北京师范大学
BEIJING NORMAL UNIVERSITY

学为人师
行为世范
北京师范大学校训

EP时代下伽玛射线暴的研究契机

报告人：高鹤（on behalf of STP2）

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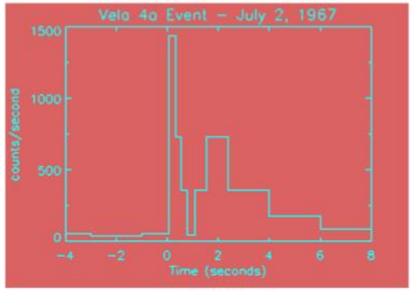
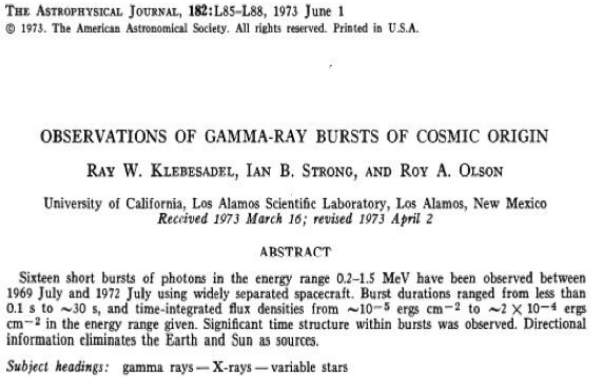
伽玛射线暴

发现：1967-1973





The Astrophysical Journal, 182:L85–L88, 1973 June 1
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OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

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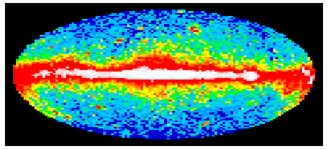
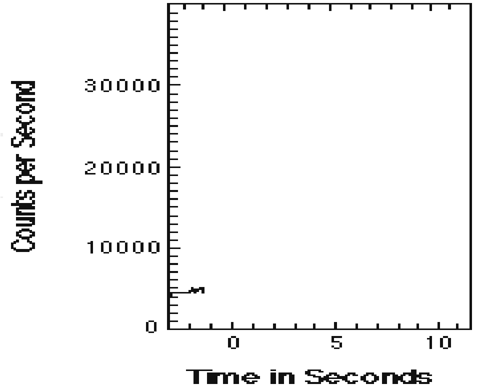
ABSTRACT

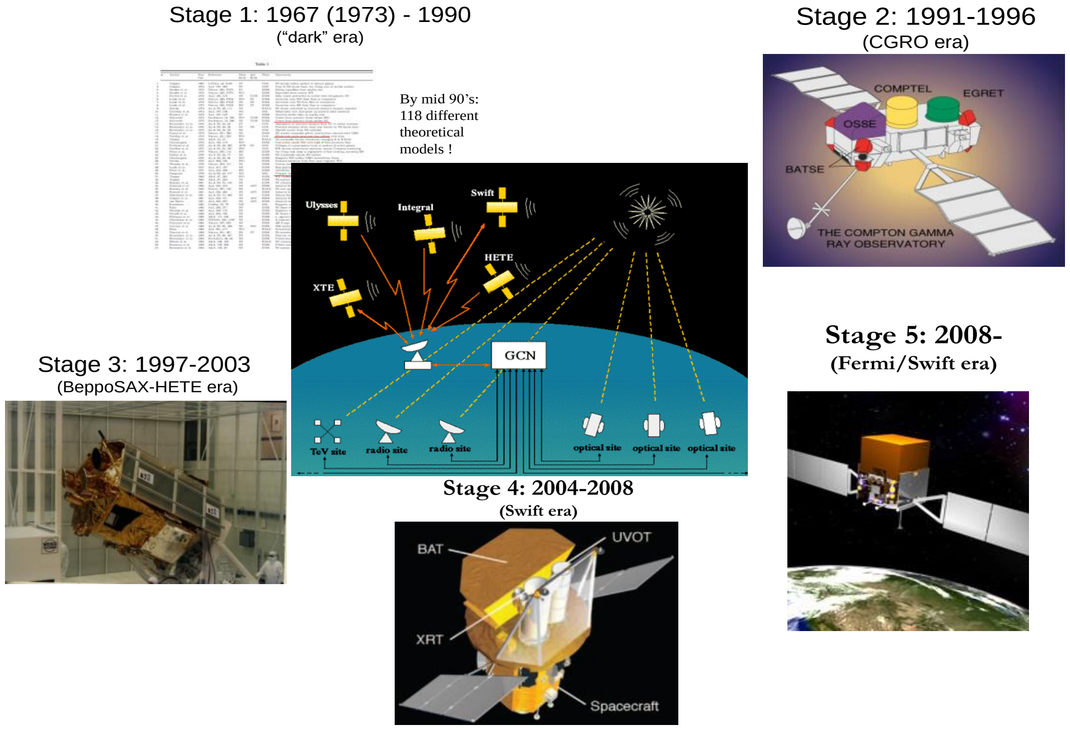
Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Subject headings: gamma rays — X-rays — variable stars

The Vela ("Watch") Satellites (1959-1985)
Monitor compliance with the 1963 Partial Test Ban Treaty by the Soviet Union







Stage 1: 1967 (1973) - 1990
("dark" era)

Stage 2: 1991-1996
(CGRO era)

Stage 3: 1997-2003
(BeppoSAX-HETE era)

Stage 4: 2004-2008
(Swift era)

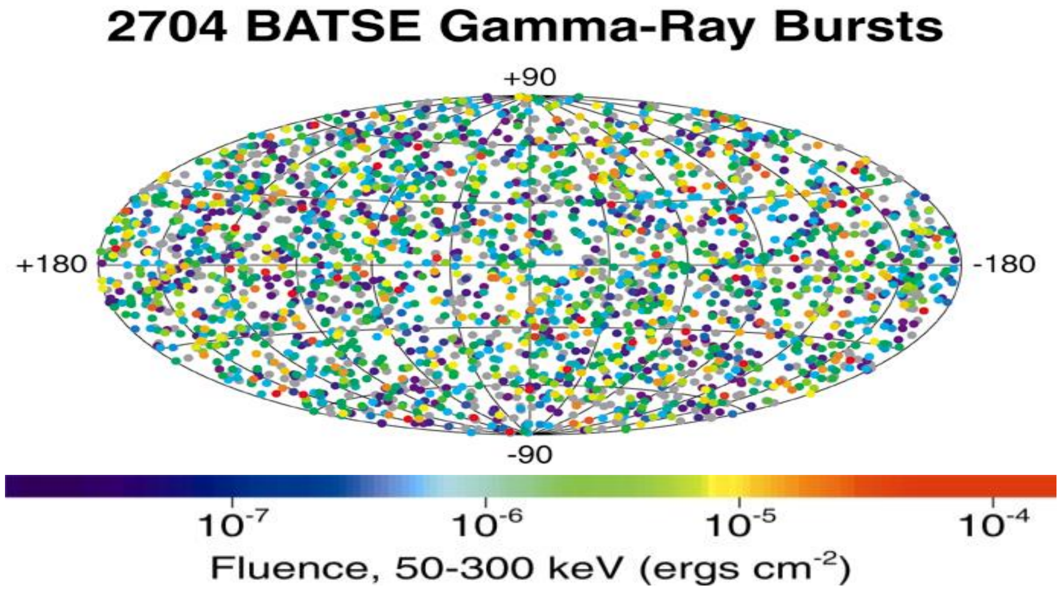
Stage 5: 2008-
(Fermi/Swift era)

伽玛暴是在宇宙空间发生的伽玛射线闪耀现象，平均每天可以观测到1-3次伽玛暴！

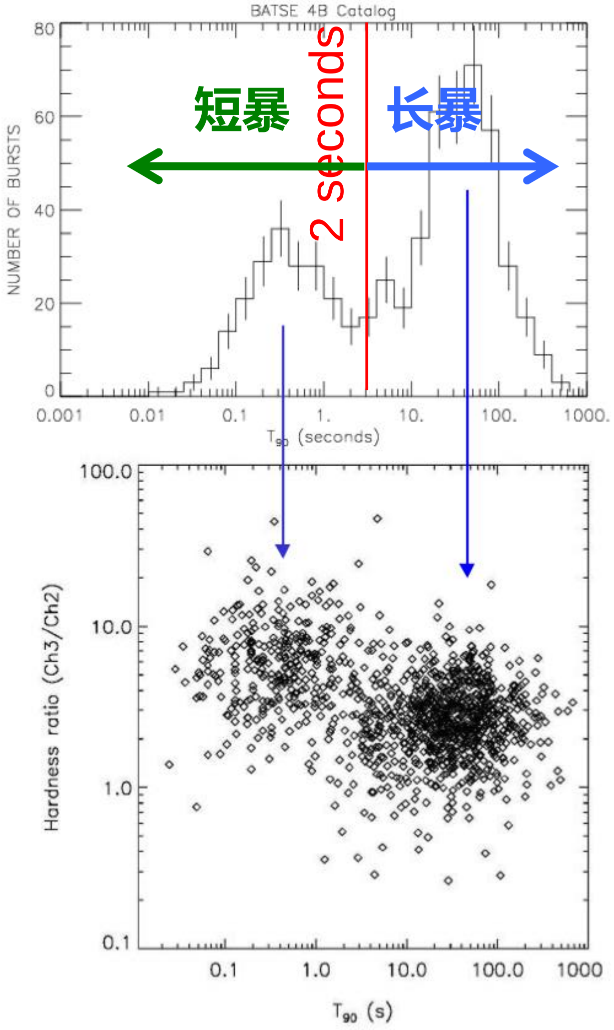
伽玛射线暴观测事实

早期样本积累：1991-1996

各项同性分布



长短暴分类

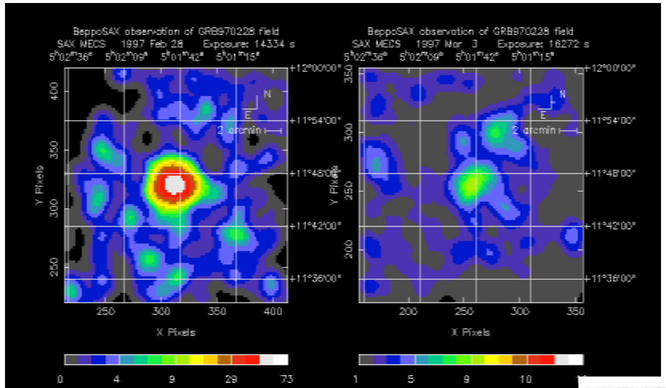


Kouveliotou et al.(1993)

- □ **伽玛暴很可能来自银河系之外**
- □ **伽玛暴有不同的起源**

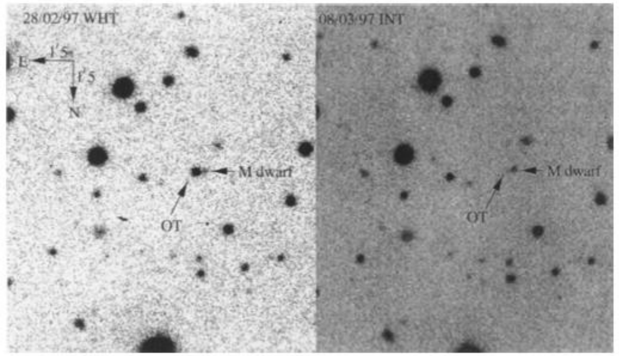
伽玛射线暴观测事实

余辉的发现



GRB 970228

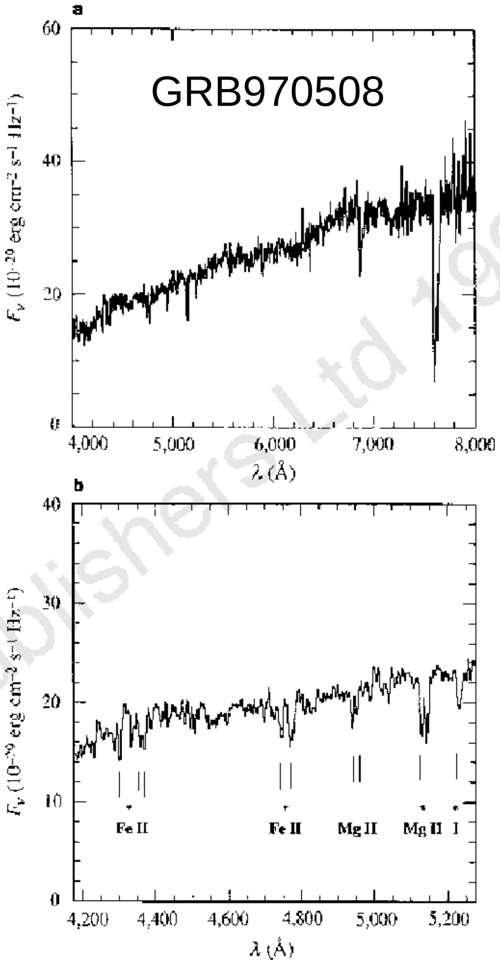
X-ray afterglow: Costa et al. 1997



Optical afterglow: van Paradijs et al. 1997

NATURE | VOL 386 | 17 APRIL 1997

红移的确定



Metzger et al. 1997

不同距离的光度估计

Galactic halo:

$$L_\gamma(\text{iso}) = 4\pi d^2 F_\gamma = 1.2\times10^{42}\,\text{erg/s}\left(\frac{d}{30\text{kpc}}\right)^2\left(\frac{F_\gamma}{10^{-5}\,\text{erg/s/cm}^2}\right)$$

Cosmological:

$$L_\gamma(\text{iso}) = 4\pi d^2 F_\gamma = 1.2\times10^{51}\,\text{erg/s}\left(\frac{d}{1\text{Gpc}}\right)^2\left(\frac{F_\gamma}{10^{-5}\,\text{erg/s/cm}^2}\right)$$

For comparison:

$L_{\otimes} \sim 10^{33}$ erg/s，$L_{gal} \sim 10^{44}$ erg/s， $L_{\text{AGN,M}} \sim 10^{48}$ erg/s

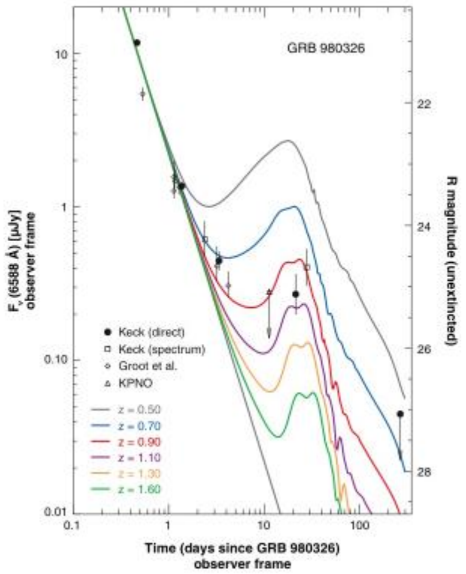
伽玛暴1秒钟释放的能量（假设各项同性释放）相当于太阳一生所释放能量

- □ **伽玛暴存在多波段辐射**
- □ **伽玛暴确定来自银河系之外**

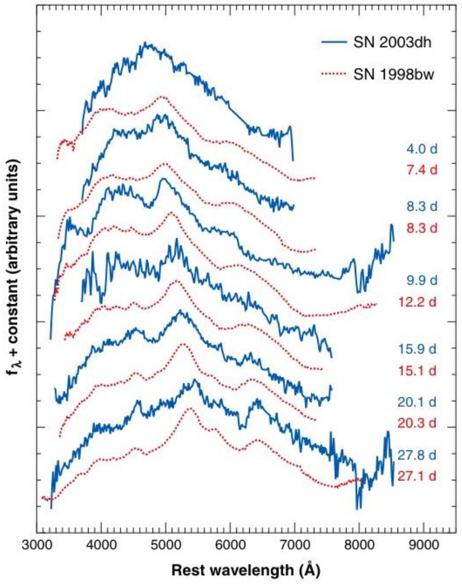
伽玛射线暴观测事实

长暴起源的确定

GRB/SN associations



Bloom et al. (1999)

