伽瑪暴（GRB）觀測史簡介

王灵俊

慧眼、SVOM及GECAM工作組

2020.11.19

摘要

在介紹伽瑪暴理論前先回顧一下過去半個世紀對伽瑪暴的觀測。伽瑪暴的發現純屬意外，但它卻深刻改變了我們對大質量恆星的演化以及緻密星並合的認識。至今仍是天文研究領域最熱門的課題之一。

參會人員

- 老师名单（共15名）：王灵俊、郭东亚、贺健健、李兵、李小波、梁晓华、刘伟、彭文溪、宋欣颖、孙建超、熊少林、尹倩青、张镇、赵小芸、郑世界

- 学生名单（共14名）：赵一、蔡策、易祁彬、肖硕、周登科、张凯、姚玉华、郭志伟、李朝洋、张鹏、刘佳聪、薛王陈、郑超、张艳秋

伽瑪暴研究的時期劃分

- 黑暗時代：1967 (Vela) – 1991(BATSE)
- 黎明前夜： 1991(BATSE) – 1997 (BeppoSAX)
- 長暴黃金期： 1997 (BeppoSAX) – 2005 (Swift)
- 短暴黃金期： 2005 (Swift)至今

伽瑪暴的發現 -- Vela衛星

- 1967年，美蘇冷戰正酣時美國發射Vela衛星以監測地面核爆，結果卻意外發現了伽瑪暴
- Scintillation X-ray detector (XC), 3-12 keV
- Gamma-ray detectors, 0.3-1.5 MeV





初步結果

1. Vela無法精確定位伽瑪暴的位置，也無法測定它們的距離，但初步判定伽瑪暴既非來自地球，也非來自太陽，而是來自深空。
2. 可能來自銀河系，也可能來自銀河系外
3. 由此出現了持續二十年的河內與河外之爭，九十年代初之前，河內派佔絕對優勢

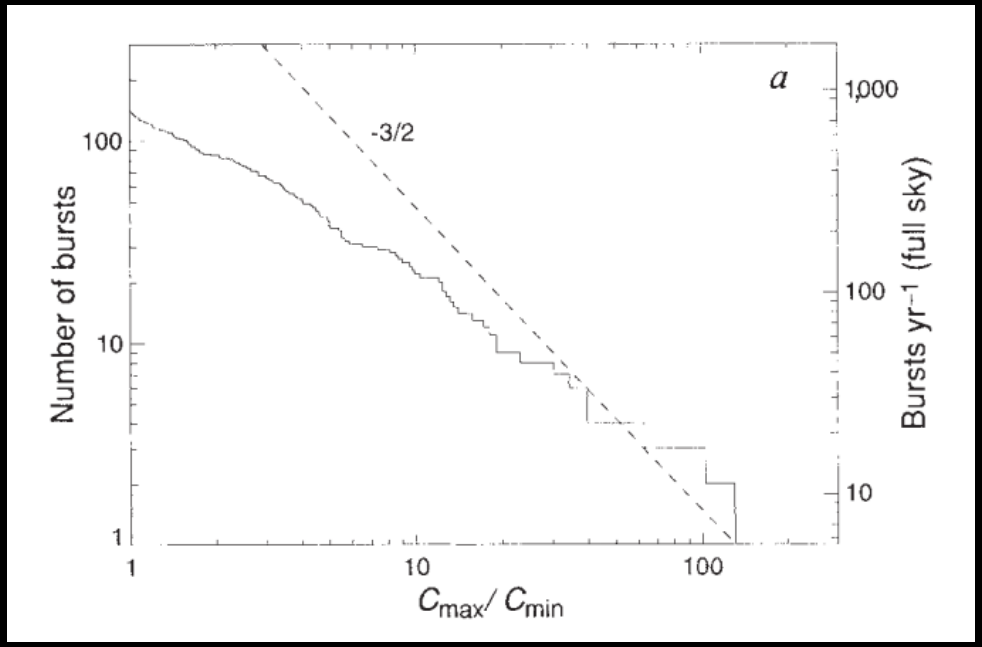
BATSE探測器 – 空間方位、強度測量

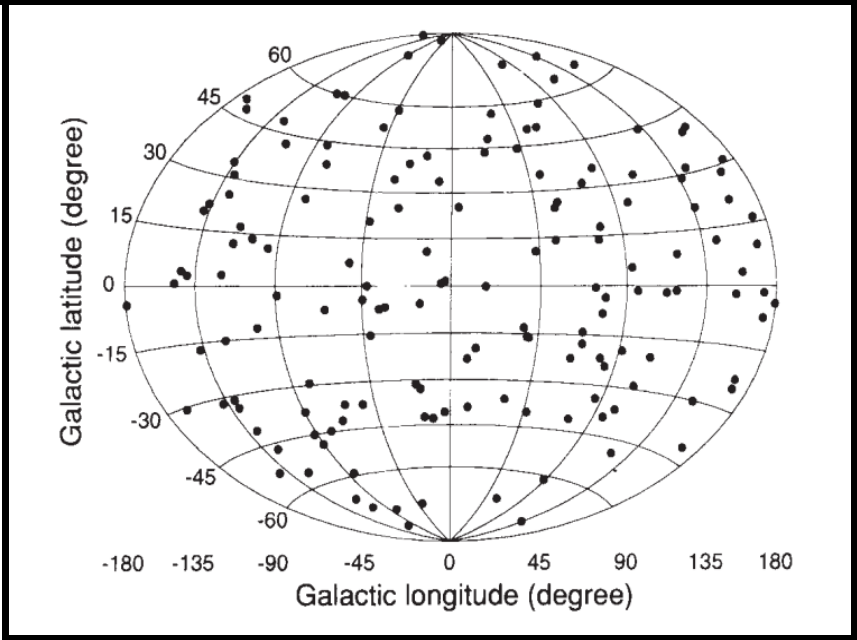
1. 1991年Compton Gamma Ray Observatory (CGRO)發射升空，其上搭載著Burst and Transient Source Experiment (BATSE)探測器。



2. BATSE有四個能量通道：20-50 keV、50-100 keV、100-300 keV、>300 keV

BATSE – 河外派取得初步勝利





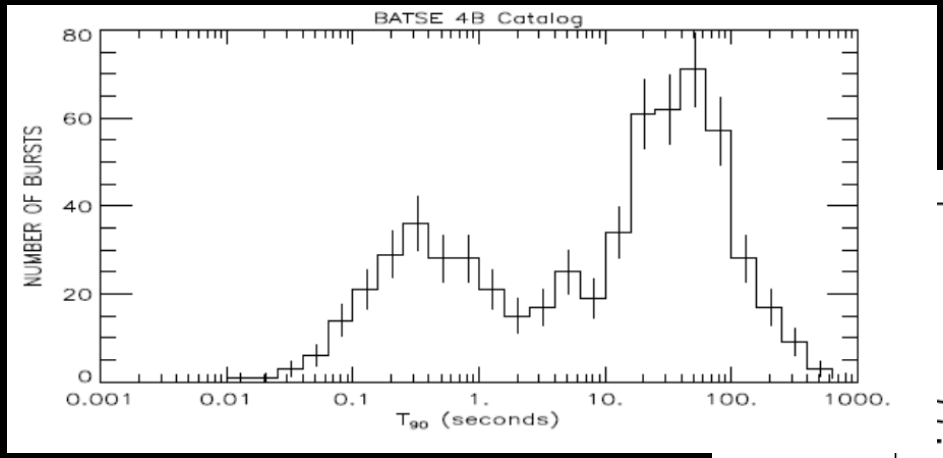
距離分佈

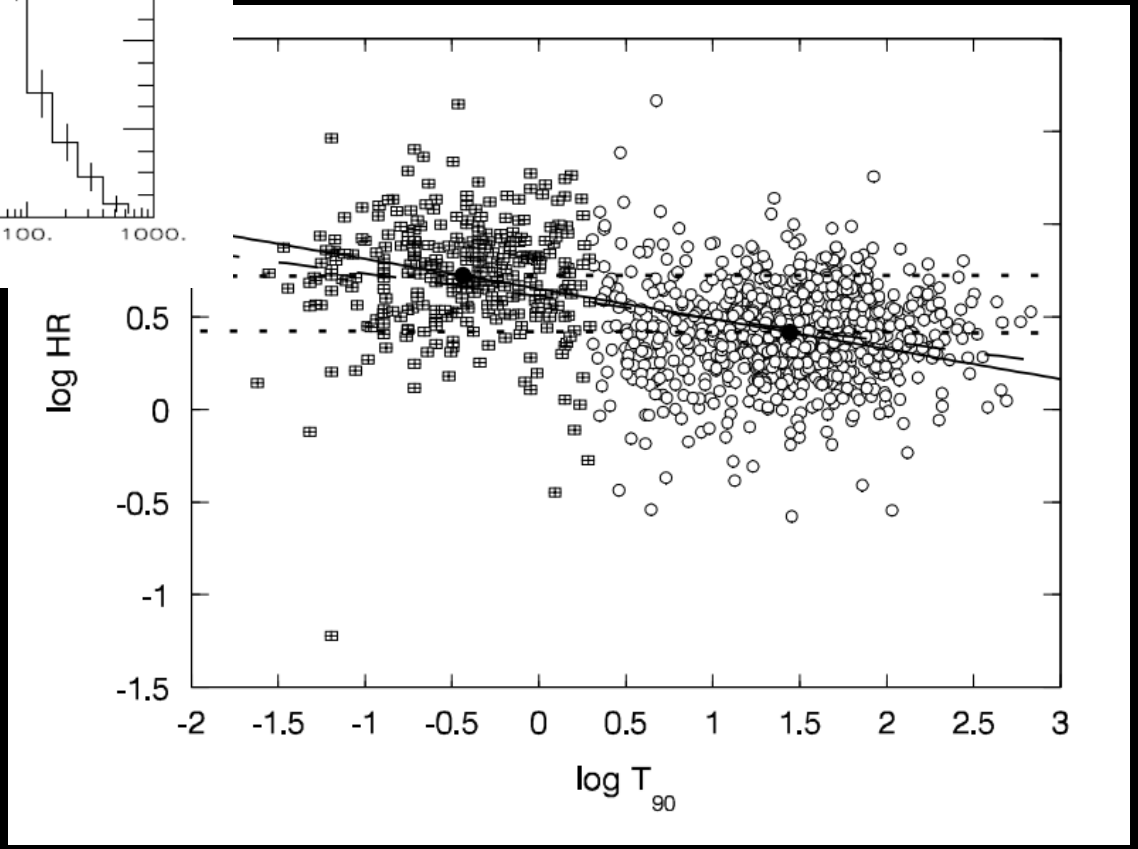
方位分佈

Meegan et al. (1992)

長暴與短暴

1993年BATSE發現伽瑪暴明顯分成長暴與短暴兩類





距離、宿主星系仍未知

部分河內派認為這不足以證明伽瑪暴起源於河外，他們堅持認為伽瑪暴可能來自銀暈

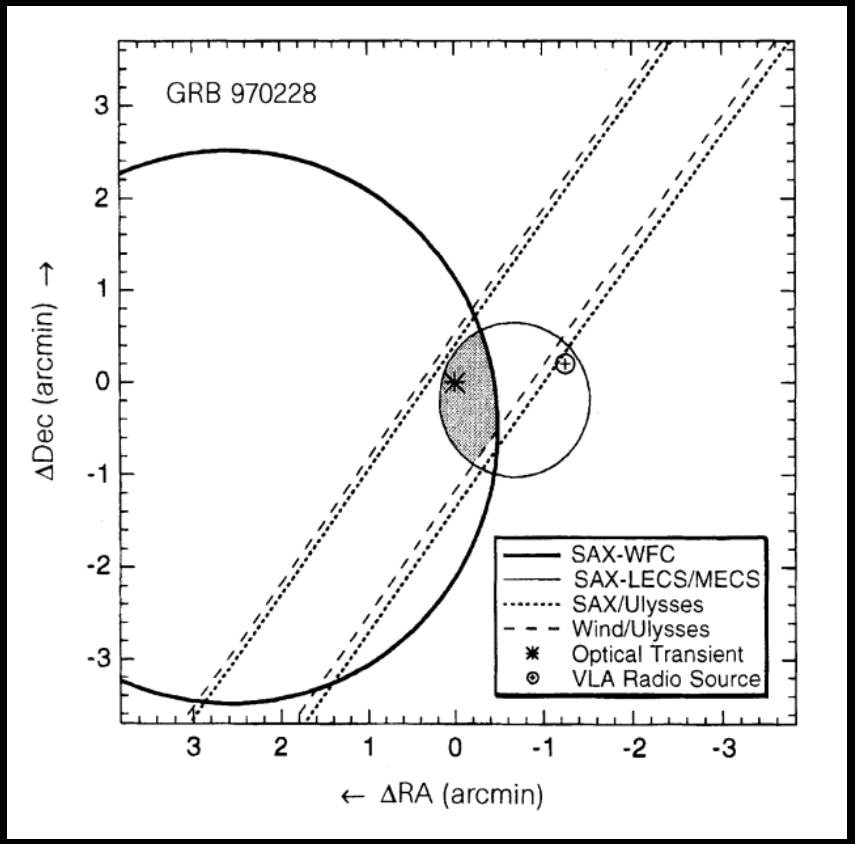
BeppoSAX衛星

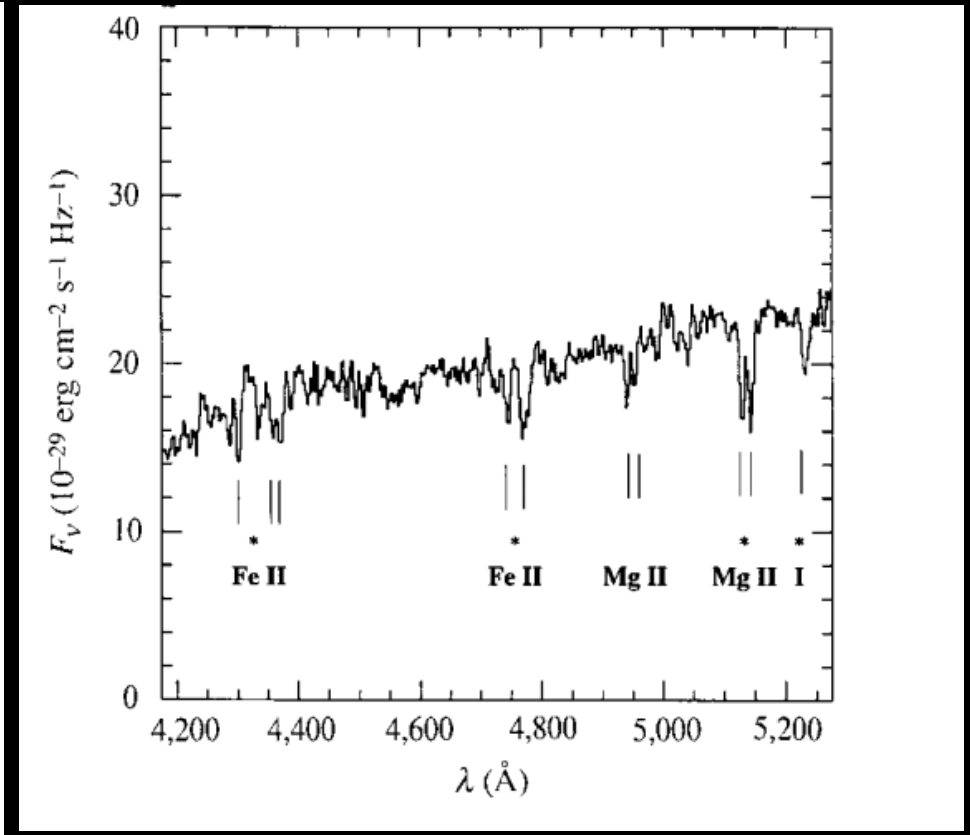
1. 1996年意大利與荷蘭聯合研製發射BeppoSAX衛星
2. BeppoSAX 有五個載荷：0.1 to 300 keV
3. 定位精度可達1-5角分



