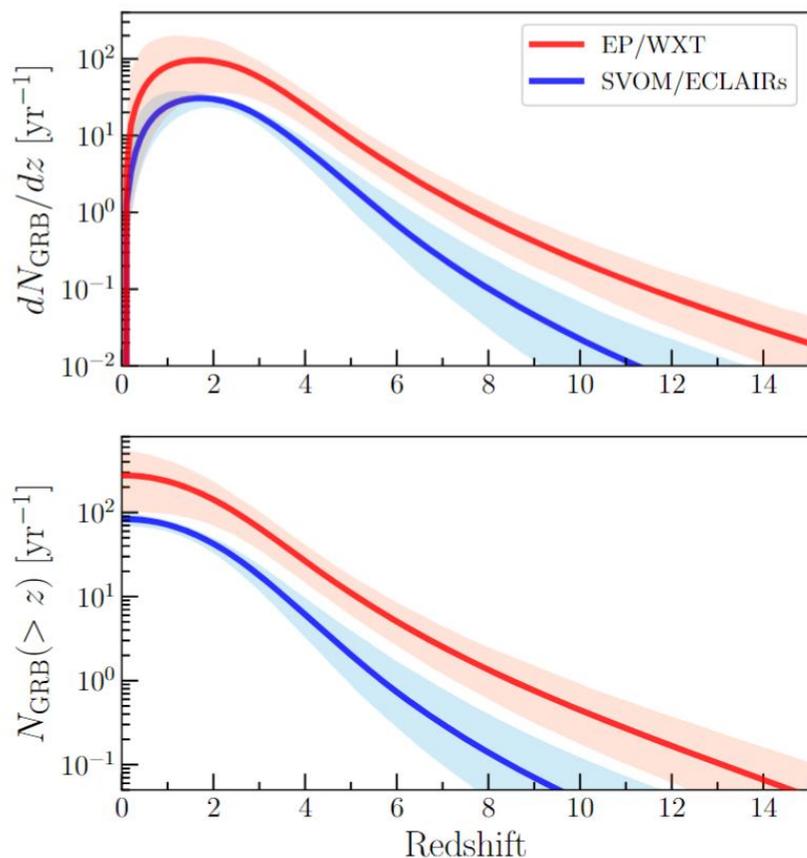


Table 3. Cumulative Detection Rates of GRBs by EP/WXT and SVOM/ECLAIRs Across Population-Synthesis Models

Model	Detection Rate $N_{\text{GRB}}(> z)$ (events yr ⁻¹)							
	EP/WXT				SVOM/ECLAIRs			
	$z > 0$	$z > 6$	$z > 8$	$z > 10$	$z > 0$	$z > 6$	$z > 8$	$z > 10$
Salvaterra et al. (2012)	276^{+264}_{-175}	$5.1^{+3.4}_{-2.4}$	$1.3^{+1.2}_{-0.7}$	$0.5^{+0.5}_{-0.3}$	83^{+16}_{-15}	$0.7^{+1.0}_{-0.4}$	$0.1^{+0.3}_{-0.1}$	$0.04^{+0.08}_{-0.03}$
Lan et al. (2021)	343^{+69}_{-54}	$3.5^{+0.9}_{-0.7}$	$0.9^{+0.3}_{-0.2}$	$0.3^{+0.1}_{-0.1}$	80^{+1}_{-1}	$0.7^{+0.2}_{-0.2}$	$0.1^{+0.1}_{-0.1}$	$0.02^{+0.02}_{-0.01}$
Ghirlanda & Salvaterra (2022)	84^{+29}_{-24}	$4.7^{+4.3}_{-2.3}$	$1.7^{+2.0}_{-1.0}$	$0.7^{+1.0}_{-0.4}$	74^{+10}_{-11}	$1.3^{+2.1}_{-0.8}$	$0.3^{+0.8}_{-0.2}$	$0.11^{+0.31}_{-0.08}$

➤ EP/WXT:

预计每年可共探测到 $\sim 276^{+264}_{-175}$.

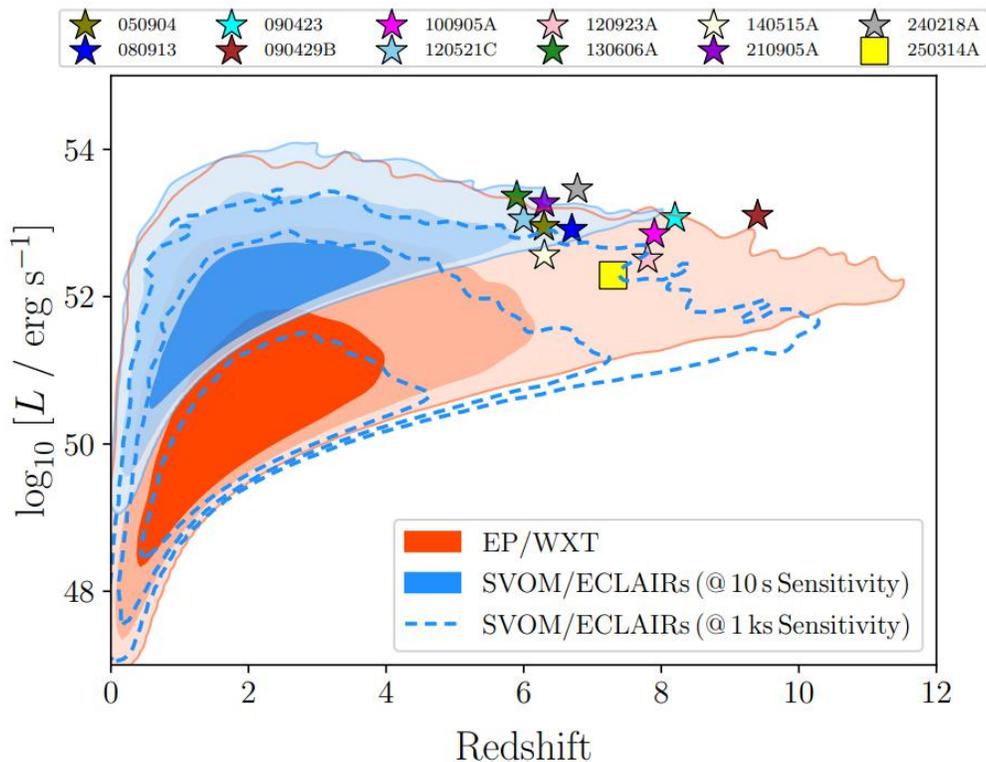
截至2025年5月, EP/WXT 共计探测到 ≈ 90 例快速X射线暂现源 (据GCN报道), 对应的探测率为 ≈ 68 events yr⁻¹.