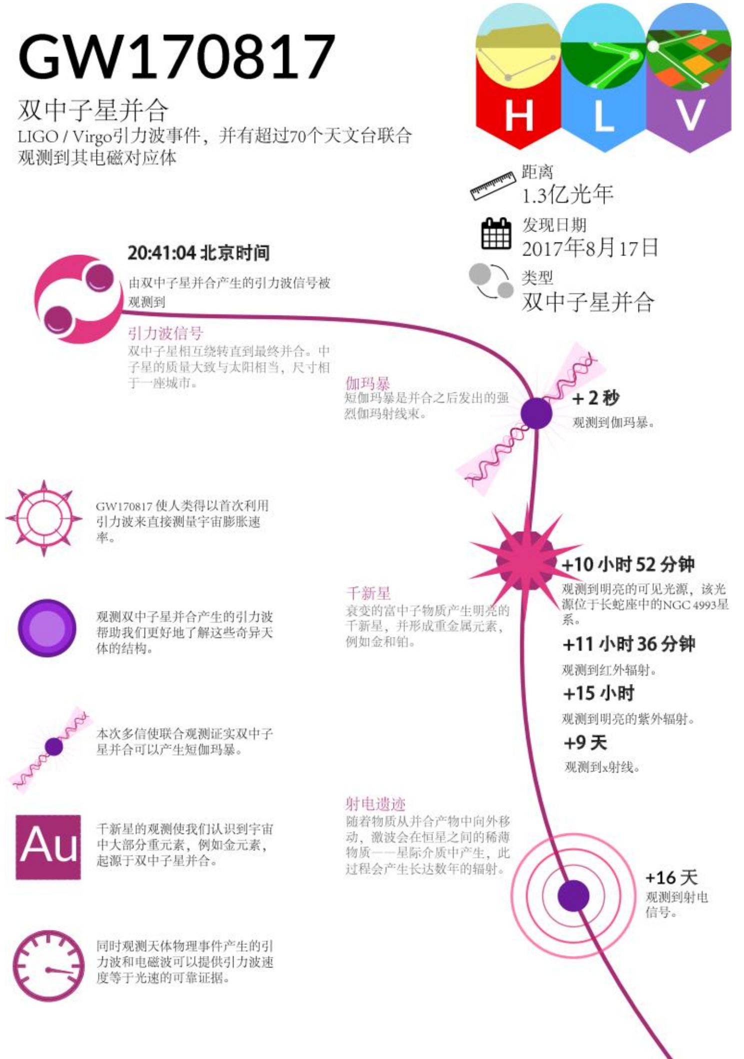


Hjorth et al. (2003)

长暴起源于大质量恒星塌缩

伽玛射线暴观测事实

短暴起源的确定



GW170817

双中子星并合

LIGO / Virgo引力波事件，并有超过70个天文台联合观测到其电磁对应体

距离
1.3亿光年

发现日期
2017年8月17日

类型
双中子星并合

20:41:04 北京时间

由双中子星并合产生的引力波信号被观测到

引力波信号

双中子星相互绕转直到最终并合。中子星的质量大致与太阳相当，尺寸相于一座城市。

伽玛暴

短伽玛暴是并合之后发出的强烈伽玛射线束。

+2 秒

观测到伽玛暴。

GW170817 使人类得以首次利用引力波来直接测量宇宙膨胀速率。

观测双中子星并合产生的引力波帮助我们更好地了解这些奇异天体的结构。

本次多信使联合观测证实双中子星并合可以产生短伽玛暴。

千新星的观测使我们认识到宇宙中大部分重元素，例如金元素，起源于双中子星并合。

同时观测天体物理事件产生的引力波和电磁波可以提供引力波速度等于光速的可靠证据。

千新星

衰变的富中子物质产生明亮的千新星，并形成重金属元素，例如金和铂。

+10 小时 52 分钟

观测到明亮的可见光源，该光源位于长蛇座中的NGC 4993星系。

+11 小时 36 分钟

观测到红外辐射。

+15 小时

观测到明亮的紫外辐射。

+9 天

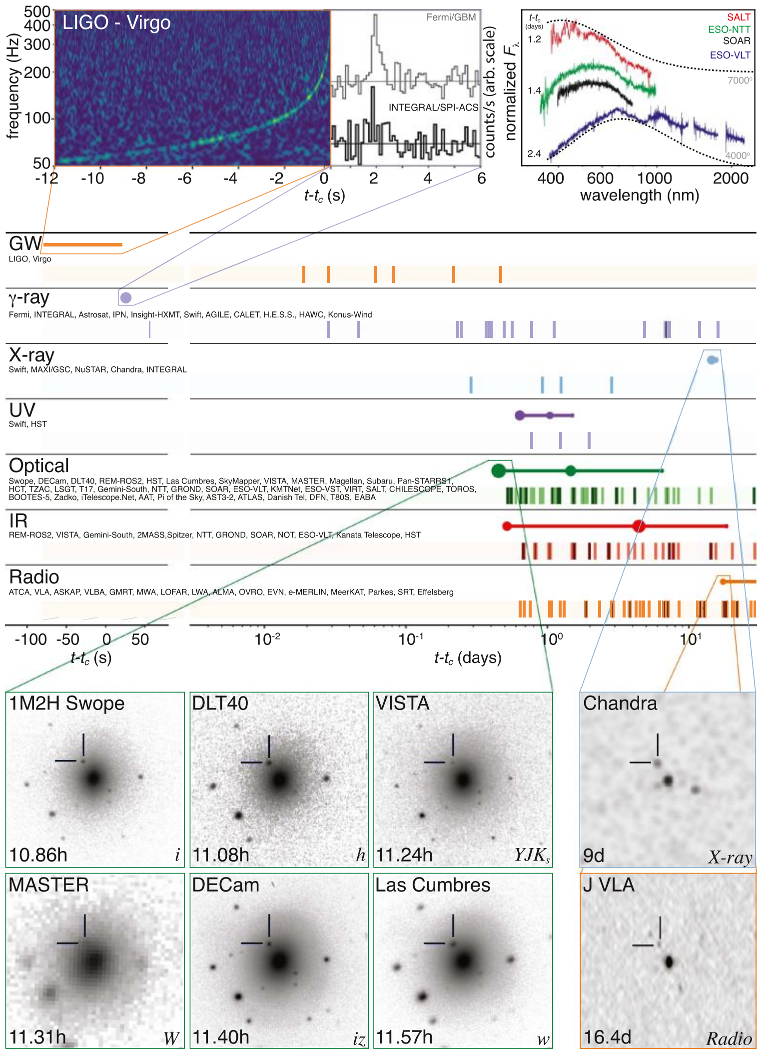
观测到x射线。

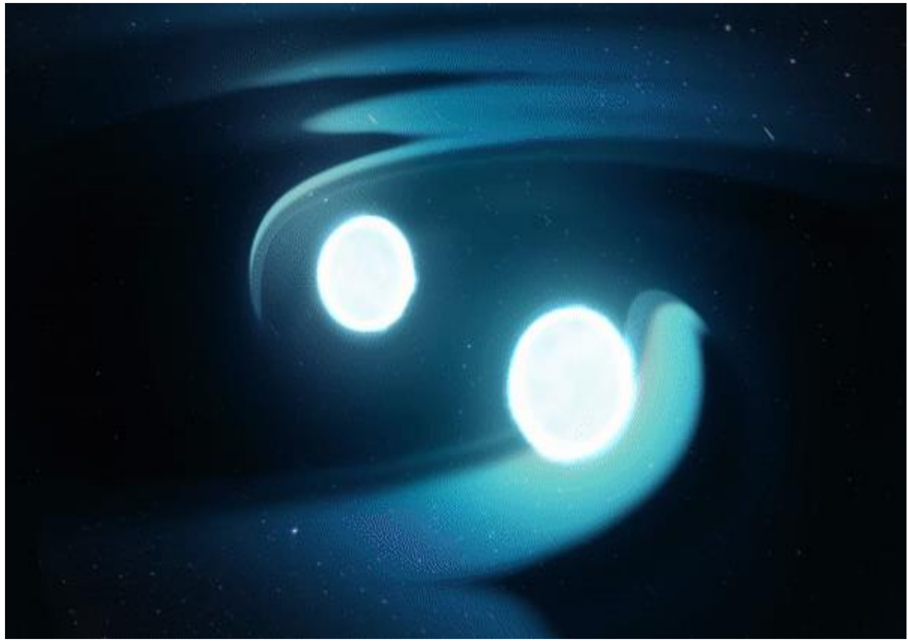
射电遗迹

随着物质从并合产物中向外移动，激波会在恒星之间的稀薄物质——星际介质中产生，此过程会产生长达数年的辐射。

+16 天

观测到射电信号。





短暴起源于双致密星并合

伽玛射线暴观测事实

极端相对论运动

Relativity at Work

* The huge luminosity of GRBs raises the “Compactness Problem”.
* The only solution is that the GRB ejecta is moving with a speed very close to speed of light!

Compactness Problem

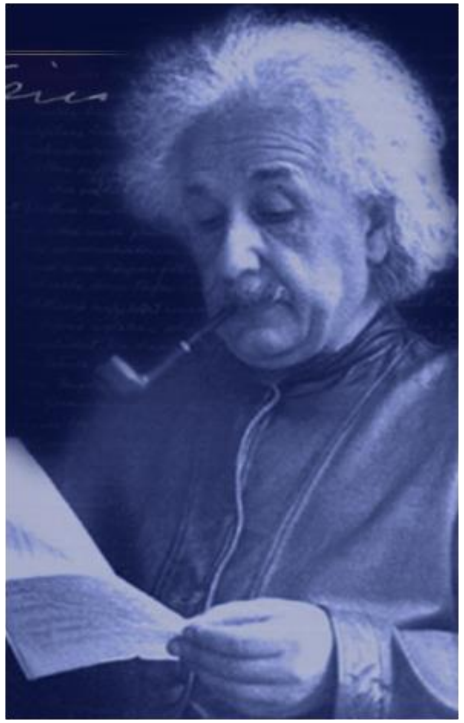
For isotropic emission, total radiated energy

$$E_0 = F(4\pi D^2)$$
$$\approx 10^{51}(F/(10^{-6}\mathrm{ergs/cm^2}))(D/(3\mathrm{Gpc}))^2.$$

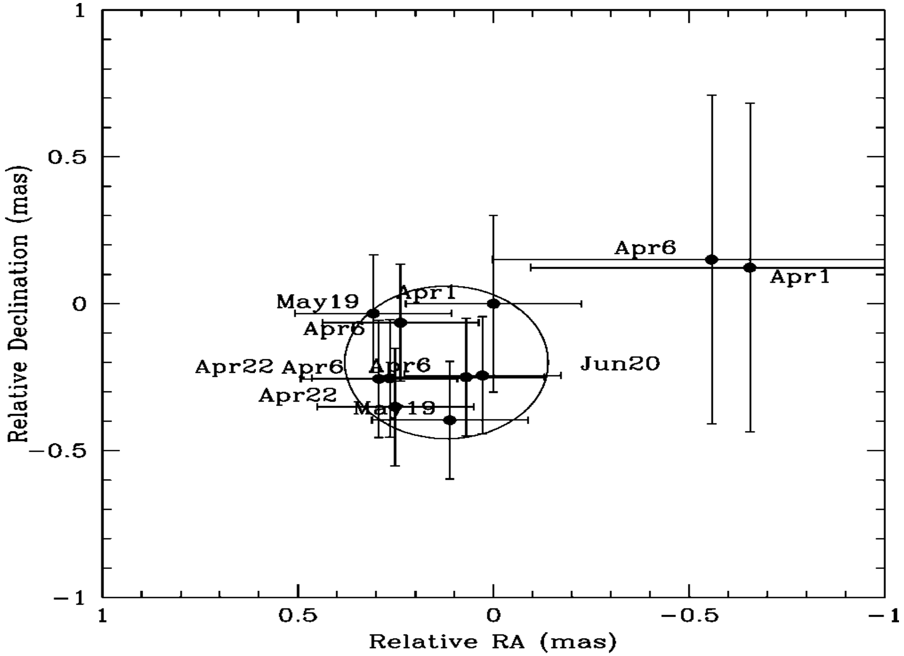
The source size $R_i = c\delta T \simeq 3\times10^7\ \mathrm{cm}\,\delta T_{-3}$. The optical depth for $\gamma\gamma \longrightarrow \mathrm{e^+e^-}$, $\tau_{\gamma\gamma}$, is very large:

$$\tau_{\gamma\gamma} = \frac{f_\mathrm{p}\sigma_\mathrm{T} F D^2}{R_i^2 m_e c^2}$$
$$\sim 10^{17} f_\mathrm{p}\left(\frac{F}{10^{-6}\mathrm{ergs/cm^2}}\right)\left(\frac{D}{3\ \mathrm{Gpc}}\right)^2\left(\frac{\delta T}{1\ \mathrm{ms}}\right)^{-2},$$

where f_p denotes the fraction of photon pairs satisfying $\sqrt{E_1E_2} > \mathrm{m_e\ c^2}$.



