The GRB-SN connection:

"Constraining GRB-SNe progenitors with multi-wavelength observations"

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- Introduction/Background

- Current Research

- Future Research

Background : Supernovae

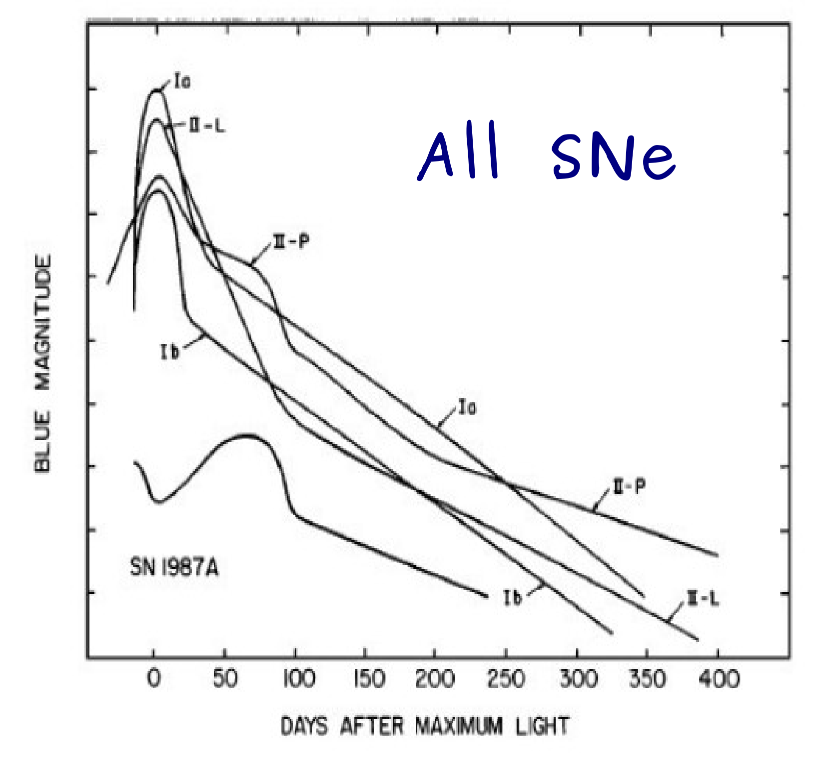
- Two Types of Supernovae (Physically):
  - Thermonuclear Detonation of white dwarf (Ia)
  - Gravitational Core-Collapse (CC) of massive stars (types II, Ib, Ic)

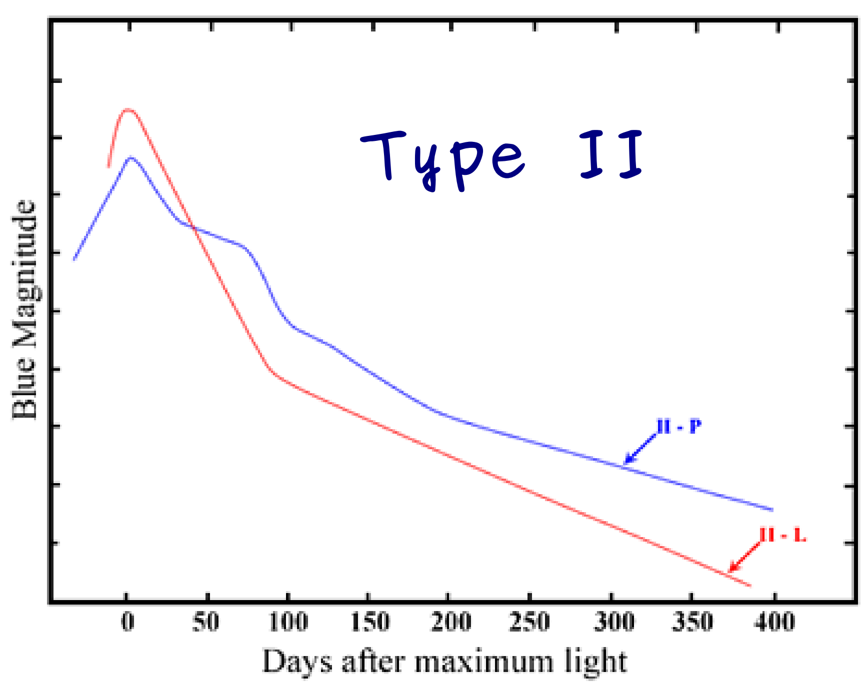
- Two Types of Supernovae (Observationally):
  - Type I: No H lines in spectra
    - Ia: No H but Si lines
    - Ib: No H, some He
    - Ic: No H, little or no He
  - Type II: Hydrogen present in spectra
    - Further sub-classes depending on LC shape.