➤ SVOM/ECLAIRs:

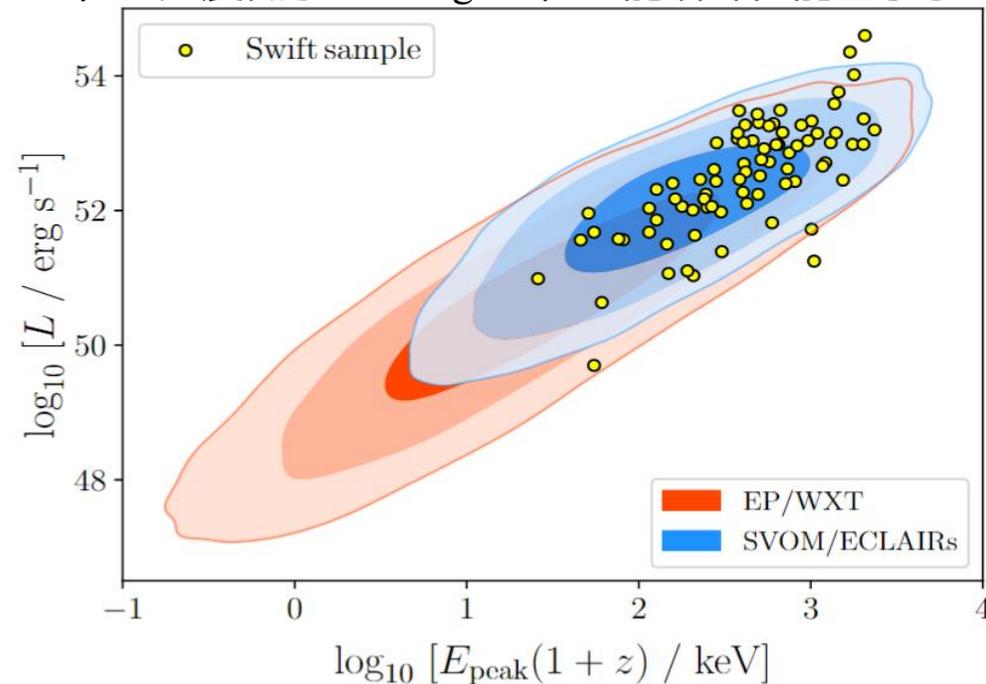
预计每年可共探测到 $\sim 83^{+16}_{-15}$.

截至2025年5月, SVOM/ECLAIRs共计探测到 ≈ 40 例GRBs (据GCN报道), 对应的探测率为 ≈ 48 events yr⁻¹.

基于S12 模型



在红移 $z < 1$ 的范围内, EP探测到的GRB中**约10%**具有以下特征: 光度低于 10^{49} erg s $^{-1}$, 且能谱峰值能量小于20 keV



相比Swift 卫星目前的探测样本以及SVOM 卫星的预期样本, EP/WXT的模拟样本的能量相对较低

EP/WXT将能探测到一类特殊的GRB群体, 其主要特征表现为软能谱和低光度(且主要为低红移事件)

Ghirlanda & Salvaterra (2022) 模型

➤ GRB爆发率:

$$\psi(z) \propto \frac{(1+z)^{q_1}}{1 + \left(\frac{1+z}{q_2}\right)^{q_3}}$$

$$q_1 = 3.33^{+0.33}_{-0.33}, q_2 = 3.42^{+0.28}_{-0.28}, q_3 = 6.21^{+0.38}_{-0.32}$$

➤ 随红移演化的GRB光度函数:

$$\phi(L, z) \propto \begin{cases} \left(\frac{L}{L_{b,z}}\right)^{-\nu_1} & L \leq L_{b,z} \\ \left(\frac{L}{L_{b,z}}\right)^{-\nu_2} & L > L_{b,z} \end{cases} \quad L_{b,z} = L_{b,0}(1+z)^\delta$$

$$\nu_1 = 0.97^{+0.05}_{-0.04}, \nu_2 = 2.21^{+0.13}_{-0.18}, \log_{10}(L_{b,0}/\text{erg s}^{-1}) = 52.02^{+0.22}_{-0.19}, \text{ and } \delta = 0.64^{+0.32}_{-0.26}$$

The GRB LF is normalized to unity by integrating over the luminosity range 10^{47} erg s^{-1} to 10^{55} erg s^{-1}

➤ 在特定能段下的GRB峰值流量:

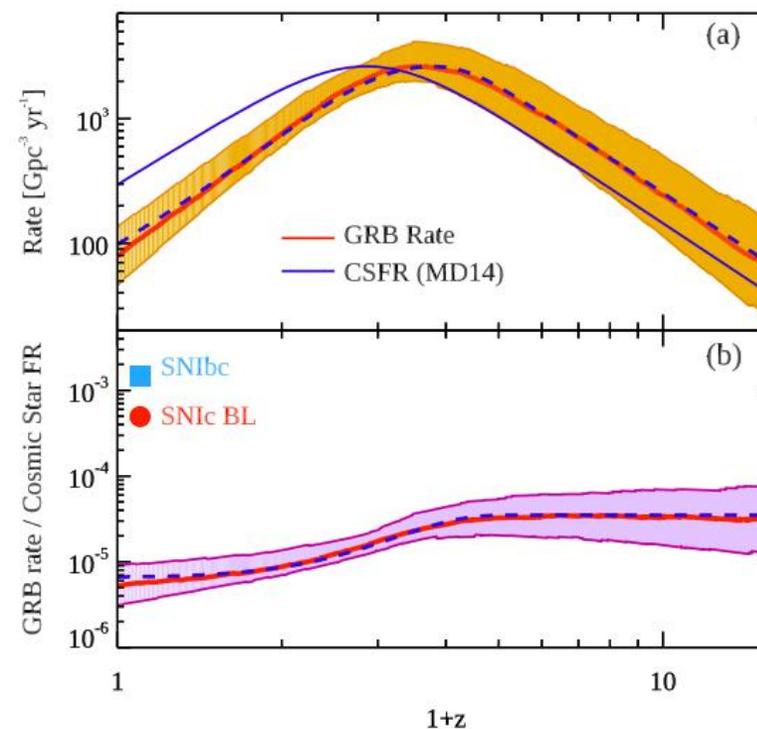
$$P_{\Delta E} = \frac{L}{4\pi d_L(z)^2} \frac{\int_{E_1}^{E_2} N(E) dE}{\int_{1\text{keV}/(1+z)}^{10^4\text{keV}/(1+z)} EN(E) dE}$$

➤ Band能谱:

$$\alpha = -1 \pm 0.2, \beta = -2.3 \pm 0.2$$

$$\log(E_p(1+z)) = -25.33 + 0.53 \log(L) \text{ with the scatter } \sigma_{\text{SC}} = 0.29$$

They analyzed the BAT6 sample, which consists of GRBs with a 15–150 keV peak flux $P \geq 2.6$ ph $\text{cm}^{-2} \text{s}^{-1}$.