GRB970228 – 長暴光學、射電餘輝

1. BeppoSAX的精確定位起到了關鍵作用
2. 地面光學望遠鏡的光譜測量顯示該暴紅移為 0.835<z<2.3。





GRB 980425/SN 1998bw

GRB 980425/SN 1998bw未得到公認

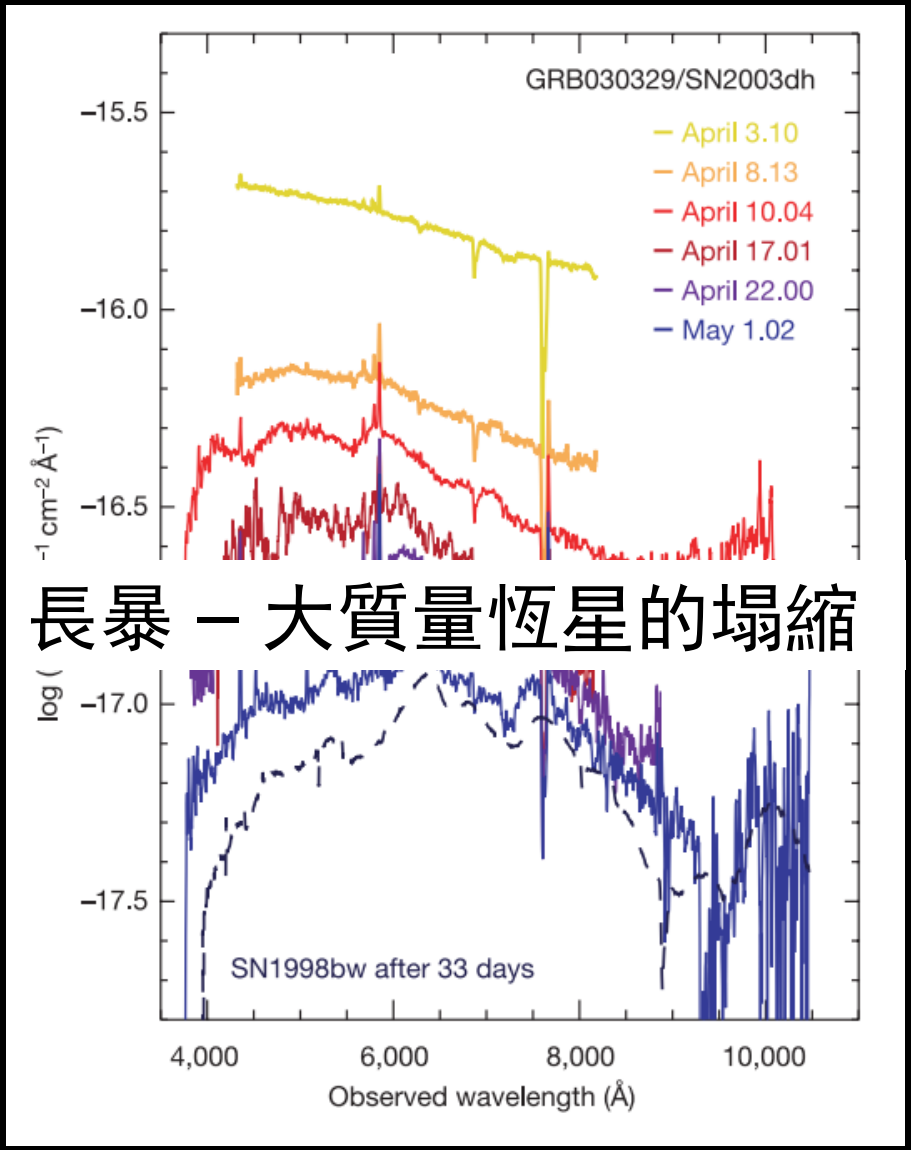
The unusual afterglow of the γ-ray burst of 26 March 1998 as evidence for a

letters to nature

An unusual supernova in the error box of the γ-ray burst of 25 April 1998

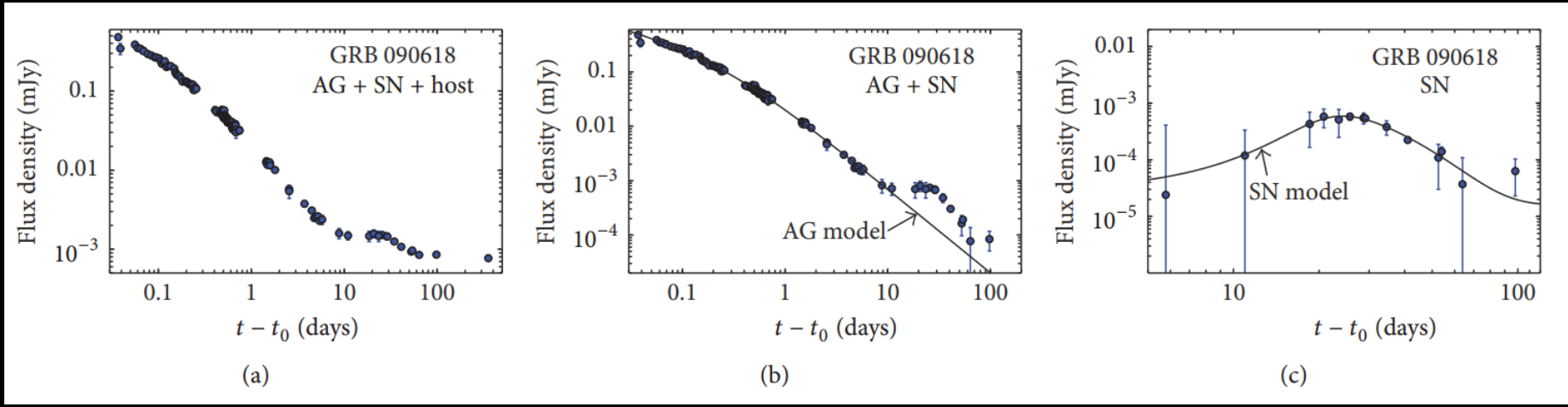
, A. C. Eichelberger*, A. Harrison*, D. A. Frail†, H. Spinrad‡, D. Stern‡, , R. A. Knop¶, I. M. Hook#

GRB030329/SN2003dh

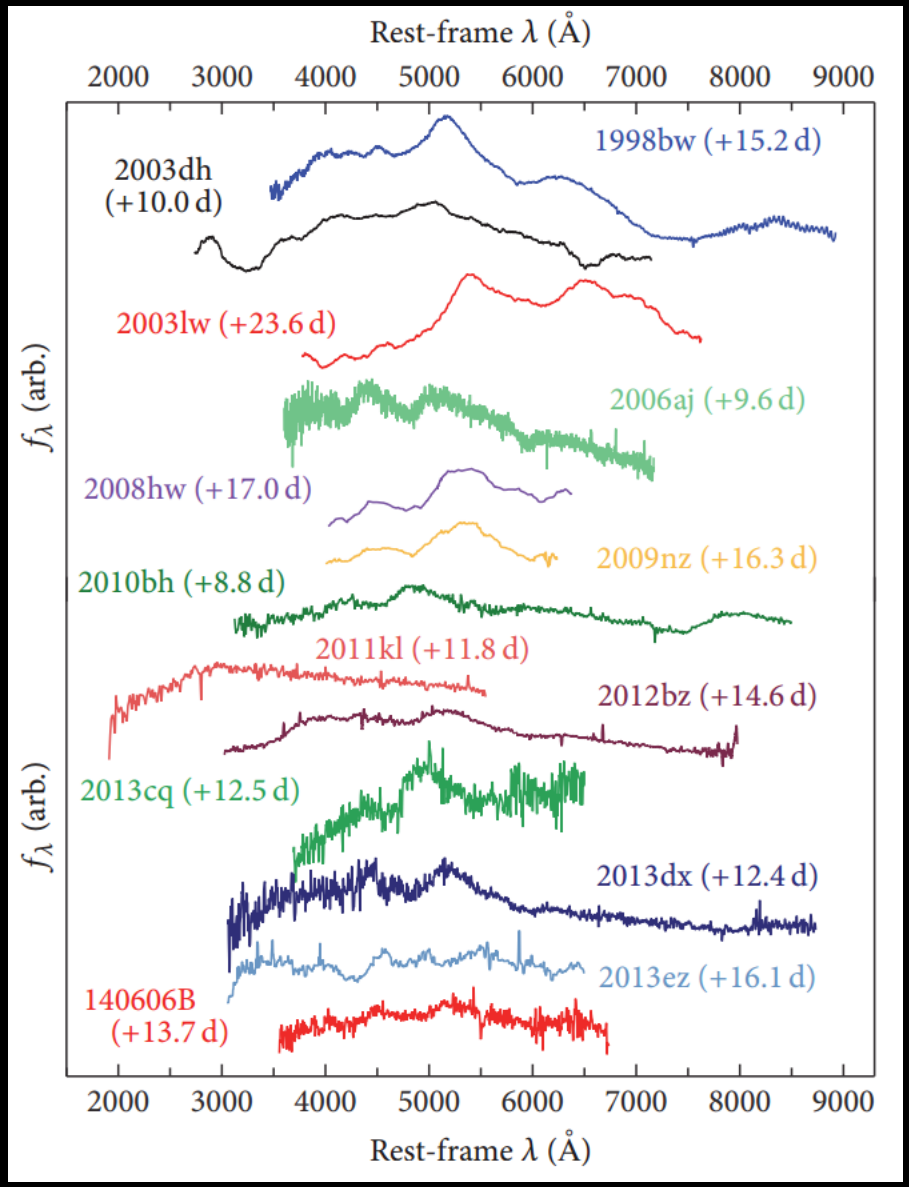


長暴－大質量恆星的塌縮

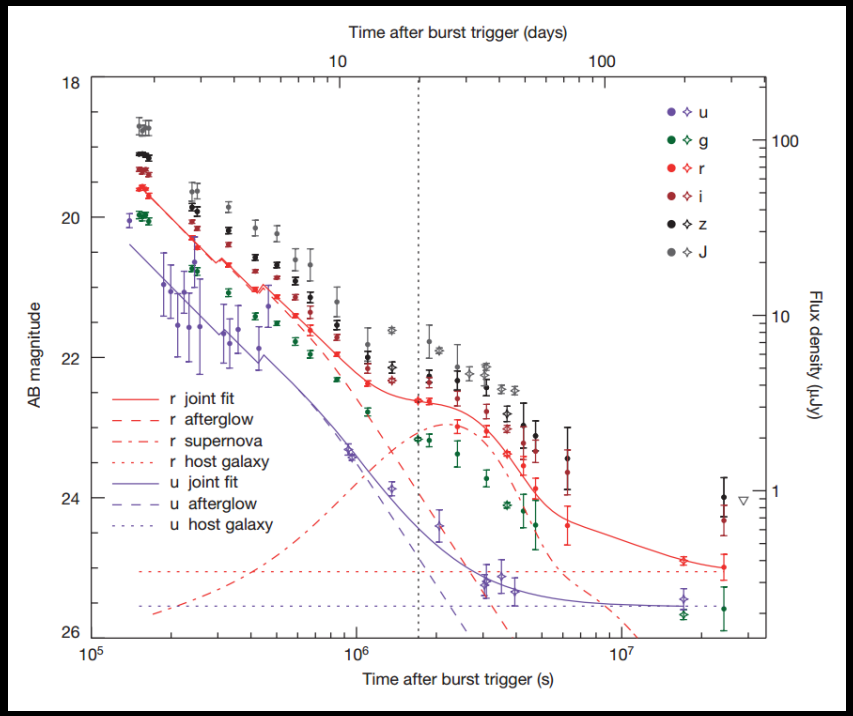
含有超新星成份的典型餘暉

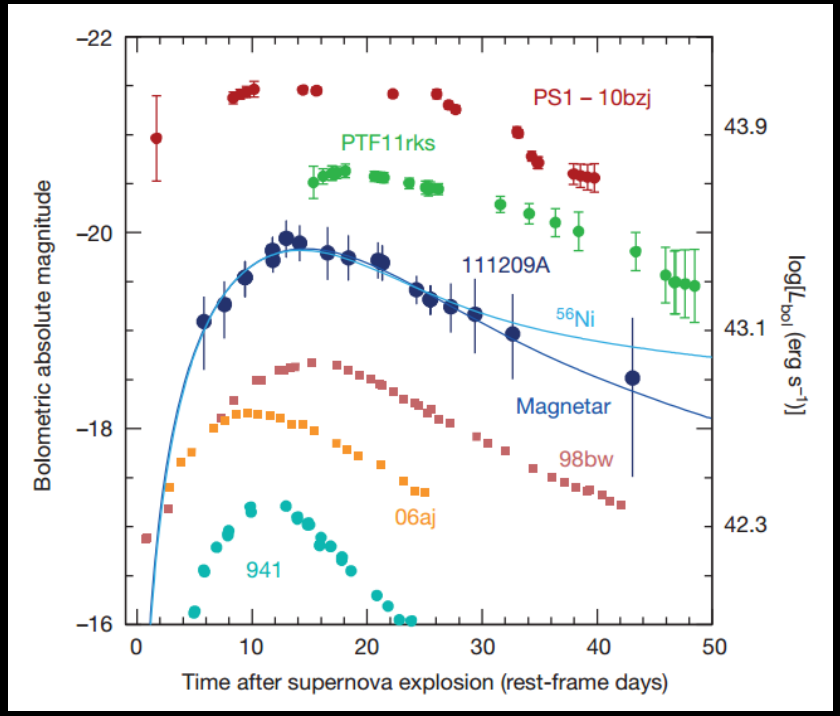


GRB-SNe的譜


Rest-frame λ (Å)
2000
3000
4000
5000
6000
7000
8000
9000
1998bw (+15.2 d)
2003dh
(+10.0 d)
2003lw (+23.6 d)
2006aj (+9.6 d)
2008hw (+17.0 d)
2009nz (+16.3 d)
2010bh (+8.8 d)
2011kl (+11.8 d)
2012bz (+14.6 d)
2013cq (+12.5 d)
2013dx (+12.4 d)
2013ez (+16.1 d)
140606B
(+13.7 d)
f_λ (arb.)
f_λ (arb.)
2000
3000
4000
5000
6000
7000
8000
9000
Rest-frame λ (Å)