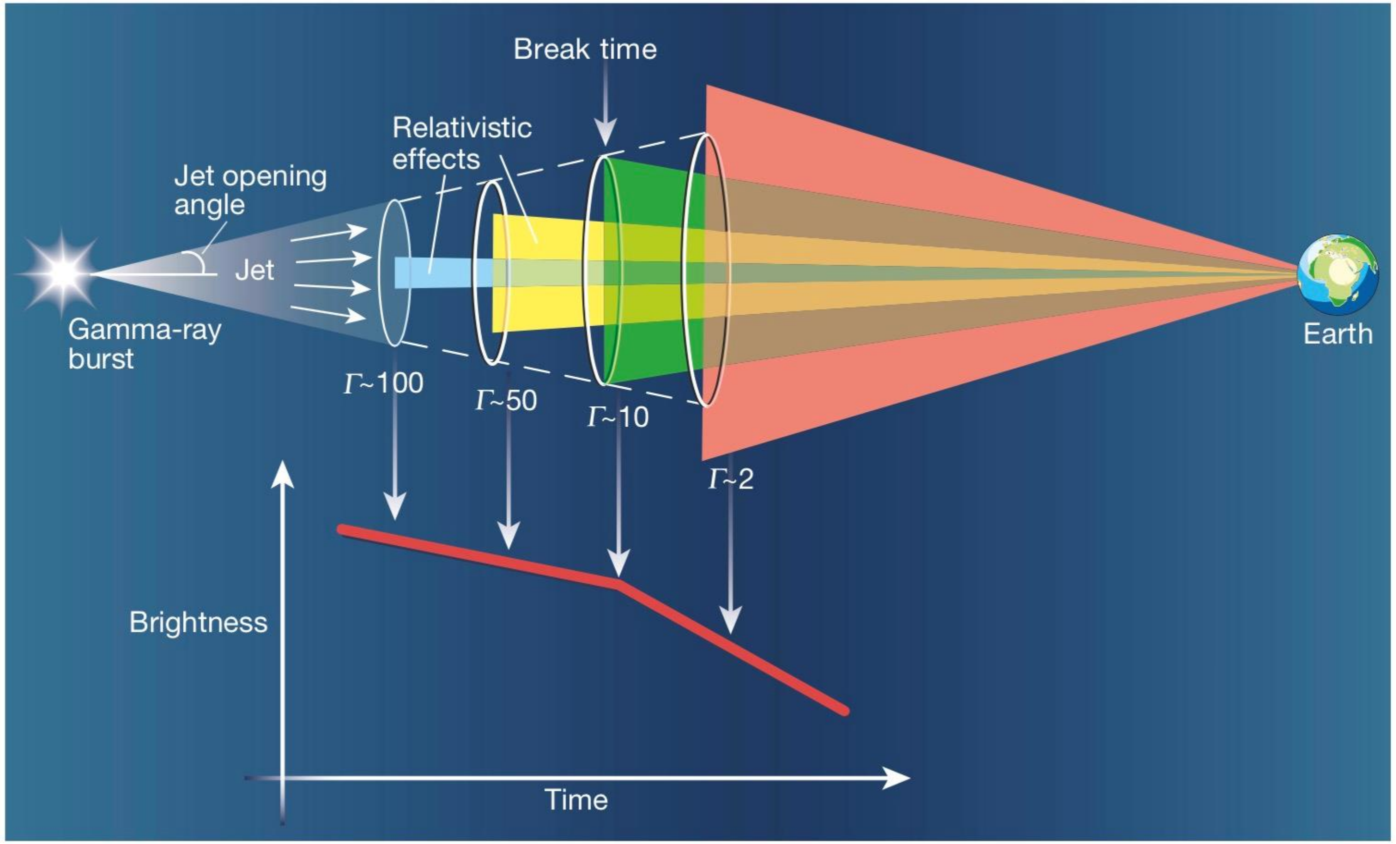
伽玛暴辐射区存在视超光速运动



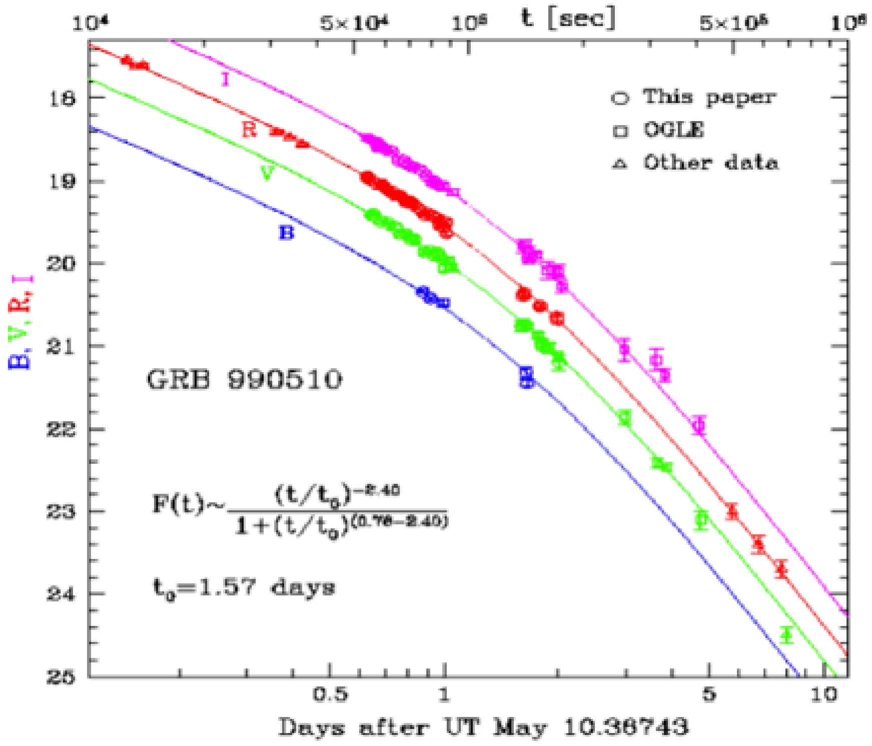
Taylor et al. 2004

伽玛射线暴观测事实

极端相对论运动的喷流

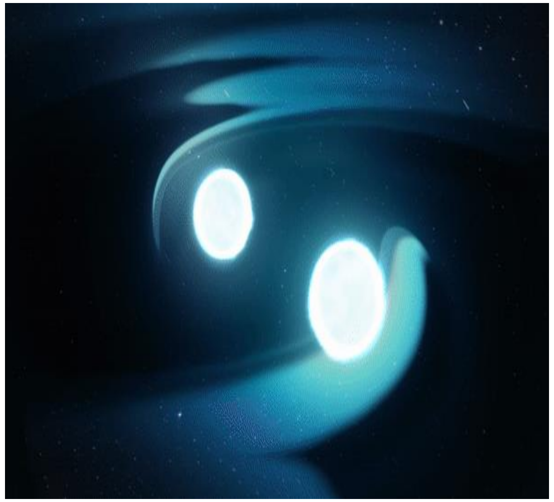


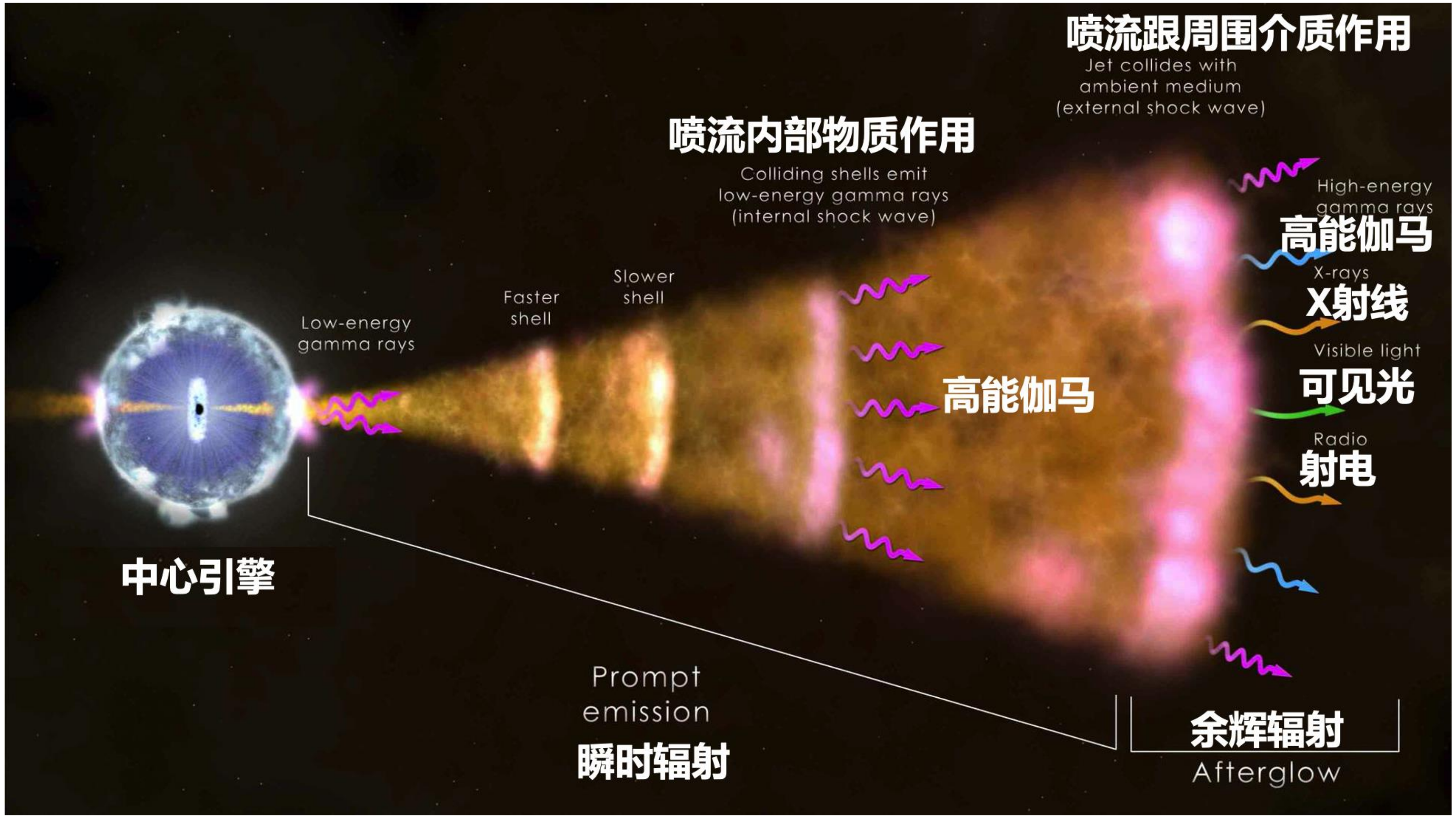
伽玛暴余辉中存在喷流拐折现象



Stanek et al. 99

伽玛射线暴基本图像




喷流跟周围介质作用
Jet collides with ambient medium (external shock wave)
喷流内部物质作用
Colliding shells emit low-energy gamma rays (internal shock wave)
Faster shell
Slower shell
Low-energy gamma rays
高能伽马
High-energy gamma rays
高能伽马
X-rays
X射线
Visible light
可见光
Radio
射电
中心引擎
Prompt emission
瞬时辐射
余辉辐射
Afterglow

伽玛射线暴研究中的待解问题

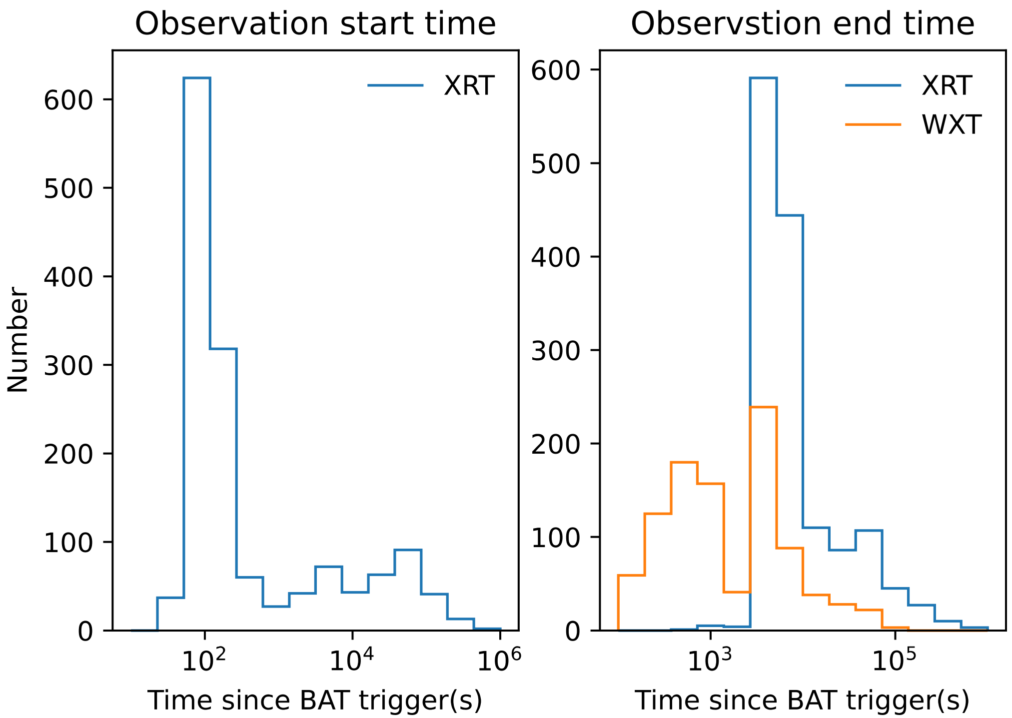
- 是否还有特殊类型前身星？
  - NS-WD？ 蓝超巨星？
- 磁星能否作为中心引擎？
- 喷流能量组分？
  - 热能主导？ 磁能主导？
- 喷流结构？
  - 结构化喷流？
- 是否是好的宇宙学探针？

EP的机遇（vs Swift/XRT）

WXT

大视场，低能段，可独立触发

- ➤ 未触发Swift/Fermi等探测器的软X射线暴
- ➤ 瞬时辐射阶段的软X射线辐射特征
- ➤ 极早期X射线余辉特征

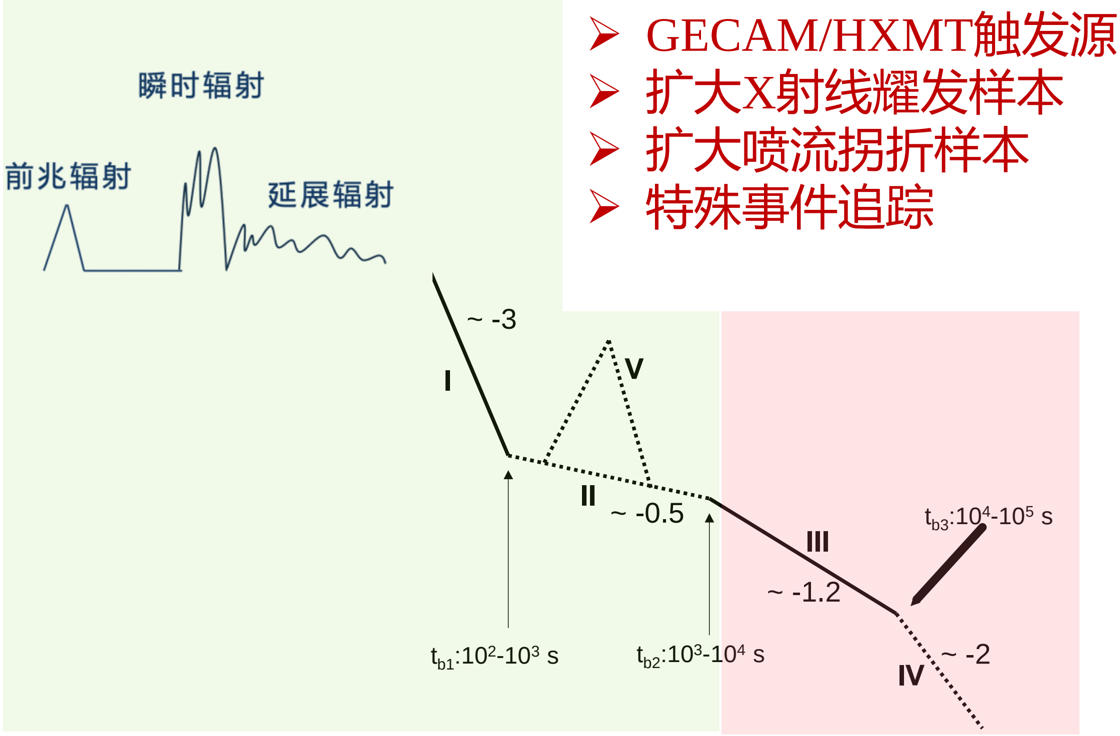

Observation start time

Observstion end time

FXT

灵敏度优于XRT

- ➤ GECAM/HXMT触发源的定位
- ➤ 扩大X射线耀发样本
- ➤ 扩大喷流拐折样本
- ➤ 特殊事件追踪



I.　早期陡降　（高纬辐射）
II.　缓慢衰减　（能量注入）
III. 正常衰减　（外激波辐射）
IV.　喷流拐折后衰减　（喷流减速）
V.　X射线耀发　（中心引擎再活动）

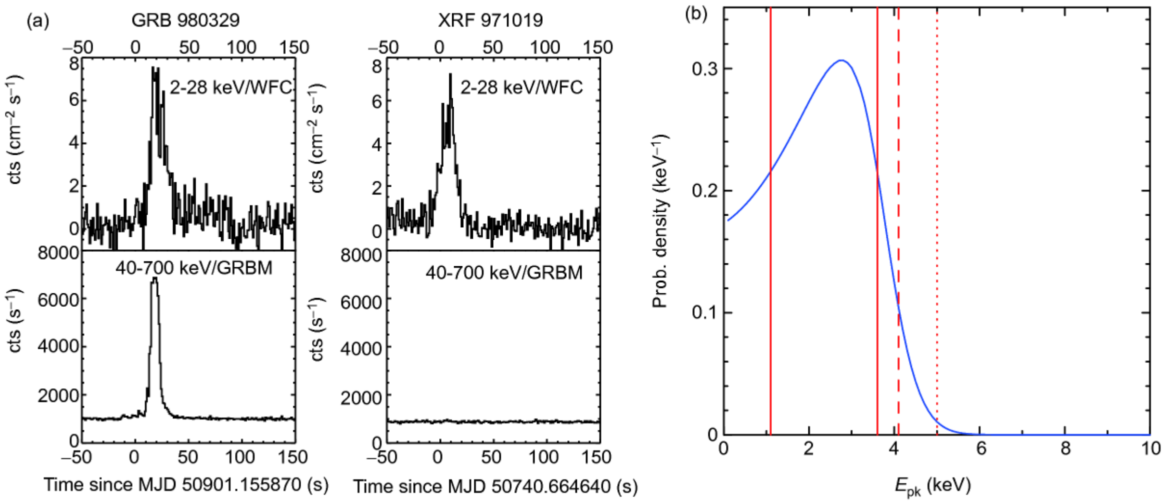
Zhang et al, 2006, ApJ

科学目标：XRF

X射线闪（XRF）

一类特殊的伽玛暴:

- ➢ 能谱峰值处在软X射线能段
- ➢ 普通伽玛暴相似的持续时间
- ➢ 正常的伽马射线探测器无触发



EP所探测到的伽玛暴绝大多数（>90%）属于XRF.