Ghirlanda & Salvaterra 2022, ApJ, 932, 10

基于Ghirlanda & Salvaterra (2022) 模型

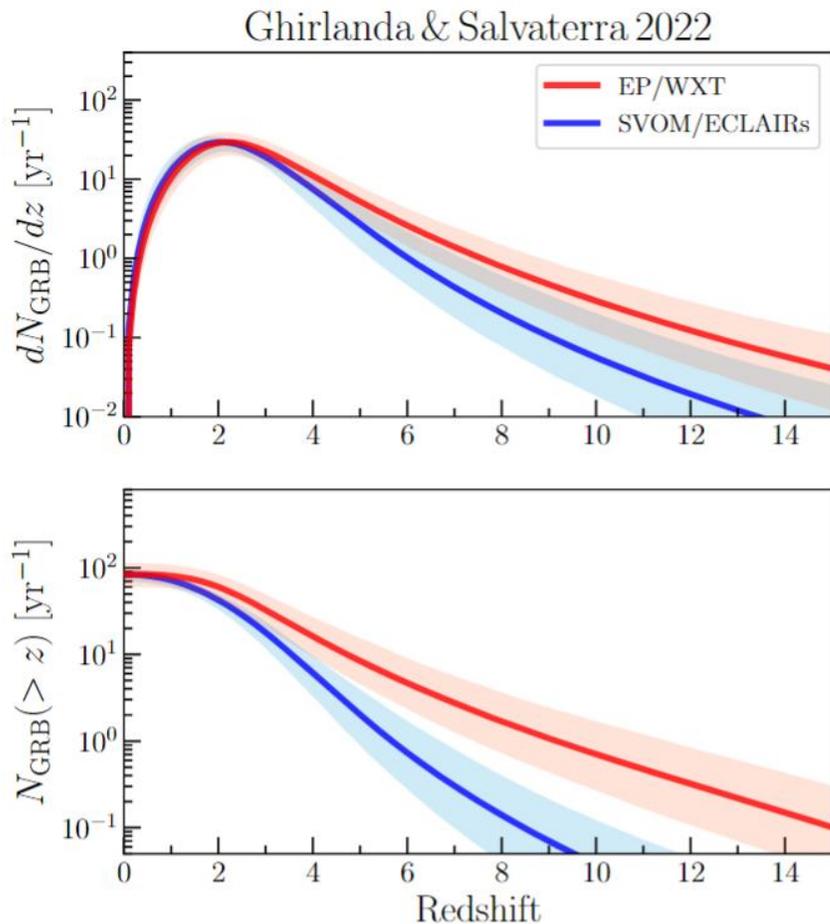


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➤ EP/WXT:

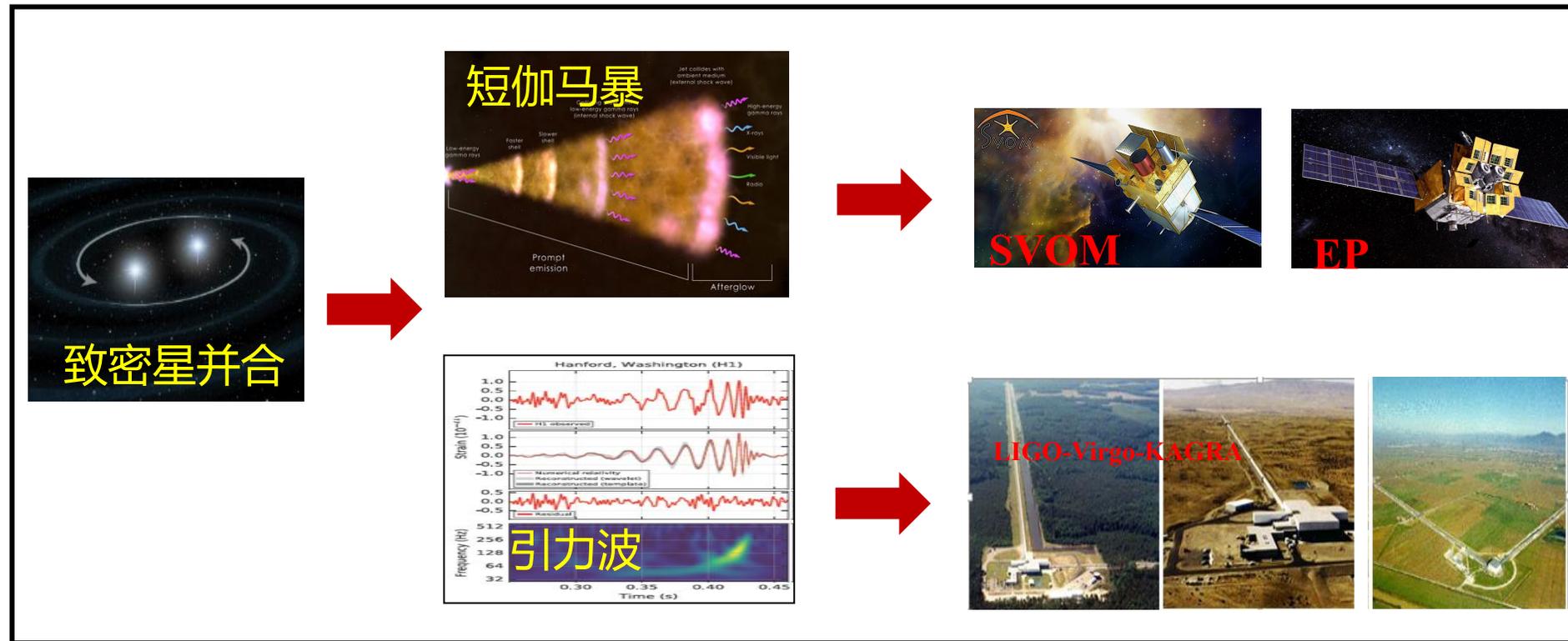
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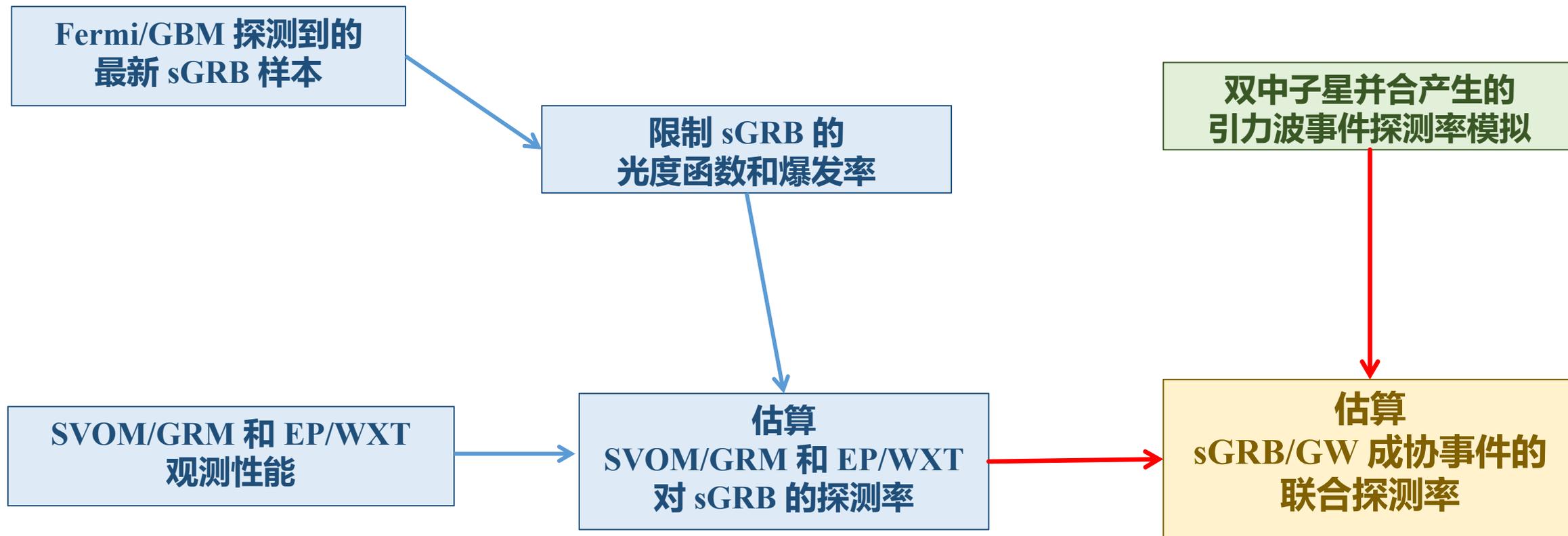
预计每年可共探测到 $\sim 74^{+10}_{-11}$.