Magnetar-powered GRB-SNe: SN 2011kl

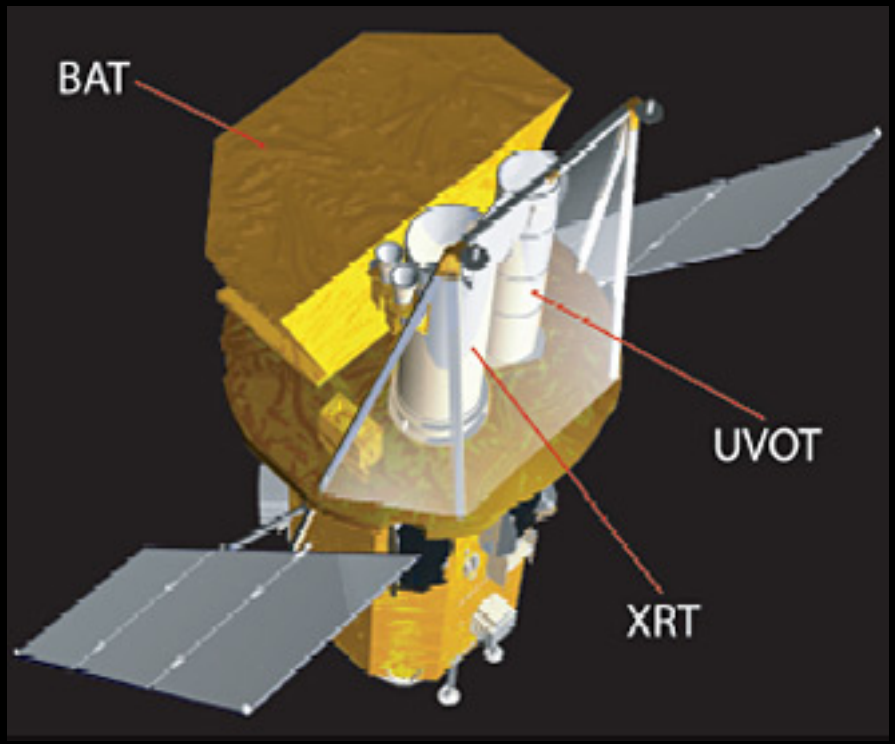




短暴餘輝與極早期餘輝

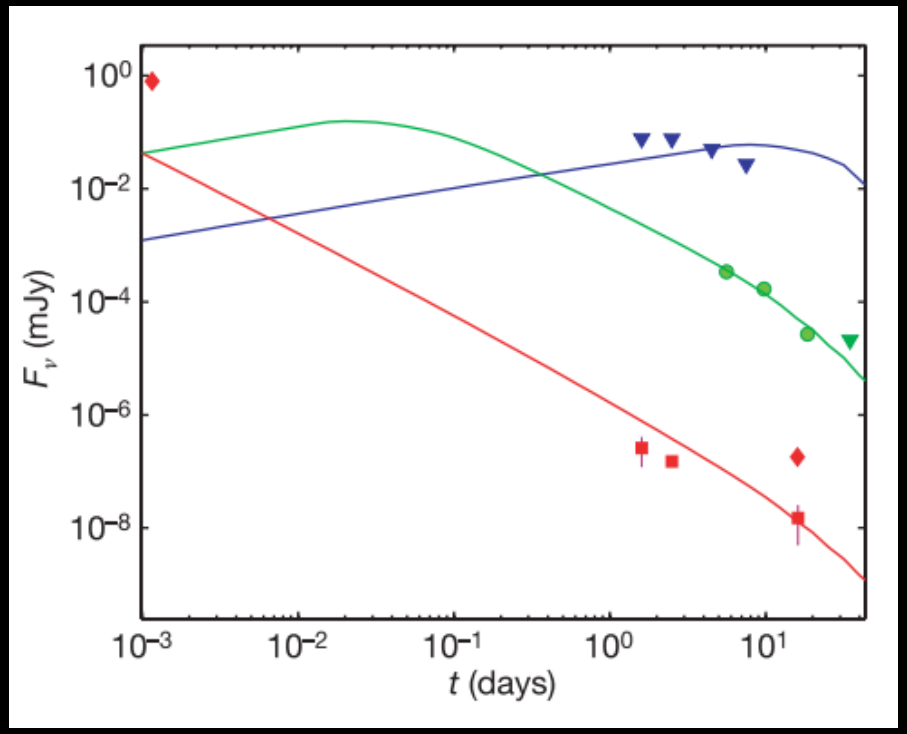
2004年Swift升空：

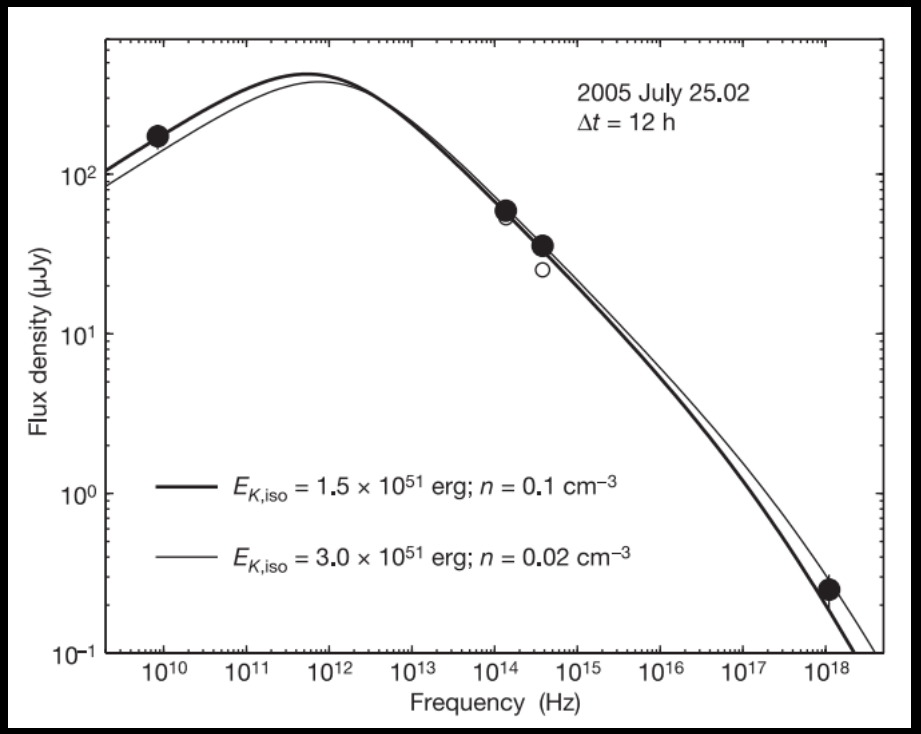
1. 快速反應能力
2. 包含X射線、紫外、光學探測器



短暴餘輝

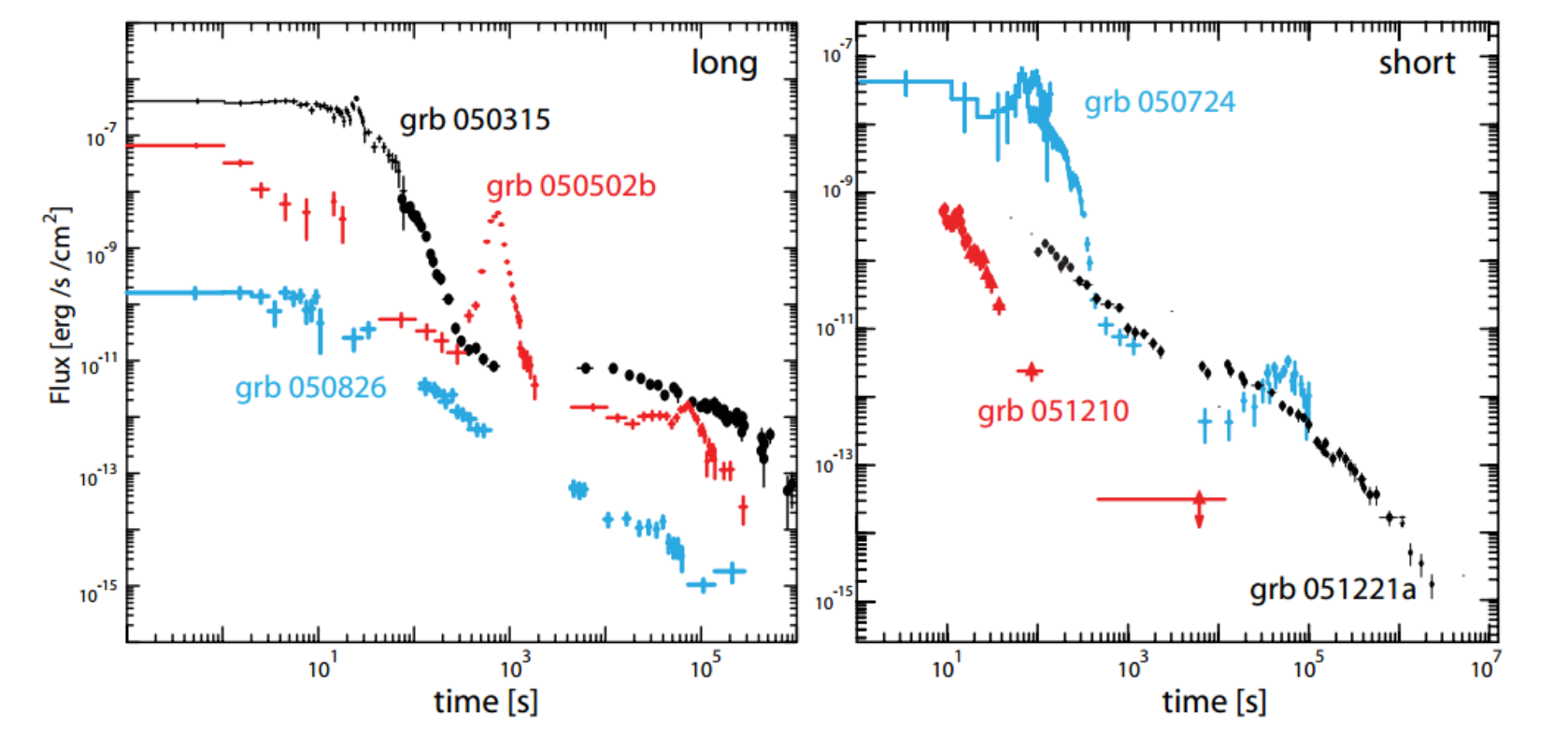
2005年發現短暴餘輝： GRB 050724、 GRB 050709





Swift的主要成就 – 磁星模型流行

早期餘輝中X射線平臺與耀發的發現，這些被認為是磁星的證據



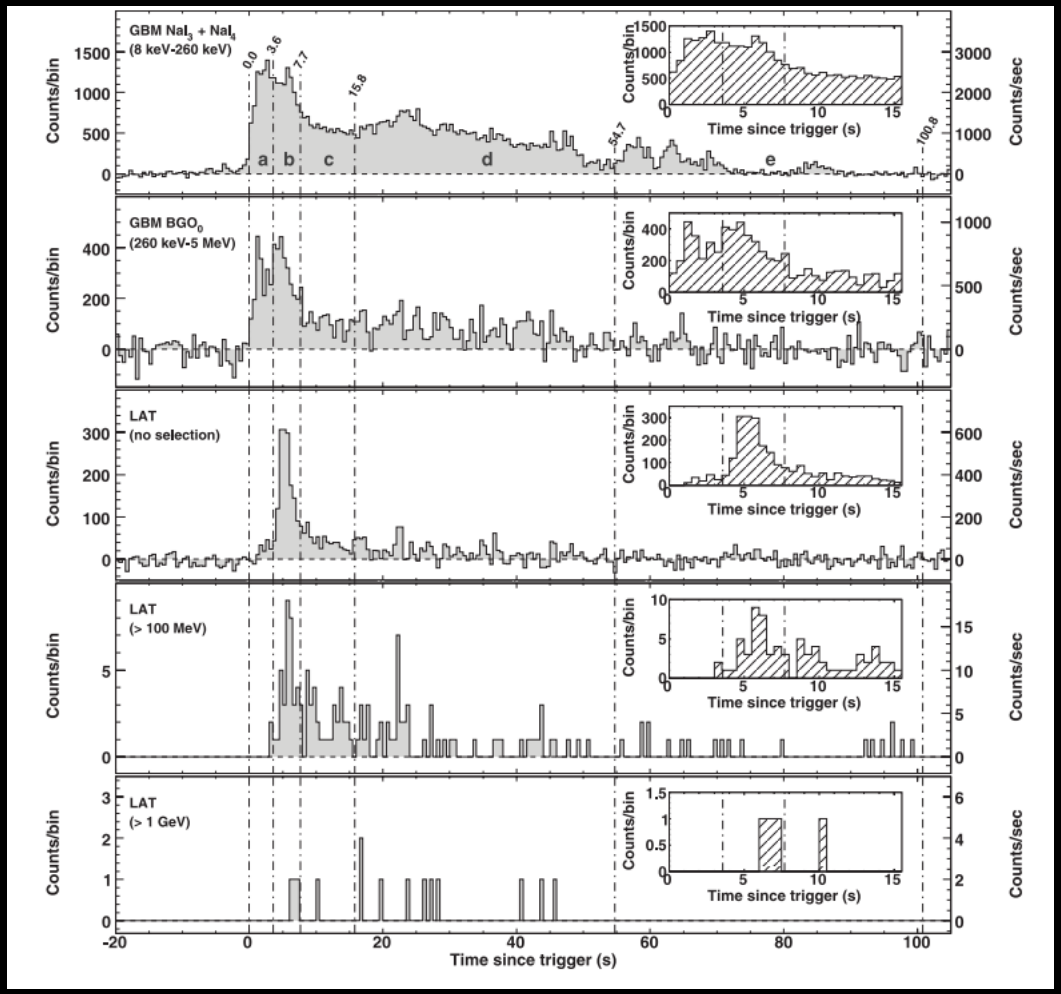
高能輻射

2008年Fermi升空：
GBM (8 keV　1 MeV) & LAT (<20 MeV　- >300 GeV)



Fermi的主要成就

高能輻射持續時間長，相比低能輻射有延遲



GRB 130427A

REPORTS

GRB 130427A: A Nearby Ordinary Monster

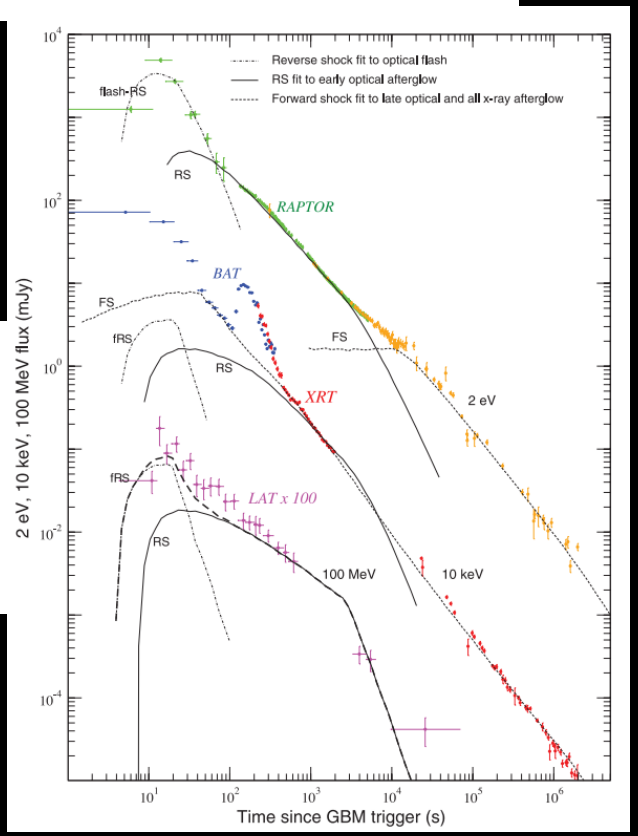
RESEARCH ARTICLES

The Bright Optical Flash and Afterglow from the Gamma-Ray Burst GRB 130427A

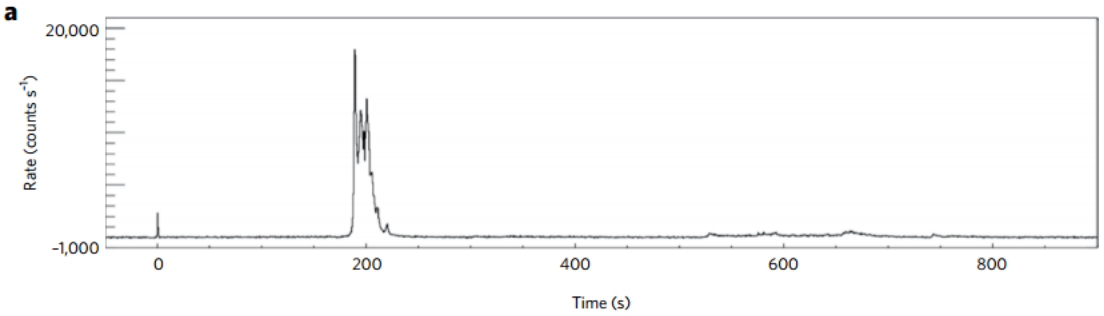
The First Pulse of the Extremely Bright GRB 130427A: A Test Lab for Synchrotron Shocks

RESEARCH ARTICLES

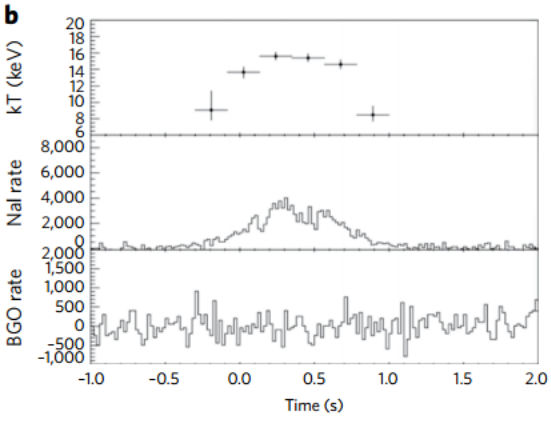
Fermi-LAT Observations of the Gamma-Ray Burst GRB 130427A