李兵, 孙惠, 王灵俊, 魏俊杰, 黄永锋, 李立新, 黎卓, 梁恩维, 吴雪峰

中国科学EP专刊

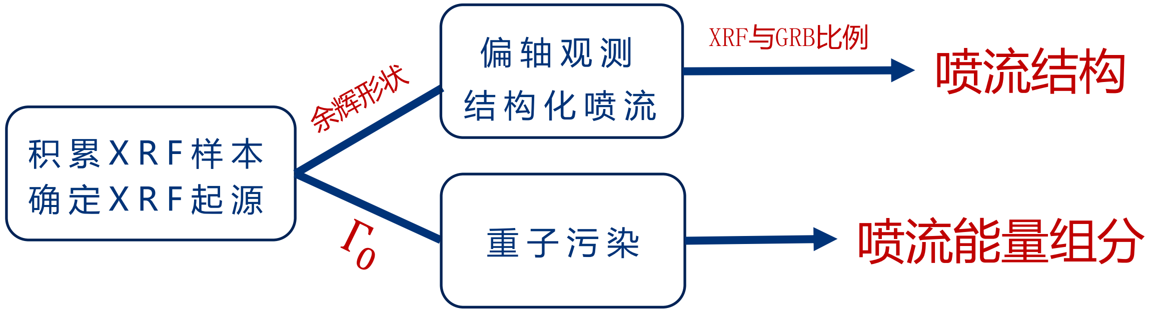
XRF可能的物理解释

- ➢ 被偏轴观测的伽玛暴
- ➢ 高度重子污染的火球产生的伽玛暴
- ➢ 结构化的喷流，大角度观测

针对XRF的研究方案

- ➢ 瞬时辐射的光变与能谱分析
- ➢ 多波段余辉的后随观测
- ➢ XRF事件率与普通GRB事件率比对

预期目标



积累XRF样本
确定XRF起源

余辉形状

Γ_0

偏轴观测
结构化喷流

重子污染

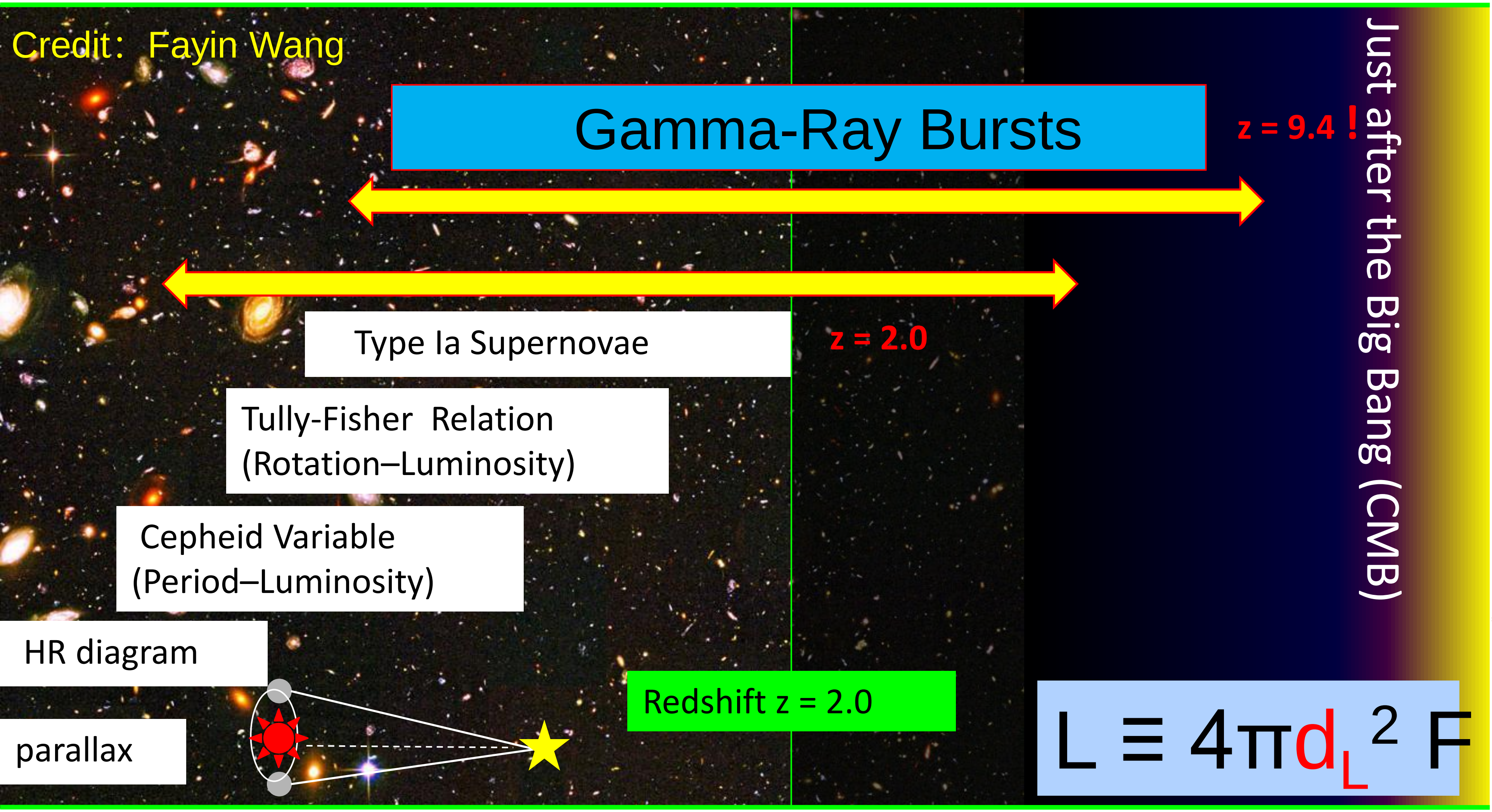
XRF与GRB比例

喷流结构

喷流能量组分

伽玛射线暴：宇宙高红移探针

Wang, Dai, & Liang 2015, New Astronomy Review



Credit：Fayin Wang

Gamma-Ray Bursts

z = 9.4 !

Just after the Big Bang (CMB)

Type Ia Supernovae

z = 2.0

Tully-Fisher Relation
(Rotation–Luminosity)

Cepheid Variable
(Period–Luminosity)

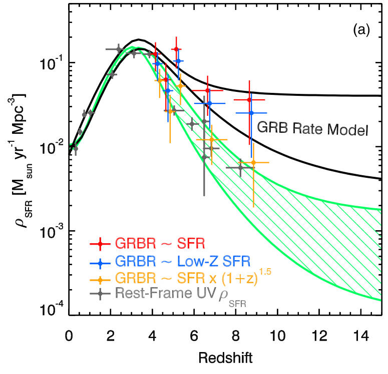
HR diagram

parallax

Redshift z = 2.0

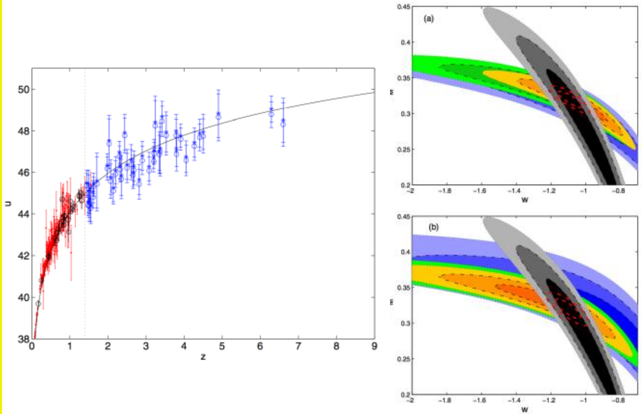
$$L \equiv 4\pi d_L^2 F$$

恒星形成率/第一代恒星



Robertson & Ellis (2012)

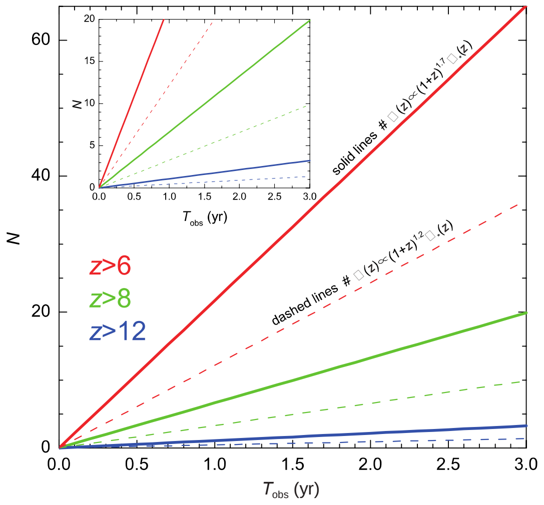
宇宙学模型



Gao, Liang & Zhu (2012)

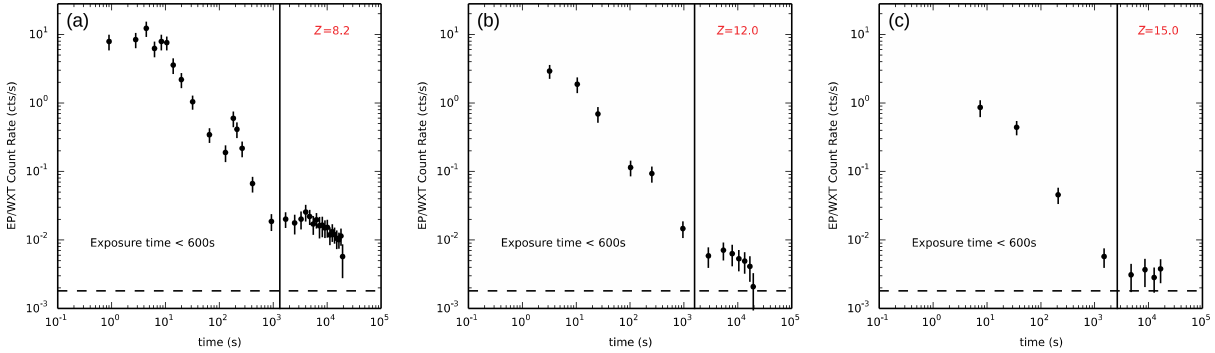
科学目标：高红移伽玛射线暴

高红移伽玛暴能谱中心红移到软X射线能段



未来EP运行3年有望探测到~65个$z>6$的伽玛暴，其中包括~20个$z>8$的伽玛暴和~3个$z>12$的伽玛暴。

EP/WXT对GRB 090423在不同红移处的模拟探测



魏俊杰, 吴雪峰, 王发印, 刘柱, 戴子高, 张冰

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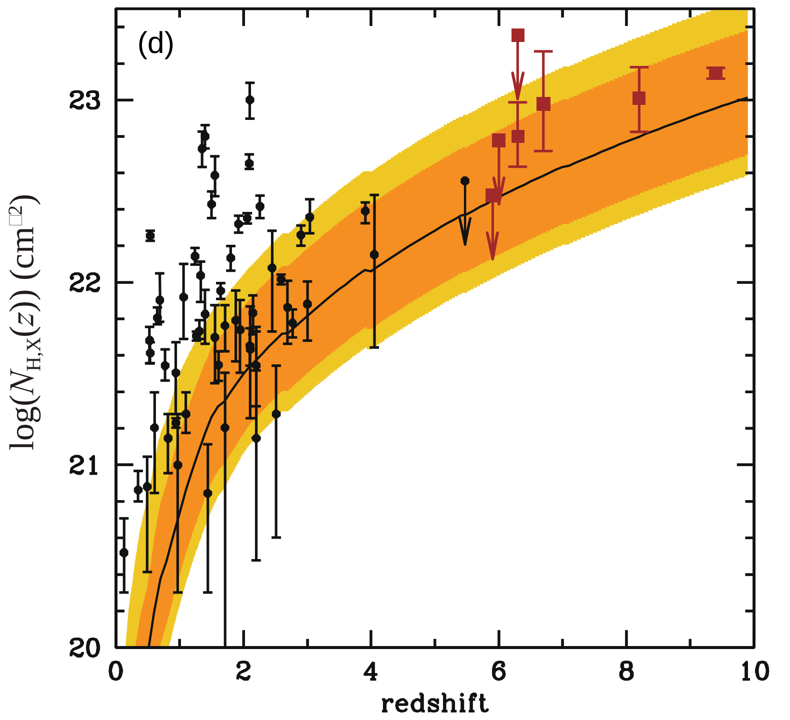
高红移伽玛暴鉴别

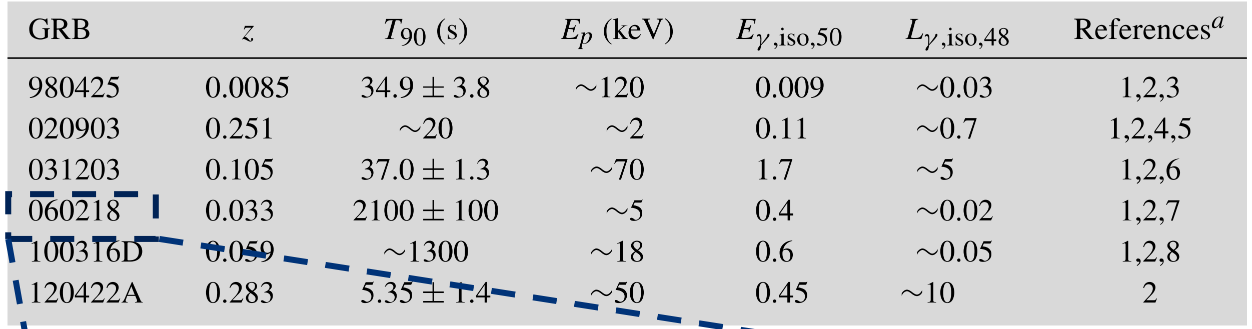
- **光学余辉后随观测**
- **超高的X射线氢柱密度($N_{H,X}$)**



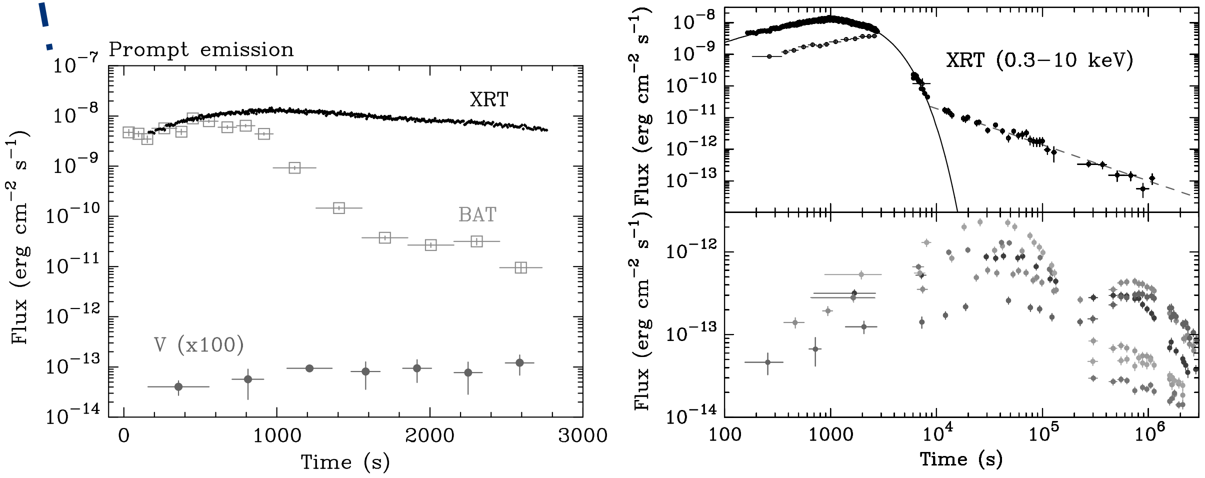
Salvaterra，2015

科学目标：低光度伽玛射线暴

（无明确）定义：瞬时辐射光度$10^{46\text{-}48}$erg/s



GRB	z	T_{90} (s)	E_p (keV)	$E_{\gamma,\mathrm{iso},50}$	$L_{\gamma,\mathrm{iso},48}$	References[a]
980425	0.0085	34.9 ± 3.8	~120	0.009	~0.03	1,2,3
020903	0.251	~20	~2	0.11	~0.7	1,2,4,5
031203	0.105	37.0 ± 1.3	~70	1.7	~5	1,2,6
060218	0.033	2100 ± 100	~5	0.4	~0.02	1,2,7
100316D	0.059	~1300	~18	0.6	~0.05	1,2,8
120422A	0.283	5.35 ± 1.4	~50	0.45	~10	2



Campana et al. 2006

理论解释

中等相对论的激波从前身星表面或(光学厚的)星风冲出来导致的.