截至2025年5月, SVOM/ECLAIRs共计探测到 ≈ 40 例GRBs (据GCN报道), 对应的探测率为 ≈ 48 events yr⁻¹.



International Gravitational Wave Networks (IGWN):

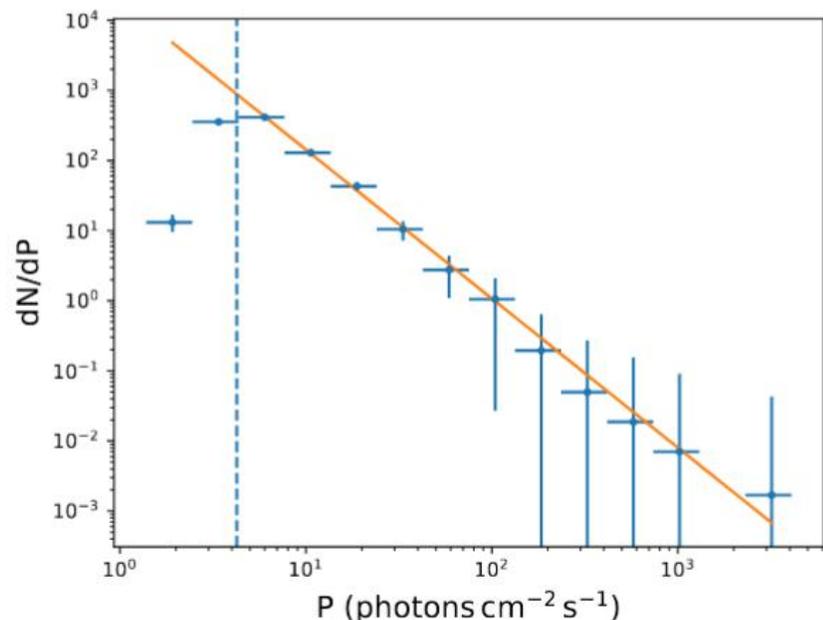
- (1) A four-detector network consisting of LIGO Hanford, Livingston, Virgo, and KAGRA (IGWN4);
- (2) A future five-detector network that includes these four detectors plus LIGO-India (IGWN5).



短伽马暴样本：Fermi GBM 源表

➤ 样本选择:

截至2023年12月15日，共553个短暴



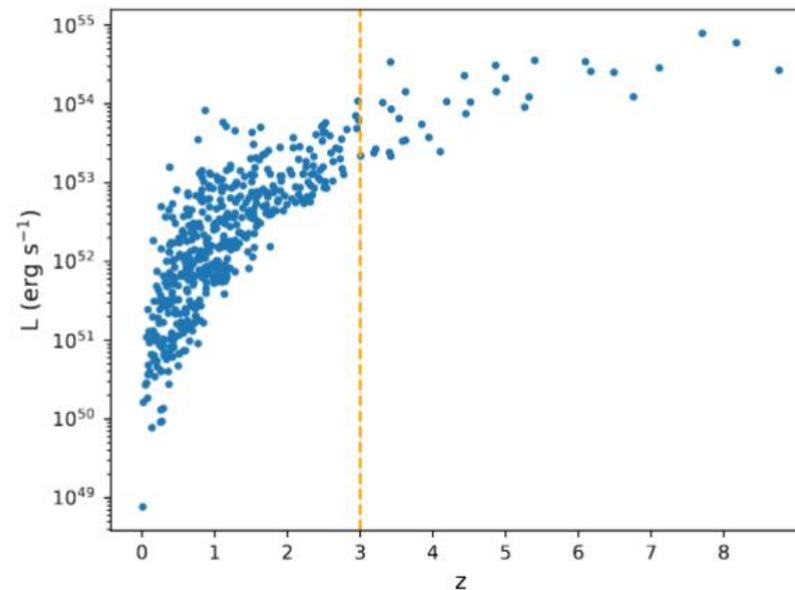
为避免引入复杂的 Fermi/GBM 触发机制，我们选取了512个 $P > 4.1 \text{ photons cm}^{-2} \text{ s}^{-1}$ 的短暴作为样本分析

短伽马暴的红移估算

➤ 经验光度关系:

(e.g., Tsutsui et al. 2013; Zhang & Wang 2018)

$$L = (7.15 \pm 0.49) \times 10^{50} \left[\frac{E_p (1+z)}{100 \text{ keV}} \right]^{1.63 \pm 0.03}$$



最终样本

478 sGRBs with $P > 4.1 \text{ photons cm}^{-2} \text{ s}^{-1}$ and $z < 3$

➤ sGRB 爆发率:

$$R_{\text{sGRB}}(z) = f_b C \int_{\tau_{\text{min}}}^{\tau_{\text{max}}} \psi_{\star}[z'(\tau)] P(\tau) d\tau$$

➤ 双致密星并合延迟时间分布:

(i) Gaussian $P(\tau) \propto \frac{1}{\sqrt{2\pi}\sigma_G} \exp\left[-\frac{(\tau - t_G)^2}{2\sigma_G^2}\right]$

(ii) Lognormal $P(\tau) \propto \frac{1}{\sqrt{2\pi}\tau\sigma_{\text{LN}}} \exp\left[-\frac{(\ln \tau - \ln t_{\text{LN}})^2}{2\sigma_{\text{LN}}^2}\right]$