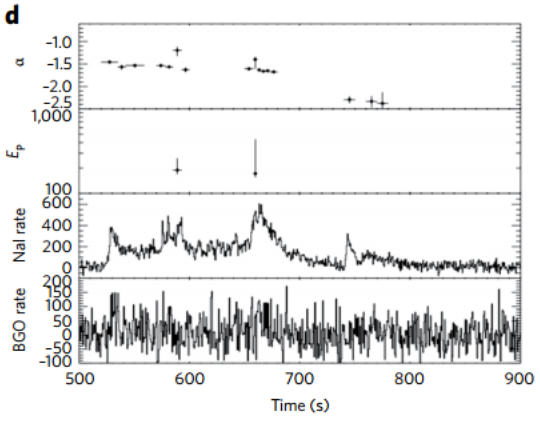


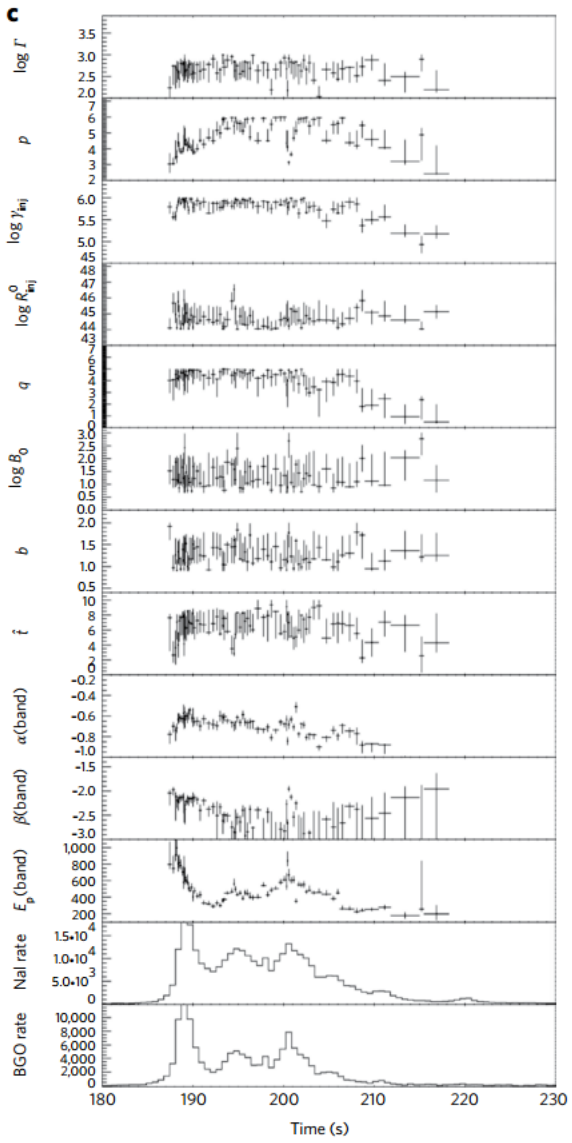
噴流的演化



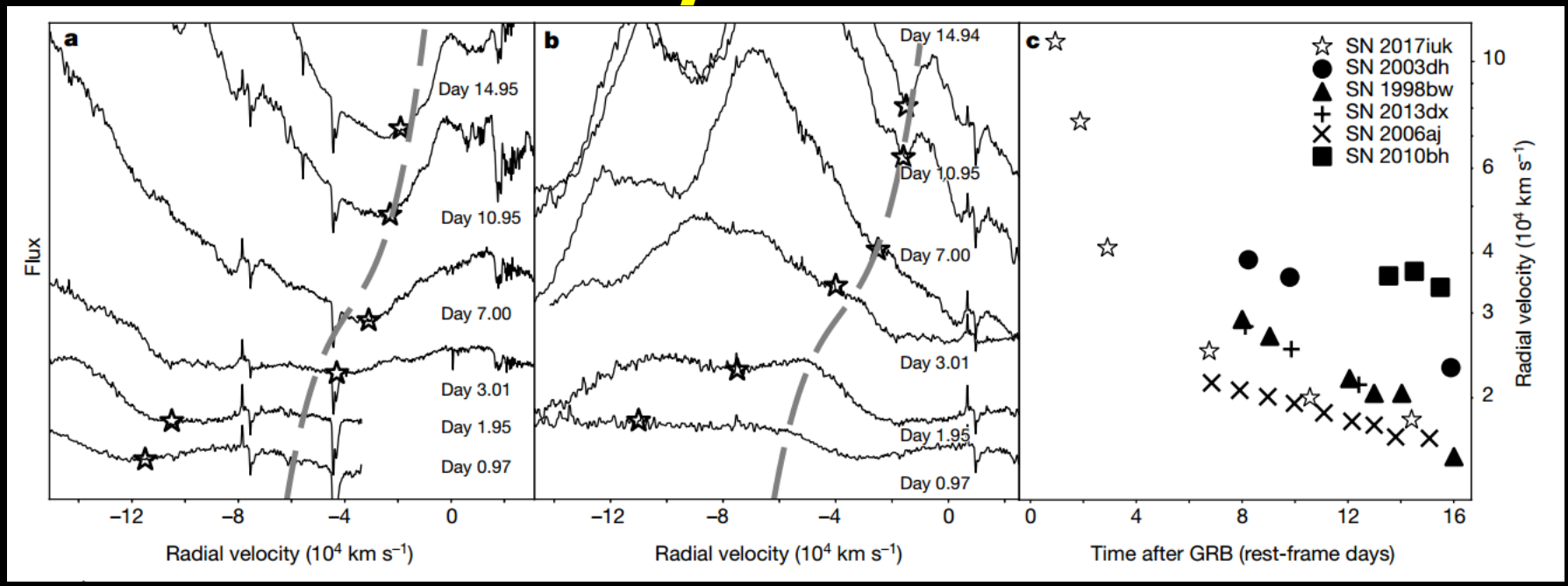
Zhang B. B. (2018)

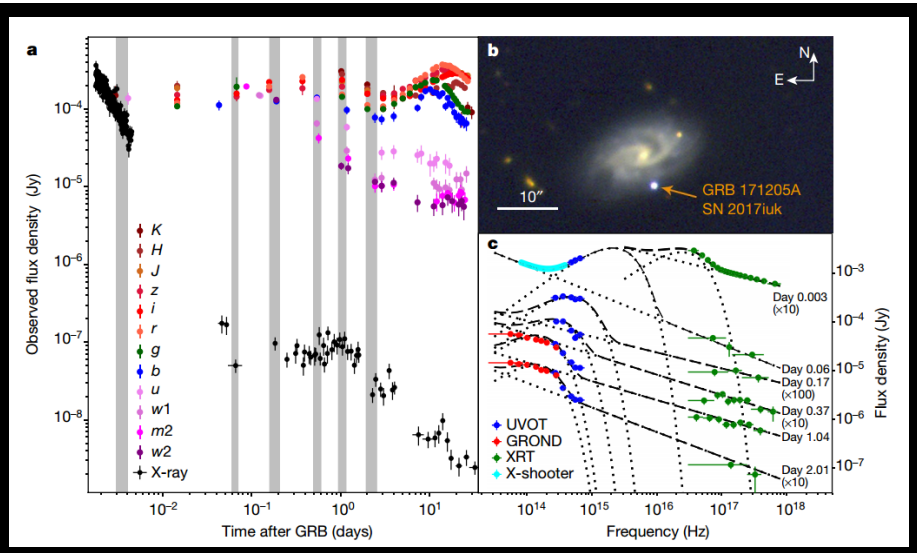






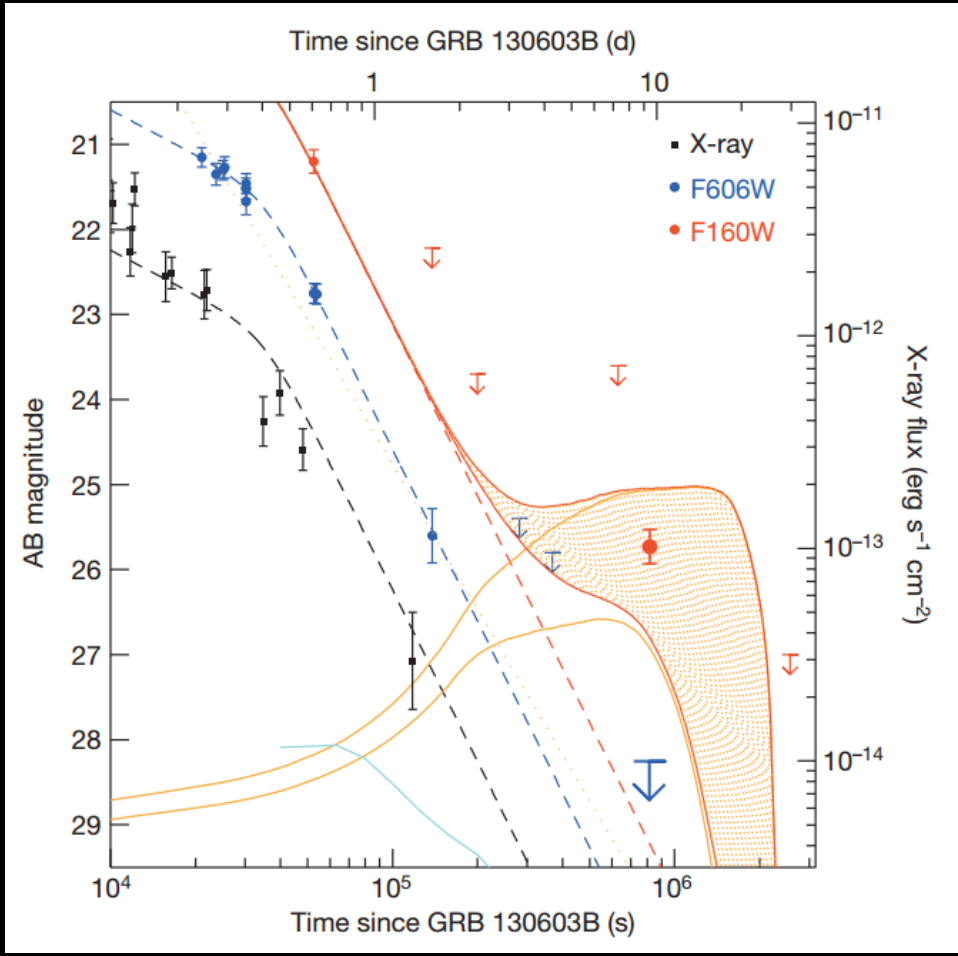
GRB 171205A/ SN 2017iuk





GRB 130603B與kilonova

By Hubble Space Telescope (HST)



Possible kilonova in archive data

GRB 060614

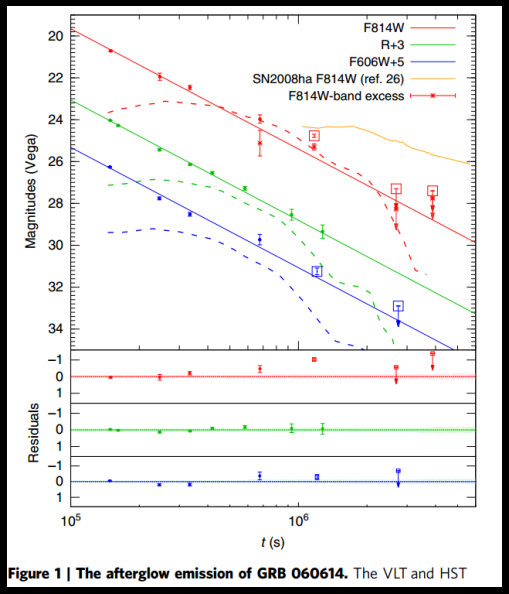
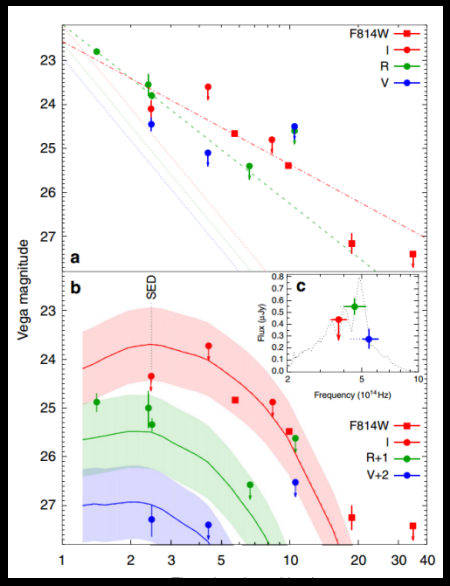
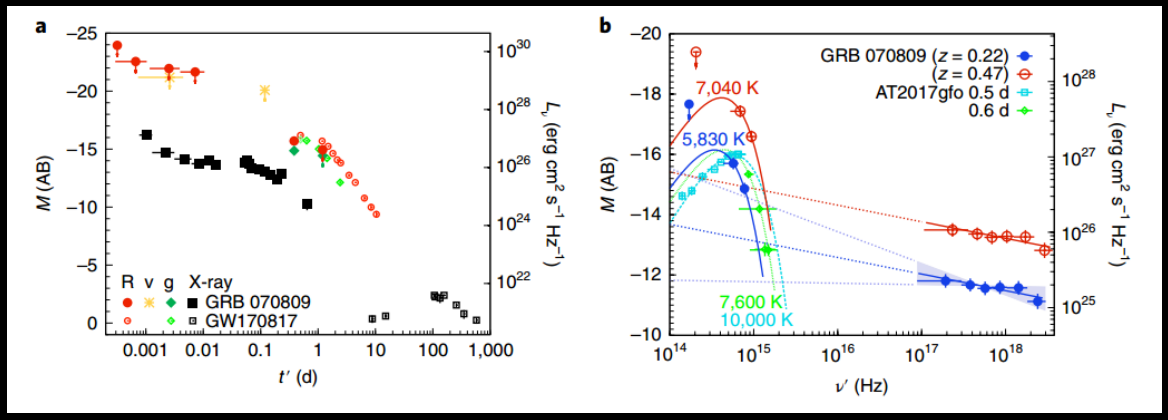