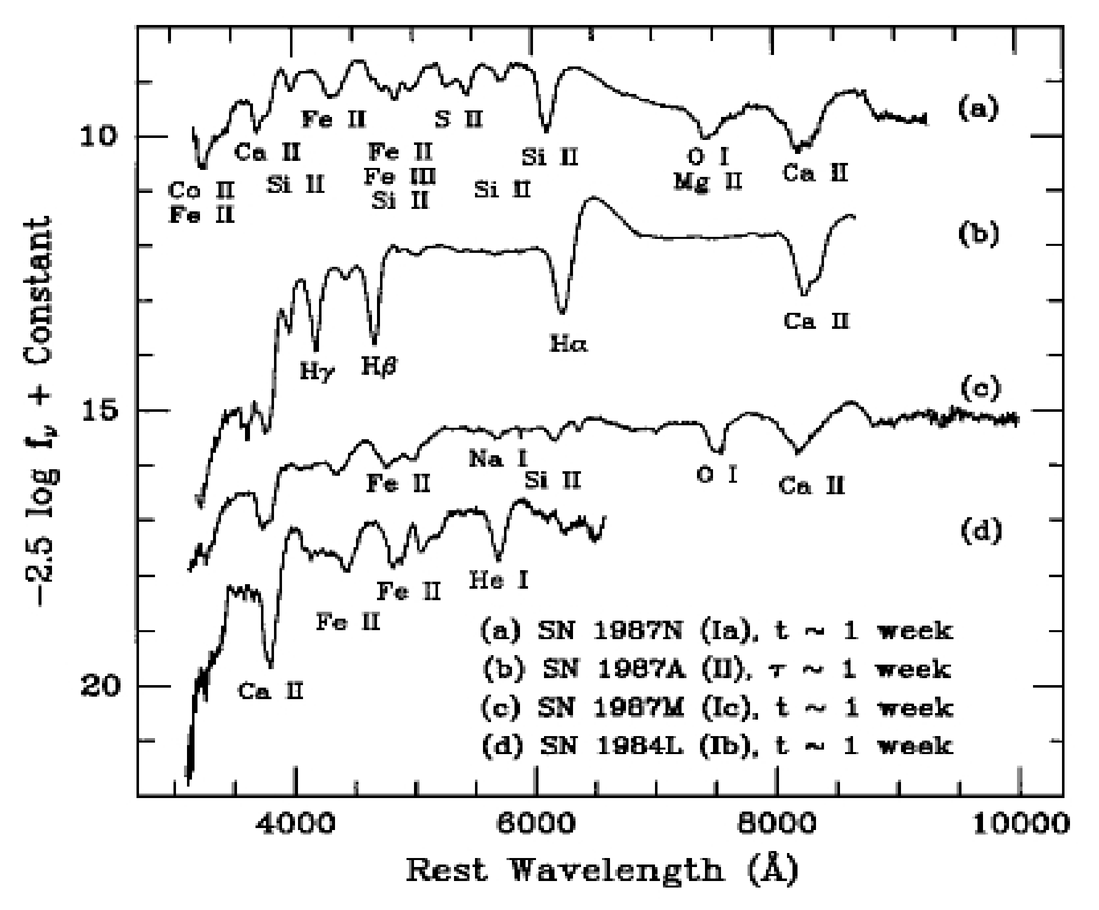
Type Ia Supernova Scenario

Core-Collapse Supernova Scenario

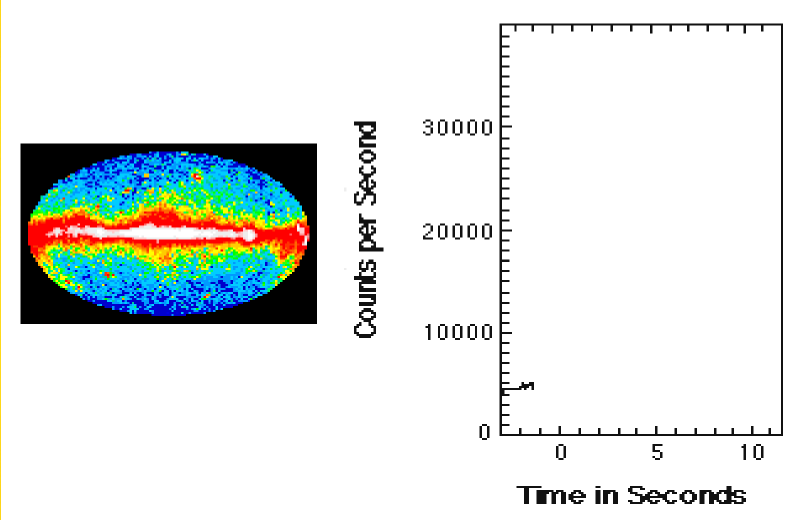
SNe LCs & Spectra

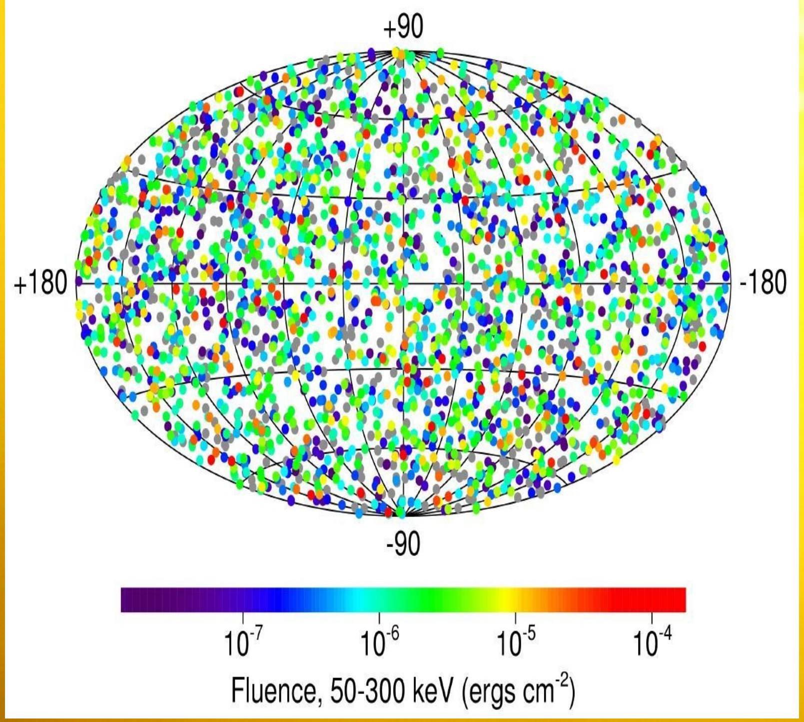


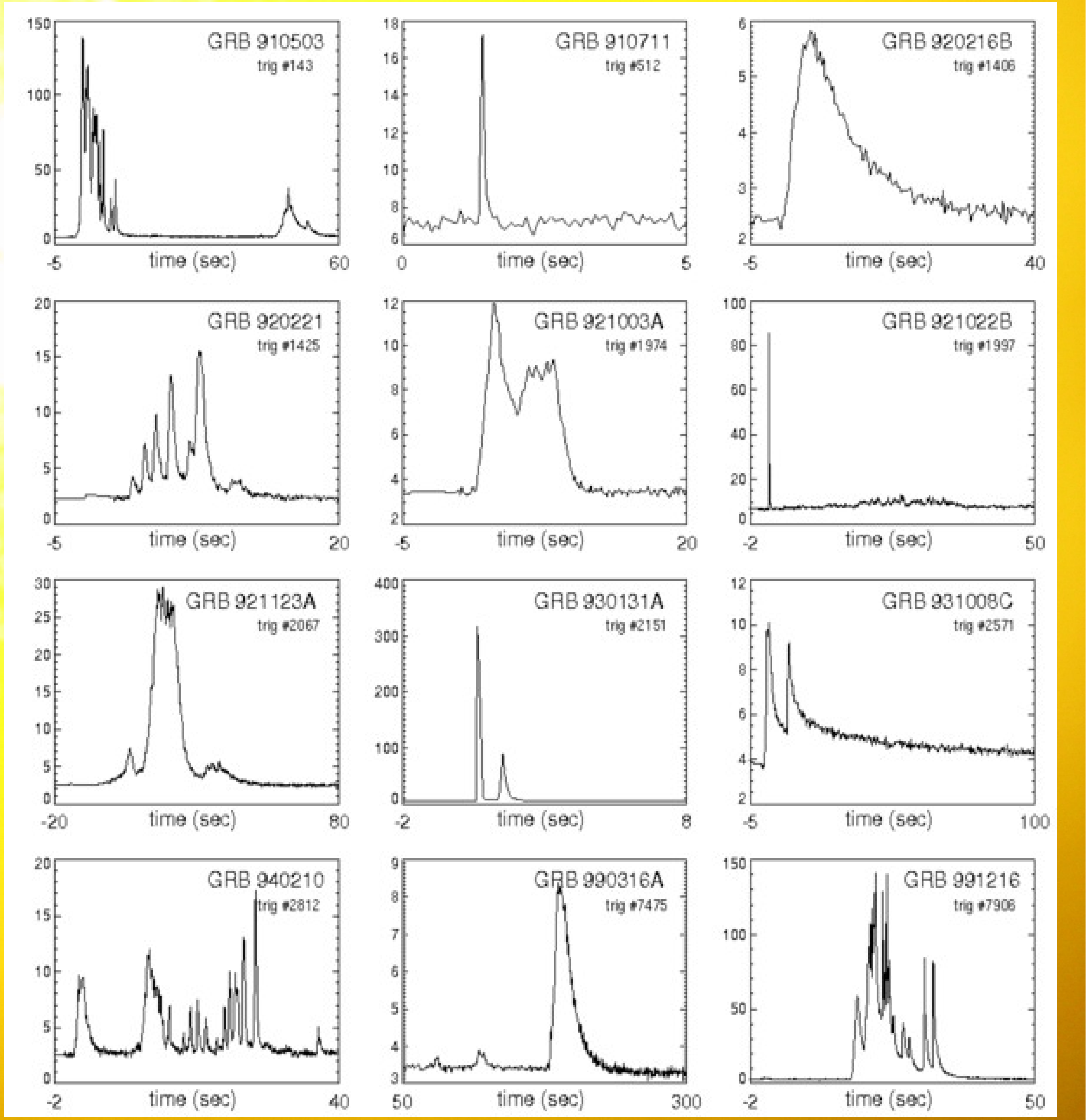




Background : Gamma Ray Bursts

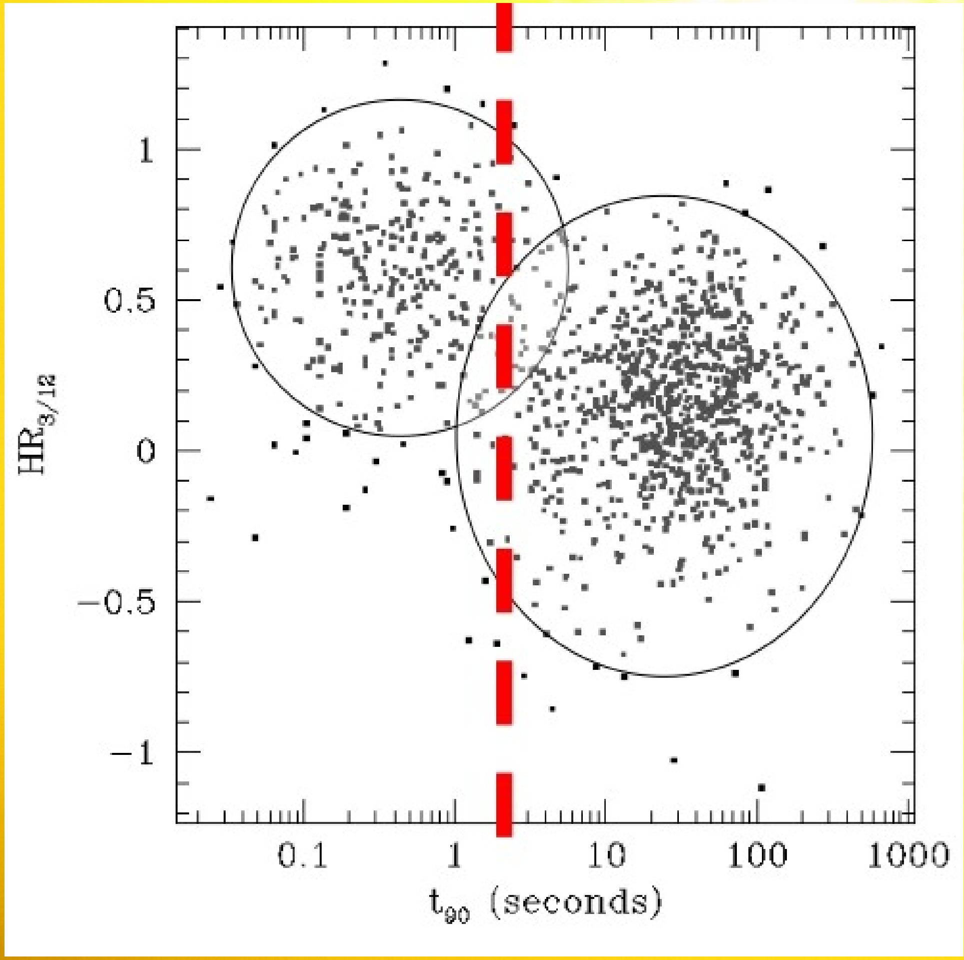


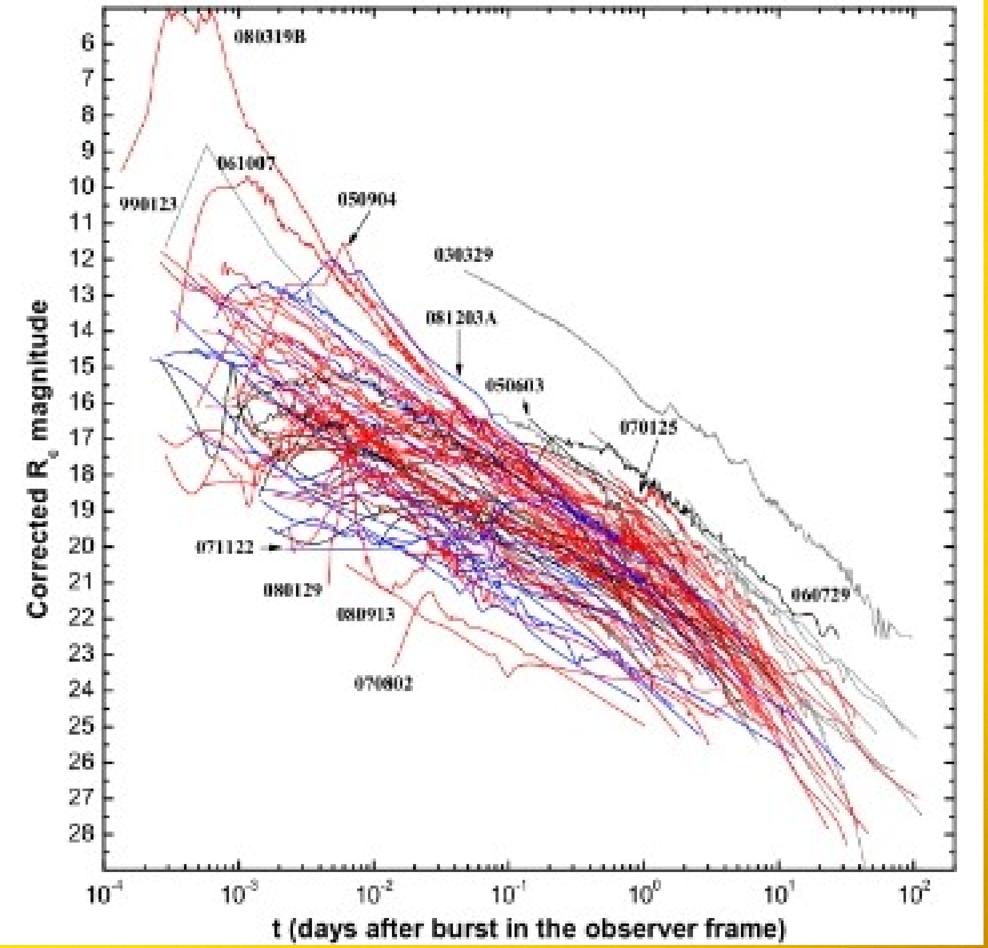




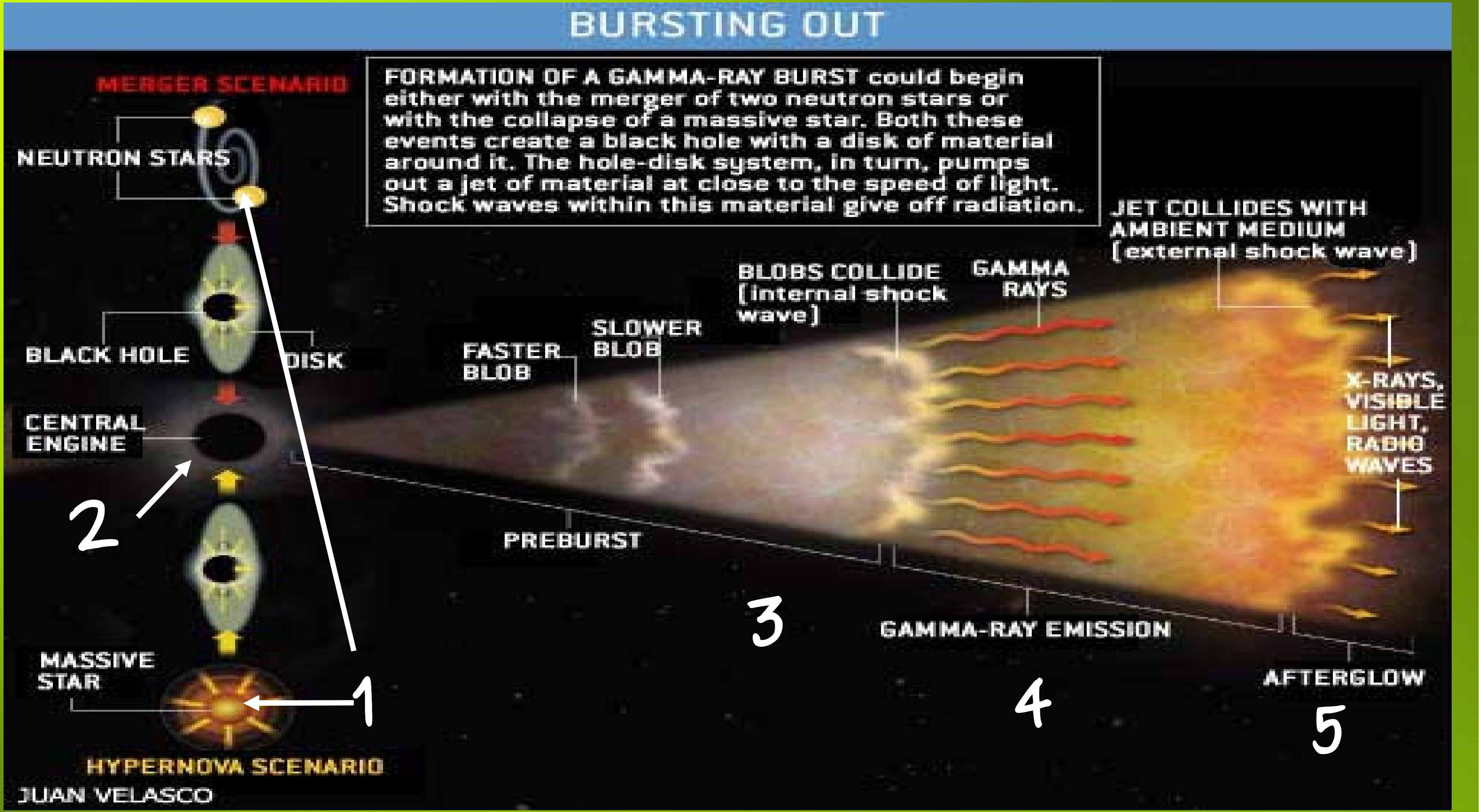
Background : Gamma Ray Bursts

$T_{90} = 2$ s



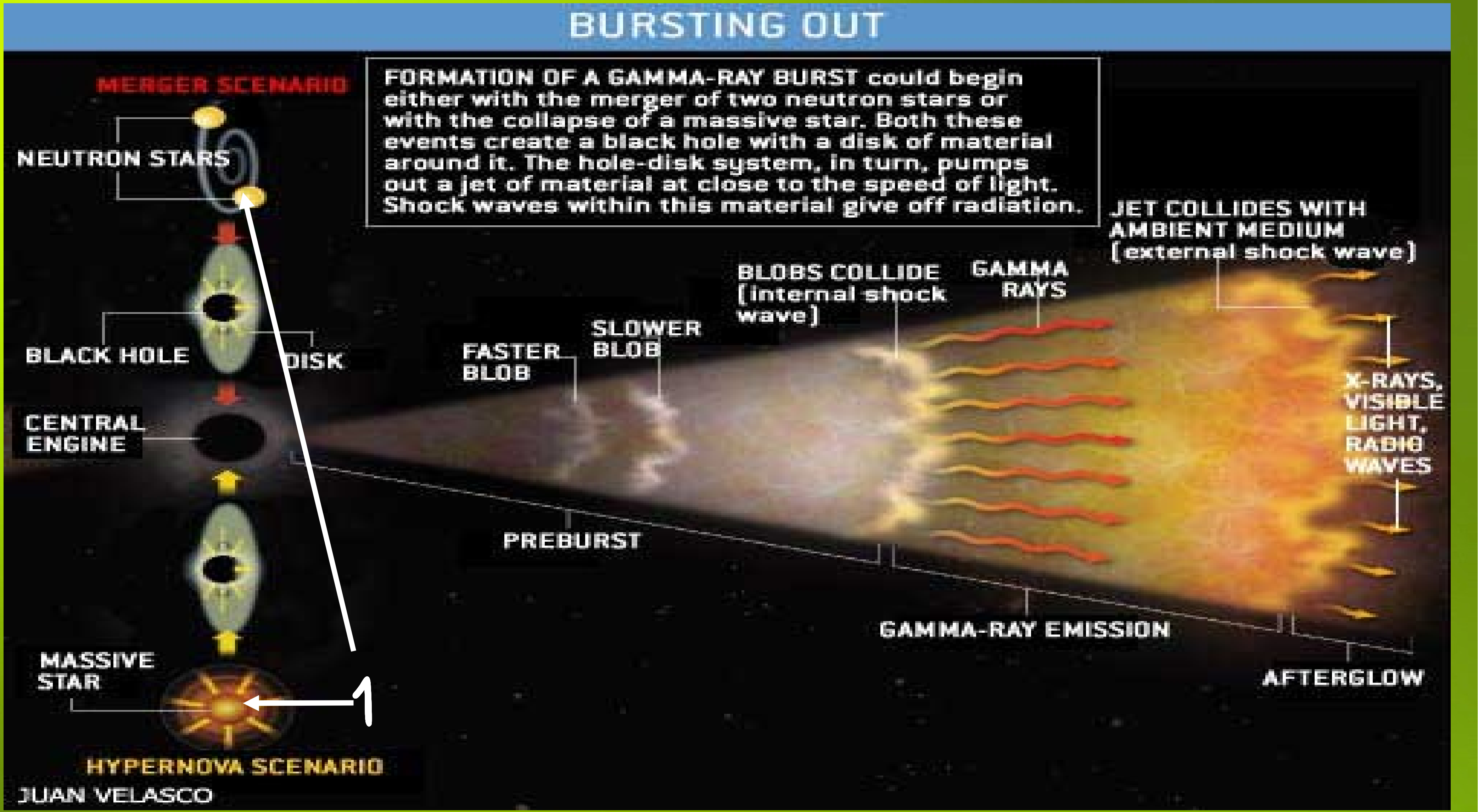


Short | Long



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.