(iii) Power law $P(\tau) \propto \tau^{-\gamma}$

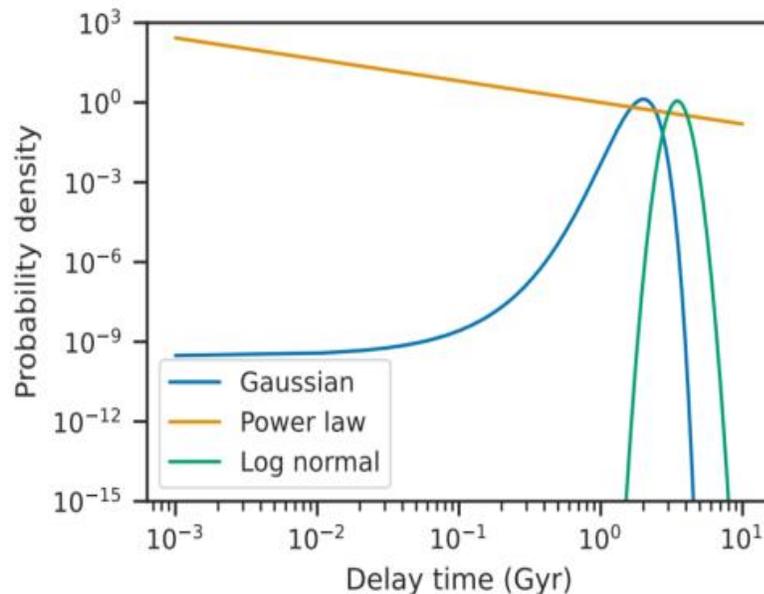
➤ sGRB 光度函数:

$$\phi(L) \propto \begin{cases} \left(\frac{L}{L_b}\right)^{-\nu_1}; & L \leq L_b, \\ \left(\frac{L}{L_b}\right)^{-\nu_2}; & L > L_b, \end{cases}$$

➤ sGRB 的预期数目:

$$N_{\text{exp}} = T f_{\text{sky}} f_{\text{not_SAA}} \int_0^{z_{\text{max}}} \frac{R_{\text{sGRB}}(z)}{1+z} \frac{dV(z)}{dz} dz$$

$$\int_{\max[L_{\text{min}}, L_{\text{lim}}(z)]}^{L_{\text{max}}} \phi(L) dL,$$



Luo et al. 2022, MNRAS, 516, 1654

□ 最大似然函数分析方法

(e.g., Chiang & Mukherjee 1998; Narumoto & Totani 2006; Ajello et al. 2009, 2012; Abdo et al. 2010)

➤ 似然函数:

$$\mathcal{L} = \exp(-N_{\text{exp}}) \prod_{i=1}^{N_{\text{obs}}} \Phi(L_i, z_i, t_i),$$

➤ 单位时间、红移和光度的 sGRB 观测率:

$$\Phi(L, z, t) = \frac{d^3 N}{dt dL dz} = f_{\text{sky}} f_{\text{not_SAA}} \frac{R_{\text{sGRB}}(z)}{1+z} \frac{dV(z)}{dz} \phi(L),$$

高崇宇、魏俊杰*、曾厚敦, 2025, MNRAS in press, arXiv:2501.03614

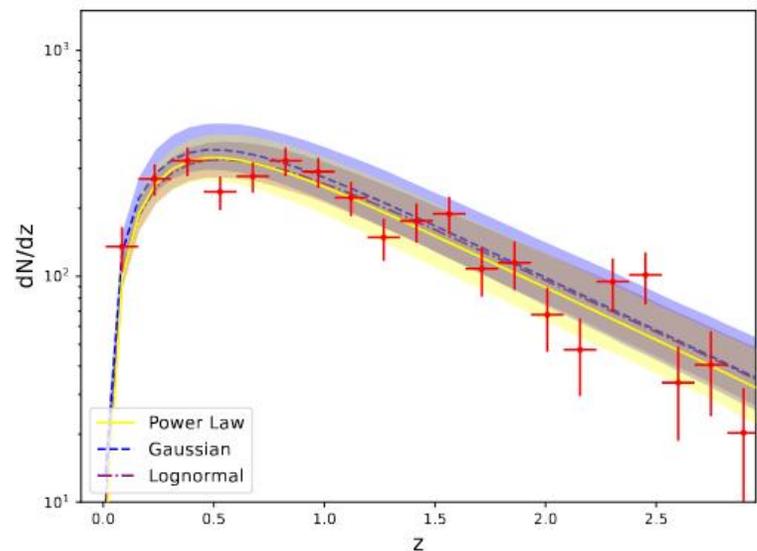


Table 2. Best-fitting parameters for different delay-time distribution models.

Delay model	Delay parameter	$\log_{10} \eta$ (M_{\odot}^{-1})	$\log_{10} L_b$ (erg s^{-1})	ν_1	ν_2	$\ln \mathcal{L}$	DIC
Gaussian	$t_G = 1.14^{+0.02}_{-0.17}$, $\sigma_G < 0.26$	$1.45^{+0.12}_{-0.08}$	$53.25^{+0.13}_{-0.18}$	$1.40^{+0.04}_{-0.04}$	$2.76^{+0.64}_{-0.35}$	-47486	94996
Lognormal	$t_{LN} = 2.14^{+0.01}_{-0.28}$, $\sigma_{LN} < 0.06$	$1.30^{+0.06}_{-0.06}$	$53.22^{+0.16}_{-0.10}$	$1.37^{+0.03}_{-0.03}$	$2.72^{+0.51}_{-0.28}$	-47520	95053
Power law	$\gamma = 2.04^{+0.44}_{-0.48}$	$1.51^{+0.06}_{-0.06}$	$53.17^{+0.10}_{-0.09}$	$1.29^{+0.04}_{-0.04}$	$2.63^{+0.24}_{-0.30}$	-47526	95058

Note. t_G , t_{LN} , and σ_G are in units of Gyr, and σ_{LN} is in units of \ln Gyr.

➤ **sGRB 的本地爆发率:**

Delay model	$R_{\text{sGRB}}(0) \text{ Gpc}^{-3} \text{ yr}^{-1}$
Gaussian	$1.37^{+0.30}_{-0.27}$
Lognormal	$1.63^{+0.44}_{-0.27}$
Power law	$1.78^{+0.12}_{-0.17}$

□ 对于 Top-hat 喷流, 集束效应因子:

$$f_b = R_{\text{sGRB}}(0) / R_{\text{BNS}}$$

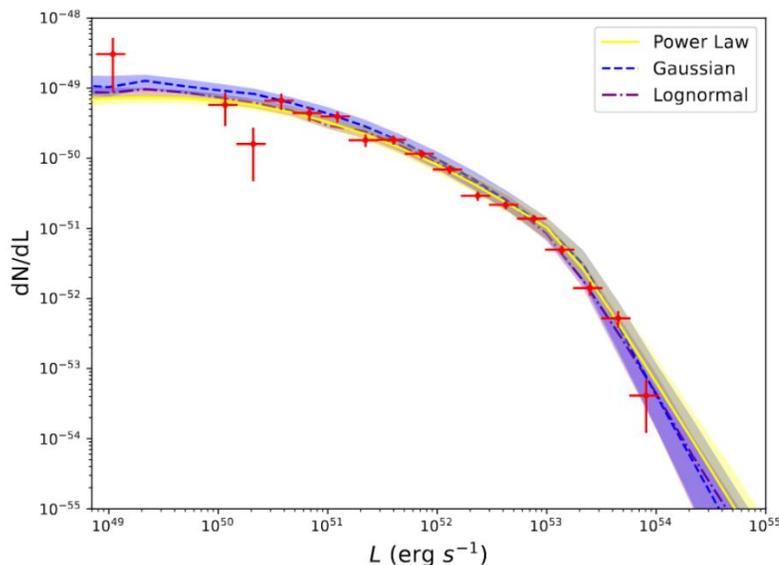
进而可估算喷流半张角为

$$\theta_j \sim 3^\circ - 12^\circ$$

➤ **双中子星并合事件率:**

$$R_{\text{BNS}} = 320^{+490}_{-240} \text{ Gpc}^{-3} \text{ yr}^{-1}$$

as inferred from the second LIGO-Virgo GW transient catalog (Abbott et al. 2021).