Figure 1 | The afterglow emission of GRB 060614. The VLT and HST

GRB 050709



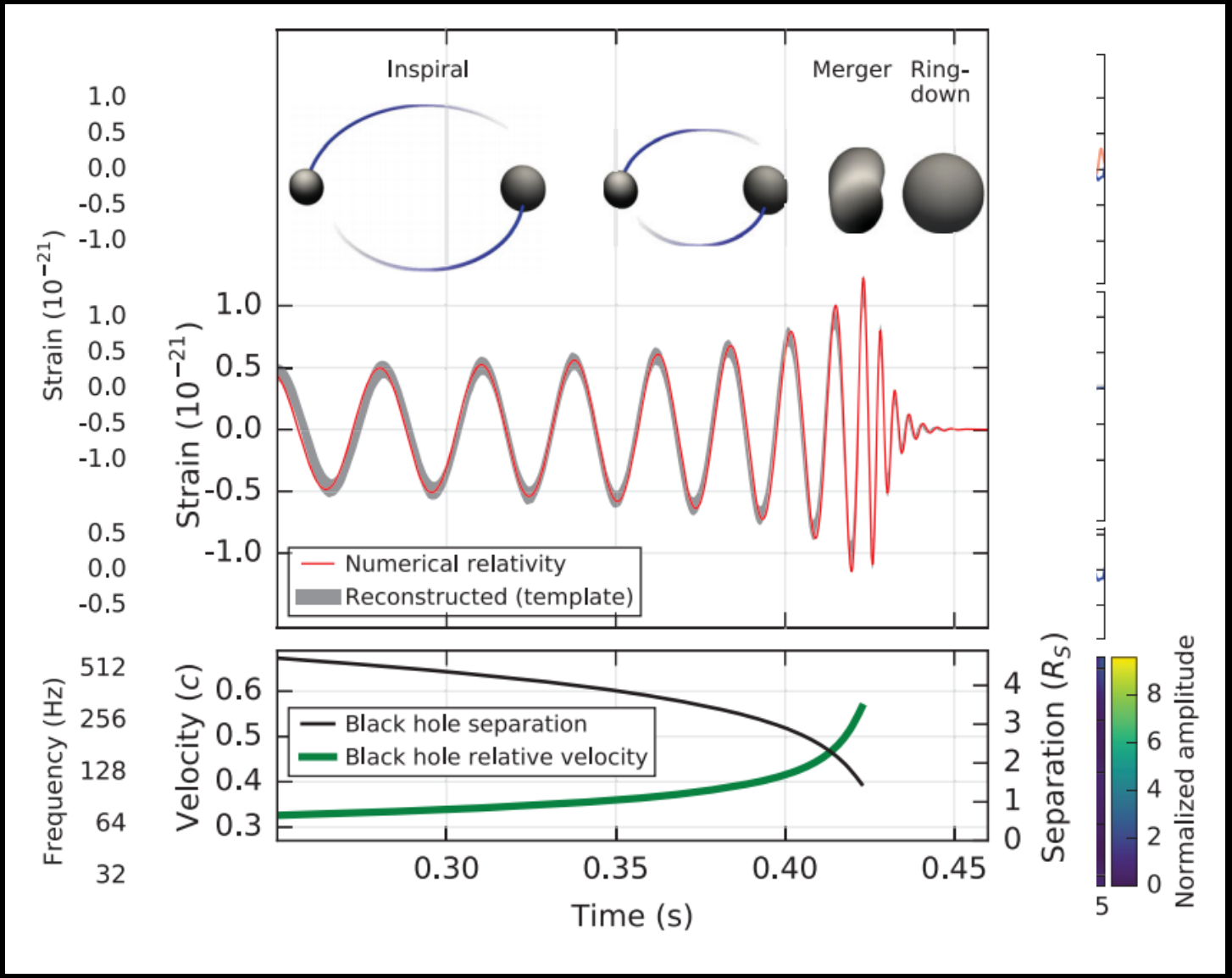


GRB 070809

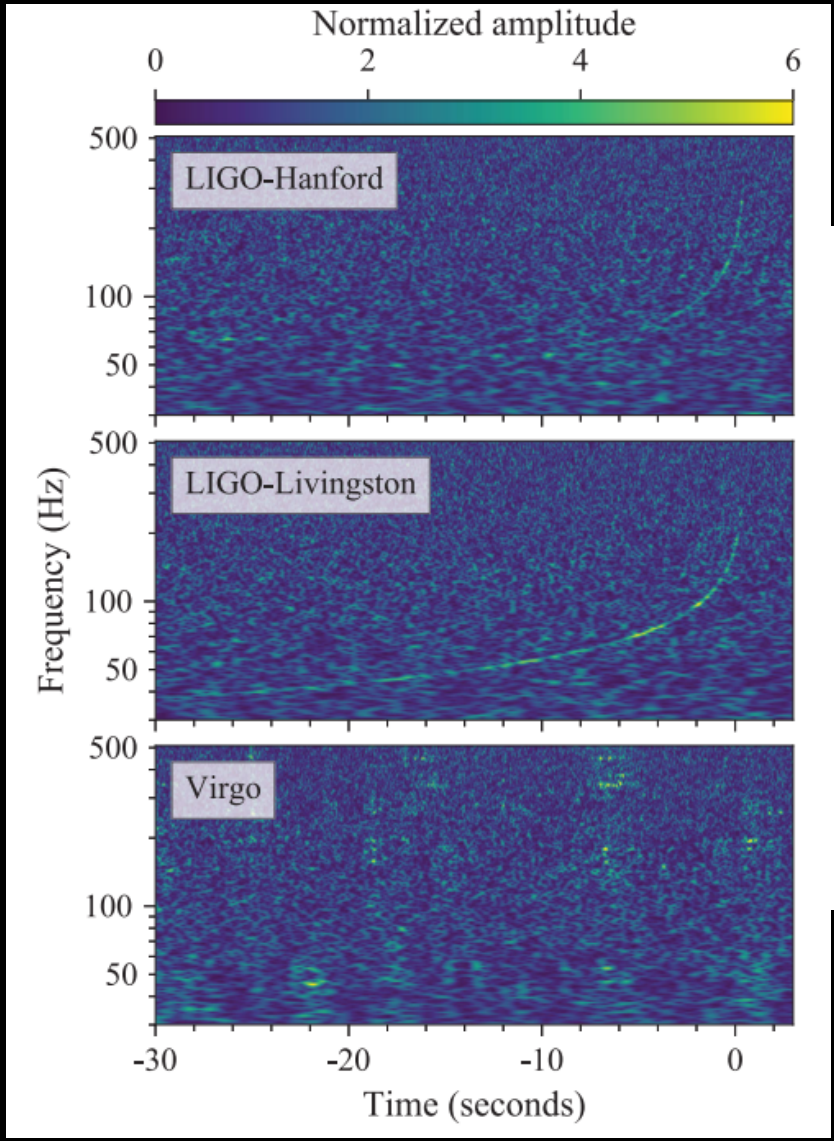
引力波探測登場 -- LIGO/Virgo

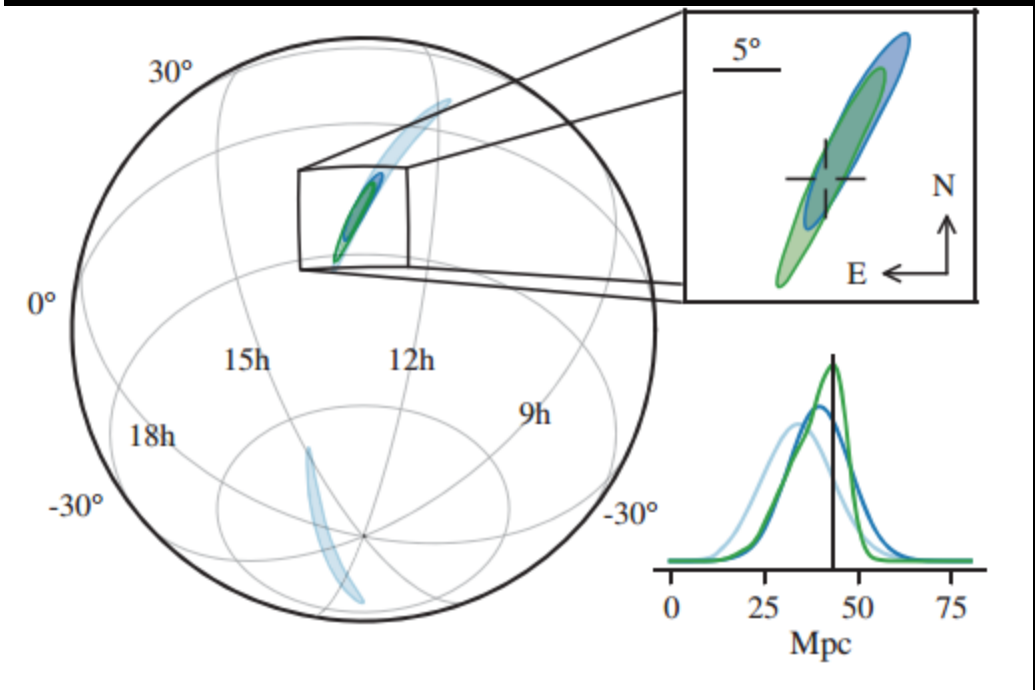


雙黑洞並合（2015）

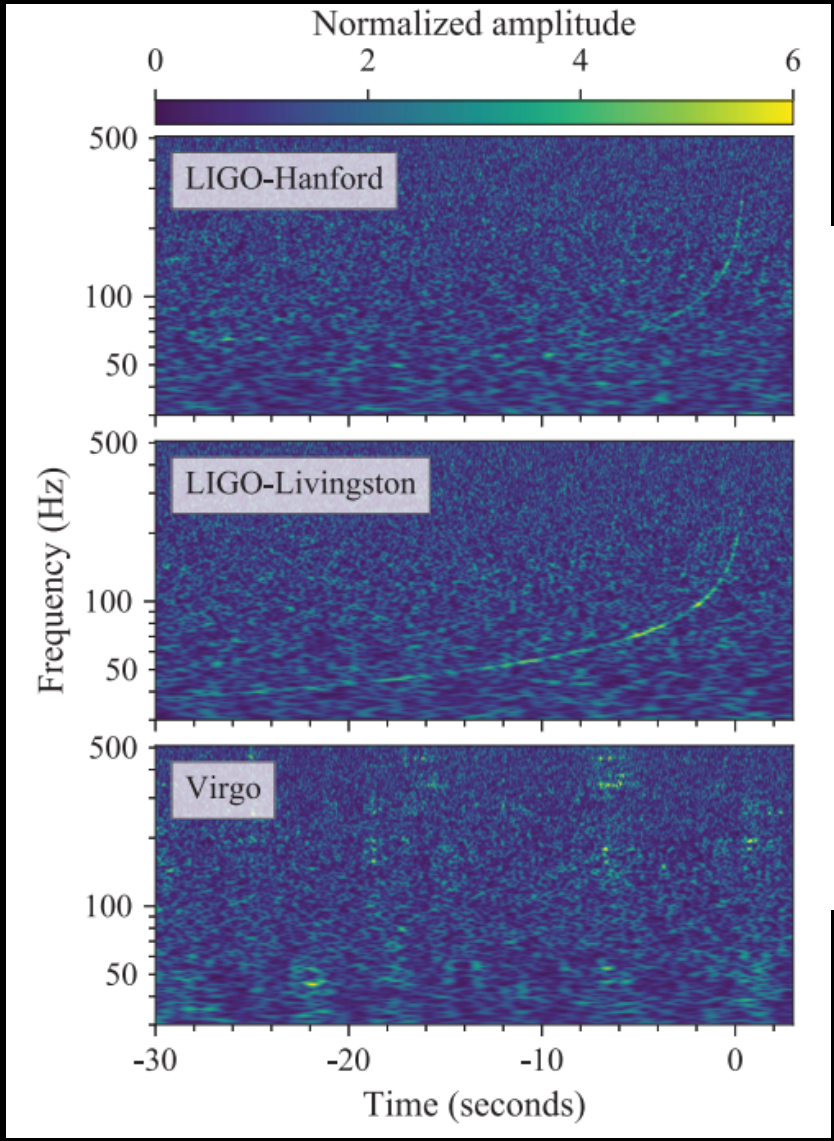

Inspiral
Merger
Ring-down
Strain (10^{-21})
Numerical relativity
Reconstructed (template)
Frequency (Hz)
Velocity (c)
Black hole separation
Black hole relative velocity
Separation (R_S)
Time (s)
Normalized amplitude