1. Progenitor
2. Central Engine
3. Outflow properties
4. Prompt emission (gamma,x-rays)
5. Afterglow (x-rays,optical,UV,IR,Radio)



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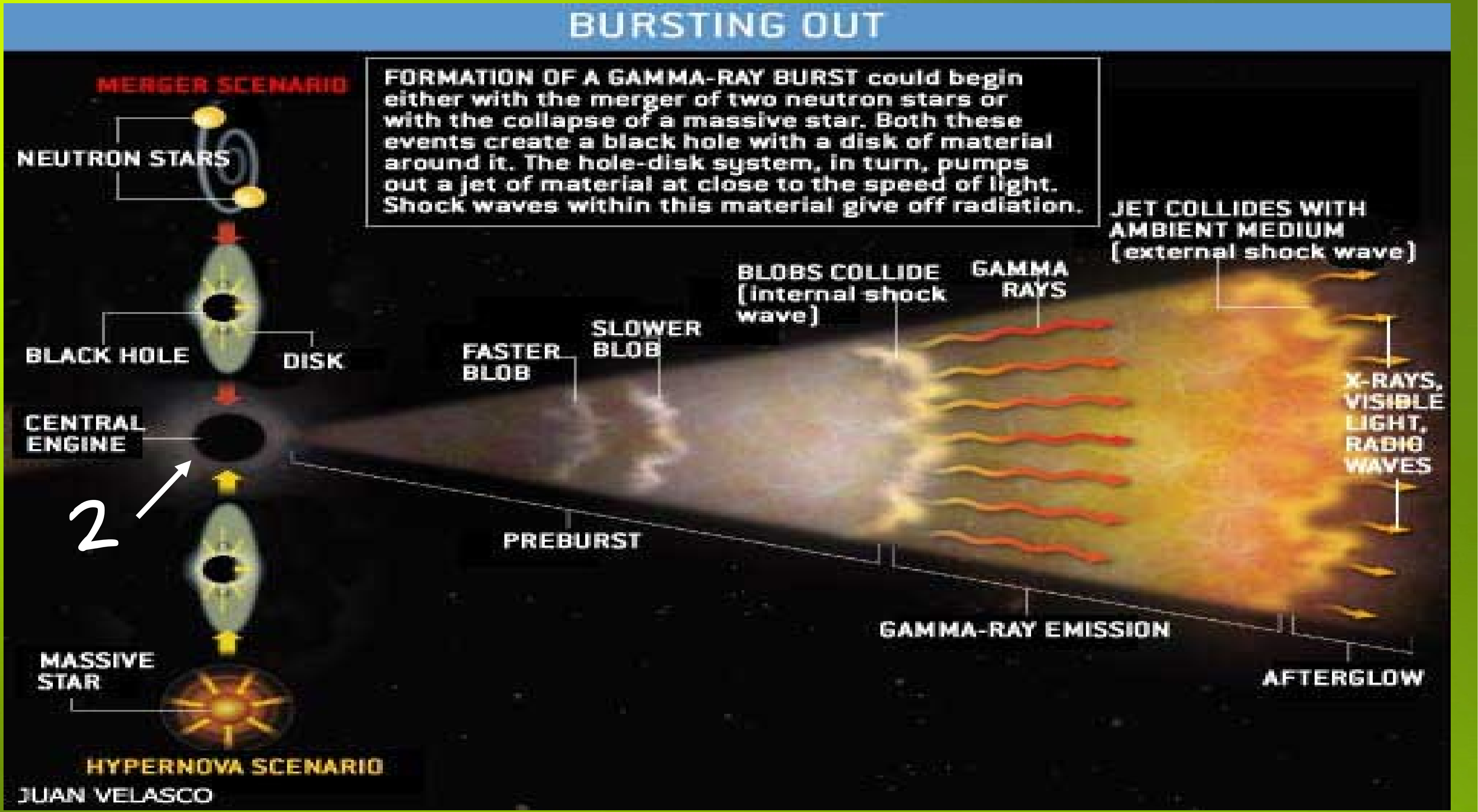
1. Progenitor

GRB : Progenitor Scenarios

Short GRB : Merger of compact objects

GRB : Progenitor Scenarios

Long GRB : Collapse of a massive star



BURSTING OUT

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2. Central Engine

GRB : Central Engine

Two popular models:

(1) Accretion near the neutrino Eddington Limit on a stellar black hole

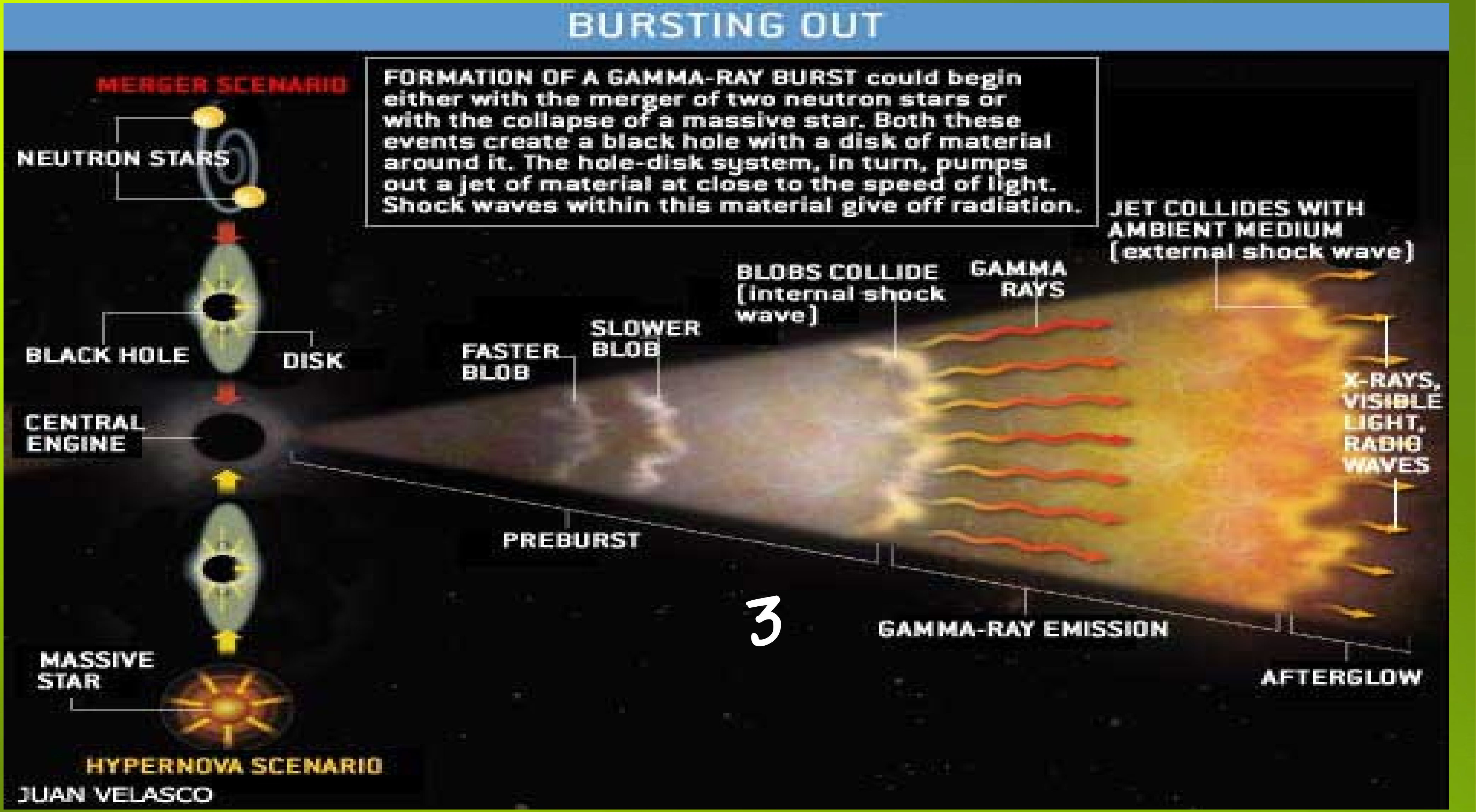
Pros: Similar accretion (at lower rates) is known for AGN and micro-quasars.

Cons: Many unknowns in the way the engine works.

(2) Millisecond Magnetar

Pros: Once formed, the physics of the outflow launching is better understood and provides late-time engine activity.

Cons: Severe disadvantage is the limited energy of 5×10^{52} ergs.



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3. Outflow properties

GRB : Outflow Properties

The outflow is relativistic.

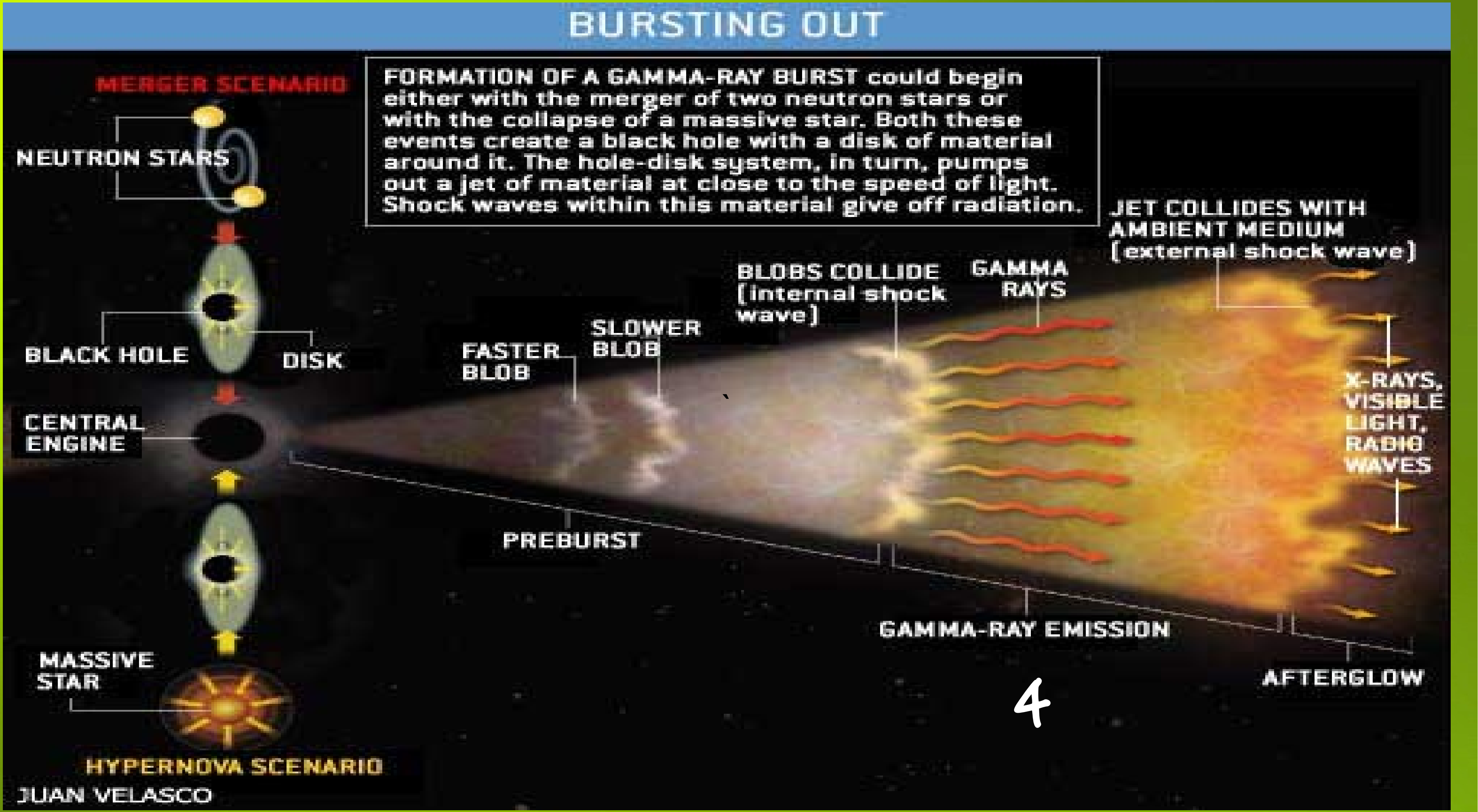
Main evidence from the requirement for low $\gamma\gamma \longrightarrow e^-e^+$ optical depth.

Emission in rest-frame is X-rays, detected at Earth a Gamma-Rays.

Also certain that at least some long GRB outflows are narrowly beamed.

Main open questions:

(1) Actual Lorentz Factor of outflow?
(2) What is the outflow geometry?
(3) What component is the most dominant? Baryonic or Poynting-Flux?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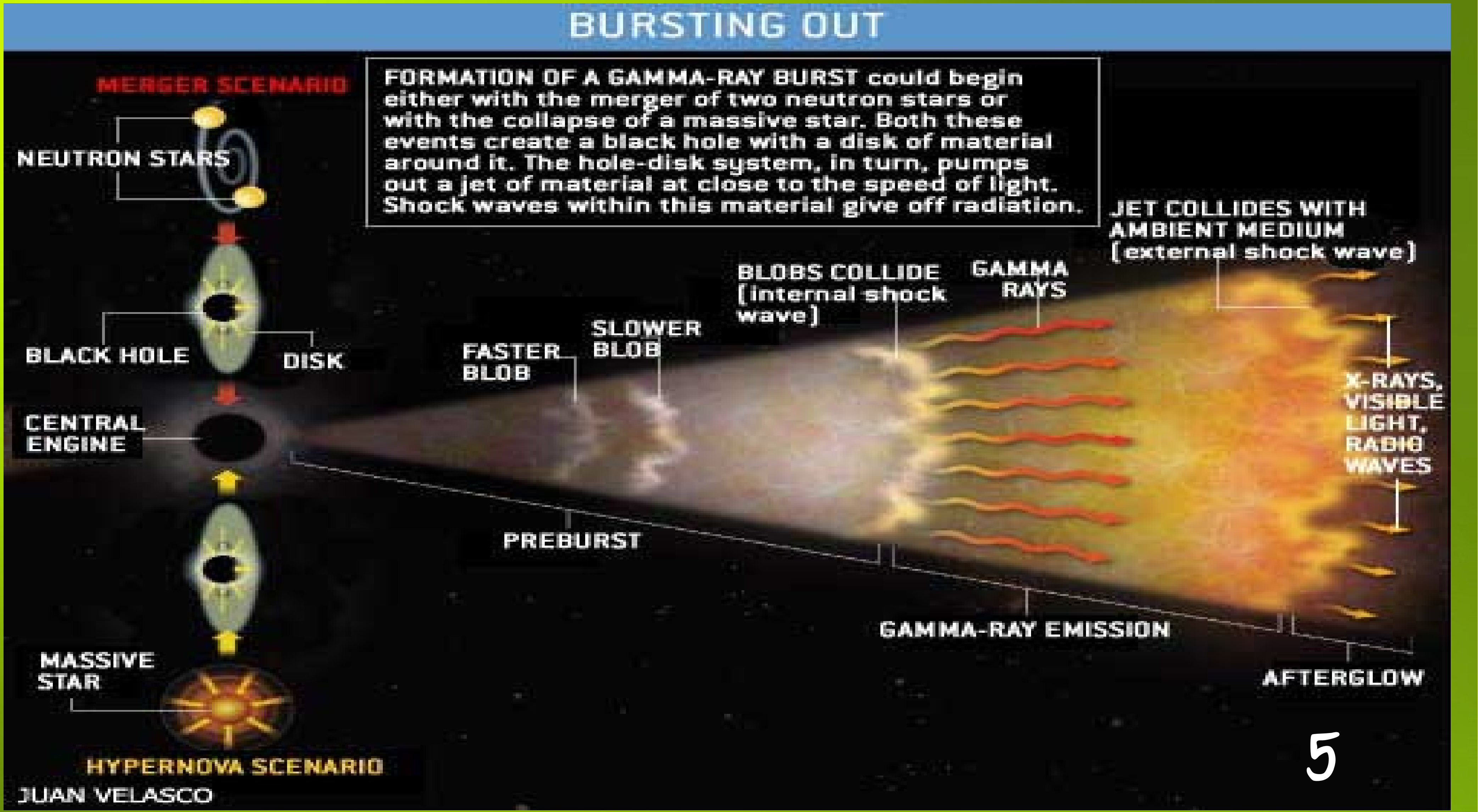
4. Prompt emission (gamma,x-rays)

GRB : Prompt Emission

Popular Model

The popular model is the internal shock model, where the outflow is dissipated by Hydrodynamical shocks created by the collision between "blobs" of material in the outflow.

Electrons in the collimated outflow are accelerated by the shocks, which cool, radiating the energy in the form of synchrotron radiation.