➤ **Python 软件包: PyCBC**

利用 PyCBC 软件包模拟引力波波形

➤ **模拟注入的双中子星并合事件为均匀分布**

$$\frac{dp(z)}{dz} \propto \frac{1}{1+z} \frac{dV(z)}{dz}$$

➤ **中子星的质量:**

满足均值为 $1.33 M_{\text{sun}}$ 和标准差为 $0.09 M_{\text{sun}}$ 的正态分布

➤ **中子星的自旋:**

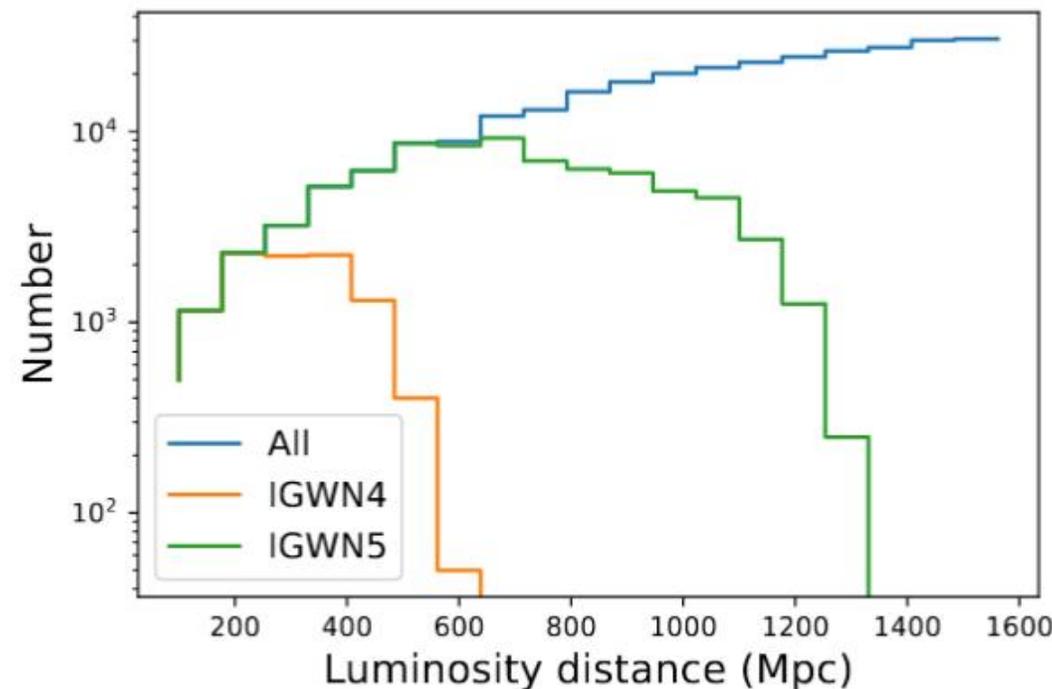
在 $0 < \chi < 0.05$ 范围内, 均匀分布

➤ 为确定哪些模拟生成的GW事件能被引力波探测网络 IGWN4和IGWN5探测到, 我们选取**信噪比SNR超过特定阈值**的事件, 即:

$$\text{SNR}_{\text{net}} = \sqrt{\sum_{\text{det}} \text{SNR}_{\text{det}}^2} \quad \text{SNR}_{\text{det}}^2 = 4 \text{Re} \left(\int_{f_{\text{min}}}^{f_{\text{max}}} df \frac{\tilde{X} \tilde{X}^*}{S_n(f)} \right)$$

➤ 我们定义信噪比 $\text{SNR}_{\text{net}} > 8$ 作为探测阈值

$z < 0.3$



短伽马暴/引力波成协事件的联合探测率

- 若考虑结构化喷流，实际观测光度为

$$L_{\text{obs}}(\theta) = LJ(\theta) \quad J(\theta) = e^{-\left(\frac{\theta}{2\theta_c}\right)^2}$$

- 观测光度函数改写为

$$\phi'(L_{\text{obs}}) \propto \int_0^{\pi/2} \phi[L_{\text{obs}}/J(\theta)] \sin\theta d\theta$$

- 双中子星并合产生的sGRB/GW成协事件的预期数目:

$$N_{\text{joint}} = T f_{\text{sky}} f_{\text{not_SAA}} \int_0^{z_{\text{lim}}} \frac{R_{\text{sGRB}}(z) R_{\text{GW}}(z)}{1+z} \frac{dV(z)}{dz} dz \int_{\max[L_{\text{min}}, L_{\text{lim}}(z)]}^{L_{\text{max}}} \phi'(L_{\text{obs}}) dL_{\text{obs}}$$

Table 3. The energy bands, flux thresholds, Sky-coverage fractions, and SAA-outage fractions of the high-energy emissions.

Mission	Energy band (keV)	Flux threshold	Sky-coverage fraction (f_{sky})	SAA-outage fraction ($f_{\text{not_SAA}}$)
Fermi/GBM	10–1000	4.1 (photons $\text{cm}^{-2} \text{s}^{-1}$)	0.7	0.85
SVOM/GRM ^(a)	1–1000	3.2 (photons $\text{cm}^{-2} \text{s}^{-1}$)	0.24	0.85
EP/WXT ^(b)	0.5–4	8.9×10^{-10} (erg $\text{cm}^{-2} \text{s}^{-1}$)	0.09	0.67