低光度暴研究方案

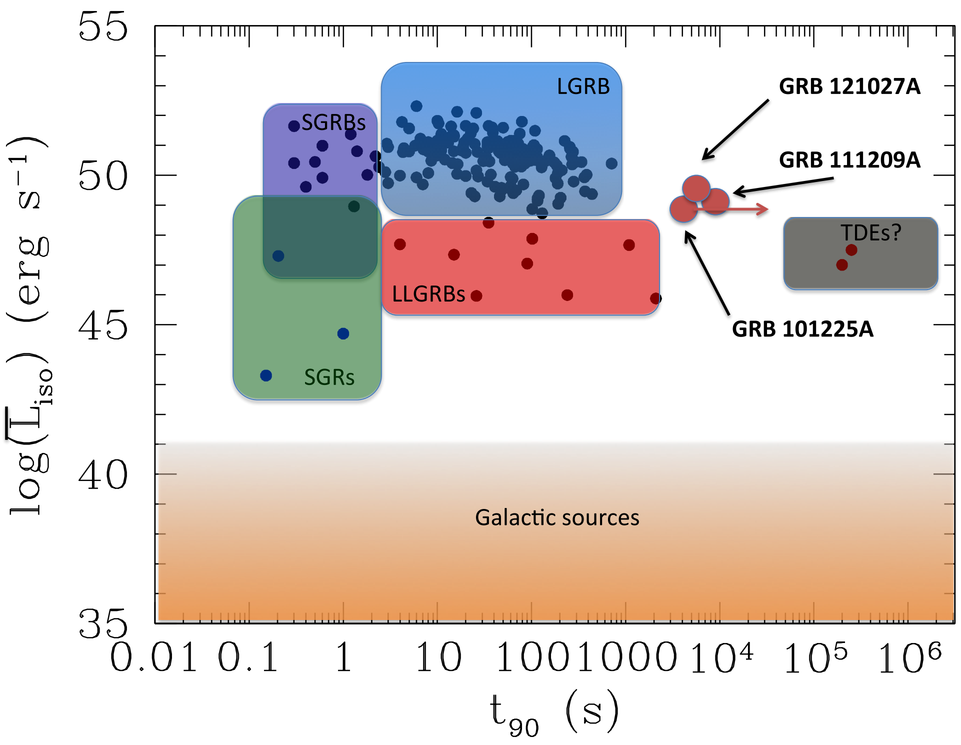
- EP自身触发低光度暴样本分析并进行后随观测
- 其他卫星触发低光度暴样本分析并进行后随观测

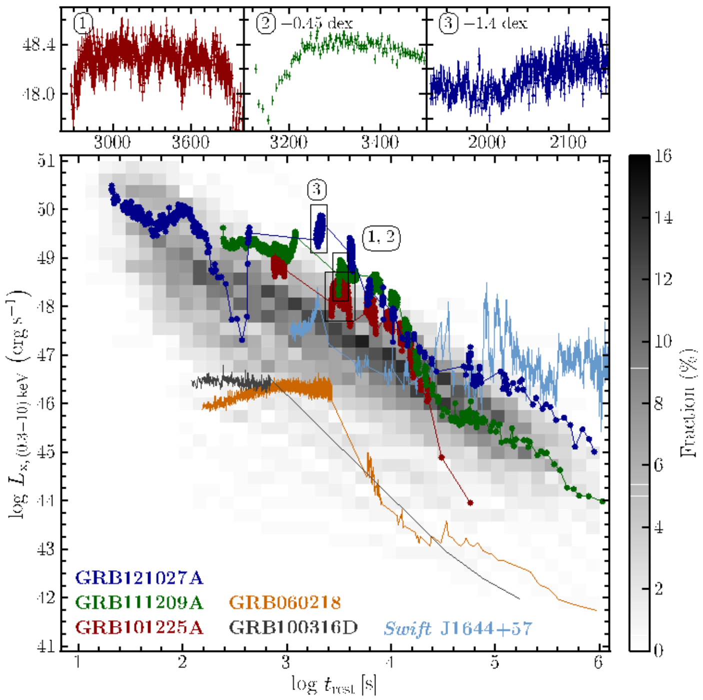
预期目标

确定低光度暴起源 → 揭示伽玛暴和超新星的关系

科学目标：超长伽玛射线暴

（无明确）定义：瞬时辐射时标大于～1000s





Gendre+ 13, Virgili+13, Stratta+ 13, Levan+ 14, Greiner+ 15 ……

理论解释

- **特殊的前身星（蓝超巨星）**
- **特殊的中心引擎（毫秒磁星）**

超长暴研究方案

- EP自身触发超长暴样本分析并进行后随观测
- 其他卫星触发超长暴样本分析并进行后随观测

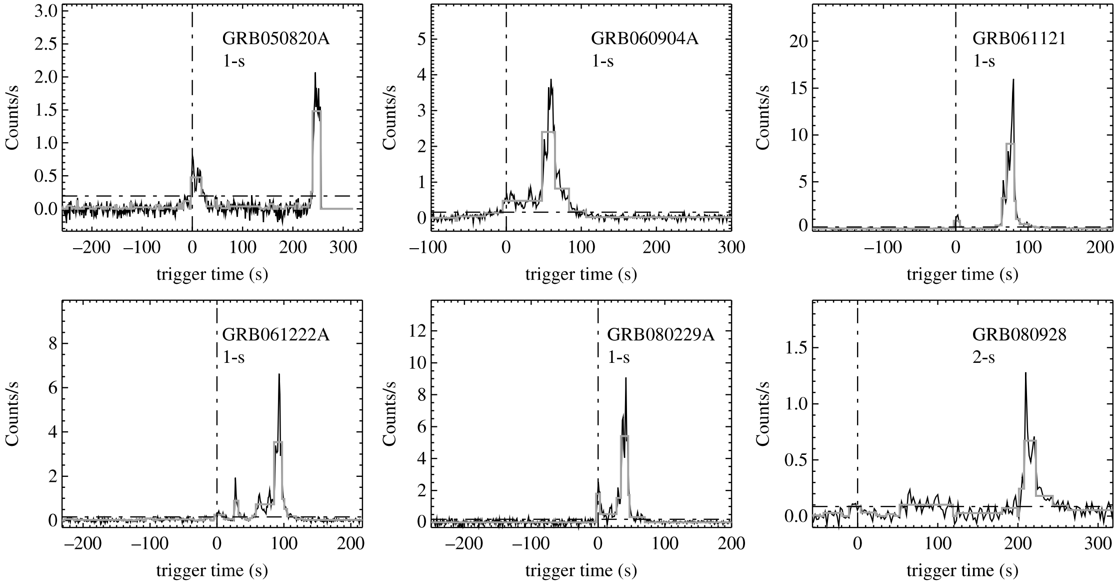
预期目标

确定超长暴起源 → 磁星能否作为中心引擎

科学目标：前兆辐射

未触发探测器的微弱信号

- 持续时间短于伽玛暴的主暴辐射, 并且比主暴要暗;
- 和伽玛暴主暴辐射之间有一个安静的时间间隔;
- 光谱明显比主暴要软, 有几个例子辐射以黑体谱为主;



Hu et al., 2014, ApJ

前兆辐射研究方案

- EP伽玛暴搜寻前兆辐射
- 其他伽玛暴，搜寻EP前兆辐射
- 其他伽玛暴，有前兆辐射的，判断前兆辐射与主暴之间是否存在辐射

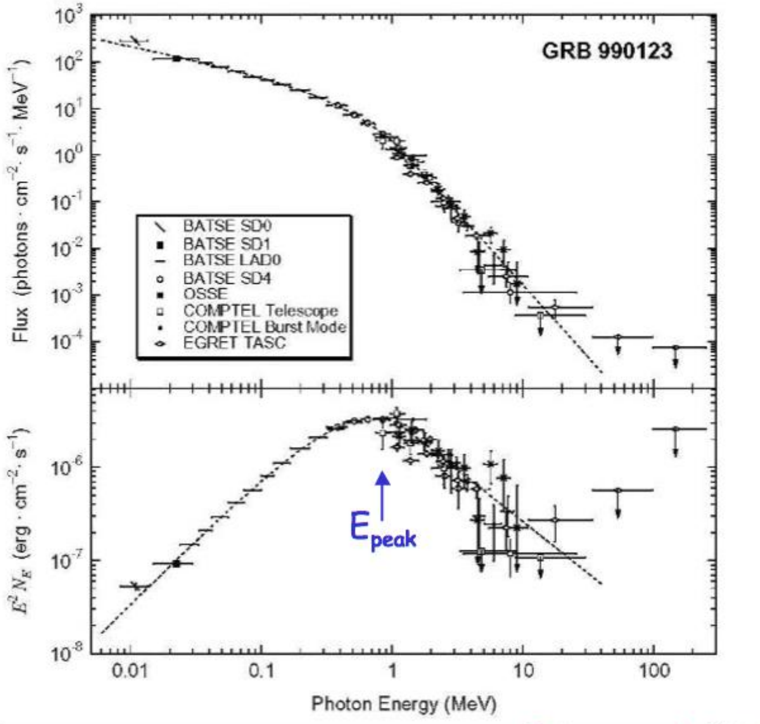
短暴前兆辐射模型

□ 并合前
  □ 中子星磁层断裂模型
  □ 中子星磁层相互作用模型
□ 并合后
  □ 激波突破模型
  □ 火球光球辐射

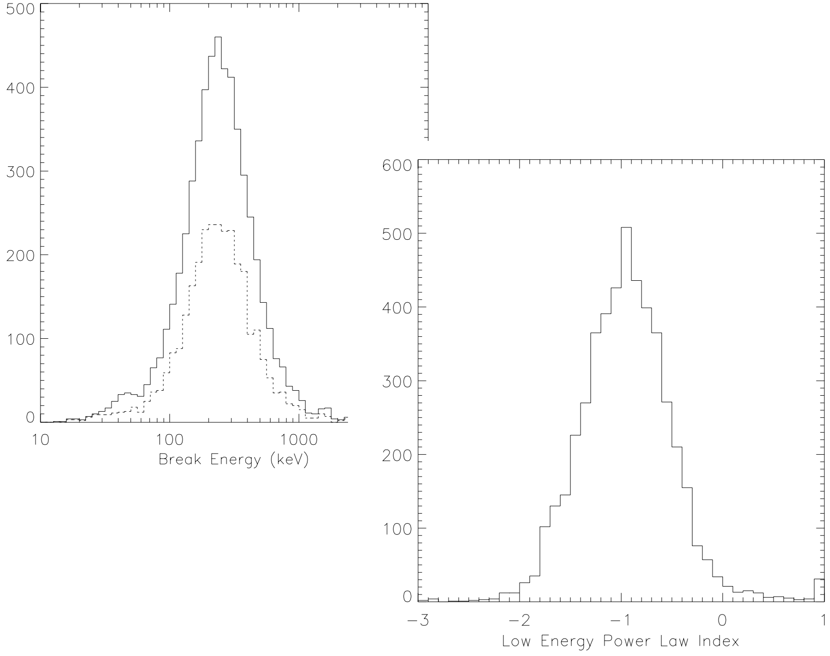
伽玛射线暴瞬时辐射光谱

Band谱：非热拐折幂律谱

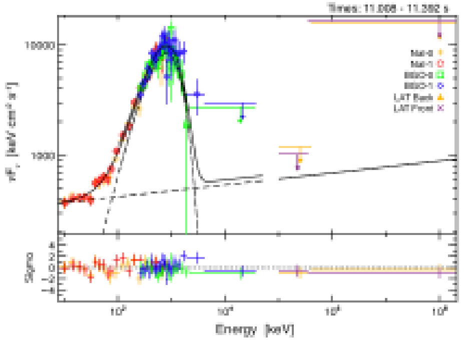
光谱形态多样化



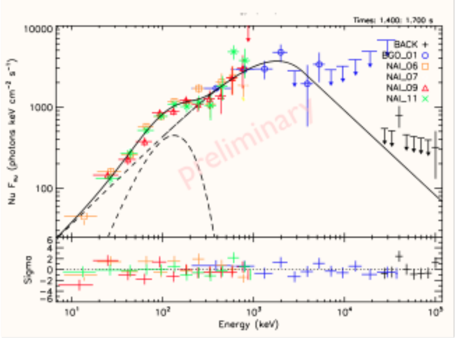
Band et al. 1993



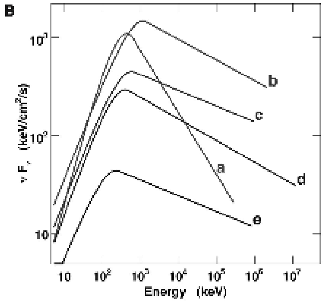
Preece et al. 2000



GRB 090902B



GRB 100724B

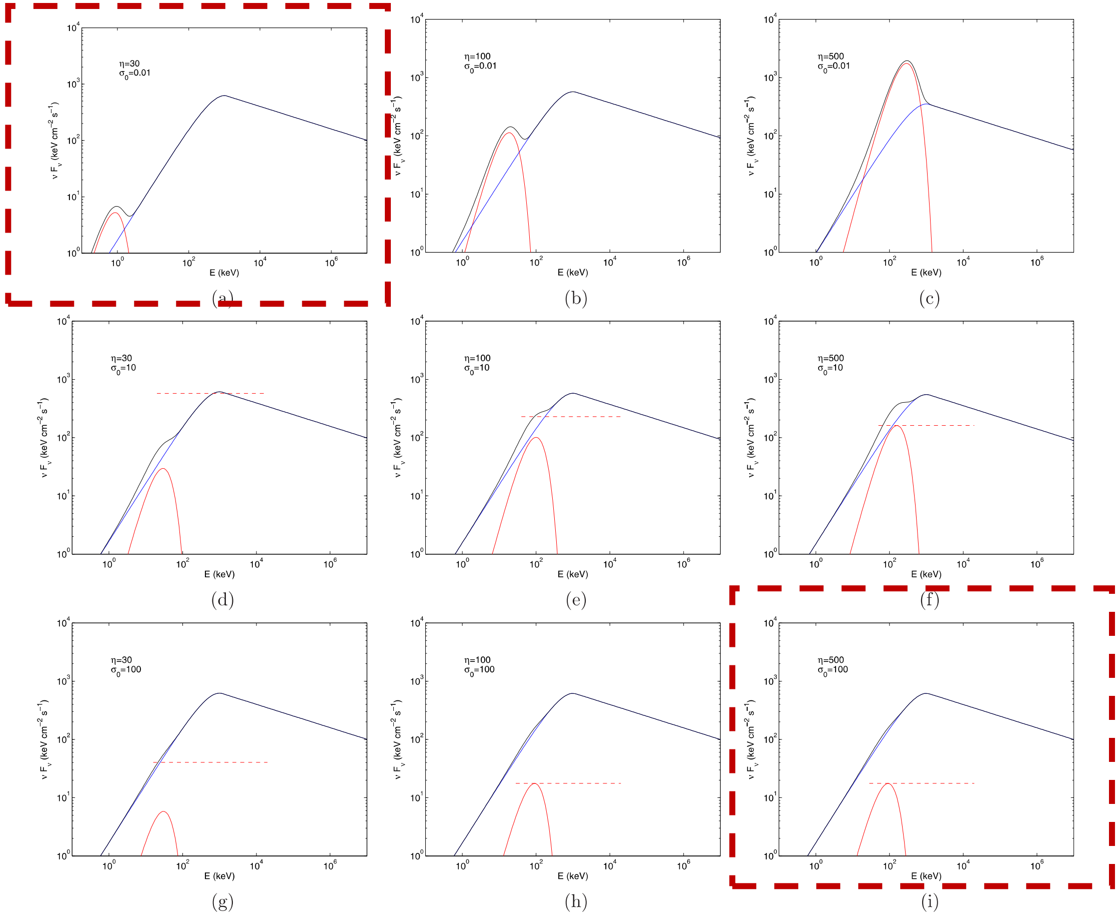


GRB 080916C

$$N(E)=\begin{cases} A\left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha}\exp\left(-\frac{E}{E_0}\right), & E<(\alpha-\beta)E_0,\\ A\left[\frac{(\alpha-\beta)E_0}{100\ \mathrm{keV}}\right]^{\alpha-\beta}\exp(\beta-\alpha)\left(\frac{E}{100\ \mathrm{keV}}\right)^{\beta}, & E\geqslant(\alpha-\beta)E_0,\end{cases}$$

科学目标：联合谱拟合

光谱形态多样化由磁化因子大小决定



(a) (b) (c)

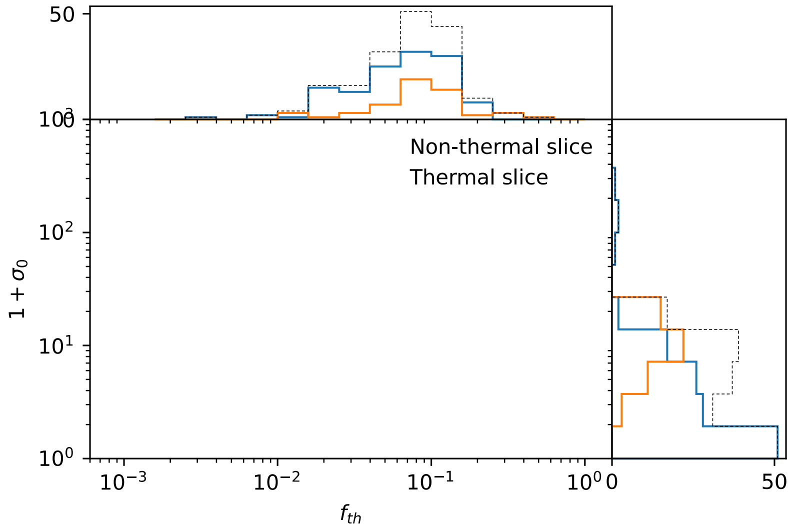
(d) (e) (f)

(g) (h) (i)

Gao & Zhang, 2015, ApJ

光球辐射缺失问题

- 大部分伽玛暴的光谱中缺少光球辐射成分
  - 大部分伽玛暴拥有较高的磁化因子
  - 光球辐射在软X射线波段



Li， Gao & Zhang, 2023

EP与其他高能卫星数据联合谱拟合

寻找缺失的光球辐射 → 喷流能量组分

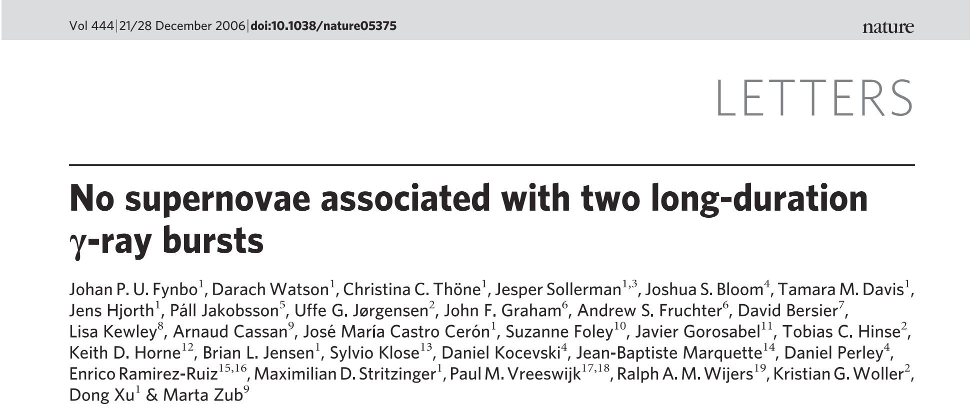
长短暴挑战者：GRB060614

nature Vol 444|21/28 December 2006|doi:10.1038/nature05374

LETTERS

An enigmatic long-lasting c-ray burst not accompanied by a bright supernova

M. Della Valle[1], G. Chincarini[2,3], N. Panagia[4,5,6], G. Tagliaferri[3], D. Malesani[7], V. Testa[8], D. Fugazza[2,3], S. Campana[3], S. Covino[3], V. Mangano[9], L. A. Antonelli[8,10], P. D'Avanzo[3,11], K. Hurley[12], I. F. Mirabel[13], L. J. Pellizza[14], S. Piranomonte[8] & L. Stella[8]