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5. Afterglow (x-rays,optical,UV,IR,Radio)

GRB : Afterglow

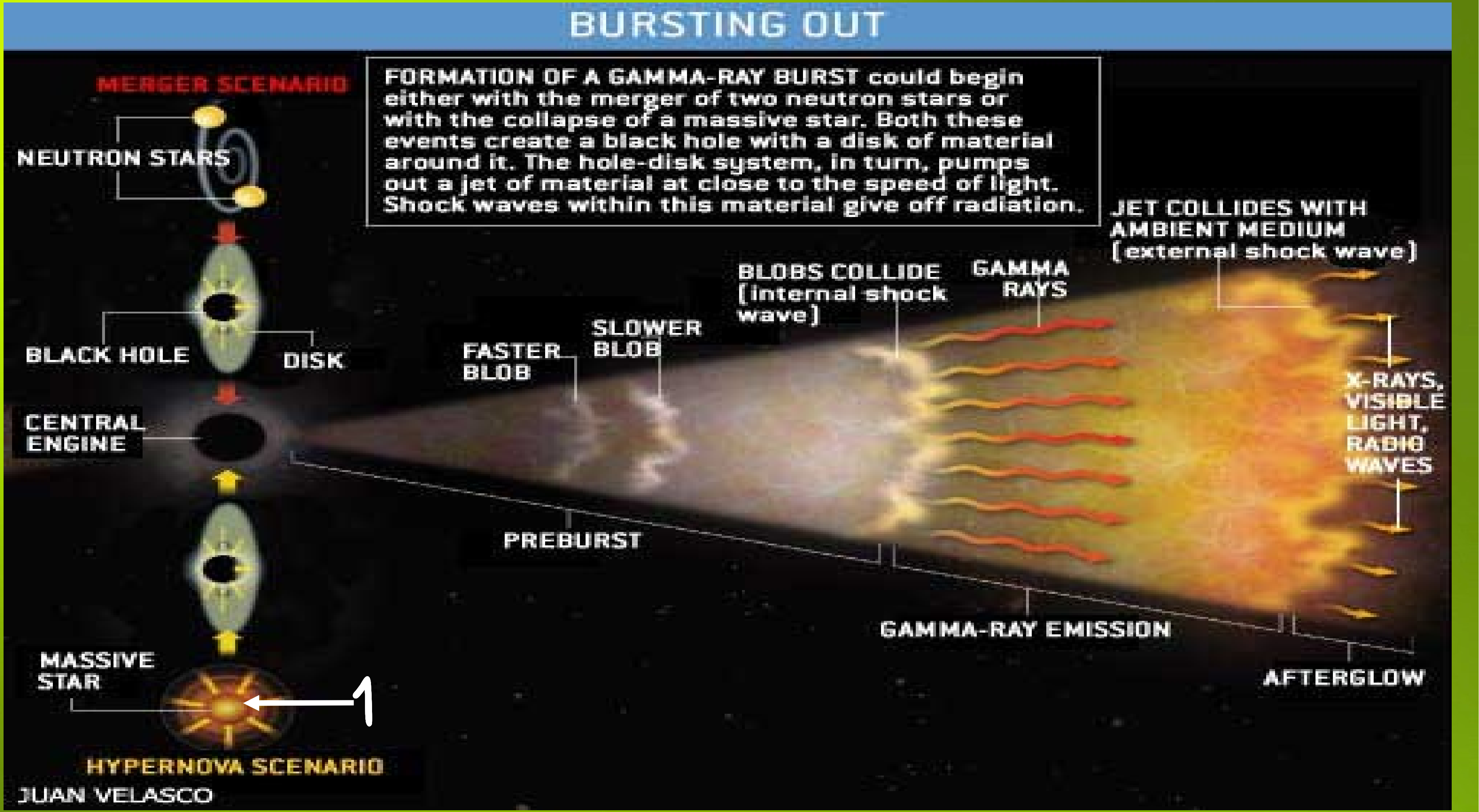
The late afterglow (X-ray, UV, optical, IR, Radio) is generated during the interaction of the collimated outflow with the circumburst medium.

Most popular model is the external forward shock model:

Electrons in the surrounding material are accelerated by the forward shocks, and radiate the energy as synchrotron radiation. The flux in the afterglow follow a power-law decay, both temporally (t) and spectrally (ν).

$$\text{flux} \propto t^{-\alpha}\ \nu^{-\beta}$$

GRB : Afterglow



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1. Progenitor (Long GRBs)

GRB – SN Connection

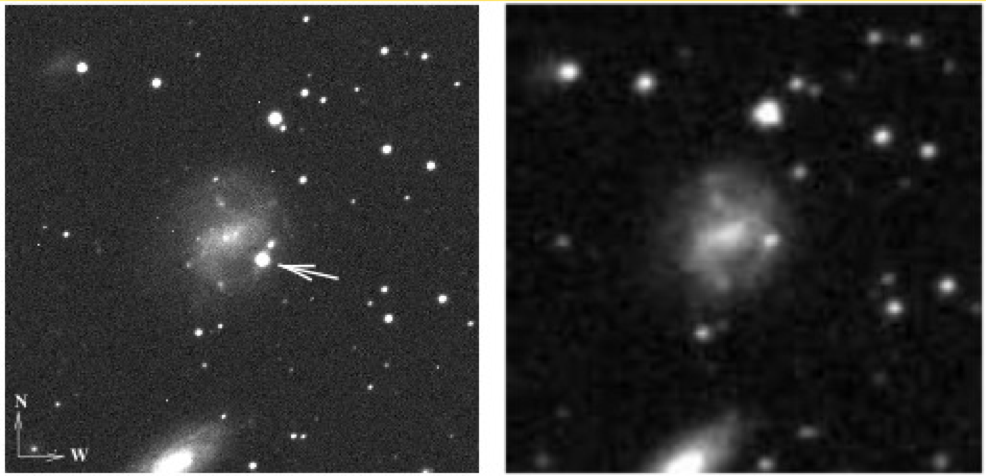
Long GRBs (L-GRBs) are thought to occur during the collapse and SNe of a massive star into a NS or BH.

So far five type Ic SNe have been spectroscopically connected to long-GRBs and XRFs:

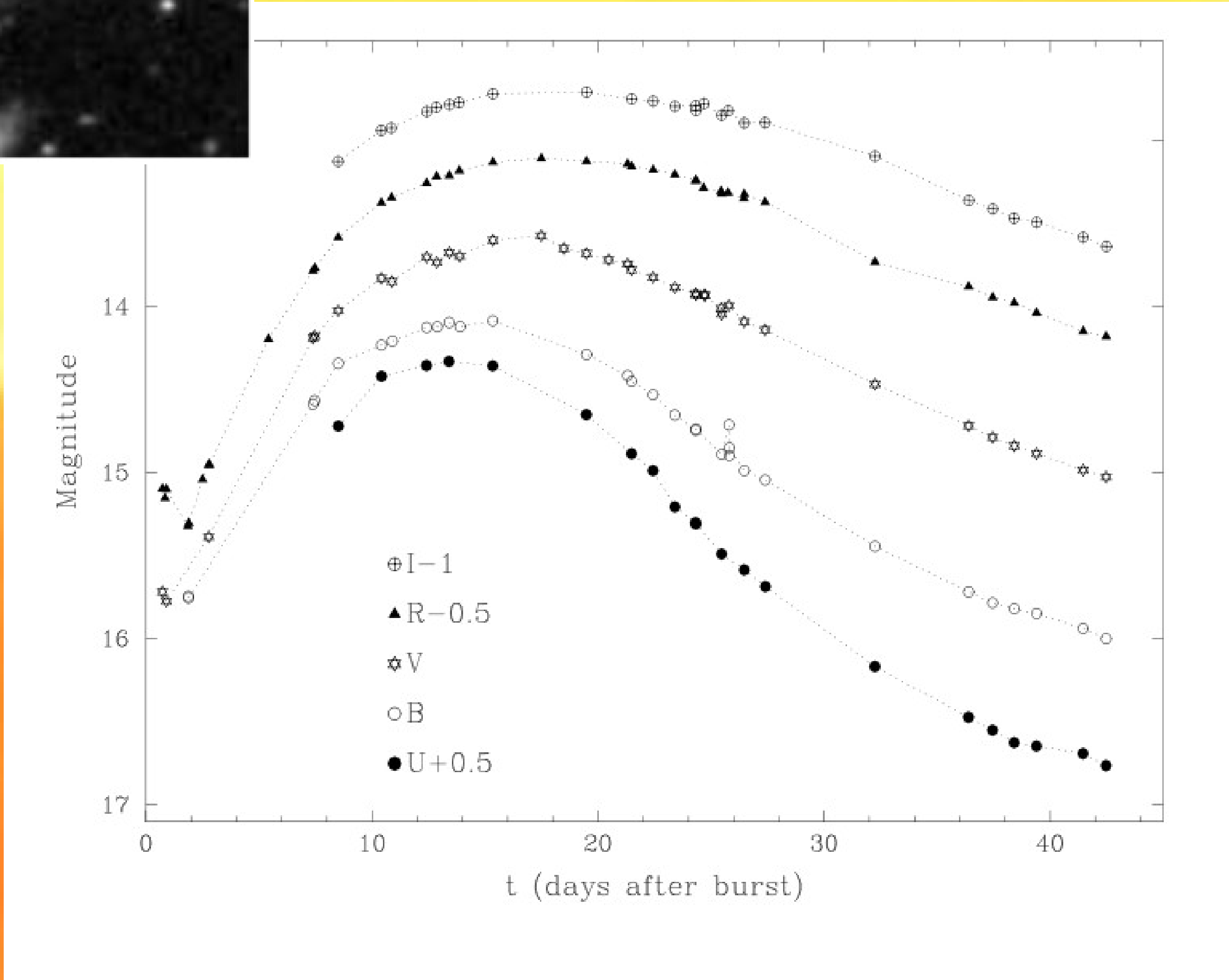
GRB	980425	/	SN	1998bw
GRB	030329	/	SN	2003dh
GRB	031203	/	SN	2003lw
XRF	060218	/	SN	2006aj
XRF	100316D	/	SN	2010bh

All of the SNe are extremely energetic (> 10^{52} erg), leading to them being dubbed "Hypernovae".