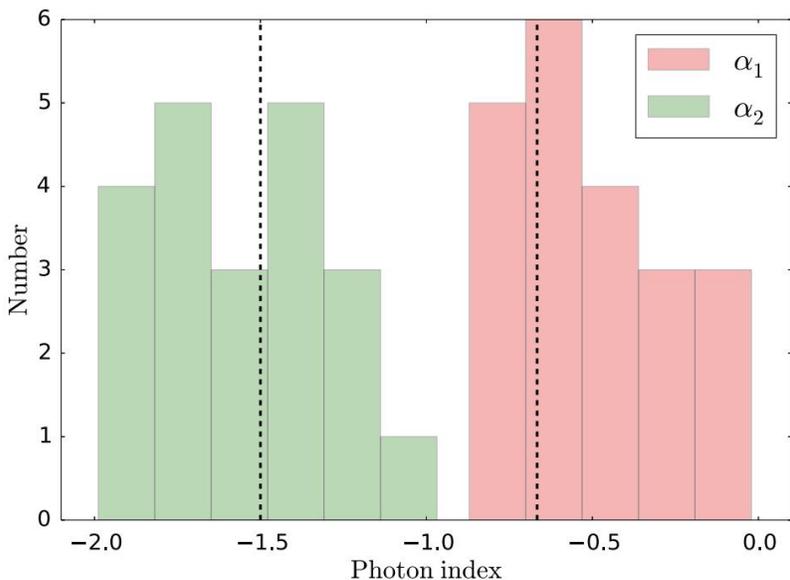
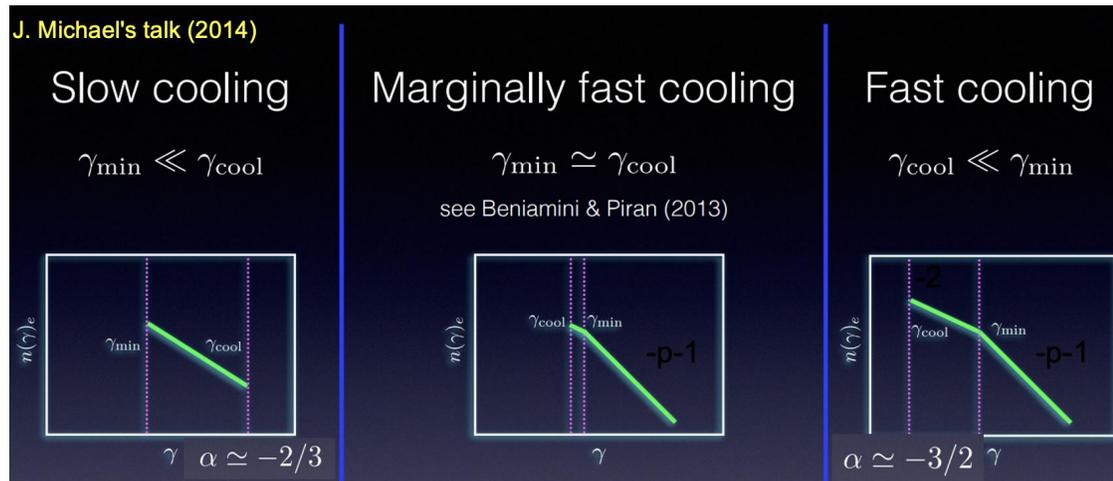
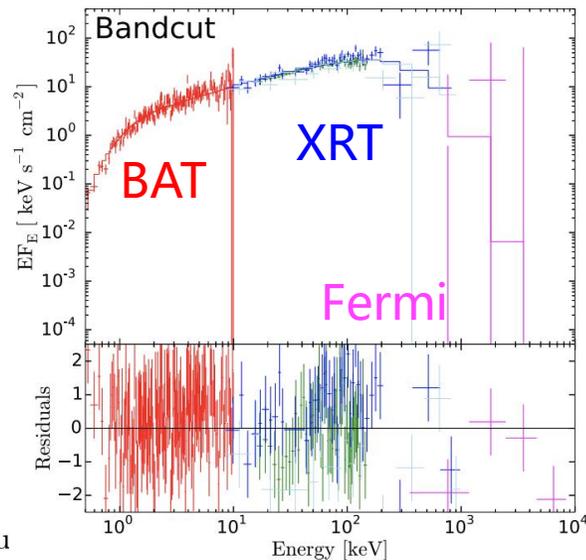
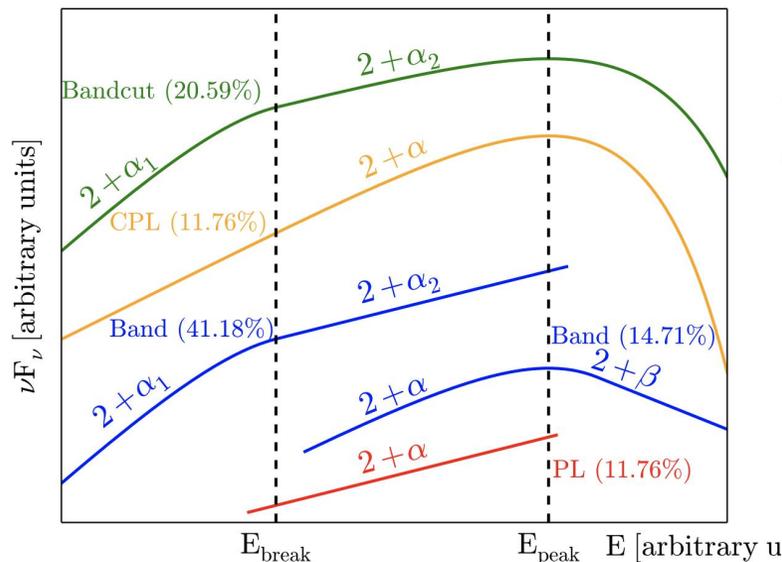
Note. (a) Wei et al. (2016), (b) Yuan et al. (2015).

- 在IGWN4时期，约每5年探测到1例 sGRB/GW 成协事件
- 当LIGO-India加入后，IGWN5 探测率提升至每年1例

$z_{\text{lim}} < 0.3$

Delay model	sGRB detection rate (yr^{-1})			IGWN4 joint detection rate (yr^{-1})			IGWN5 joint detection rate (yr^{-1})		
	Fermi/GBM	SVOM/GRM	EP/WXT	Fermi/GBM	SVOM/GRM	EP/WXT	Fermi/GBM	SVOM/GRM	EP/WXT
Gaussian	$3.28^{+0.48}_{-0.58}$	$2.69^{+0.32}_{-0.40}$	$0.78^{+0.09}_{-0.11}$	$0.24^{+0.03}_{-0.03}$	$0.09^{+0.01}_{-0.01}$	$0.02^{+0.01}_{-0.01}$	$1.18^{+0.17}_{-0.21}$	$0.69^{+0.10}_{-0.12}$	$0.24^{+0.03}_{-0.04}$
Lognormal	$2.82^{+0.22}_{-0.31}$	$2.06^{+0.16}_{-0.22}$	$0.76^{+0.08}_{-0.06}$	$0.21^{+0.03}_{-0.02}$	$0.08^{+0.00}_{-0.00}$	$0.02^{+0.00}_{-0.01}$	$1.03^{+0.19}_{-0.10}$	$0.59^{+0.10}_{-0.06}$	$0.21^{+0.01}_{-0.02}$
Power law	$3.19^{+0.31}_{-0.35}$	$1.99^{+0.28}_{-0.25}$	$0.57^{+0.08}_{-0.07}$	$0.21^{+0.02}_{-0.02}$	$0.08^{+0.01}_{-0.00}$	$0.02^{+0.01}_{-0.01}$	$1.12^{+0.14}_{-0.11}$	$0.57^{+0.06}_{-0.06}$	$0.16^{+0.01}_{-0.01}$