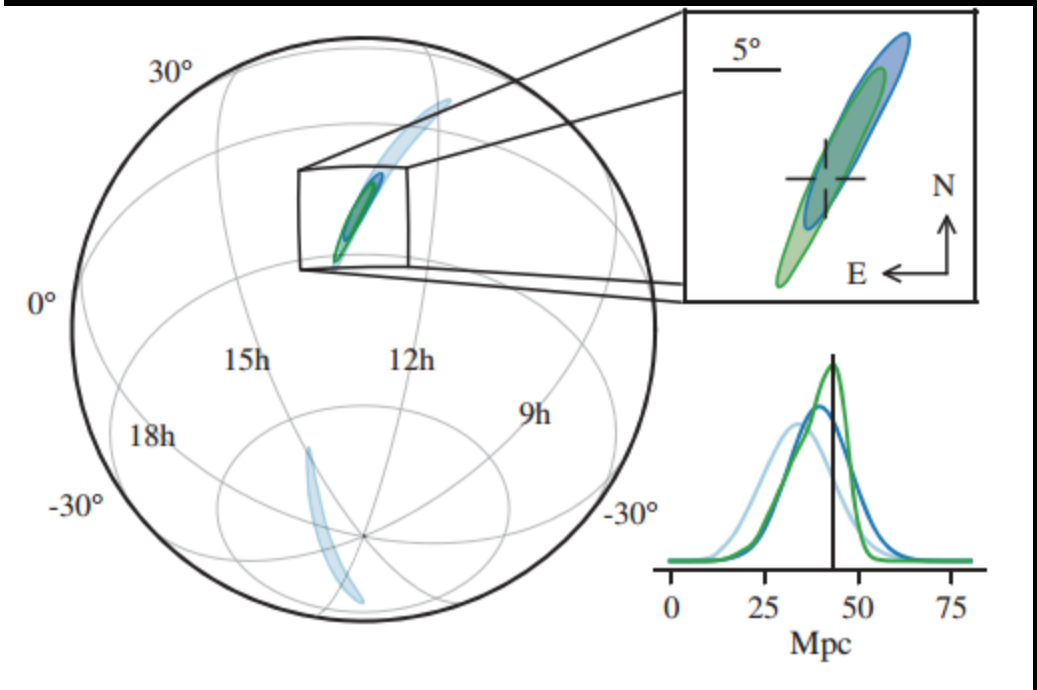
GW170817/GRB 170817A



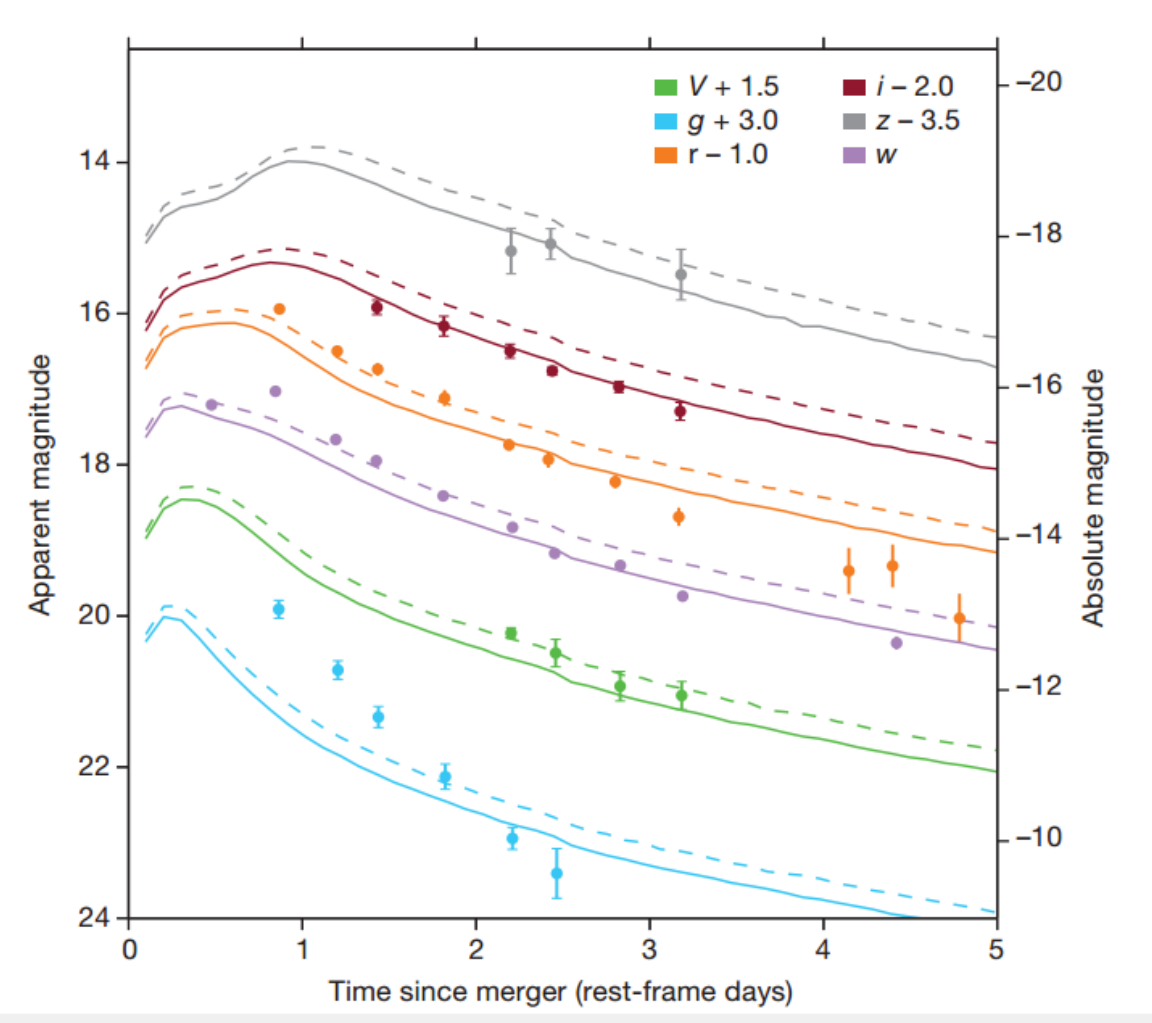


GW170817/GRB 170817A

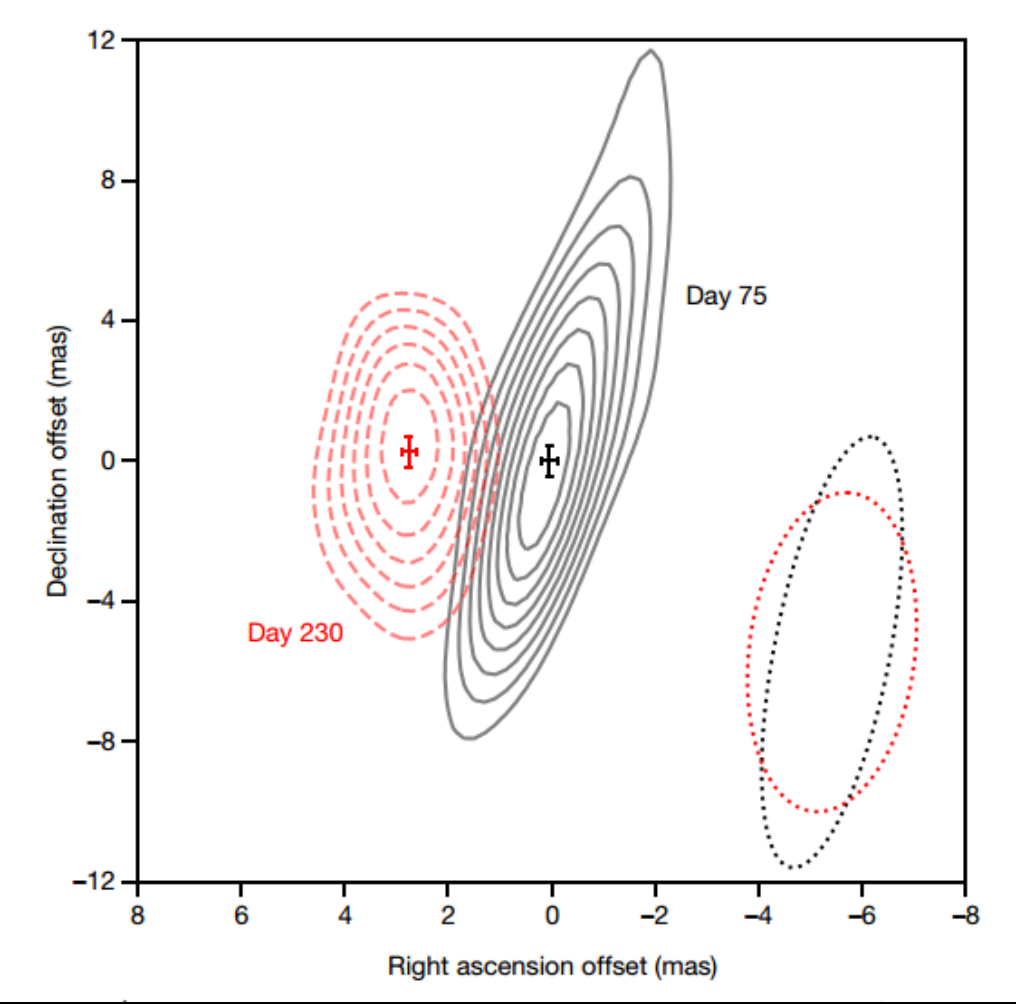




AT 2017gfo associated w/ GRB 170817A



Superluminal motion in GRB 170817A



Article

Identification of strontium in the merger of two neutron stars

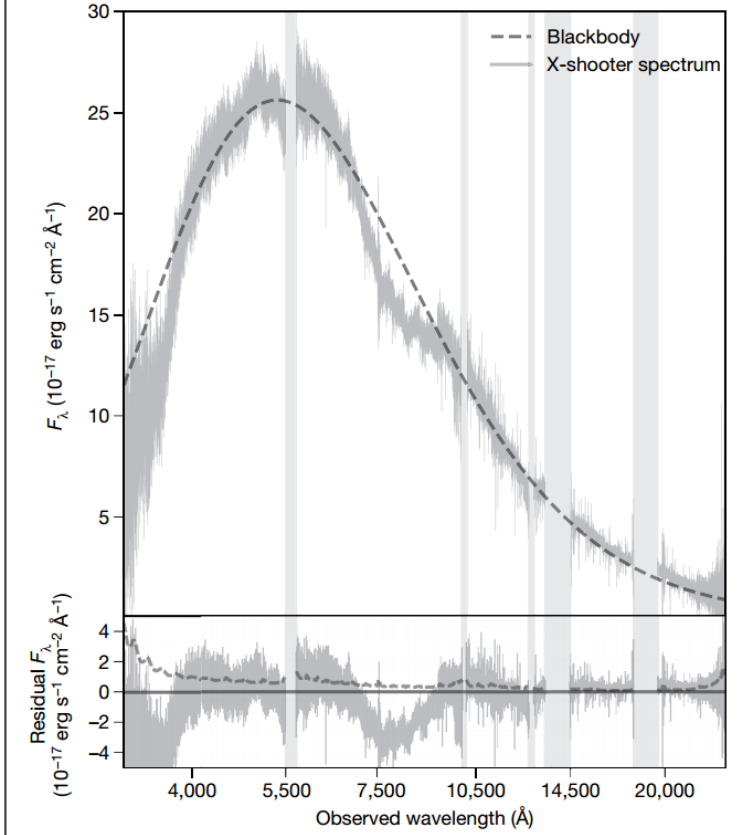
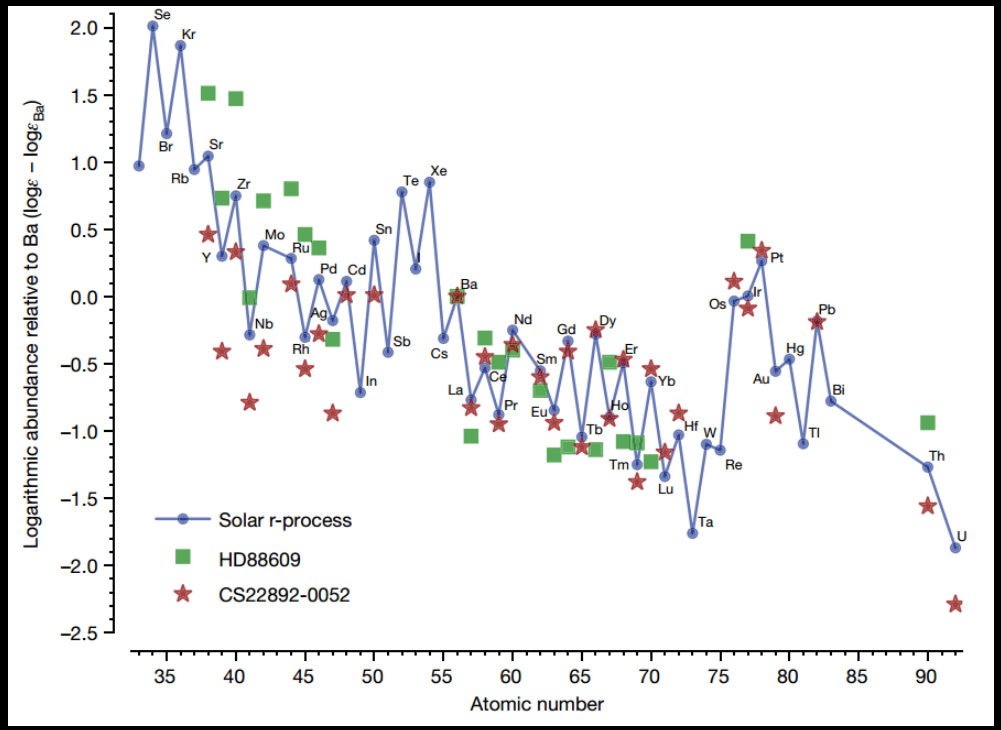


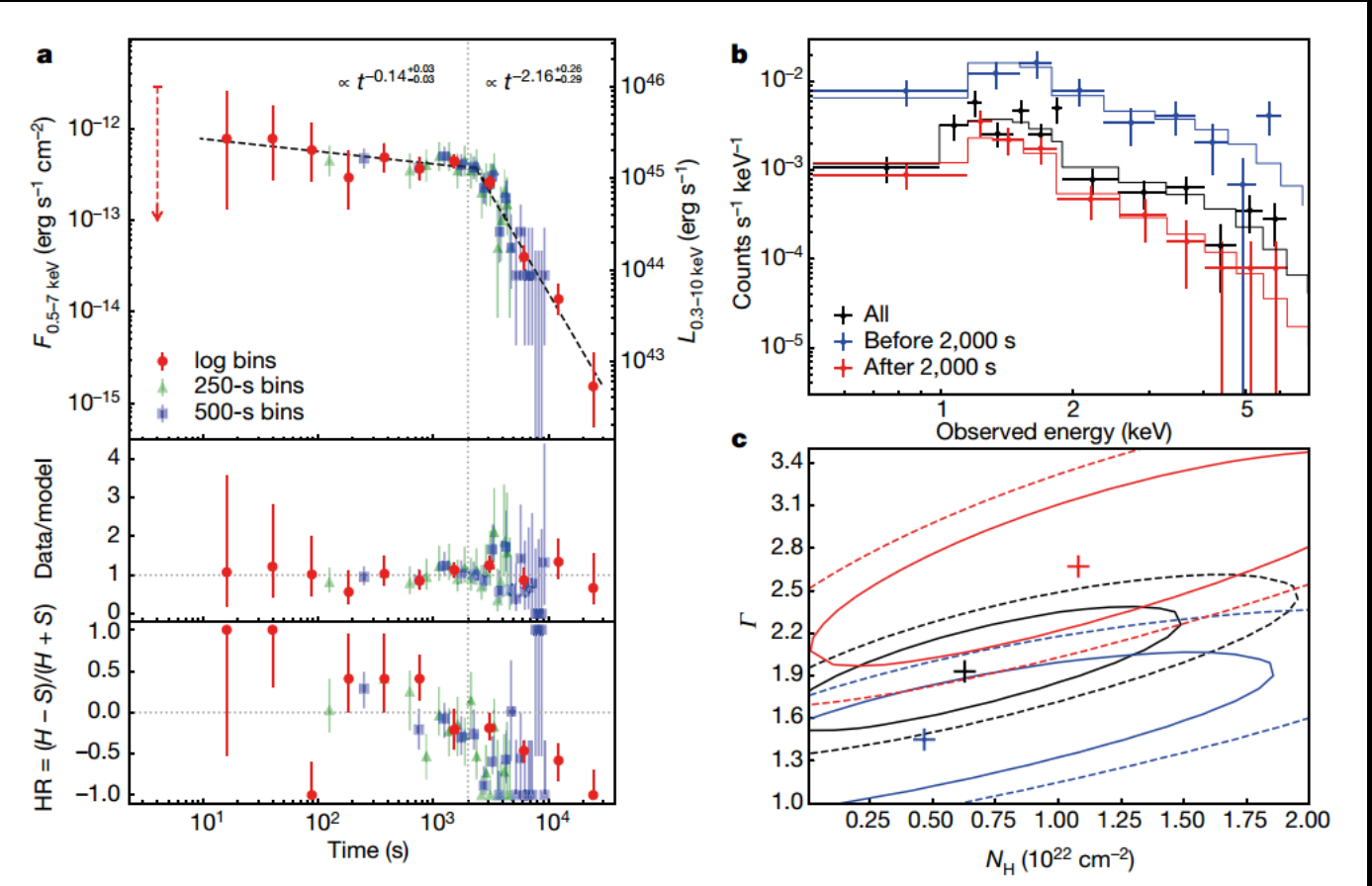
Fig. 1 | Spectrum of the kilonova AT2017gfo, showing broad absorption



LETTER

https://doi.org/10.1038/s41586-019-1079-5

A magnetar-powered X-ray transient as the aftermath of a binary neutron-star merger



Polarization of afterglow

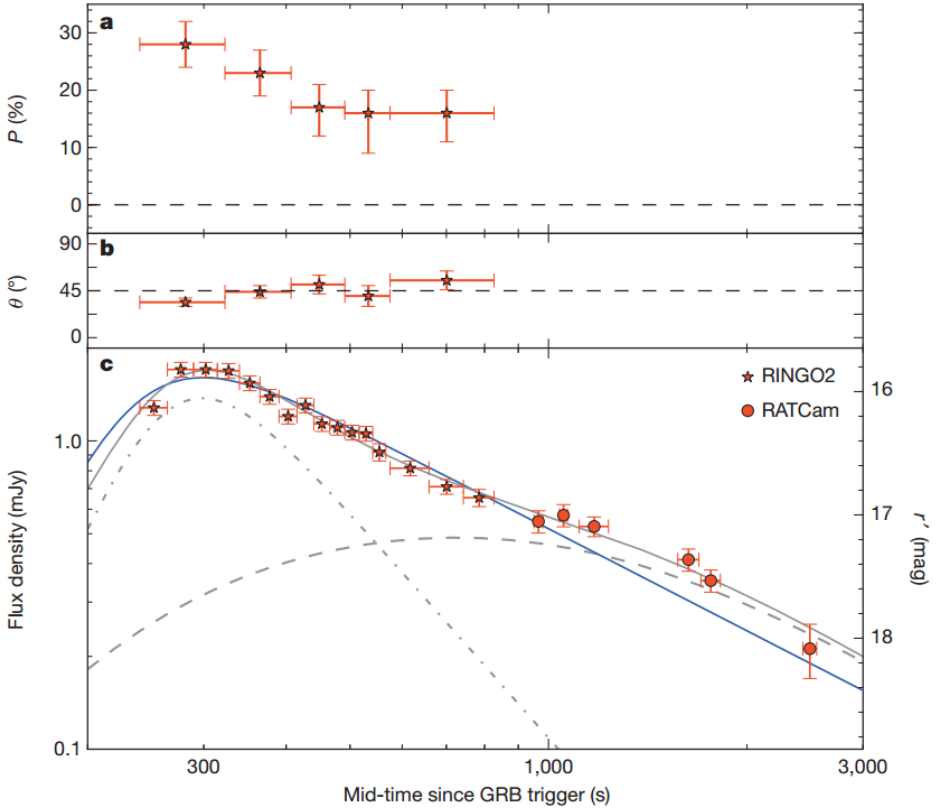
GRBs contain magnetized baryonic jets with large-scale uniform fields that can survive long after the initial explosion.

Vol 462|10 December 2009|doi:10.1038/nature08590

Ten per cent polarized optical emission GRB 090102

LETTER

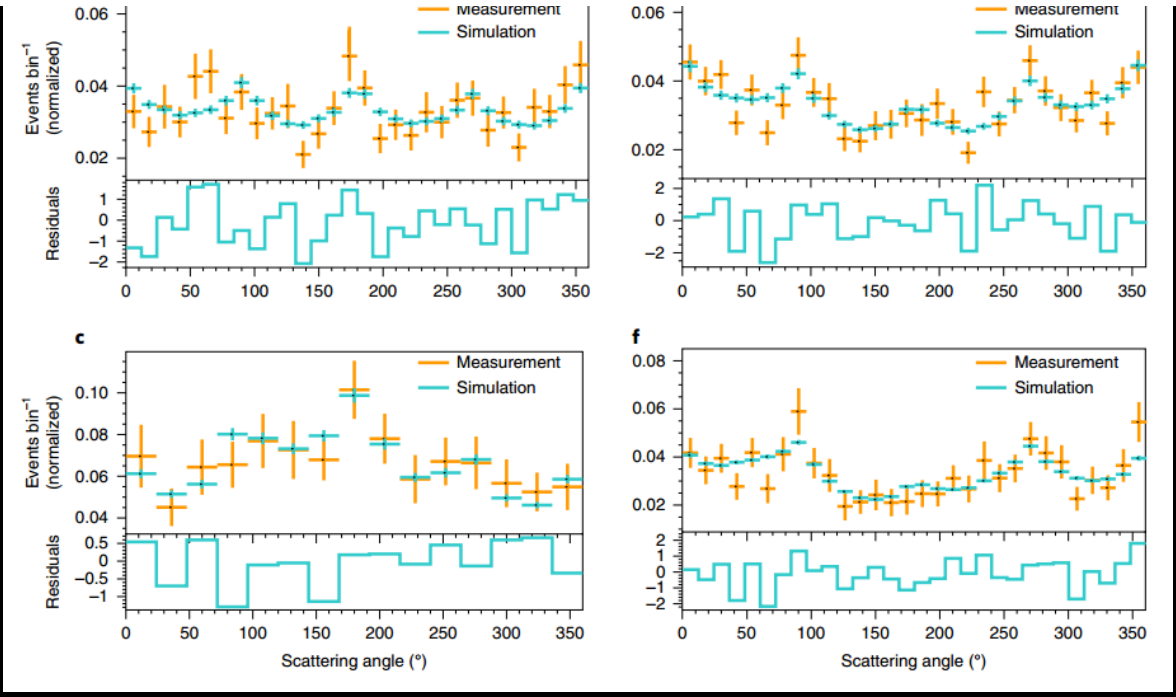
Highly polarized light from stab fields in GRB 120308A



Polarization measurements of the prompt emission of GRBs

LETTERS
https://doi.org/10.1038/s41550-018-0664-0
nature astronomy

Detailed polarization measurements of the prompt emission of five gamma-ray bursts



TeV emission from GRB 190114C

Article

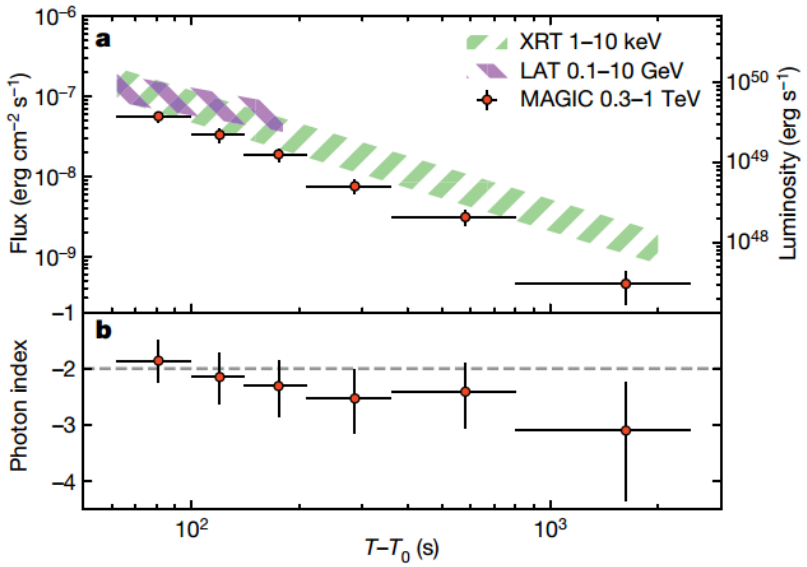


Fig. 1 | Light curves in the kiloelectronvolt, gigaelectronvolt and teraelectronvolt bands, and spectral evolution in the teraelectronvolt band for GRB 190114C. a, Light curves in units of energy flux (left axis) and apparent

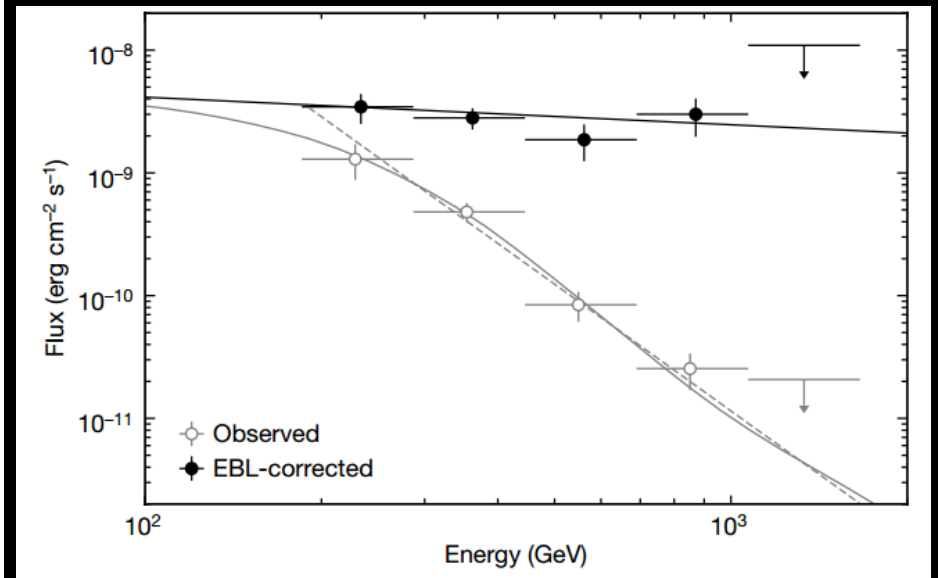


Fig. 2 | Spectrum above 0.2 TeV averaged over the period between T_0 + 62 s and T_0 + 2,454 s for GRB 190114C. Spectral-energy distributions for the