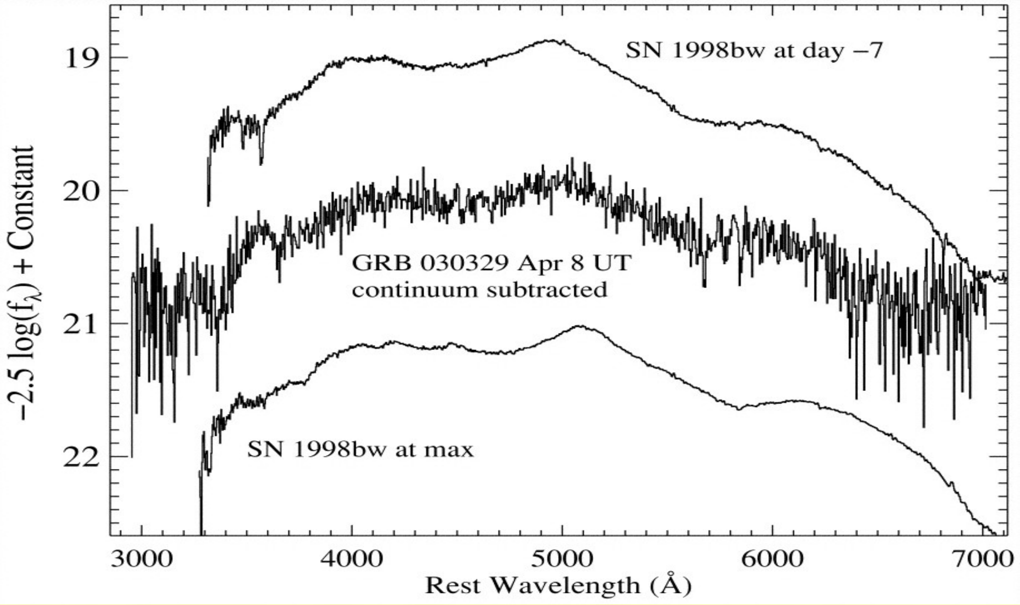
GRB – SN Connection: GRB 980425



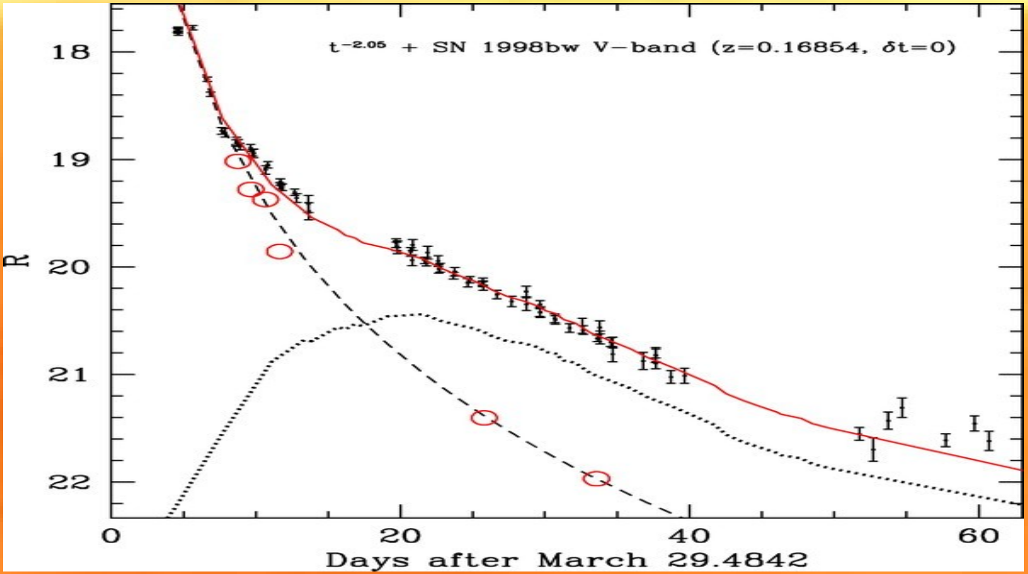
Galama et al. 1998



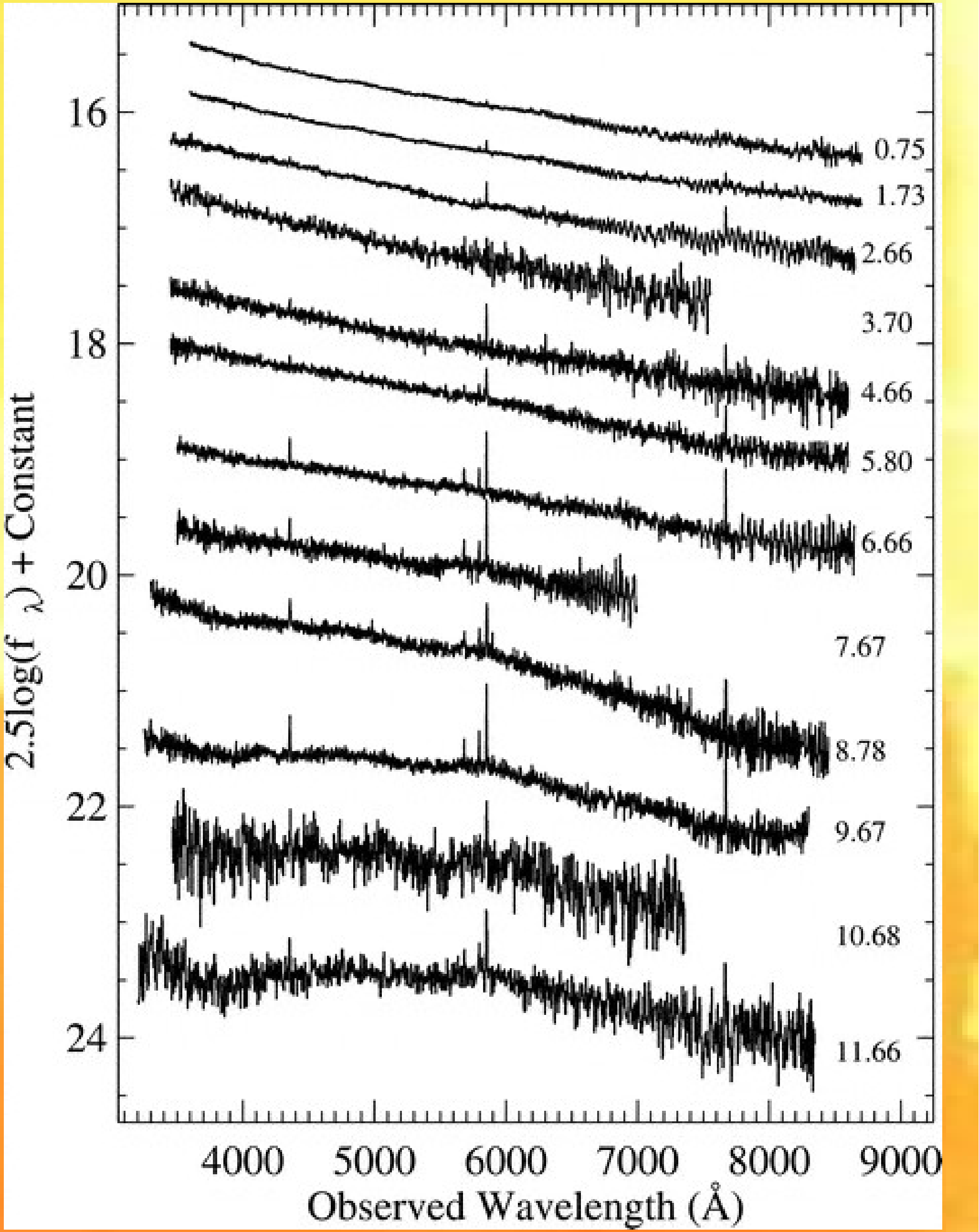
GRB – SN Connection: GRB 030329



Stanek et al. 2003



Matheson et al. 2003



Matheson et al. 2003

GRB – SN Connection

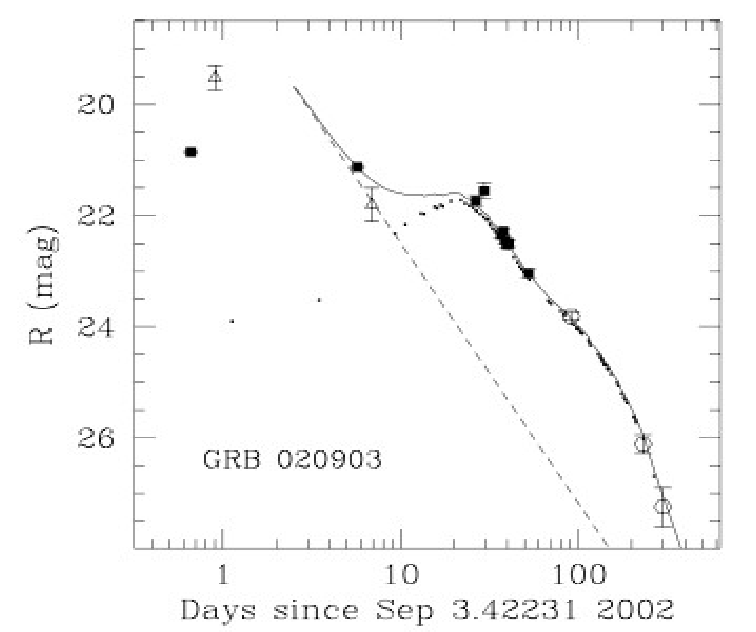
In addition to the spectroscopic connection, numerous photometric inferences have been seen.

(1) Late-time "bumps" in optical/NIR LCs.

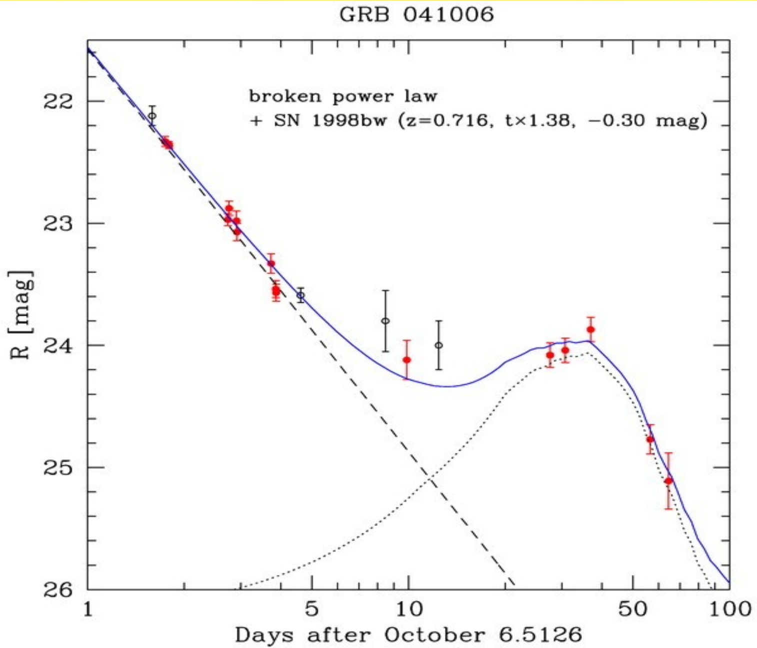
(2) Colour changes indicative of light coming from a core-collapse SN.

(3) Late-time spectrum similar to SN 1998bw.

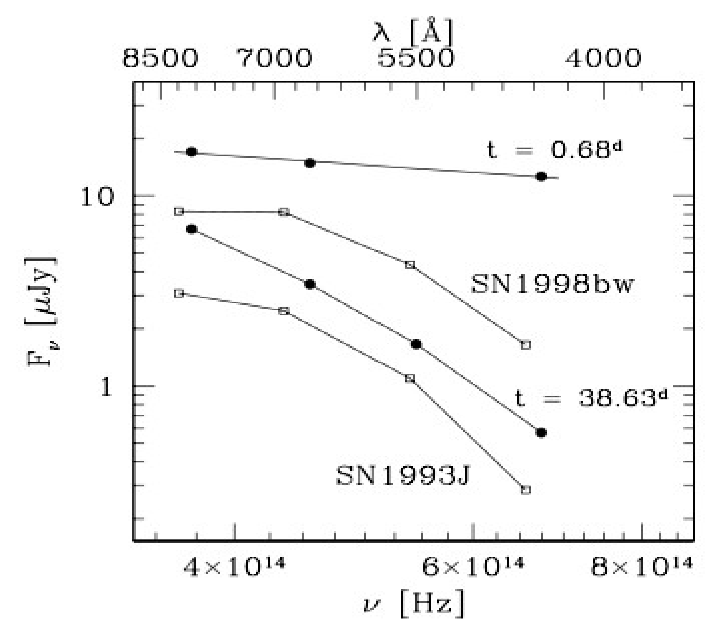
GRB – SN Connection: SN Bumps



Bersier et al. 2006



Stanek et al. 2005



…many red bumps seen in the literature, but these bumps are usually not very well sampled.

GRB - SN Connection

Many questions remain:

(1) For all of the GRB-SNe apart from GRB 030329, the GRBs are intrinsically *under-luminous.*

(2) Many events defy explanation:

  (1) XRT 080109 - Shock breakout?

  (2) GRBs 060505 & 060614 - no SNe.

  (3) Through modelling it appears some events form a BH (980425,031203), while others form only a NS.

GRB - SN Connection

So while the GRB-SN Connection has been established, many questions still remain:

(1) What kind of progenitors produce these events?

(2) Are the progenitors all the same?

(3) Why do some massive stars form a GRB/XRF while most do not?

...Thus more data is needed to address these questions...

GRB 060729

Detected by Swift on July 29, 2007. (Grupe et al. 2006)

T90 = 115 s

z = 0.54 (Thoene et al. 2006; Fynbo et al. 2009)

Had a remarkably bright X-ray afterglow that was still visible 430 days after the initial trigger (Grupe et al. 2010)

Plateau phases seen in X-ray, UV and optical LCs, which was attributed to prolonged activity by the central engine (Xu et al. 2008)

GRB 060729

Procedure:

(1) Optical photometry collected on HST & Ground-based telescopes

(2) Image subtraction on HST images (subtract host flux from Ground-based images)

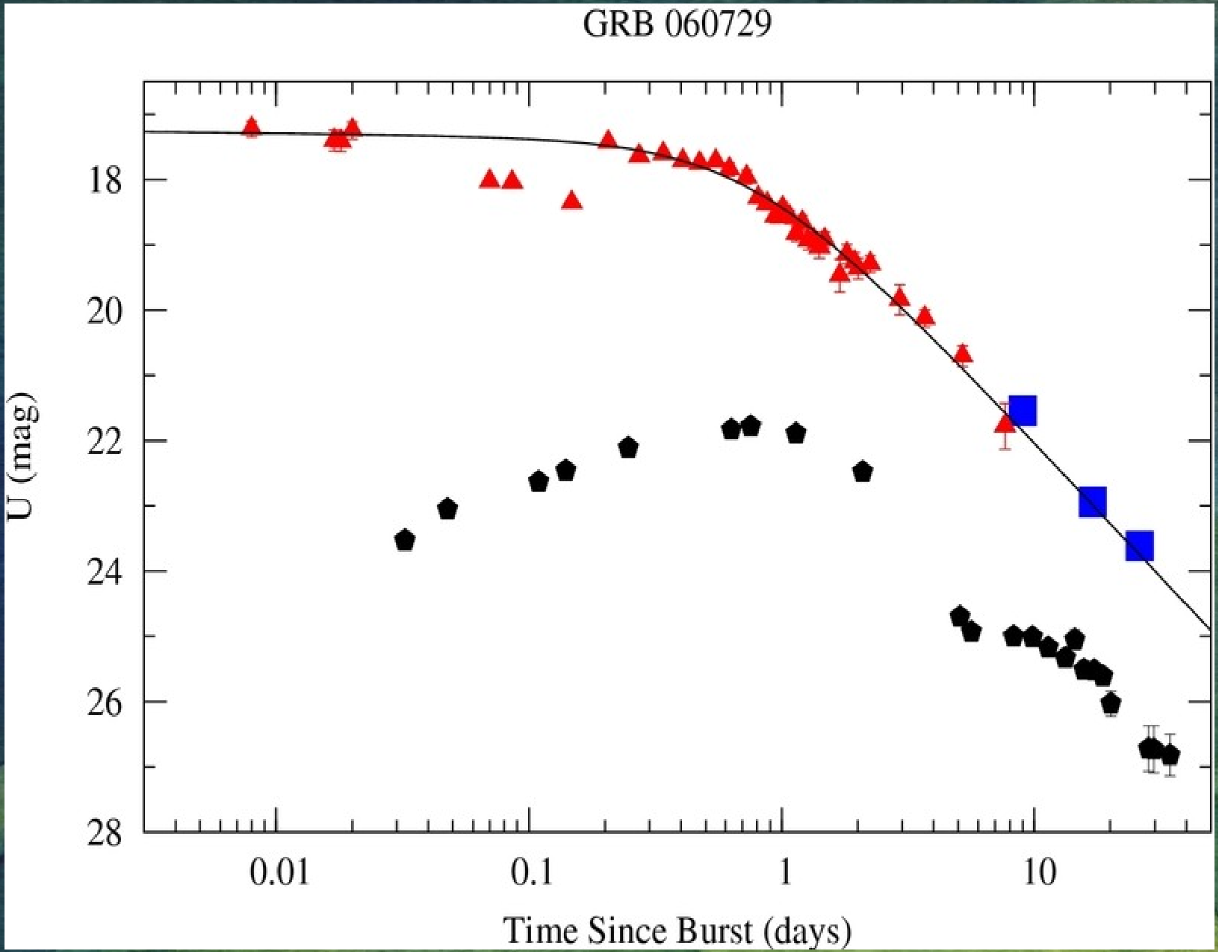
(3) Model afterglow & subtract from the host-subtracted LCs to make "SN" LCs

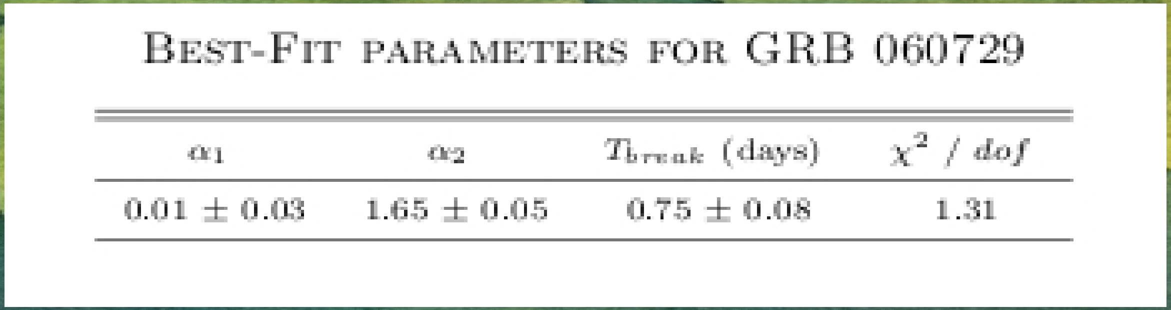
Important

Three sources of flux for the event:

HOST, AFTERGLOW, SUPERNOVA

GRB 060729





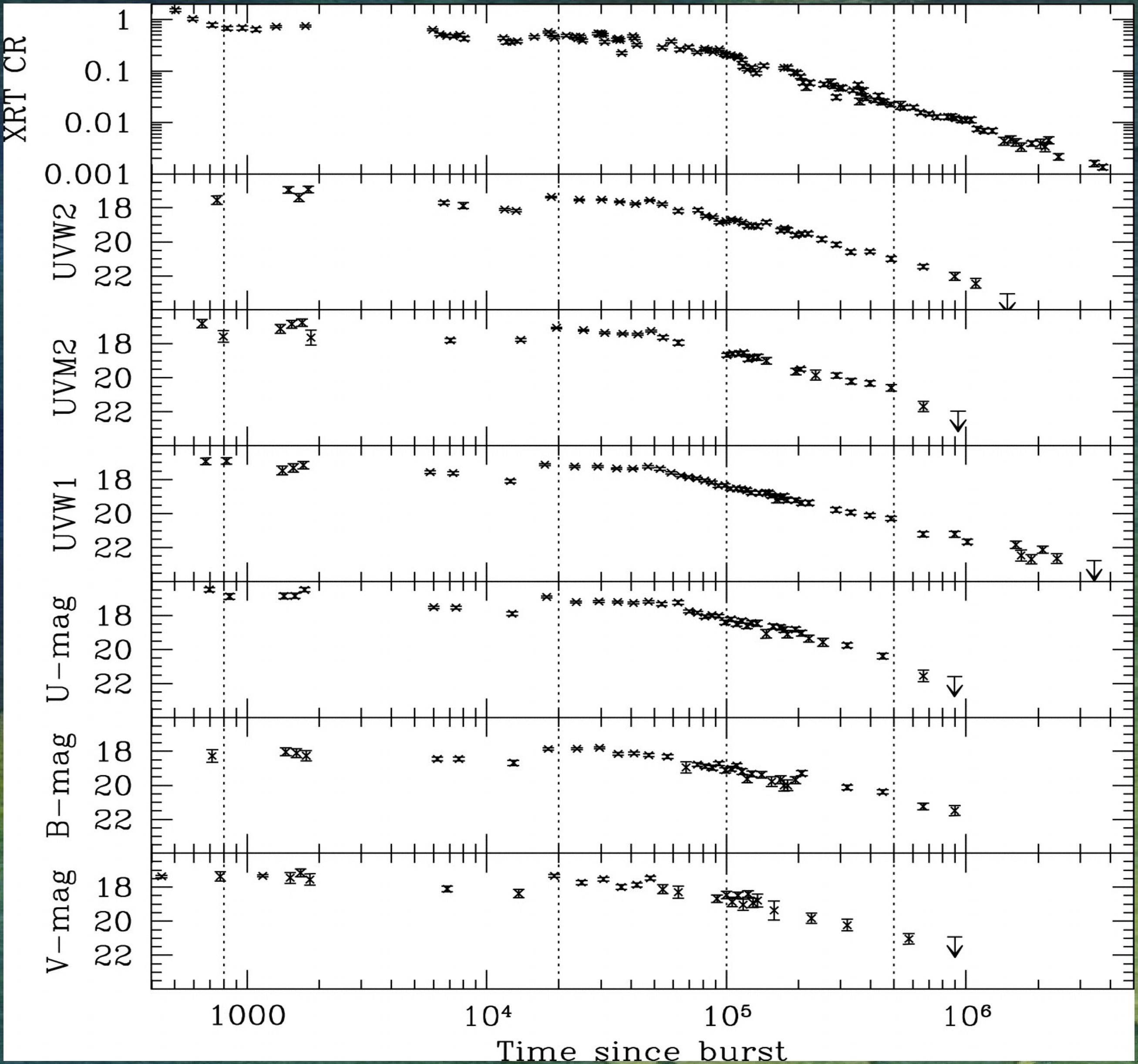
Best-Fit parameters for GRB 060729

α_1	α_2	T_{break} (days)	χ^2 / dof
0.01 ± 0.03	1.65 ± 0.05	0.75 ± 0.08	1.31

Cano et al. 2011
(under review MNRAS)

R '08

GRB 060729



Grupe et al. 2007

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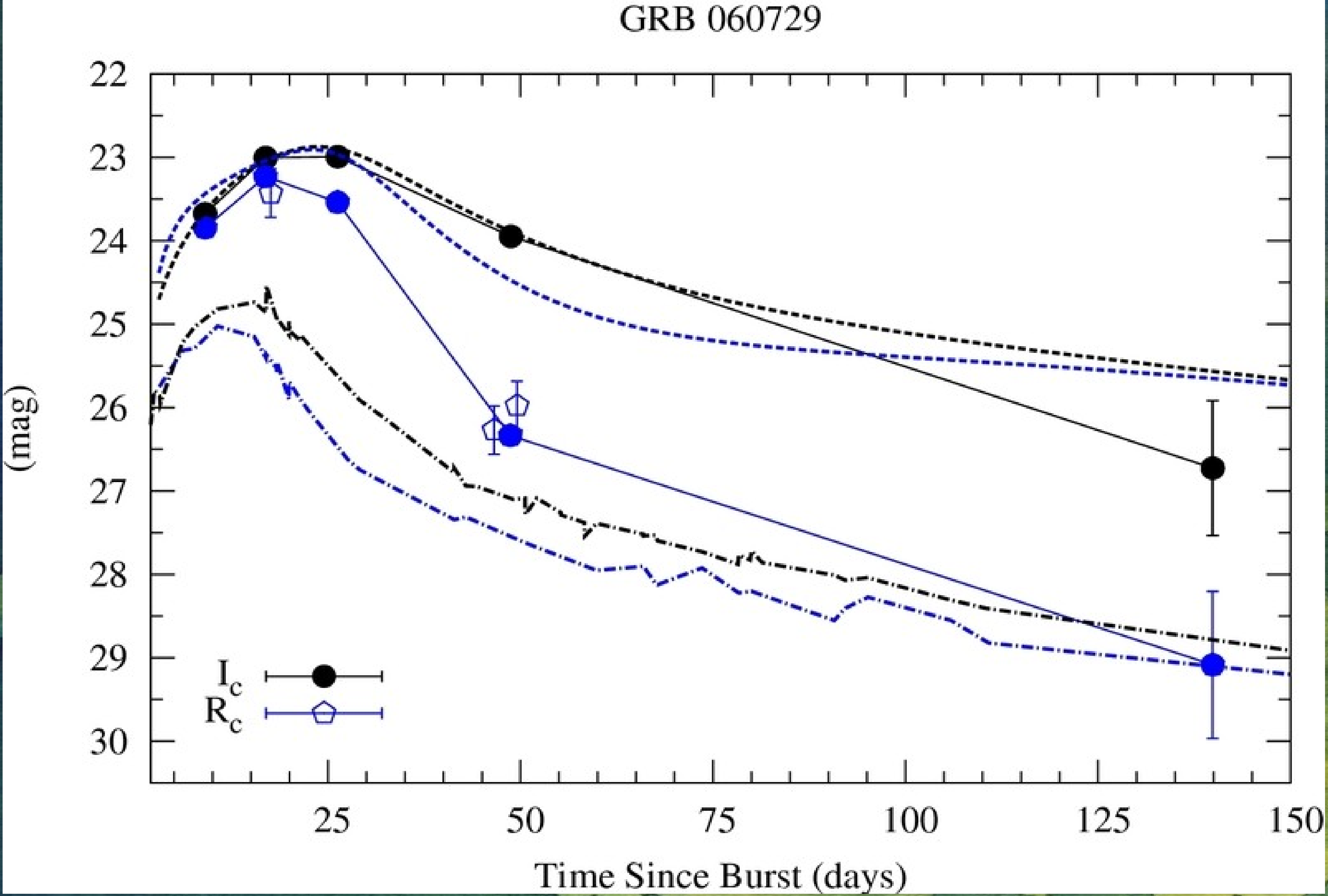

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Cano et al. 2011 (under review MNRAS)

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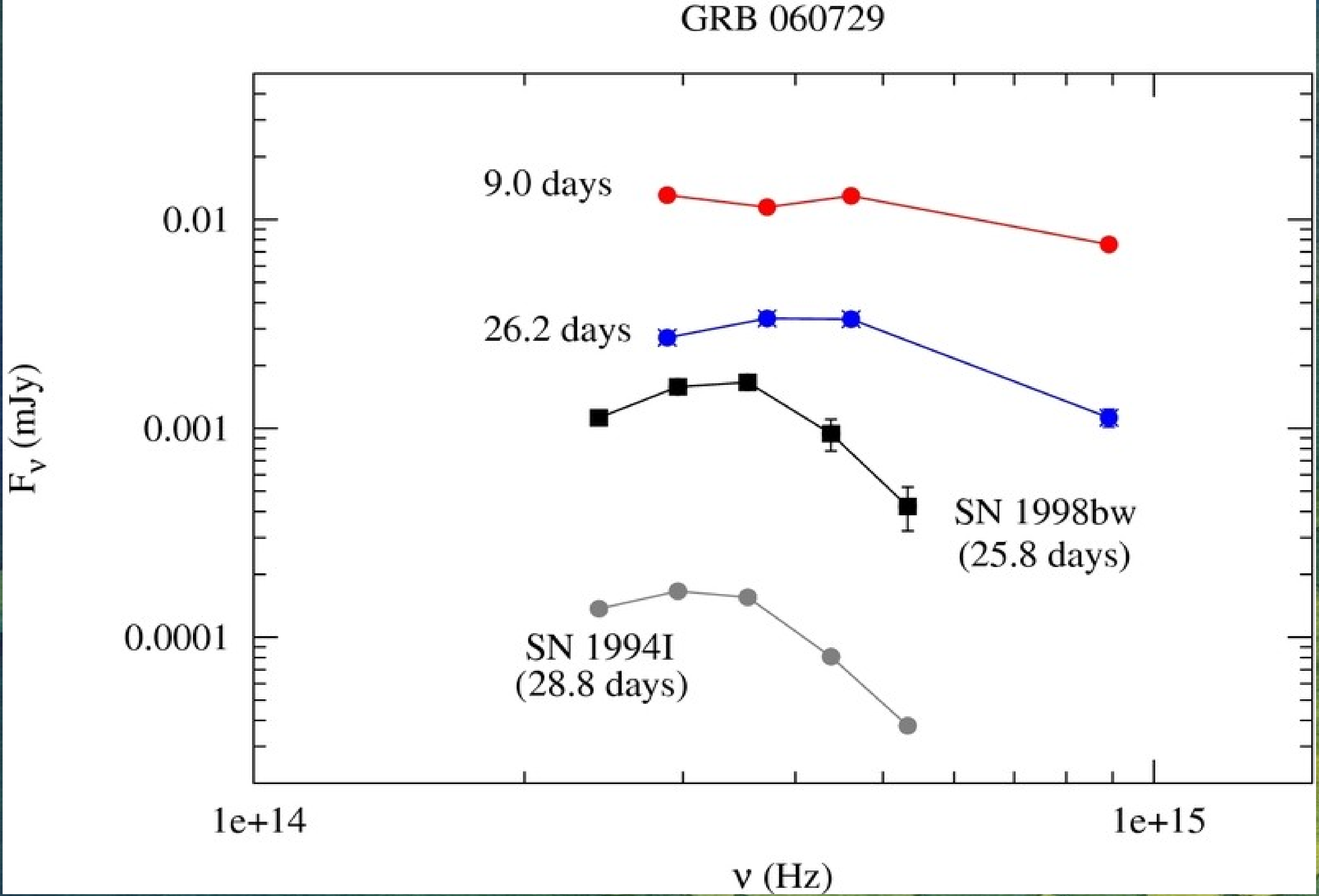

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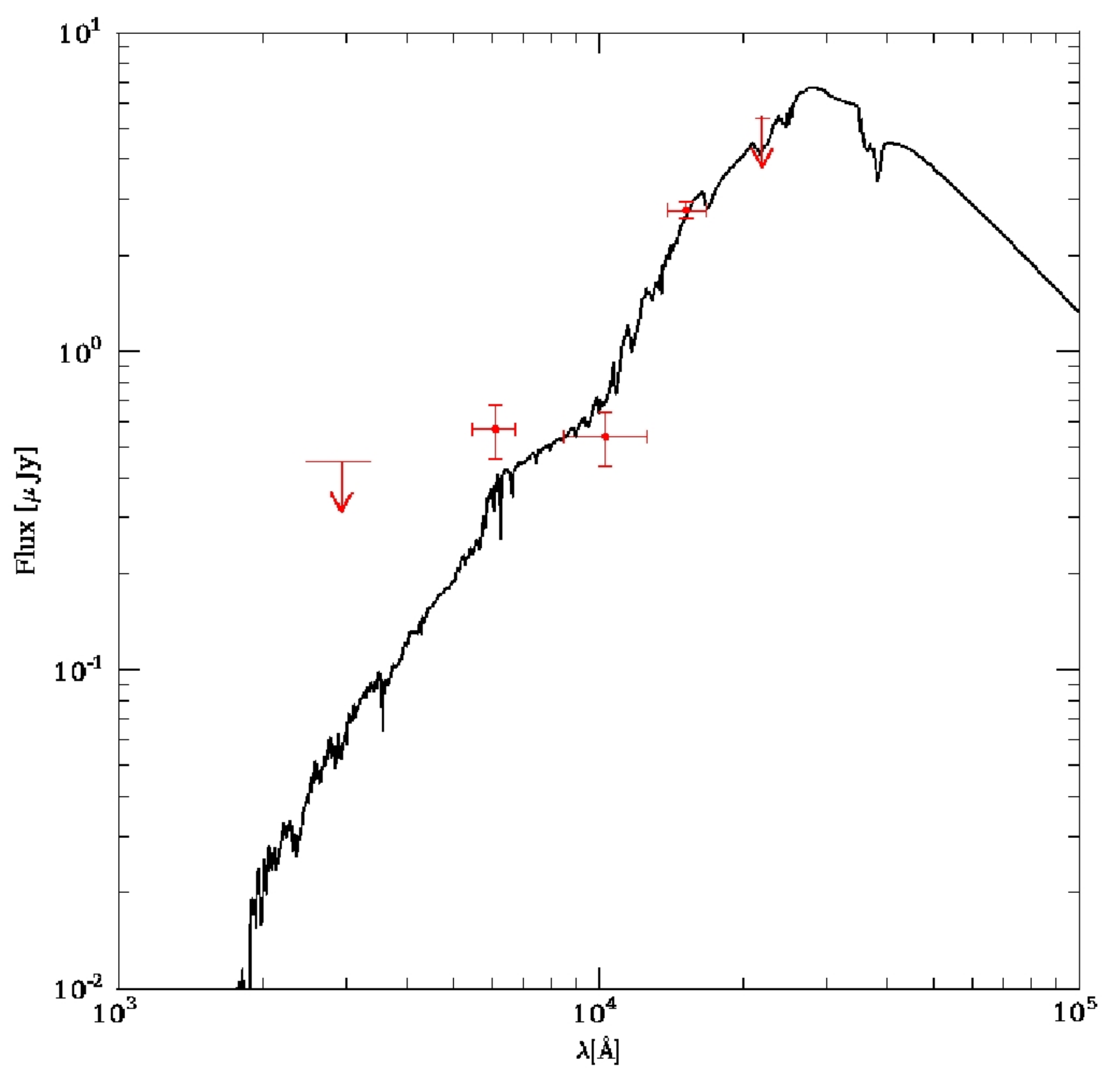
GRB 060729



SED modelling of host:

Best fit models are for a dusty galaxy with young stellar-population and low metallicity.

Av,host = 1.8 +/- 0.5 mag

However, at the site of the GRB, the rest-frame extinction is small:

Av < 0.18 mag

(Schady et al. 2010)

Cano et al. 2011 (under review MNRAS)

GRB 090618

GRB 090618 was discovered by Swift on June 18, 2009 (Schady et al. 2009).

T90 = 113 s

z = 0.54 (Cenko et al. 2009; Fatkhullin et al 2009.)