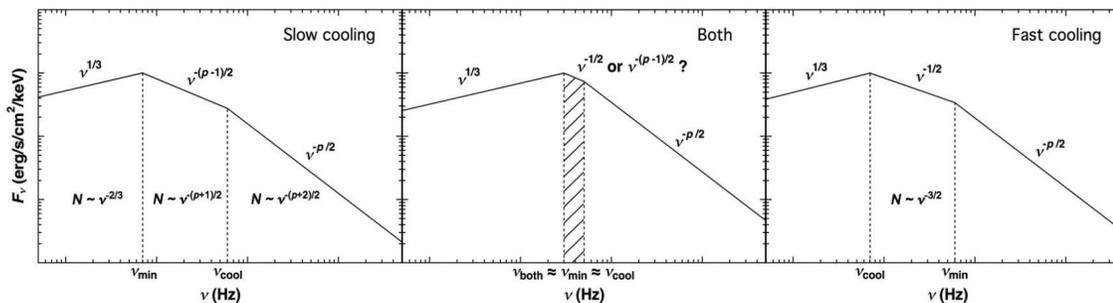
高崇宇、魏俊杰*、曾厚敦, 2025, MNRAS in press, arXiv:2501.03614



$$\langle \alpha_1 \rangle = -0.15 \pm 0.24$$

$$\langle \alpha_2 \rangle = -1.56 \pm 0.26$$

- 有迹象表明62%的伽马暴能谱在低能端存在拐折
- 该现象与冷却中的电子同步辐射形态有自然的对应关系



EP+Fermi+Swift 的联合能谱分析能够给出可靠结论

结构化喷流

幂率分布喷流

$$\epsilon(\theta) \equiv \frac{dE}{d\Omega} = \begin{cases} \epsilon_0 & \text{if } \theta \leq \theta_0, \\ \epsilon_0 \left(\frac{\theta}{\theta_0}\right)^{-k} & \text{if } \theta_0 < \theta < \theta_m. \end{cases}$$

Dai & Gou (2001)

Rossi, Lazzati & Rees (2002)

高斯分布喷流

$$\epsilon(\theta) = \epsilon_0 \exp \left[- (1/2)(\theta/\theta_0)^2 \right]$$

Zhang & Meszaros (2002)

余辉偏轴观测特性

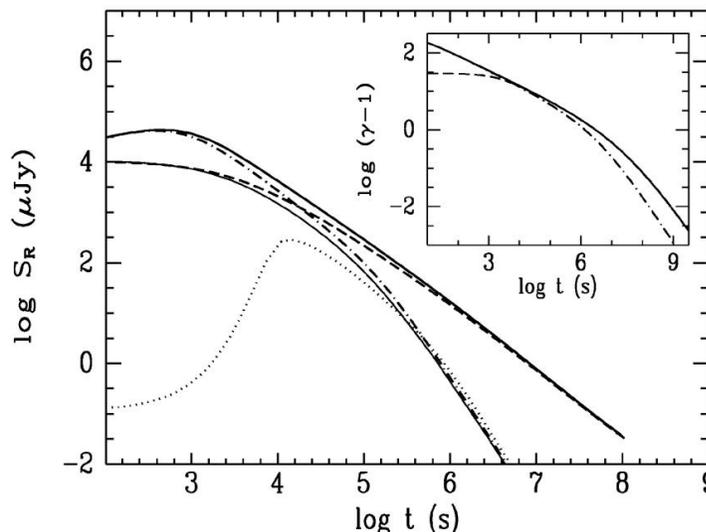
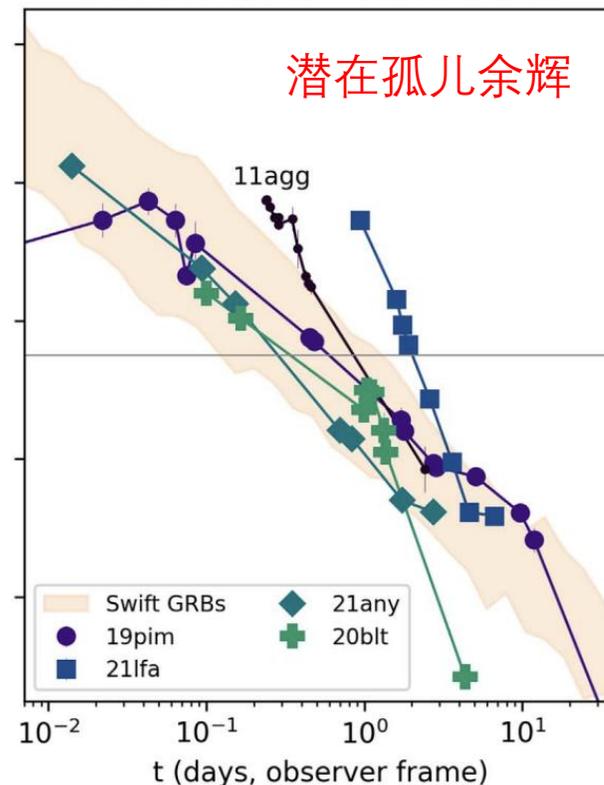


Figure 1. Theoretical *R*-band light curves of GRB afterglows. In our calculations we have taken the following common parameters: the isotropic energy $E_0 = 10^{53}$ erg, the interstellar medium density $n = 1 \text{ cm}^{-3}$, electron energy fraction $\xi_e = 0.1$, magnetical energy fraction $\xi_B^2 = 10^{-4}$, electron power-law energy index $p = 2.5$, and the luminosity distance $d = 1$ Gpc. For jets, we take the initial half opening angle $\theta_0 = 0.1$. The thick solid line is plotted for a usual isotropic GRB with $\gamma_0 = 300$. The dashed line represents an isotropic FGRB orphan with $\gamma_0 = 30$. The dash-dotted line corresponds to an on-axis jetted GRB with $\gamma_0 = 300$, and the dotted line is for a jetted but off-axis GRB orphan with viewing angle $\theta_{\text{obs}} = 0.15$. The thin solid line is for a beamed FGRB with $\gamma_0 = 30$, $\theta_{\text{obs}} = 0$. The inset shows the evolution of the Lorentz factor correspondingly. Note that $\gamma(t)$ of the beamed FGRB is not shown, as it is too close to the dashed curve at early times and too close to the dash-dotted line at late times.

ZTF 巡天候选体

No Associated Detected GRB



由于缺乏严格的时间零点信息，光学巡天确认偏轴喷流的效率很低

EP是全世界搜寻偏轴暴最强大的利器！



总结



- EP正在高效累积伽马暴/快速X射线暂现源样本，并且在高红移/偏轴伽马暴，以及内禀弱/慢喷流方面具有独特的优势
- EP正在引领我们对内禀弱/慢喷流基本性质的认识，包括喷流速度与几何，例如：EP240414a、EP241021a、EP241113a、EP241217a、EP250108a等
- 多波段的后随（尤其射电）对严格限制喷流几何结构具有重要作用
- 大量快速X射线暂现源的物理起源仍不清楚，它们或代表着已知现象（如伽马暴、TDE、FBOT等）在参数空间的延拓，或是一类全新的现象
- EP给我们带来了无限可能的发现机遇，引领我们拓展理论研究的边界，祝愿大家围绕EP多出成果、出好成果！

谢谢!