Vol 444|21/28 December 2006|**doi:10.1038/nature05375** nature

LETTERS

No supernovae associated with two long-duration γ-ray bursts

Johan P. U. Fynbo[1], Darach Watson[1], Christina C. Thöne[1], Jesper Sollerman[1,3], Joshua S. Bloom[4], Tamara M. Davis[1], Jens Hjorth[1], Páll Jakobsson[5], Uffe G. Jørgensen[2], John F. Graham[6], Andrew S. Fruchter[6], David Bersier[7], Lisa Kewley[8], Arnaud Cassan[9], José María Castro Cerón[1], Suzanne Foley[10], Javier Gorosabel[11], Tobias C. Hinse[2], Keith D. Horne[12], Brian L. Jensen[1], Sylvio Klose[13], Daniel Kocevski[4], Jean-Baptiste Marquette[14], Daniel Perley[4], Enrico Ramirez-Ruiz[15,16], Maximilian D. Stritzinger[1], Paul M. Vreeswijk[17,18], Ralph A. M. Wijers[19], Kristian G. Woller[2], Dong Xu[1] & Marta Zub[9]

Vol 444|21/28 December 2006|doi:10.1038/nature05373 nature

LETTERS

A novel explosive process is required for the c-ray burst GRB 060614

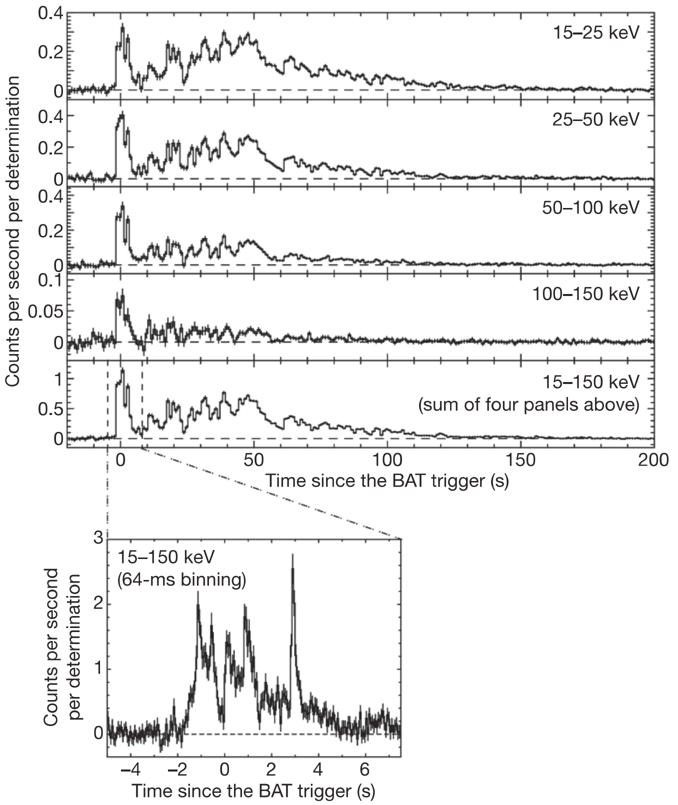
A. Gal-Yam[1], D. B. Fox[2], P. A. Price[3], E. O. Ofek[1], M. R. Davis[4], D. C. Leonard[4], A. M. Soderberg[1], B. P. Schmidt[5], K. M. Lewis[5], B. A. Peterson[5], S. R. Kulkarni[1], E. Berger[6,7], S. B. Cenko[1], R. Sari[1], K. Sharon[8], D. Frail[9], D.-S. Moon[1], P. J. Brown[2], A. Cucchiara[2], F. Harrison[1], T. Piran[10], S. E. Persson[6,7], P. J. McCarthy[6,7], B. E. Penprase[11],

nature Vol 444|21/28 December 2006|doi:10.1038/nature05376

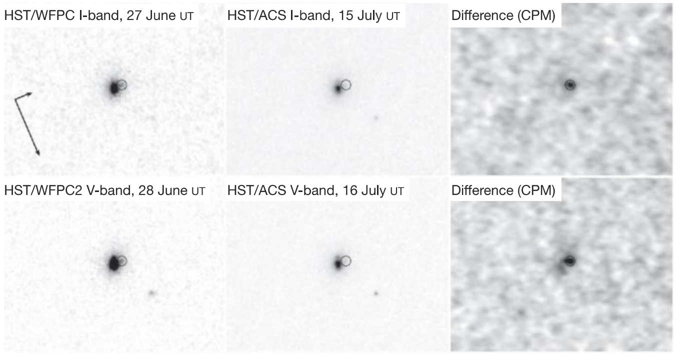
LETTERS

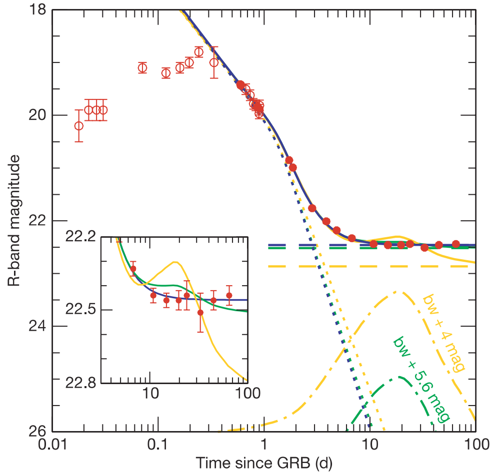
A new c-ray burst classification scheme from GRB 060614

N. Gehrels[1], J. P. Norris[1], S. D. Barthelmy[1], J. Granot[2], Y. Kaneko[3], C. Kouveliotou[4], C. B. Markwardt[1,5], P. Mészáros[6,7], E. Nakar[8], J. A. Nousek[6], P. T. O'Brien[9], M. Page[10], D. M. Palmer[11], A. M. Parsons[1], P. W. A. Roming[6], T. Sakamoto[1,12], C. L. Sarazin[13], P. Schady[6,10], M. Stamatikos[1,12] & S. E. Woosley[14]

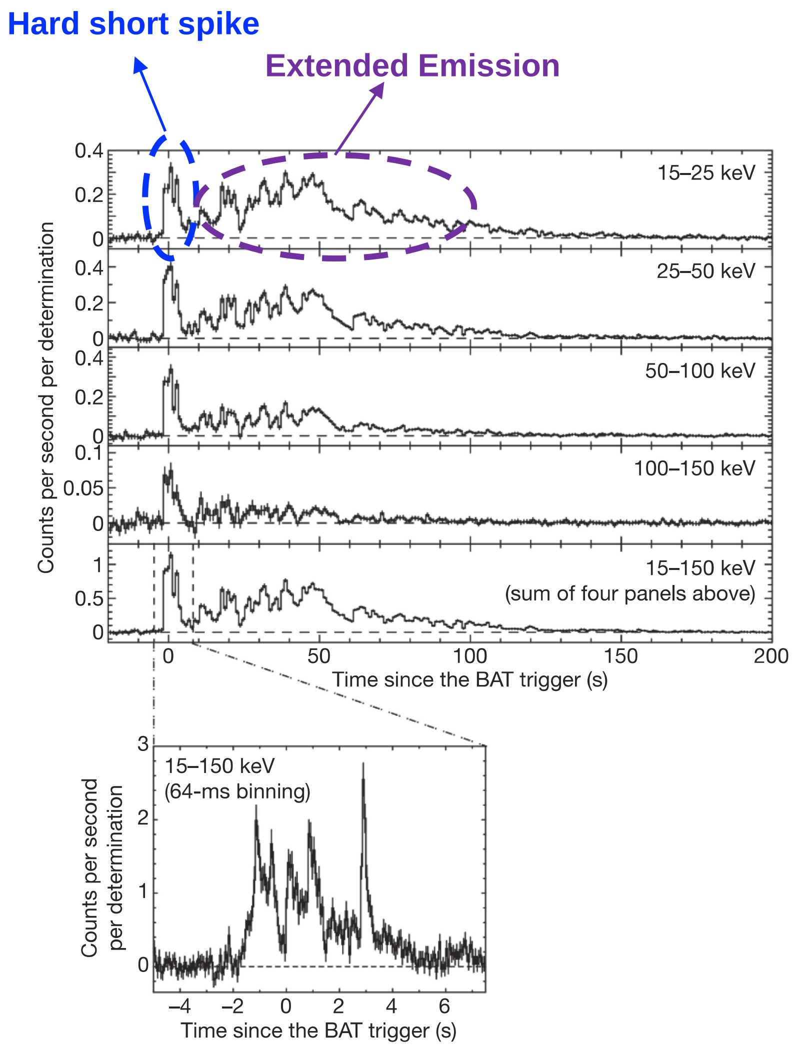


- T_{90}>2s
- 低红移
- 没有SN成协





GRB060614：引入延展辐射概念稀释矛盾

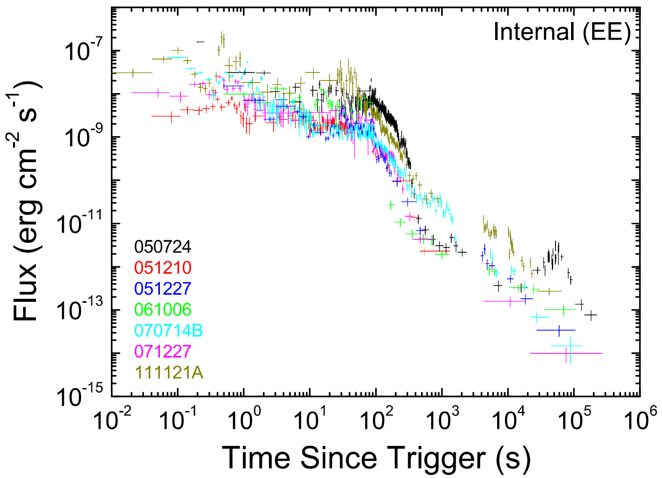


nature Vol 438|15 December 2005|**doi:10.1038/nature04238**

LETTERS

The afterglow and elliptical host galaxy of the short γ-ray burst GRB 050724

E. Berger[1], P. A. Price[2], S. B. Cenko[3], A. Gal-Yam[4], A. M. Soderberg[4], M. Kasliwal[4], D. C. Leonard[4], P. B. Cameron[4], D. A. Frail[5], S. R. Kulkarni[4], D. C. Murphy[1], W. Krzeminski[6], T. Piran[7], B. L. Lee[8], K. C. Roth[9], D.-S. Moon[3], D. B. Fox[4], F. A. Harrison[3], S. E. Persson[1], B. P. Schmidt[10], B. E. Penprase[11], J. Rich[10], B. A. Peterson[10] & L. L. Cowie[2]

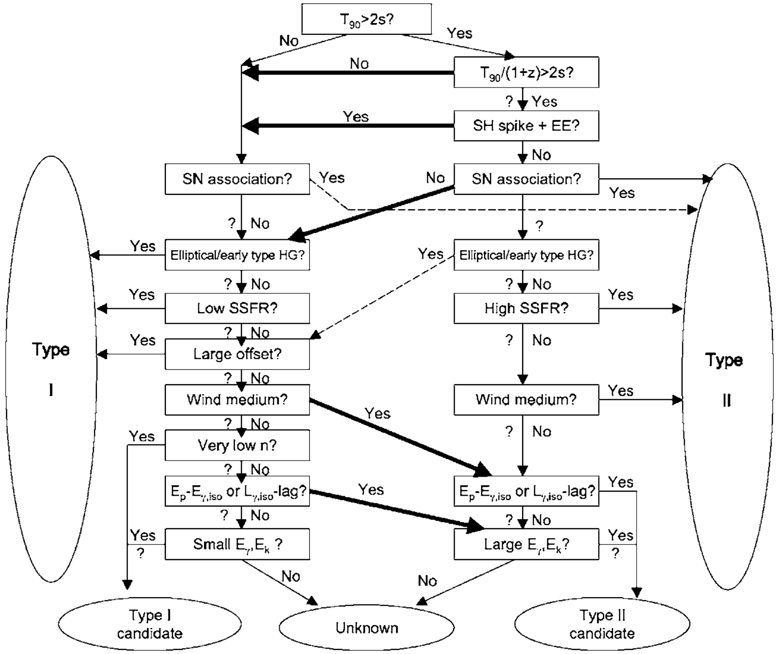


20% 短暴有延展辐射，包括GRB050724

Sakamoto et al. 2011 ApJS；Lv et al. 2015 ApJ

物理分类方案

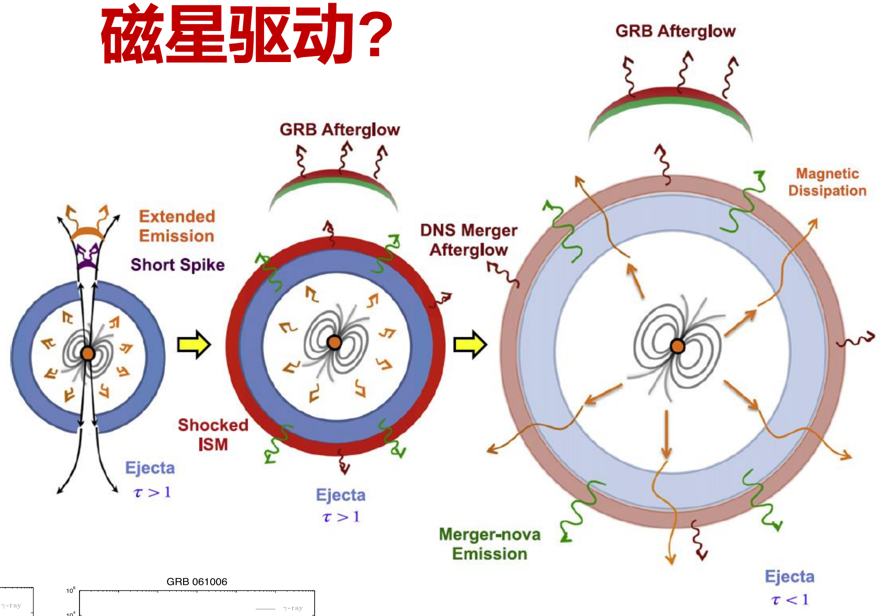
◆ **Type I: 并合起源**
◆ **Type II: 塌缩起源**

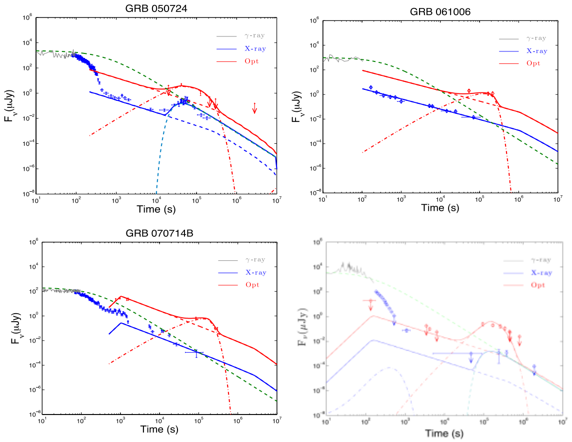


Zhang et al. 2009 ApJ

延展辐射

磁星驱动?