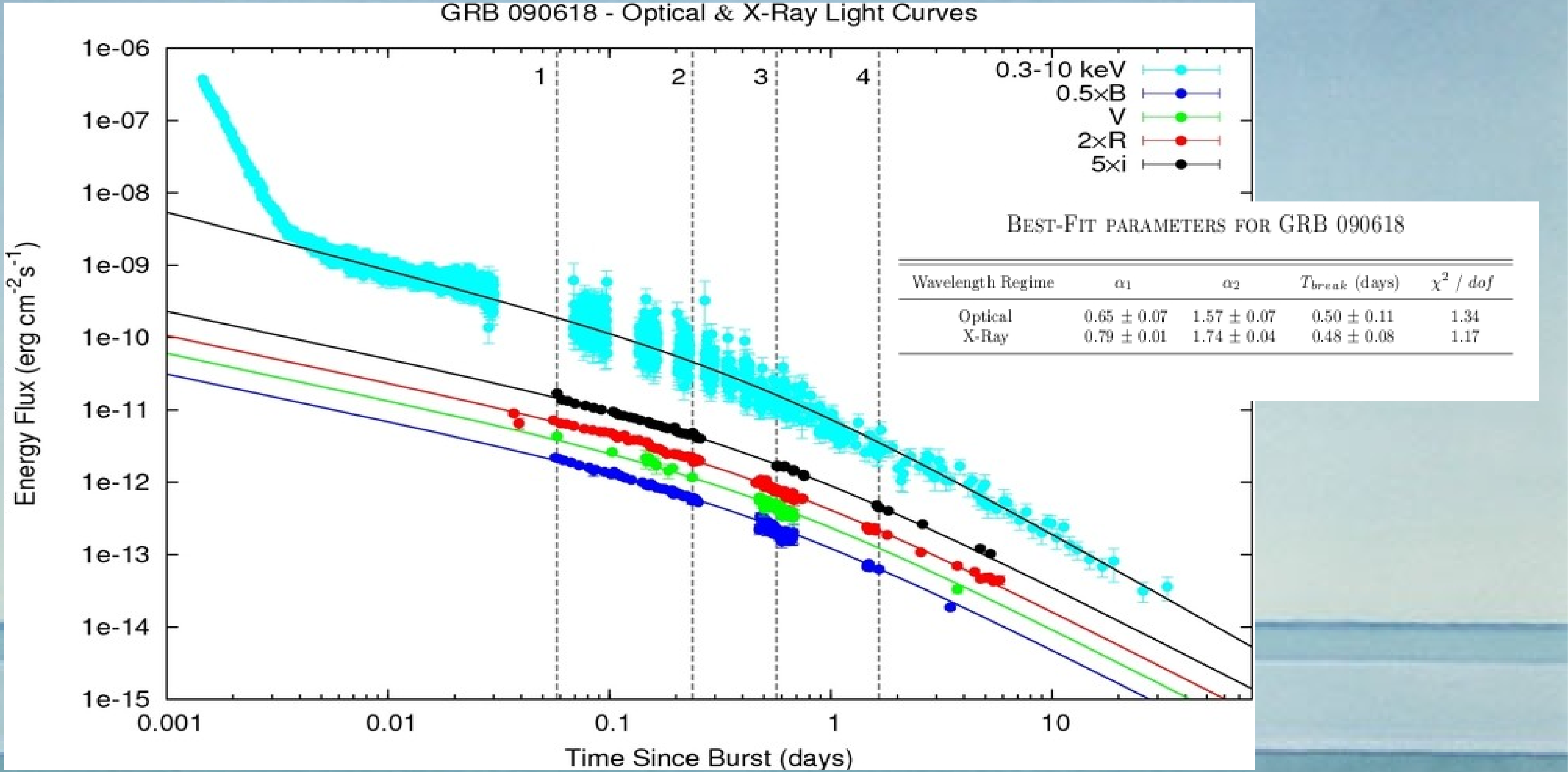
Eiso = 2.57 x 10^{53} ergs (Ghirlanda et al. 2010)

Optical data collected on 14 ground-based telescopes; Radio data collected on 3 telescopes; Swift XRT data.

Same procedure as for GRB 060729.

Cano et al. 2011 (under review MNRAS)

GRB 090618



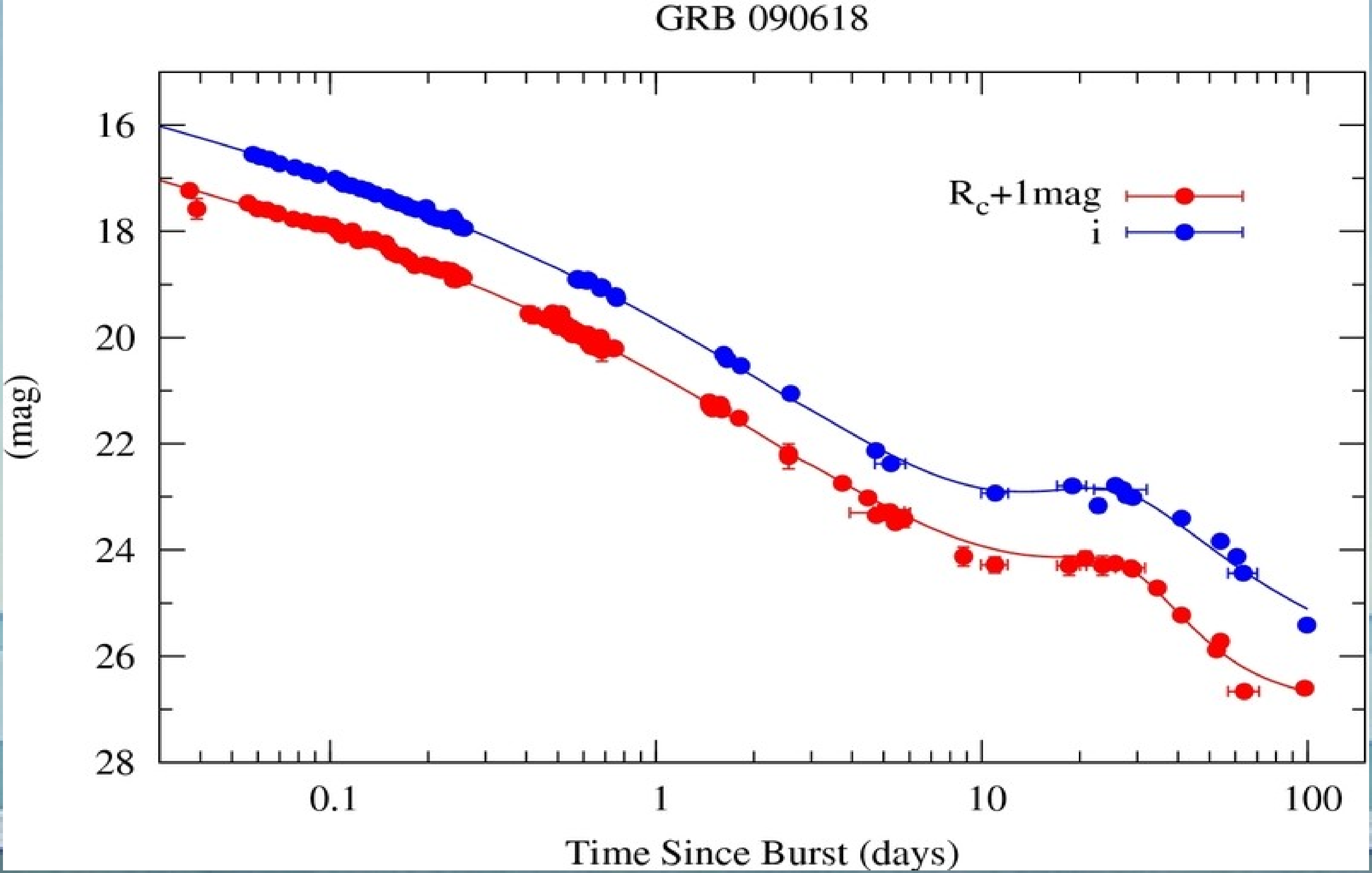
BEST-FIT PARAMETERS FOR GRB 090618

Wavelength Regime	α_1	α_2	T_{break} (days)	χ^2 / *dof*
Optical	0.65 ± 0.07	1.57 ± 0.07	0.50 ± 0.11	1.34
X-Ray	0.79 ± 0.01	1.74 ± 0.04	0.48 ± 0.08	1.17

The break at $t-t_0=0.5$ days implies an opening angle of $\theta_{jet} = 1.5°$, and a corrected gamma-ray emission of $E_{\gamma,\theta} = 8 \times 10^{49}$ erg

Cano et al. 2011 (under review MNRAS)

GRB 090618



Cano et al. 2011 (under review MNRAS)

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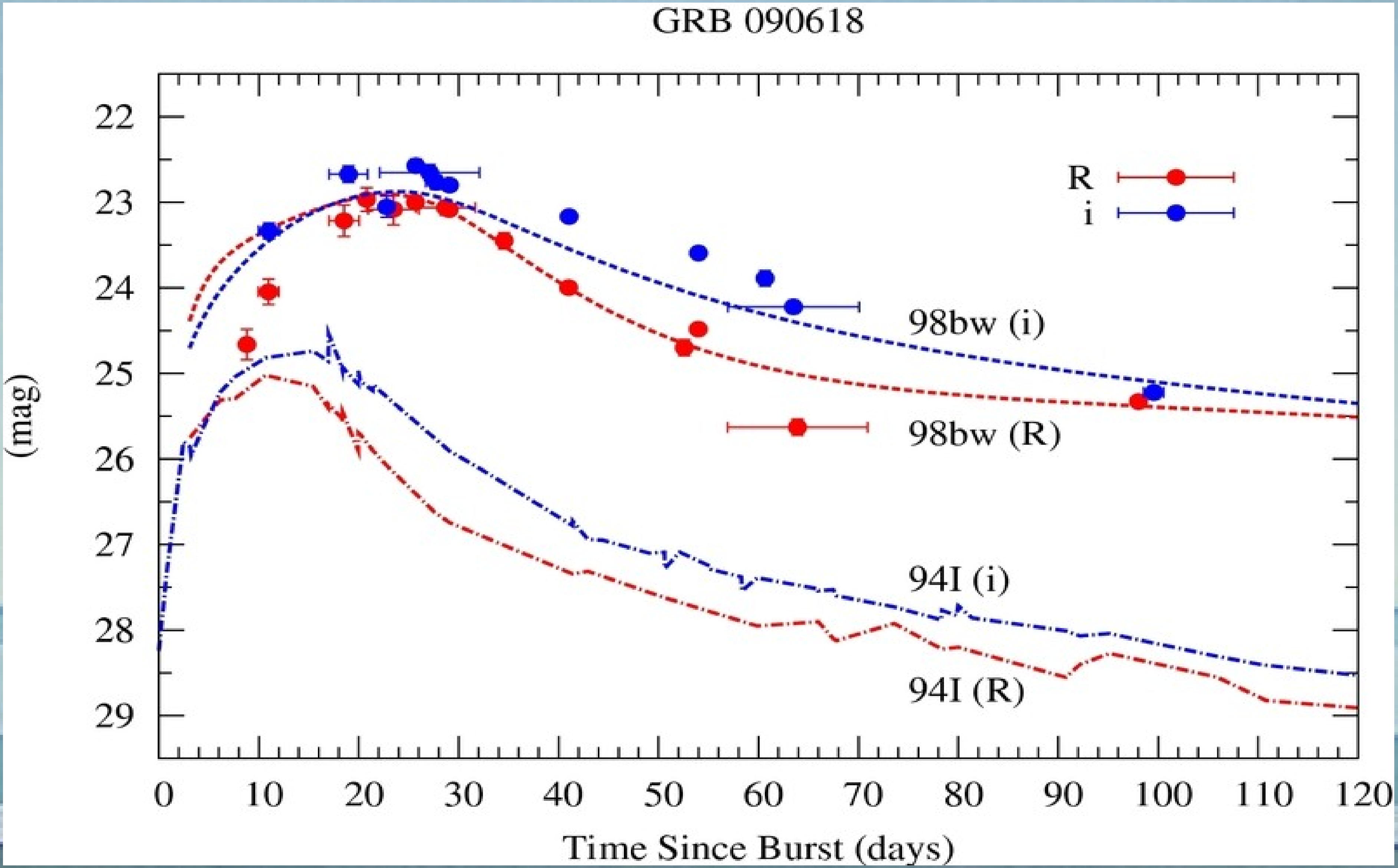

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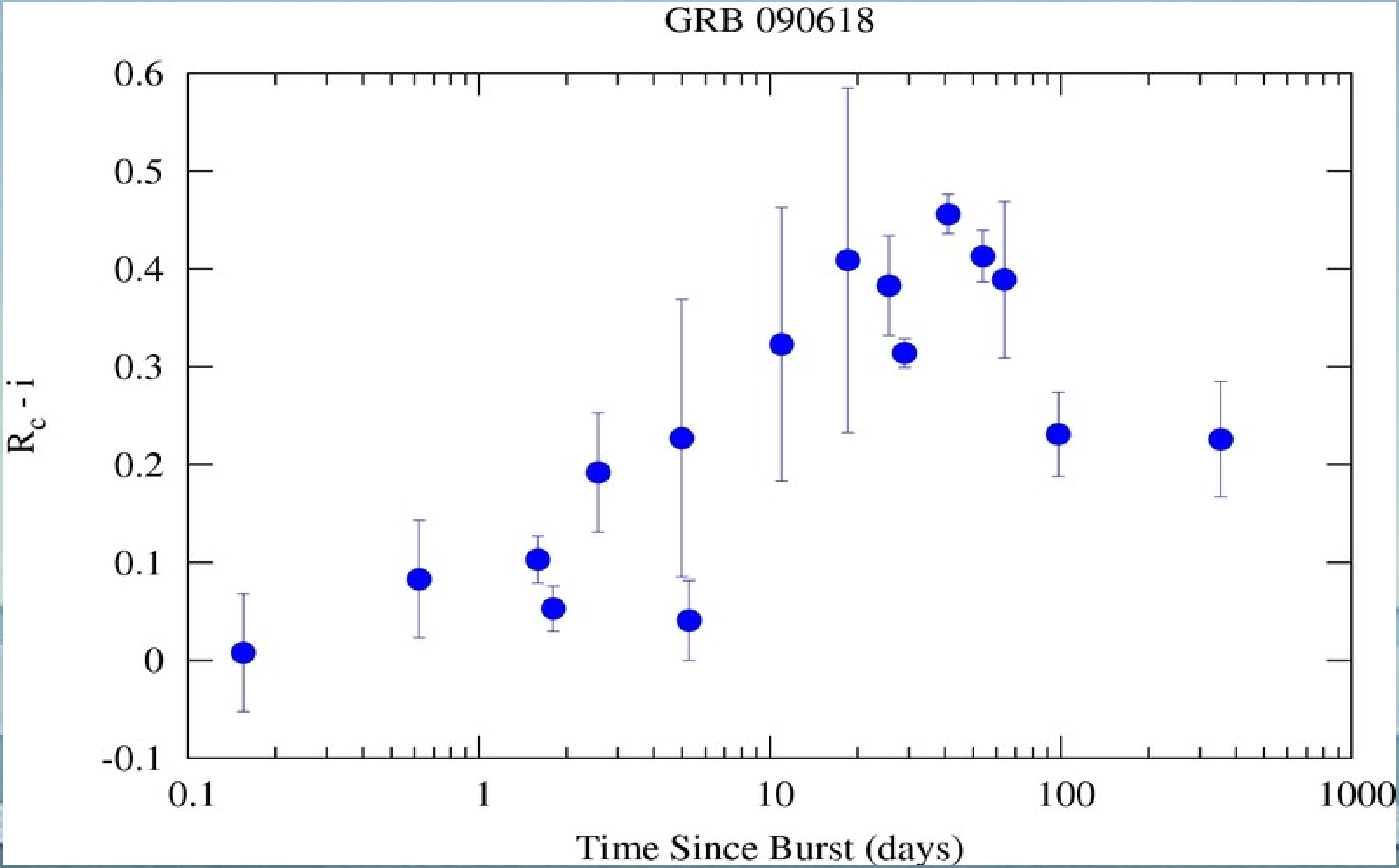