Article

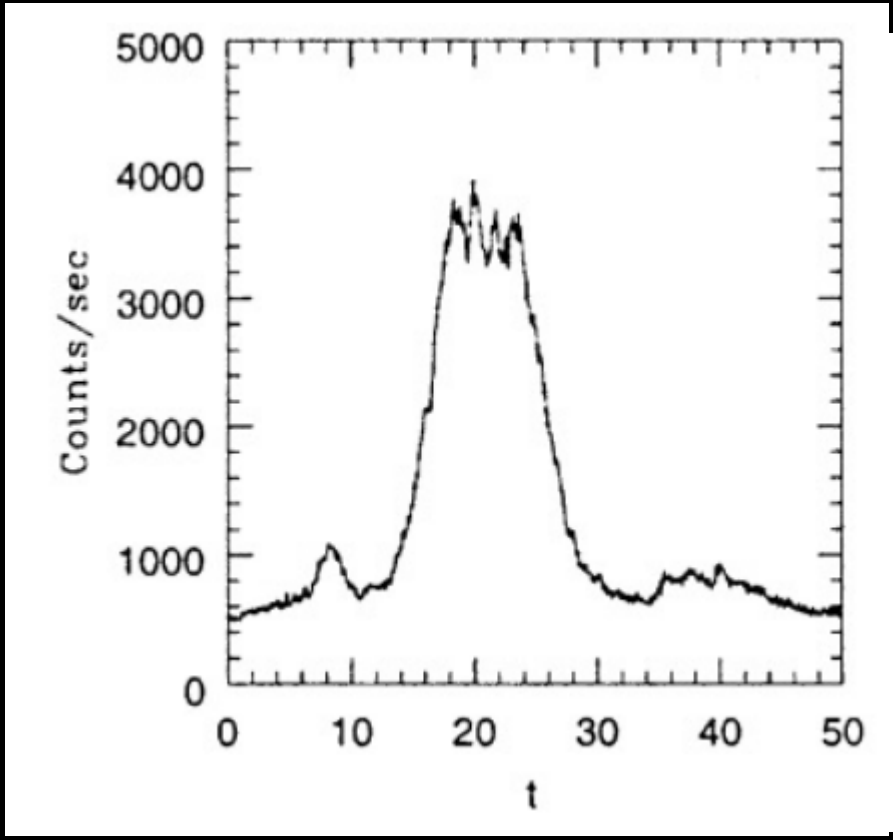
Observation of inverse Compton emission from a long γ-ray burst