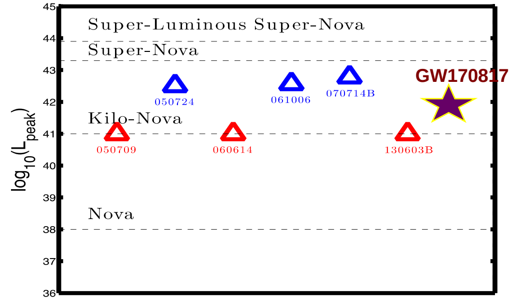
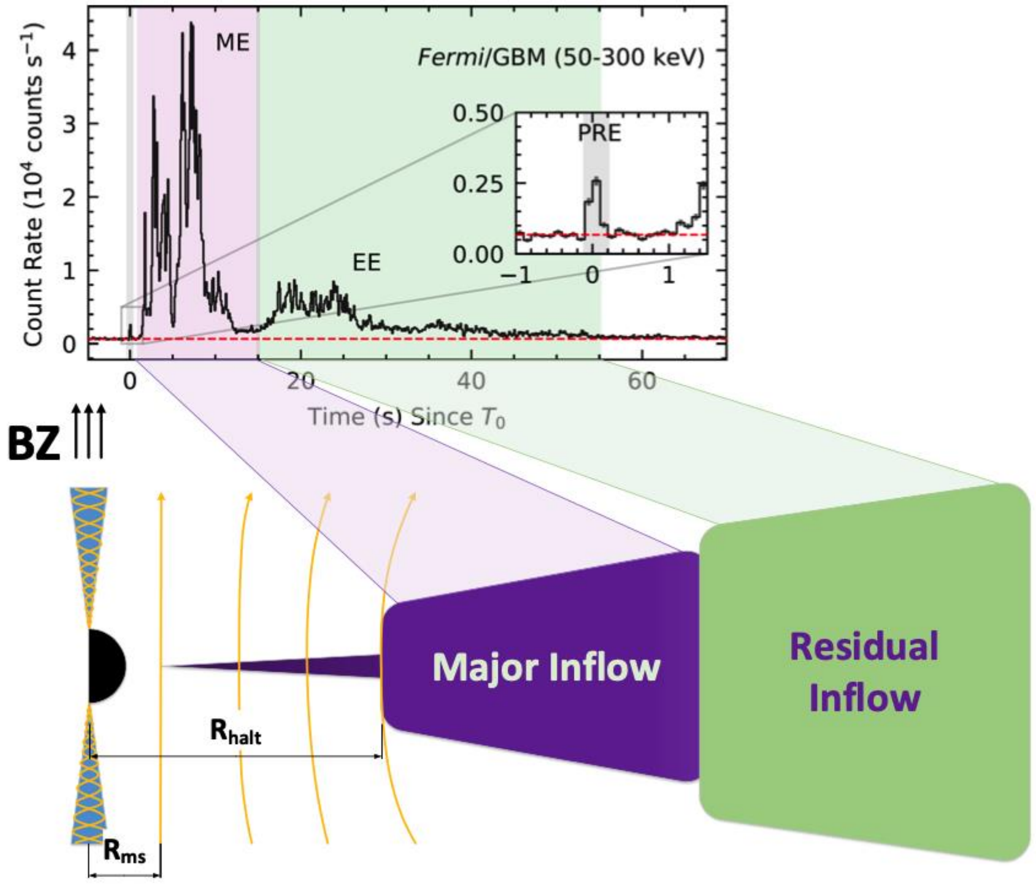


FIG. 2.— Peak luminosity for all claimed “kilo-novae” and magnetar-powered merger-novae.

Gao et al., 2015, 2017, ApJ

黑洞回落吸积驱动?



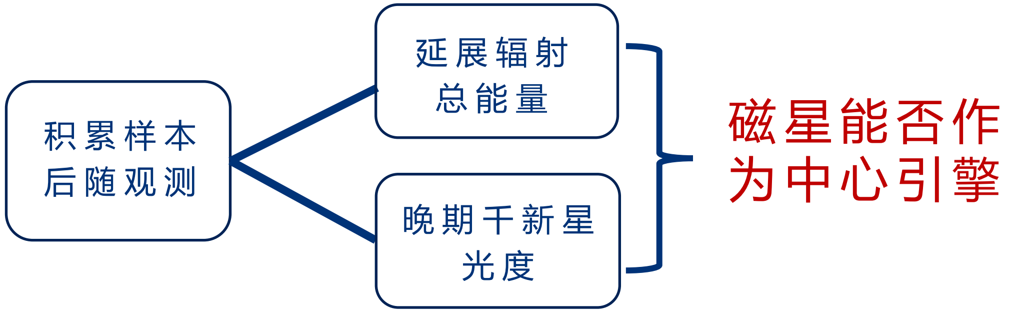
Liu et al. 2012, ApJ; Gao, Lei & Zhu 2022 ApJL

科学目标：延展辐射

针对延展辐射的研究方案

- 延展辐射能谱偏软
  - 对其他卫星触发的短暴进行数据搜寻，拓展延展辐射样本
  - 对延展辐射样本触发多波段后随观测
  - 确定延展辐射样本占短暴比例

预期目标



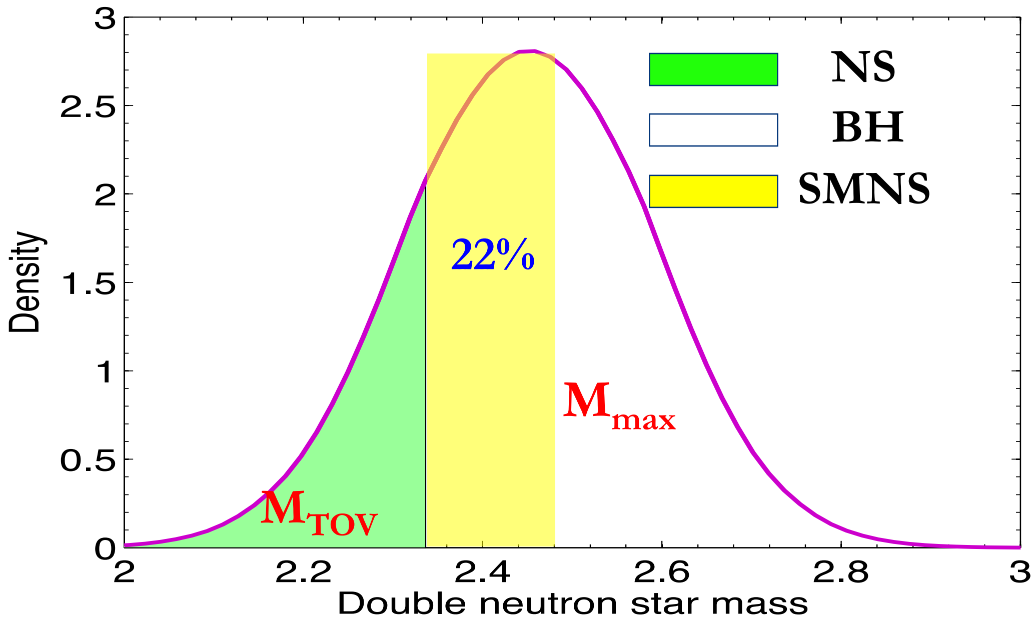
积累样本后随观测

延展辐射总能量

晚期千新星光度

磁星能否作为中心引擎

利用延展辐射的比例限制中子星最大质量



$$M_{\max} = M_{TOV}\left(1+aP^{b}\right)$$

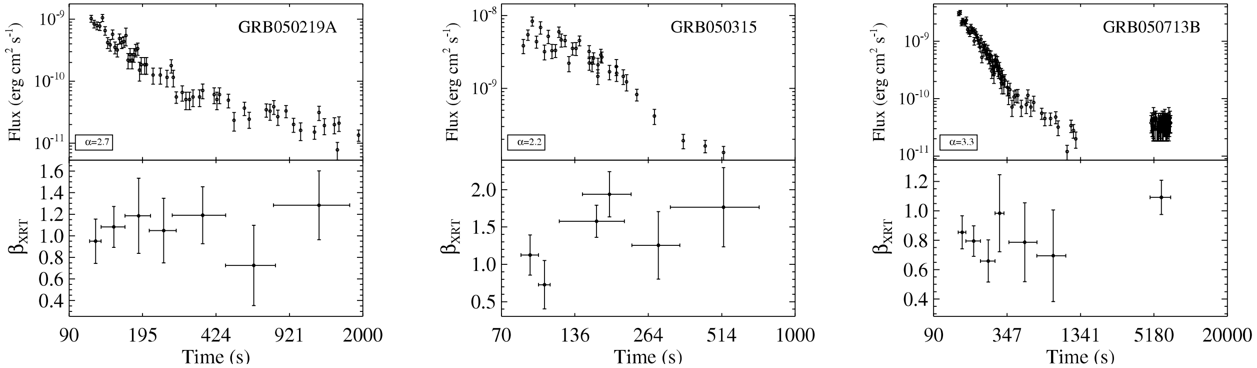
□ **双中子星系统中子星质量分布**

□ **延展辐射表征双中子星并合产生大质量中子星**

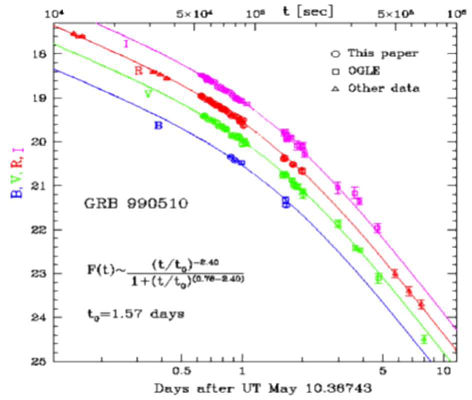
Gao et al., 2016 PRD, 93, 044065

科学目标：辐射区位置

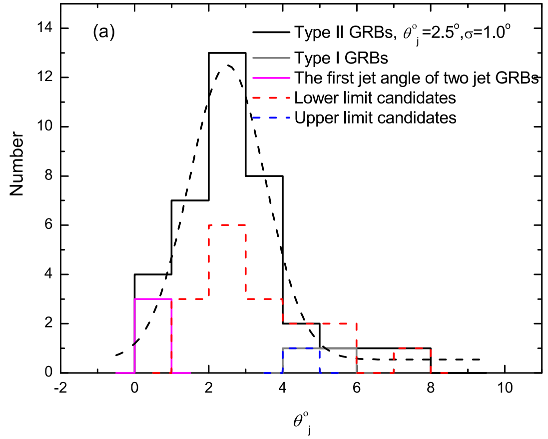
早期余辉陡降



晚期喷流拐折



Stanek et al. 99



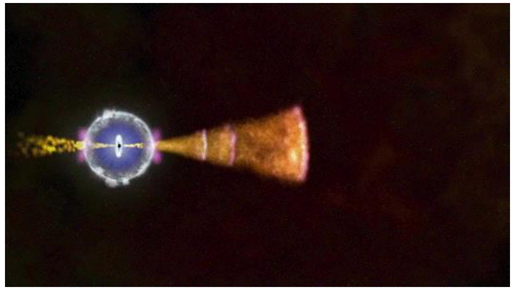
Wang et al. 2018 ApJ

早期陡降与晚期喷流拐折同时观测可限制辐射区位置

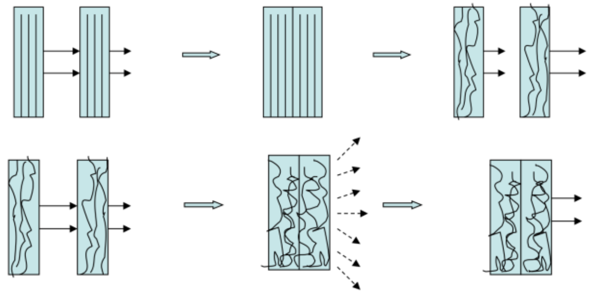
$$\boxed{t_{\rm tail} \le (1+z)\left(\frac{R_{\rm GRB}}{c}\right)(1-\cos\theta_j) \simeq (330\ {\rm s})\left(\frac{1+z}{2}\right) R_{{\rm GRB},15}\theta_{j,-1}^2,}$$

辐射区位置 → 喷流能量组分

内激波模型： $R_{GRB} \sim 10^{12\text{-}13}$cm



ICMART模型： $R_{GRB} \sim 10^{15}$cm



Zhang & Yan 2011 ApJ

科学目标：搜寻被引力透镜化伽玛射线暴

伽玛射线：

▲ 伽马射线暴探测器定位误差较大以及GRB缺乏红移测量

▲ 理论模型不确定性、非全天观测的伽马射线探测器 (BATSE: FoV = 0.6(整天)以及~2390/3323天)

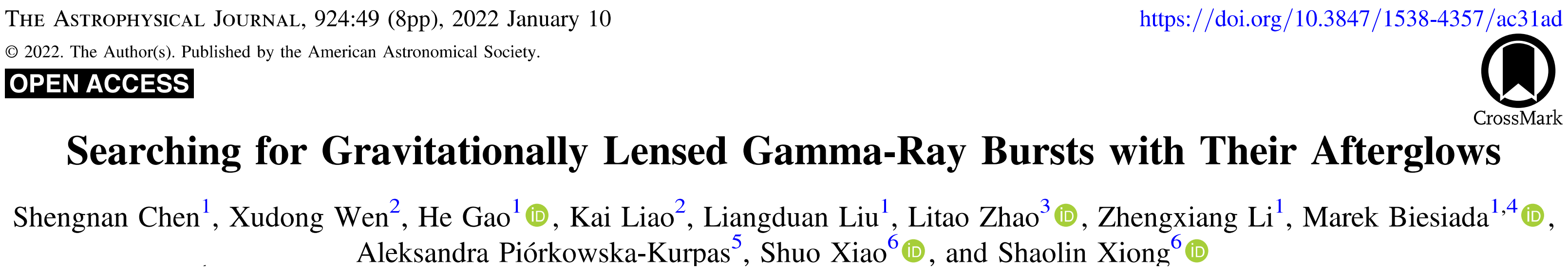
⬢ 伽马波段GRB辐射时间短暂、背景干扰因素以及GRB探测器定位误差大

多波段余辉：

- 宽带辐射(光学、X射线…)、可探测时间范围广(长达年)、光变曲线形状简单、物理模型清晰、卫星和地面多波段探测器

① $\theta \sim 0.1''(M_l/10^{10}M_\odot)^{1/2}(D_lD_s/D_{ls}/Gpc)^{-1/2}$ (Swift/XRT: $18''$; $1m$(光学): $\sim 1''$)

② $t_{delay} \sim 50s(M_l/10^6M_\odot)$　　多重图像无法被分辨→ 叠加信号



THE ASTROPHYSICAL JOURNAL, 924:49 (8pp), 2022 January 10
https://doi.org/10.3847/1538-4357/ac31ad

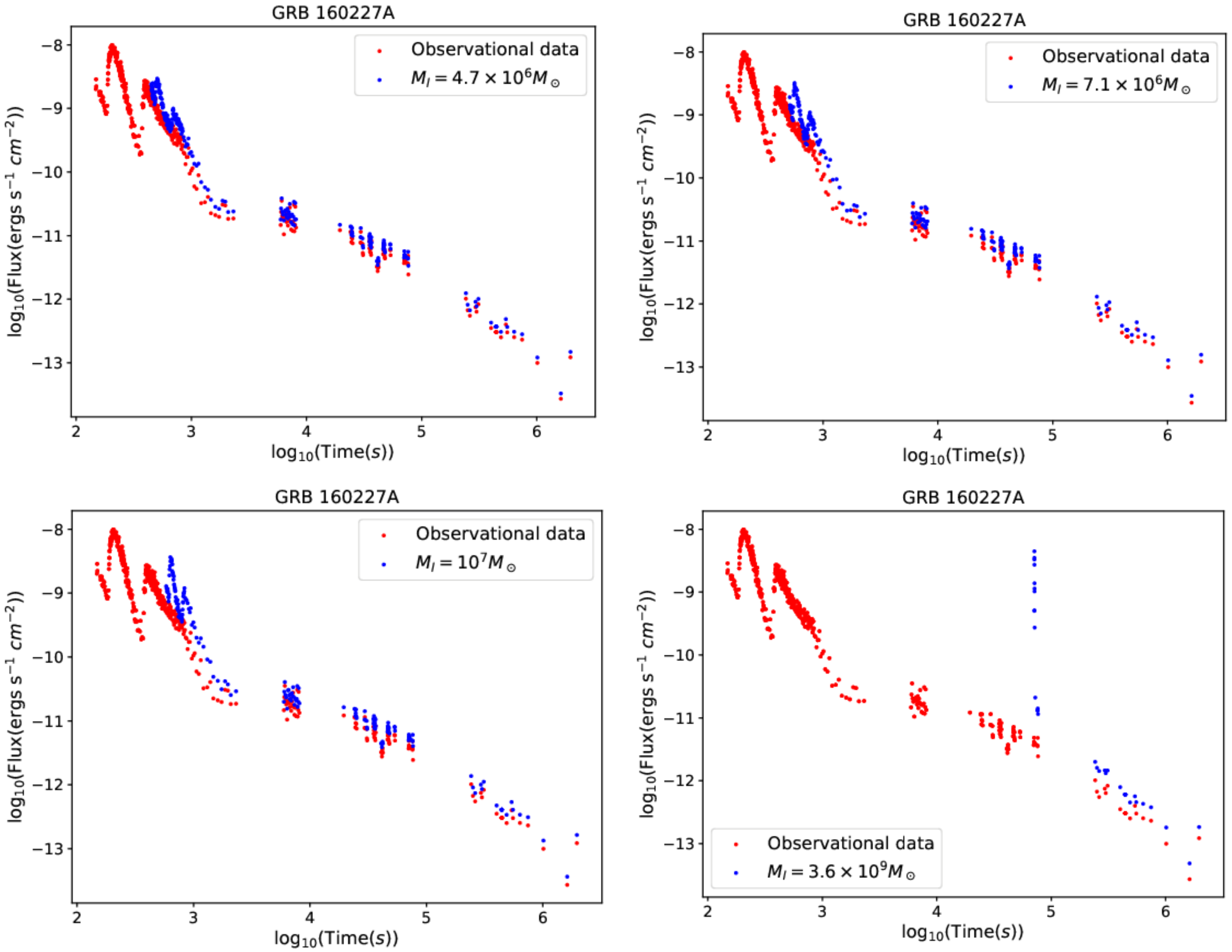
CrossMark

Searching for Gravitationally Lensed Gamma-Ray Bursts with Their Afterglows

Shengnan Chen[1], Xudong Wen[2], He Gao[1], Kai Liao[2], Liangduan Liu[1], Litao Zhao[3], Zhengxiang Li[1], Marek Biesiada[1,4], Aleksandra Piórkowska-Kurpas[5], Shuo Xiao[6], and Shaolin Xiong[6]

科学目标：搜寻被引力透镜化伽玛射线暴

GRB 160227A的X射线波段余辉的引力透镜效应模拟

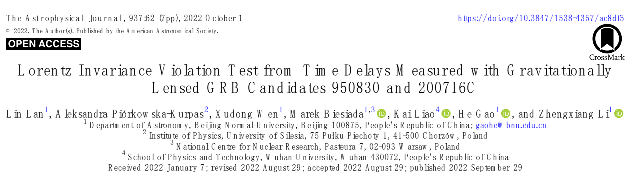


透镜化伽玛暴搜寻方案

- 早期多耀发线性时间下分析
- 晚期极陡上升

透镜化伽玛暴应用

- 精确测量H_0
- 限制原初黑洞等暗物质组分
- 限制LIV等基本物理问题


The Astrophysical Journal, 937:62 (7pp), 2022 October 1 https://doi.org/10.3847/1538-4357/ac8df5
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Lorentz Invariance Violation Test from Time Delays Measured with Gravitationally Lensed GRB Candidates 950830 and 200716C

Lin Lan[1], Aleksandra Piórkowska-Kurpas[2], Xudong Wen[1], Marek Biesiada[1,3], Kai Liao[4], He Gao[1], and Zhengxiang Li[1]
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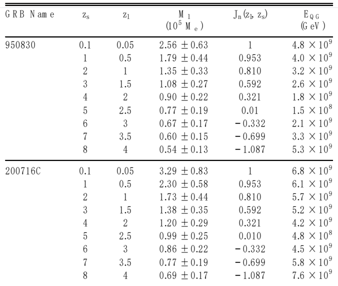
[2] Institute of Physics, University of Silesia, 75 Pułku Piechoty 1, 41-500 Chorzów, Poland
[3] National Centre for Nuclear Research, Pasteura 7, 02-093 Warsaw, Poland
[4] School of Physics and Technology, Wuhan University, Wuhan 430072, People's Republic of China
Received 2022 January 7; revised 2022 August 29; accepted 2022 August 29; published 2022 September 29



GRB Name	z_s	z_l	M_l ($10^5 M_\odot$)	$J_n(z_l, z_s)$	E_{QG} (GeV)
950830	0.1	0.05	2.56 ± 0.63	1	4.8×10^9
	1	0.5	1.79 ± 0.44	0.953	4.0×10^9
	2	1	1.35 ± 0.33	0.810	3.2×10^9
	3	1.5	1.08 ± 0.27	0.592	2.6×10^9
	4	2	0.90 ± 0.22	0.321	1.8×10^9
	5	2.5	0.77 ± 0.19	0.01	1.5×10^8
	6	3	0.67 ± 0.17	−0.332	2.1×10^9
	7	3.5	0.60 ± 0.15	−0.699	3.3×10^9
	8	4	0.54 ± 0.13	−1.087	5.3×10^9
200716C	0.1	0.05	3.29 ± 0.83	1	6.8×10^9
	1	0.5	2.30 ± 0.58	0.953	6.1×10^9
	2	1	1.73 ± 0.44	0.810	5.7×10^9
	3	1.5	1.38 ± 0.35	0.592	5.2×10^9
	4	2	1.20 ± 0.29	0.321	4.2×10^9
	5	2.5	0.99 ± 0.25	0.010	4.8×10^8
	6	3	0.86 ± 0.22	−0.332	4.5×10^9
	7	3.5	0.77 ± 0.19	−0.699	5.8×10^9
	8	4	0.69 ± 0.17	−1.087	7.6×10^9

LIV下光子存在色散关系

不受内禀时间差影响

$$E^2 - p^2 c^2 = s_\pm E^2 \left(\frac{E}{E_{QG}}\right)^n,$$

等效于不同能量光子共动距离不同

$$r_{LIV}(z) = \int_0^z \frac{c}{H(z')}\left[1 - \frac{n+1}{2}\left(\frac{E}{E_{QG}}\right)^n (1+z')^n\right] dz',$$

最终不同能量光子到达时间不同

$$\begin{aligned}\Delta t_{LIV} &= t_l - t_h \\ &= -\frac{n+1}{2}\left(\frac{E}{E_{QG}}\right)^n \frac{J_n(0, z)}{H_0},\end{aligned}$$

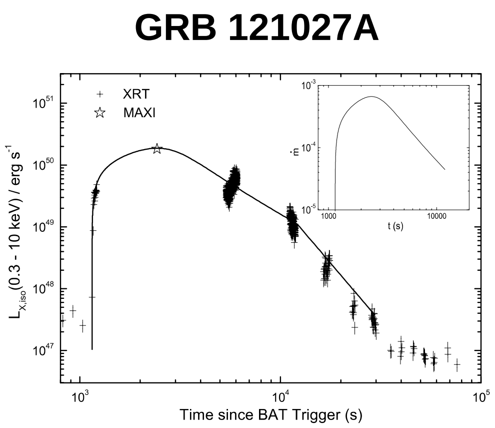
在透镜系统下，不同能量光子爱因斯坦半径不同

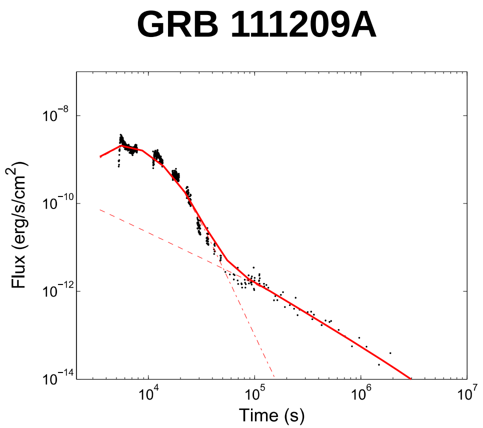
$$\theta_E = \sqrt{\frac{4GM_l}{c^2}\frac{D_{ls}}{D_s D_l}}, \quad D_l = \frac{r(z_l)}{1+z_l}; D_s = \frac{r(z_s)}{1+z_s}; D_{ls} = \frac{r(z_s) - r(z_l)}{1+z_s}.$$

LIV下不同像高低能量光子到达时间差不同

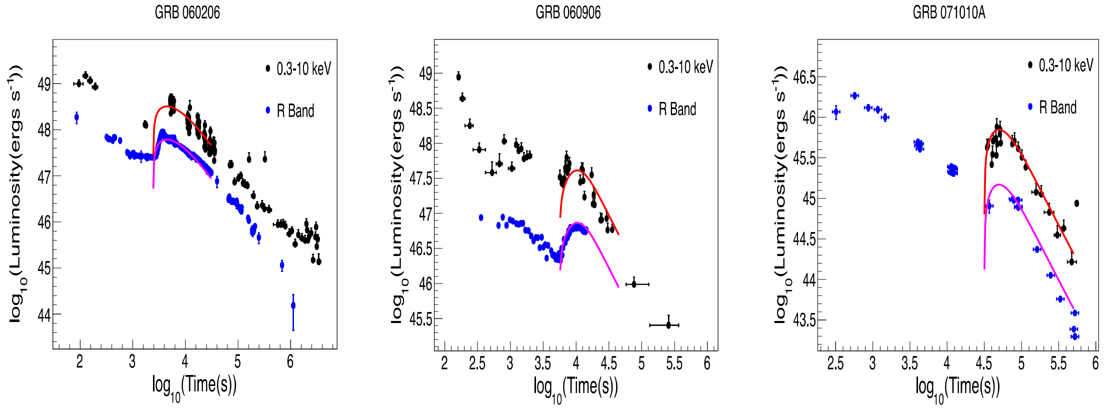
$$\begin{aligned}\Delta_{\rm LIV}(\Delta t_{\rm PM}) &:= \Delta t_{\rm LIV,PM} - \Delta t_{\rm PM} \\ &= -\frac{4GM_l}{c^3}(1+z_l)\frac{r-1}{\sqrt{r}}\frac{n+1}{4}\left(\frac{E}{E_{QG}}\right)^n J_n(z_l, z_s).\end{aligned}$$

科学目标：巨耀发





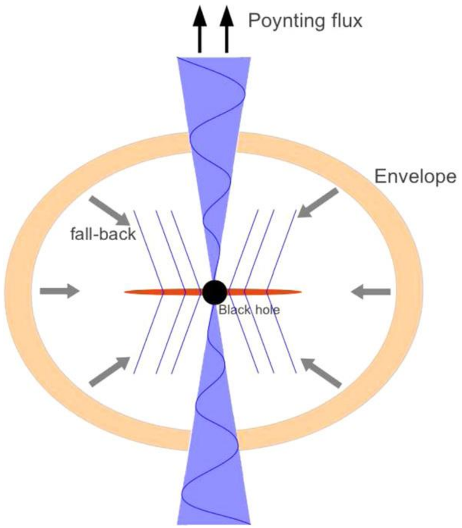
在21例Swift长暴中找到巨耀发候选体



Zhao et al. 2021 ApJ

“回落吸积模型”

大部分的前身星包层都被抛射出去了，但是有少量包层在较晚的时间回落回来，被中心黑洞吸积产生新的喷流，从而产生X射线巨耀发。

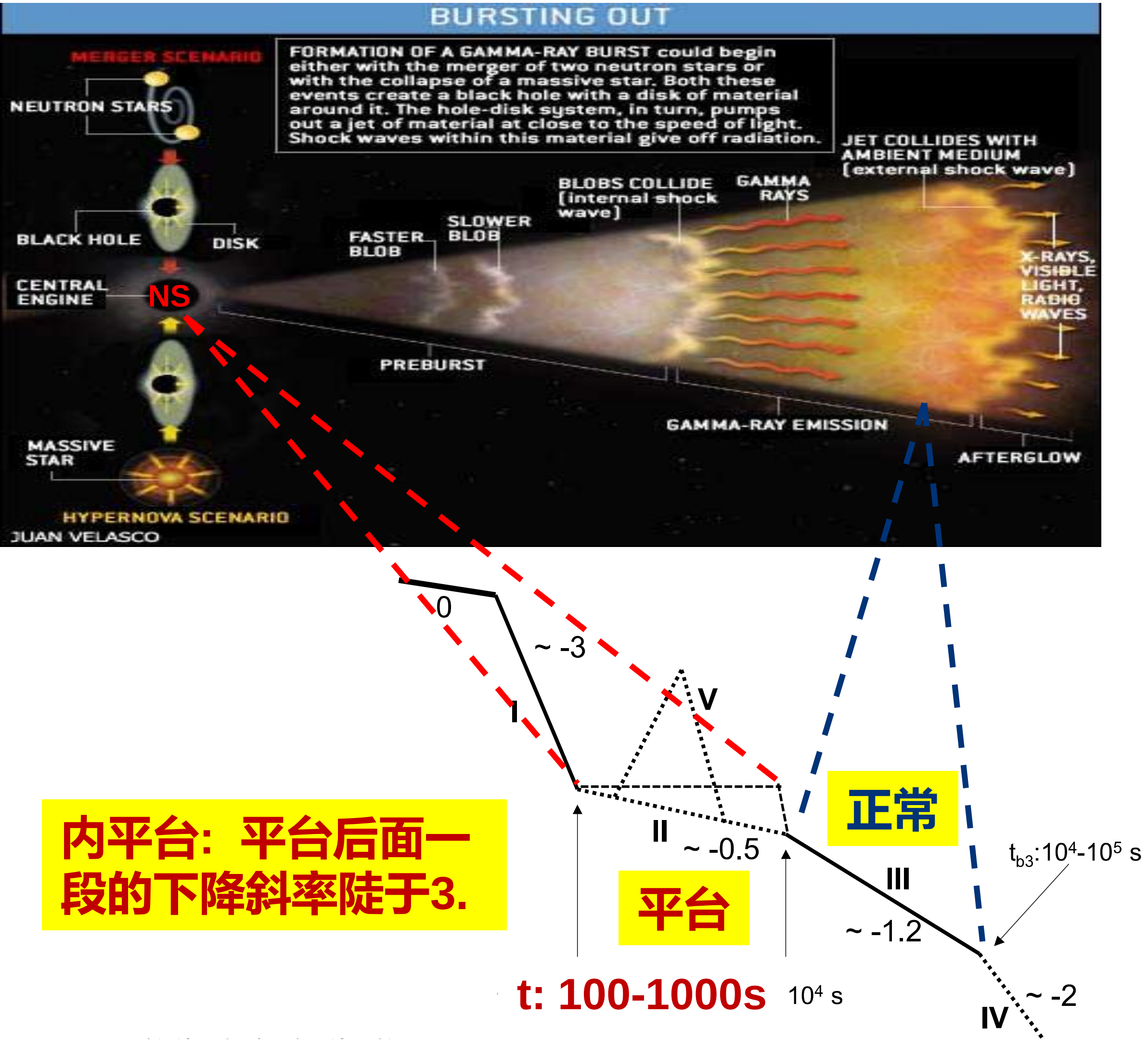


Wu et al. 2013 ApJL; Gao et al. 2016 ApJ

预期目标

确定巨耀发起源 → 是否还有特殊类型前身星

科学目标：内平台后期监测

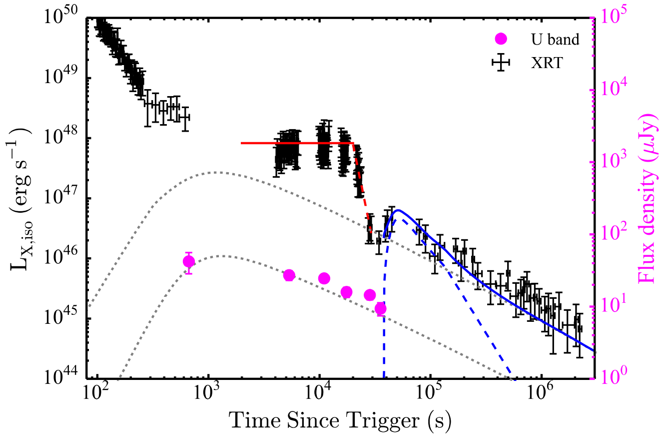


FORMATION OF A GAMMA-RAY BURST could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.

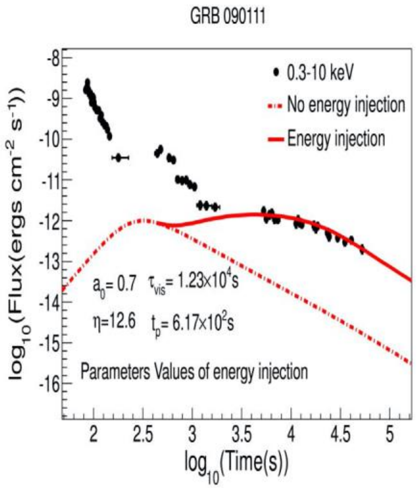
内平台：平台后面一段的下降斜率陡于3.

Rowlinson et al. 2010,2013; Lü & Zhang (2014); Lü et al. (2015)

内平台后出现耀发与新平台



Chen, Lei et al. 2017



Zhao, Gao et al. 2020

预期目标

确定内平台起源 → 磁星能否作为中心引擎

总结与讨论

- WXT独立触发
  - XRF、高红移暴、超长暴、低光度暴
- WXT瞬时辐射联合探测
  - 前兆辐射、光球辐射、延展辐射
- WXT极早期余辉
  - 陡降时标、引力透镜、巨耀发
- FXT晚期余辉跟踪
  - 内平台后耀发与双平台

- 是否还有特殊类型前身星？
- 磁星能否作为中心引擎？
- 喷流能量组分？
- 喷流结构？
- 是否是好的宇宙学探针？

谢谢聆听，欢迎批评指正！