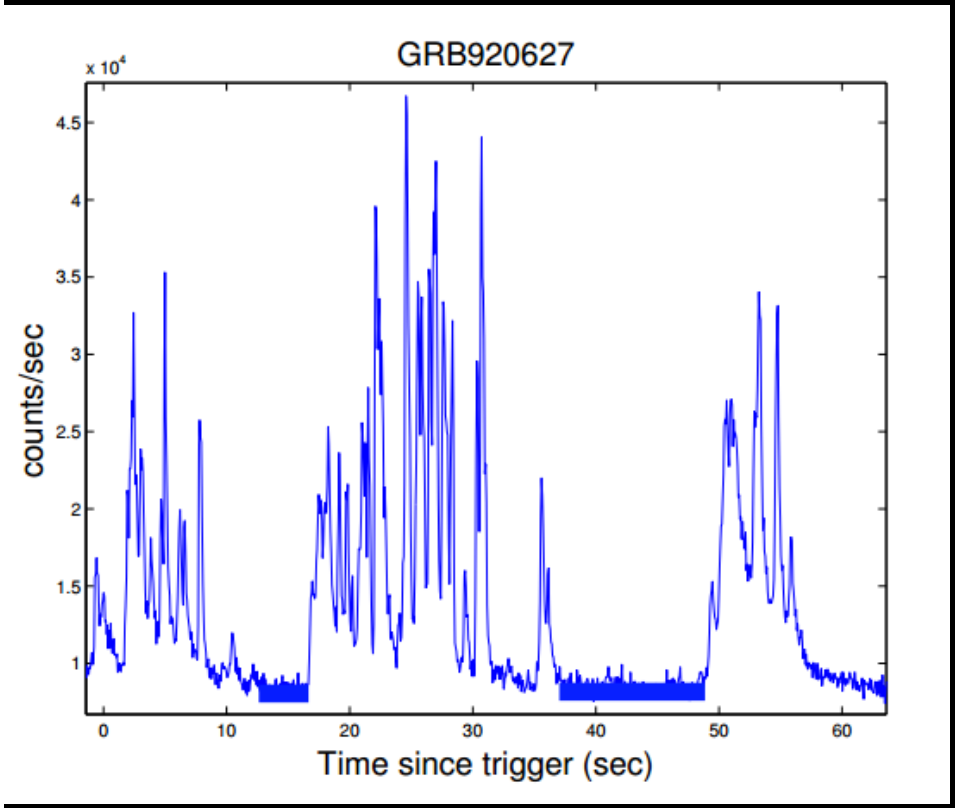
Article

A very-high-energy component deep in the γ-ray burst afterglow

伽瑪暴的觀測特性 – 瞬時輻射

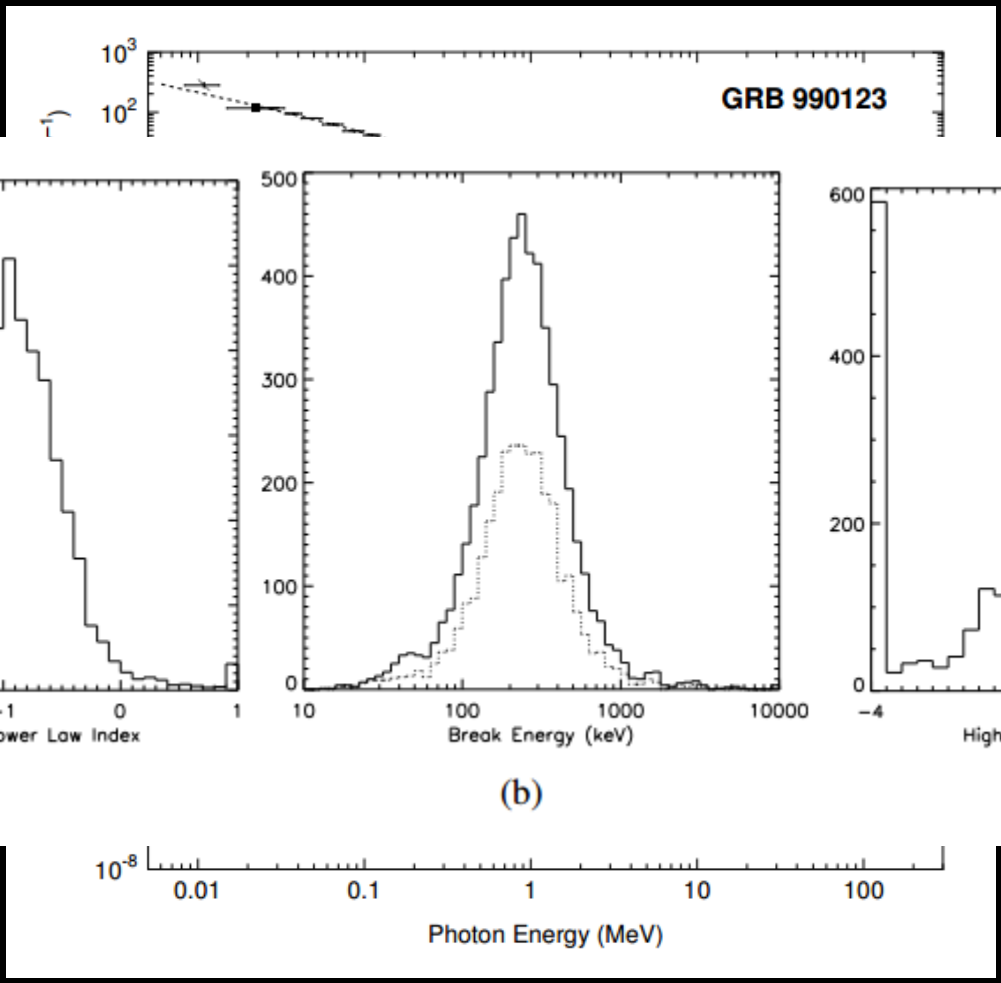
有單脈衝、多脈衝，有寧靜期





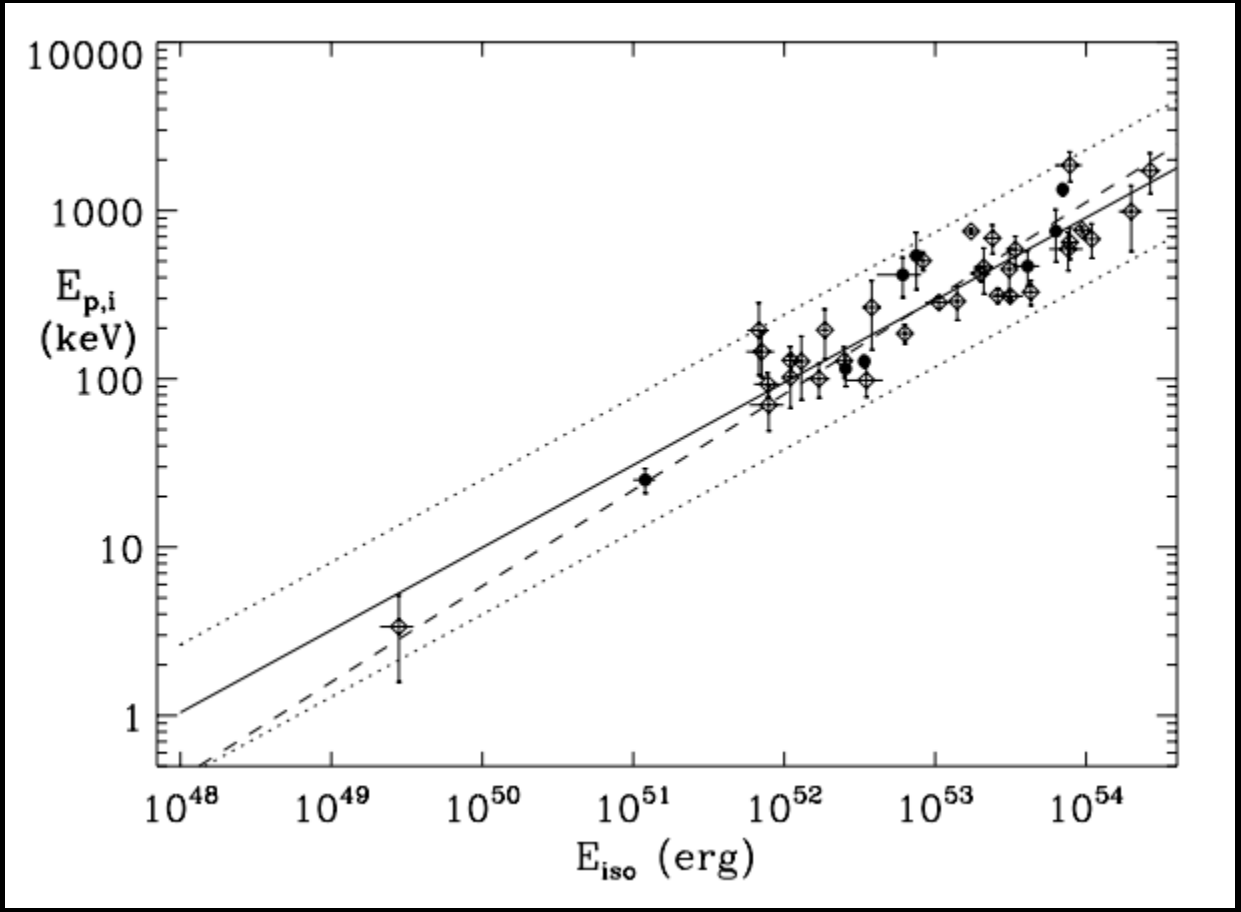
伽瑪暴的觀測特性 – 瞬時輻射

長暴能譜一般為band譜，短暴則為冪率譜或截斷冪律譜



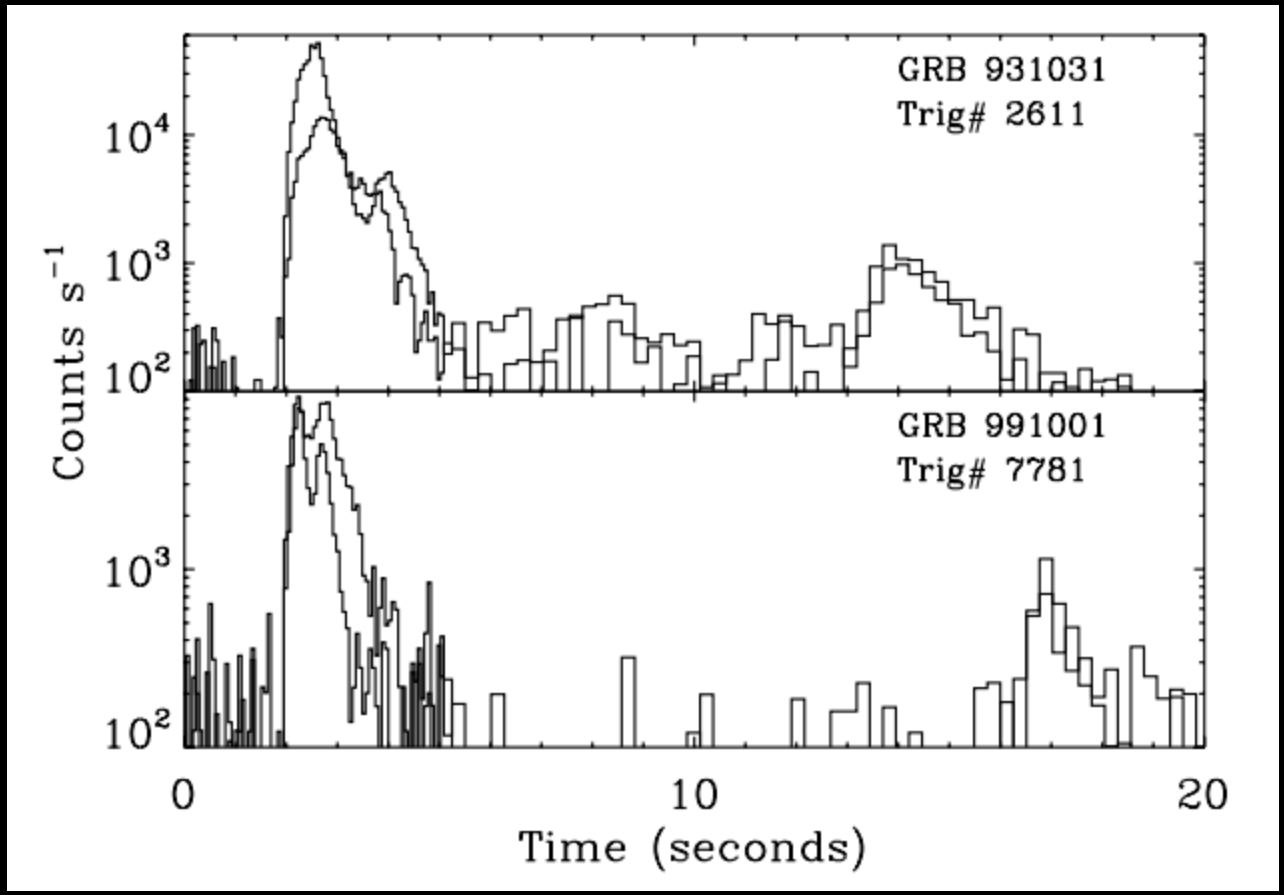
伽瑪暴的觀測特性 – 瞬時輻射

Amati關係



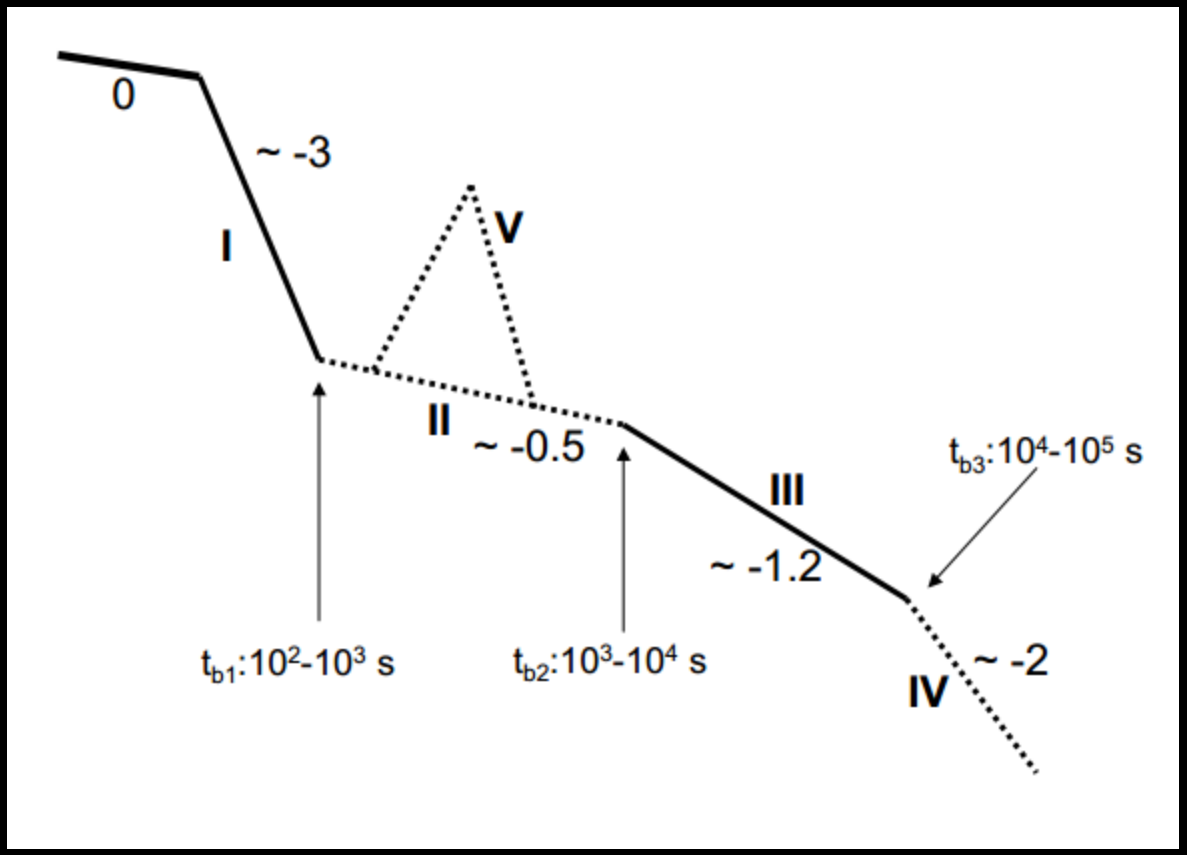
短暴的延展輻射

- 延展輻射的譜比較軟，甚至比長暴的譜都軟
- 延展輻射的能量時常可超過瞬時輻射



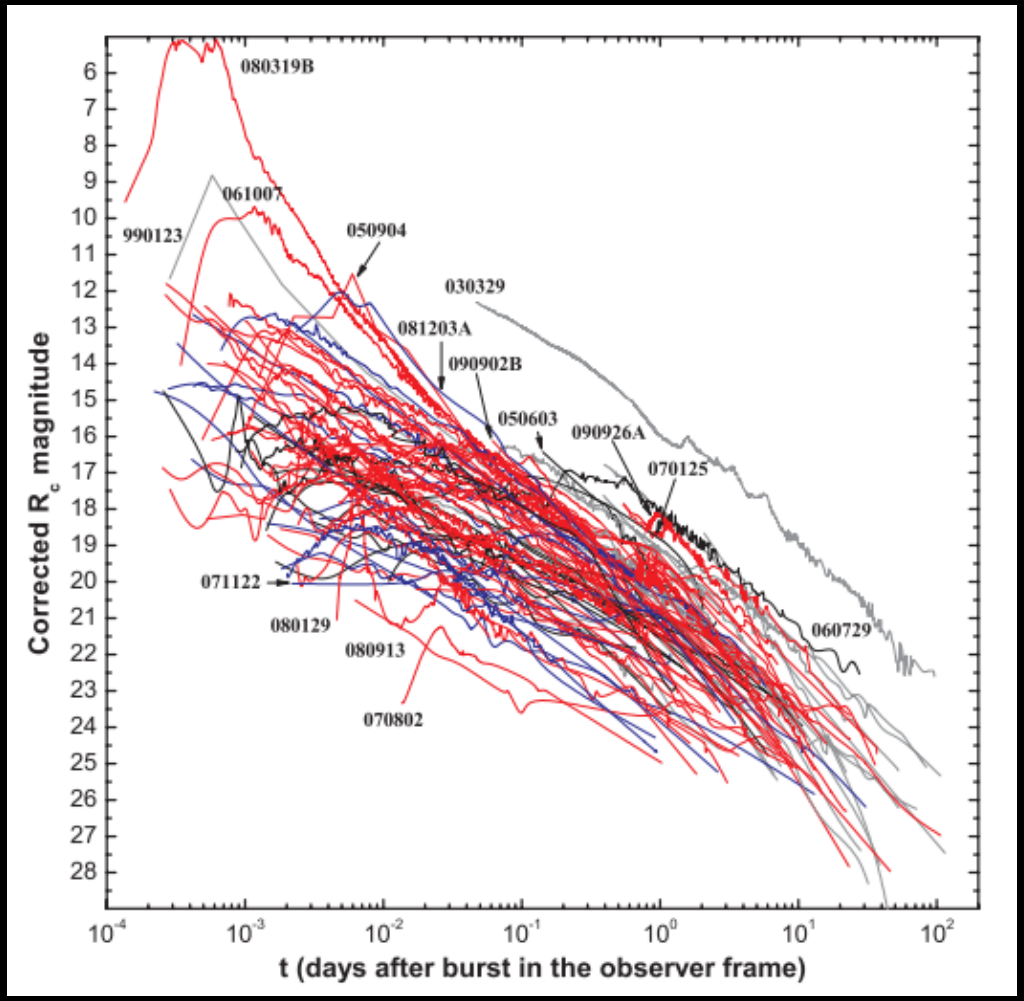
伽瑪暴的觀測特性 – 餘輝

X射線餘輝特征最多樣



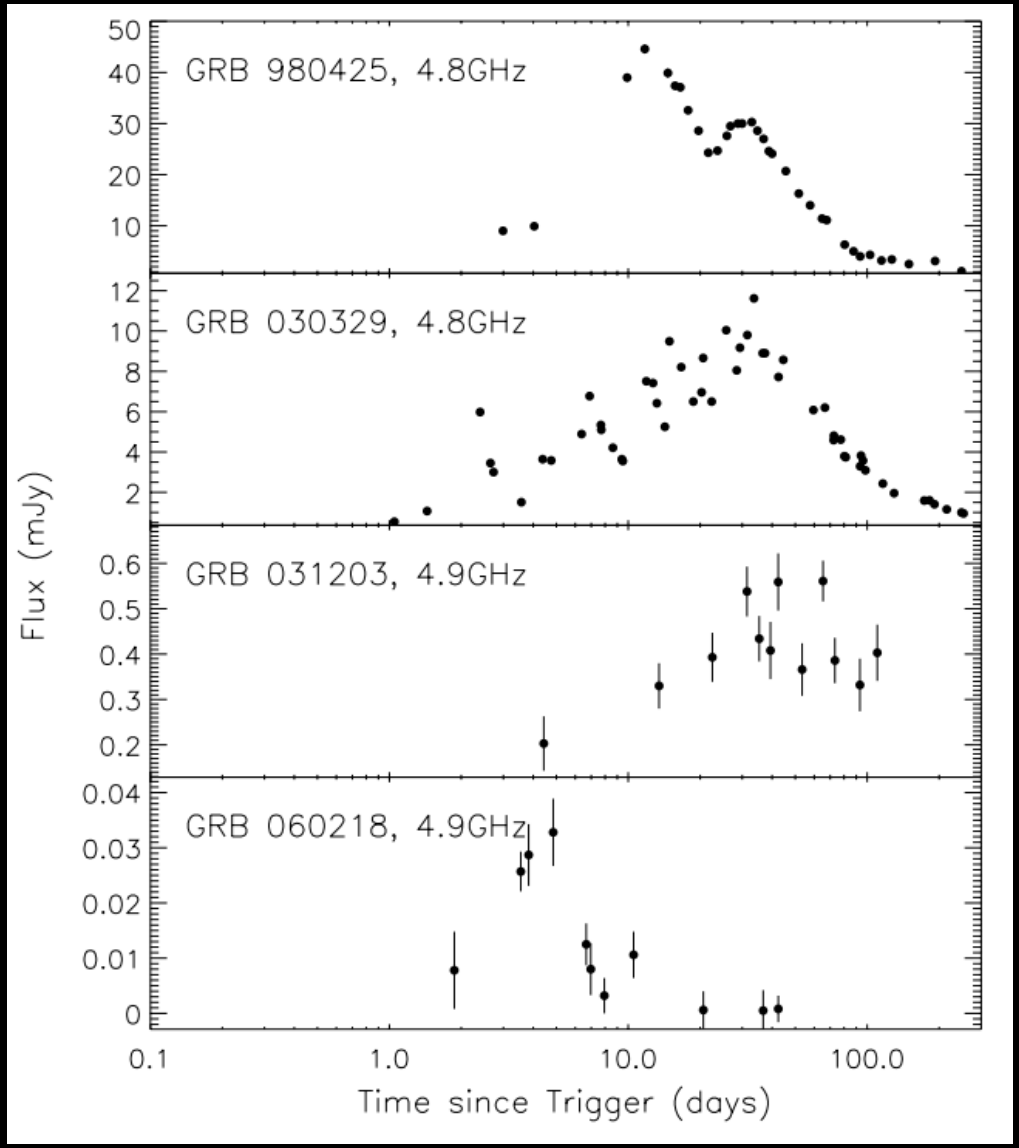
伽瑪暴的觀測特性 – 餘輝

光學餘輝也具有多樣性



伽瑪暴的觀測特性 – 餘輝

射電餘輝可達數年



長暴與短暴的特征比較

	短暴	長暴
基本特徵		
BATSE 觀測到的全天爆發率	$\approx 170\mathrm{yr}^{-1}$	$\approx 500\ \mathrm{yr}^{-1}$
BATSE 觀測到的本地爆發率密度	$\sim 10\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$	$\sim 0.5\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
宿主星系類型	早與晚	晚型
宿主星系比恒星形成率	$\lesssim 1\ \mathrm{M}_\odot/\mathrm{yr}/(\mathrm{L}/\mathrm{L}_*)$	$\sim 10\ \mathrm{M}_\odot/\mathrm{yr}/(\mathrm{L}/\mathrm{L}_*)$
觀測到的紅移中值	≈ 0.5	≈ 2
與超新星成協	否	是(至少部分如此)
前身星	NS-BH/NS-NS/?	大質量恒星
瞬時輻射		
典型的*BATSE* 持續時間	≈ 0.8 s	≈ 30 s
最佳譜擬合模型	冪率+ 指數截斷	Band 函數
$E_{\gamma,\mathrm{iso}}$	$10^{49} - 10^{51}$ erg	$10^{52} - 10^{54}$ erg
$L_{\gamma,\mathrm{iso}}$	$10^{50} - 10^{52}$ erg/s	$10^{50} - 10^{52}$ erg/s
觀測到的平均流量密度	$\sim 5 \cdot 10^{-10}\ \mathrm{GeV/cm^2/s/sr}$	$\sim 10^{-8}\ \mathrm{GeV/cm^2/s/sr}$
本地能量輸出率	$\sim 10^{51}\ \mathrm{erg\ Gpc^{-3}\ yr^{-1}}$	$\sim 10^{53}\ \mathrm{erg\ Gpc^{-3}\ yr^{-1}}$
輸出的總能量	$\sim 10^{63}$ erg	$\sim 10^{66}$ erg
X射綫餘輝		
X射綫暗	部分暴	沒有
正常衰減($\sim t^{-1}$)	是	是
緩慢衰減($\sim t^{-0.25}$)	是	是
X射綫耀發	是	是
火球模型		
洛倫茲因子	$\gtrsim 30$	$\gtrsim 100$
瞬時輻射能源	內部機制	內部機制
餘輝能源	外激波	外激波
同步自康普頓	$Y \ll 1$	$Y \gtrsim 1$
早期餘輝與瞬時輻射	明顯分離	有可能重疊
早期餘輝(重子流)	光學暗	光學明亮
伽瑪射綫效率	$\sim 10\%$	$\gtrsim 10\%$
X射綫暗的餘輝	$n \lesssim 10^{-5}\ \mathrm{cm}^{-3}$	-
平均噴流因子	$1 < f_b^{-1} \lesssim 100$	$f_b^{-1} \sim 75$

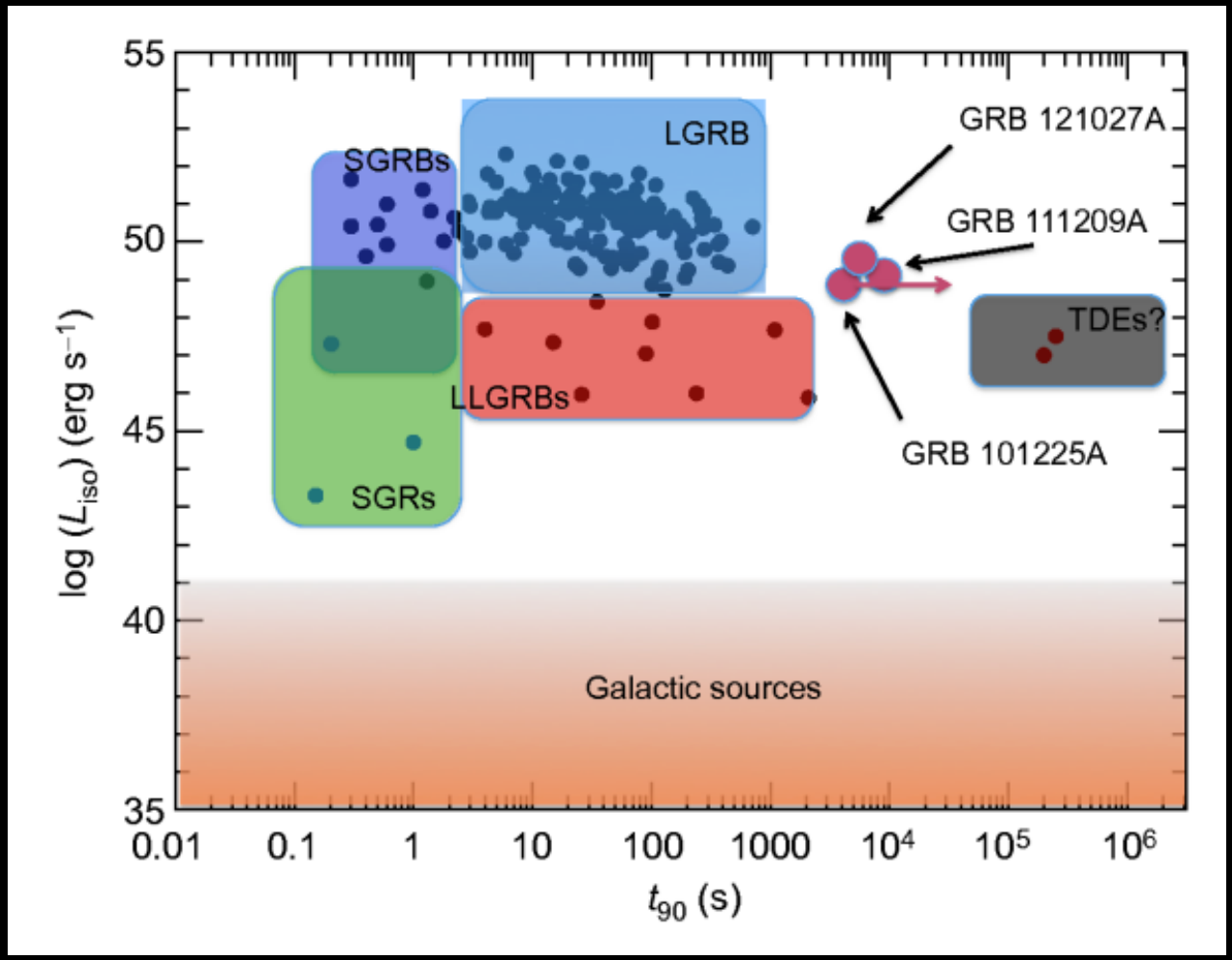
伽瑪暴的觀測特性 – 環境

- 長暴平均紅移<z> = 2
- 宿主星系為漩渦星系或不規則星系
- 一般位於星系的恆星形成區

1. 短暴平均紅移<z> = 0.5
2. 宿主星系為橢圓星系或漩渦星系或不規則星系
3. 一般位於星系的外圍
4. 相當一部分短暴無法確定宿主星系

特殊類型伽瑪暴

超長暴、低光度伽瑪暴



伽瑪暴的非典型特征

- 暗暴：沒有光學餘輝
- 帶有延展輻射的短暴
- 未觀測到超新星成份的幾個近鄰長暴：GRB 060614、GRB 060505、GRB 111005

目前亟待解決的問題

- 中心引擎
- 短暴延展輻射
- 噴流：是否磁化？結構如何？能源機制？
- GRB-SNe：中心為磁星還是黑洞？光變曲線由磁星驅動還是鎳驅動？爆發能問題？
- 宇宙線是否與伽瑪暴有關？

谢谢！