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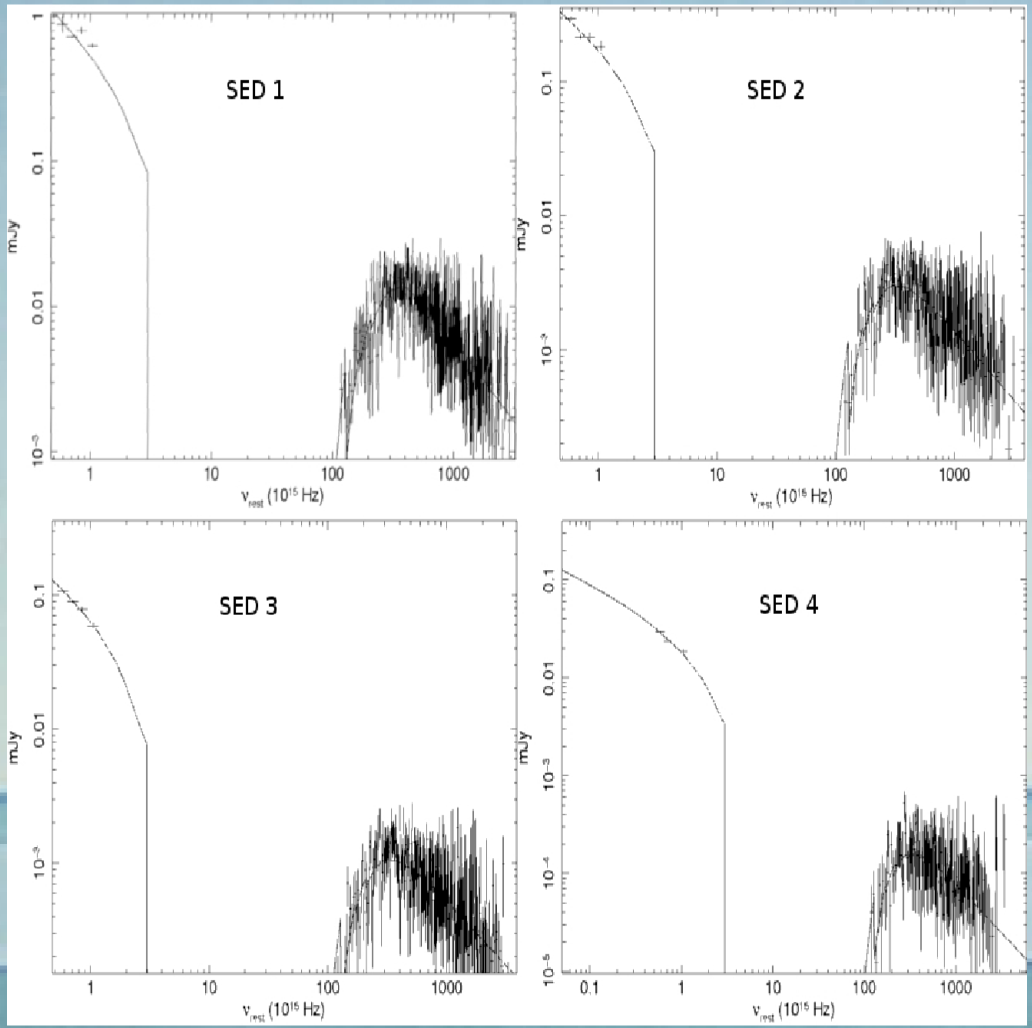


Determined rest-frame extinction from X-ray to optical SED.

Found:

(1) small rest-frame extinction:

Av = 0.3 +/- 0.1 mag

(2) Each epoch well fit by broken power-law:

beta_opt=0.5, beta_x=1.0

(3) Break freq. Decreasing with time-indicating ISM environment (not wind).

Cano et al. 2011 (under review MNRAS)

GRB 090618

We have modelled our optical, X-ray and radio data at 1.68 days assuming:

(1) Jet-like evolution

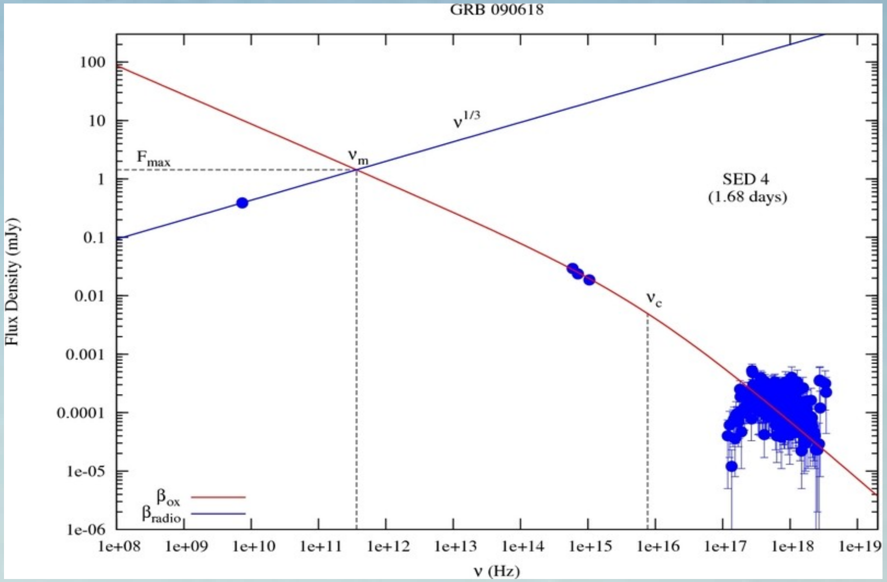
(2) No self-absorption

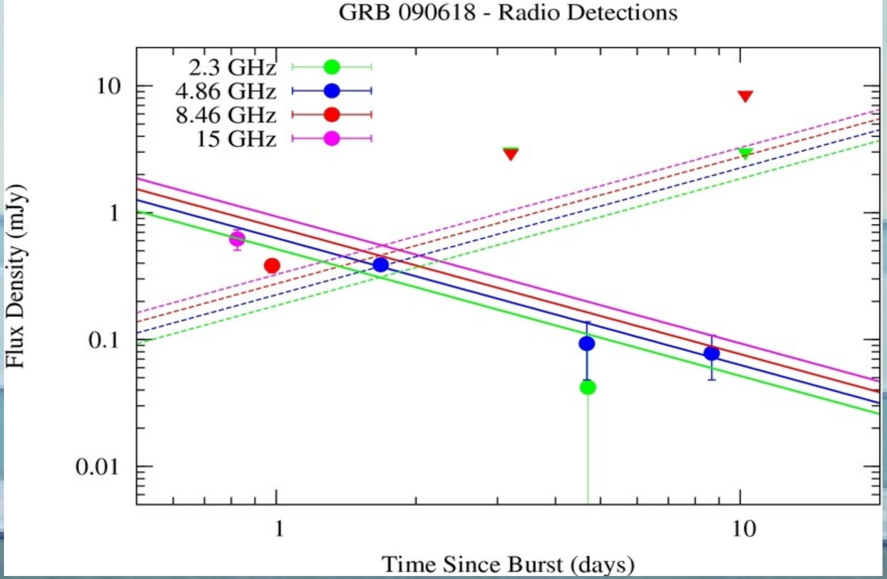
(3) $f_\nu \propto \nu^{1/3}$ for ν below ν_m

We find a typical freq of the electrons:

$\nu_m = 3.66 \times 10^{11}$ Hz

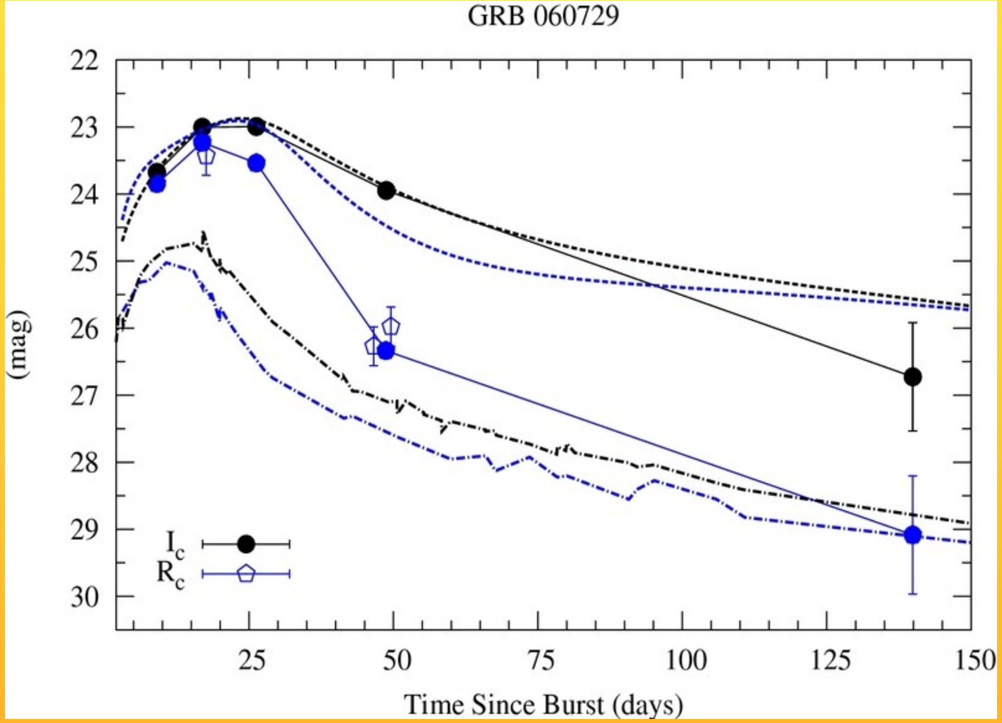
Then modelled the radio data using the above assumptions and the results of the SED modelling.

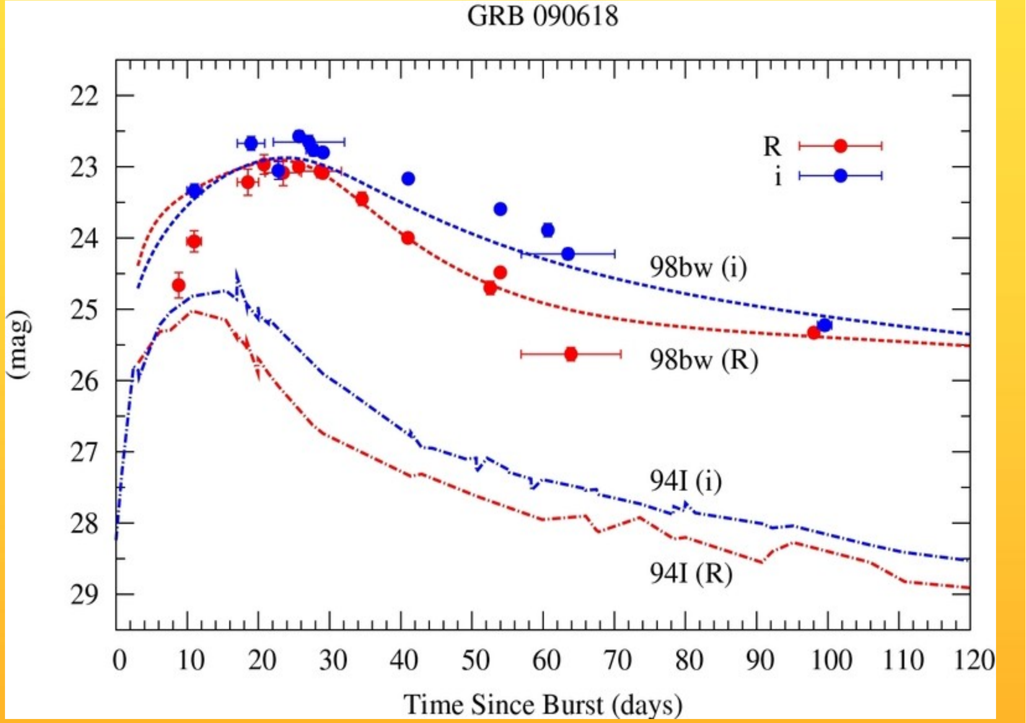


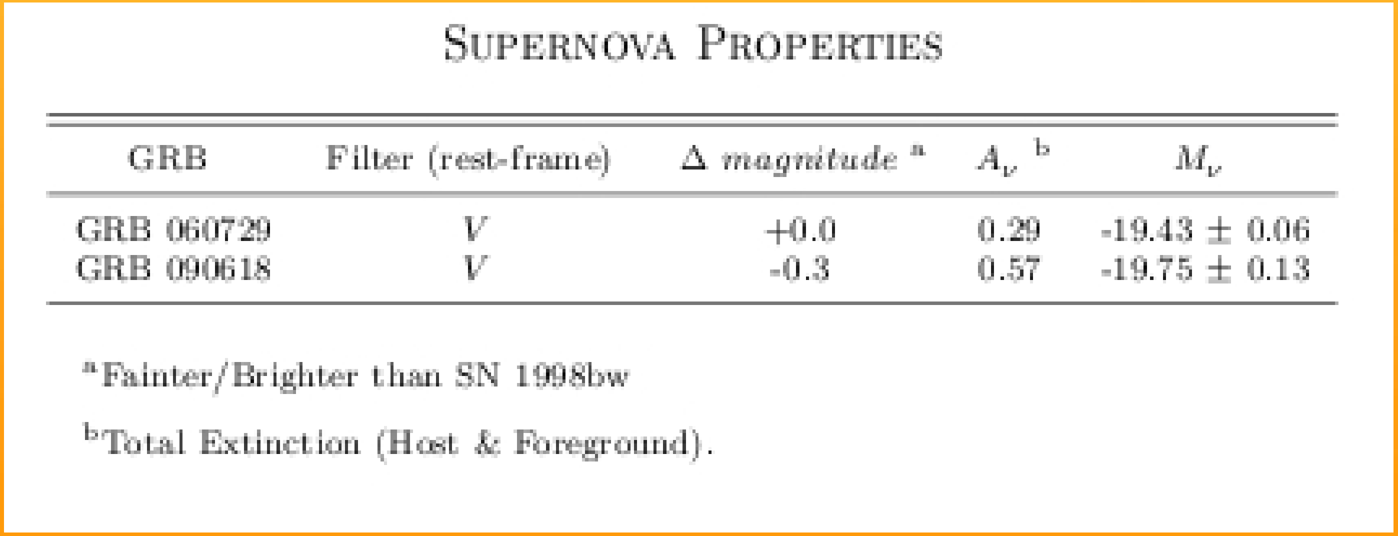


Cano et al. 2011 (under review MNRAS)

The SNe







SUPERNOVA PROPERTIES

GRB	Filter (rest-frame)	Δ *magnitude* [a]	A_V [b]	M_V
GRB 060729	V	+0.0	0.29	-19.43 ± 0.06
GRB 090618	V	-0.3	0.57	-19.75 ± 0.13

[a] Fainter/Brighter than SN 1998bw

[b] Total Extinction (Host & Foreground).

GRB–SNe vs Local Ibc SNe

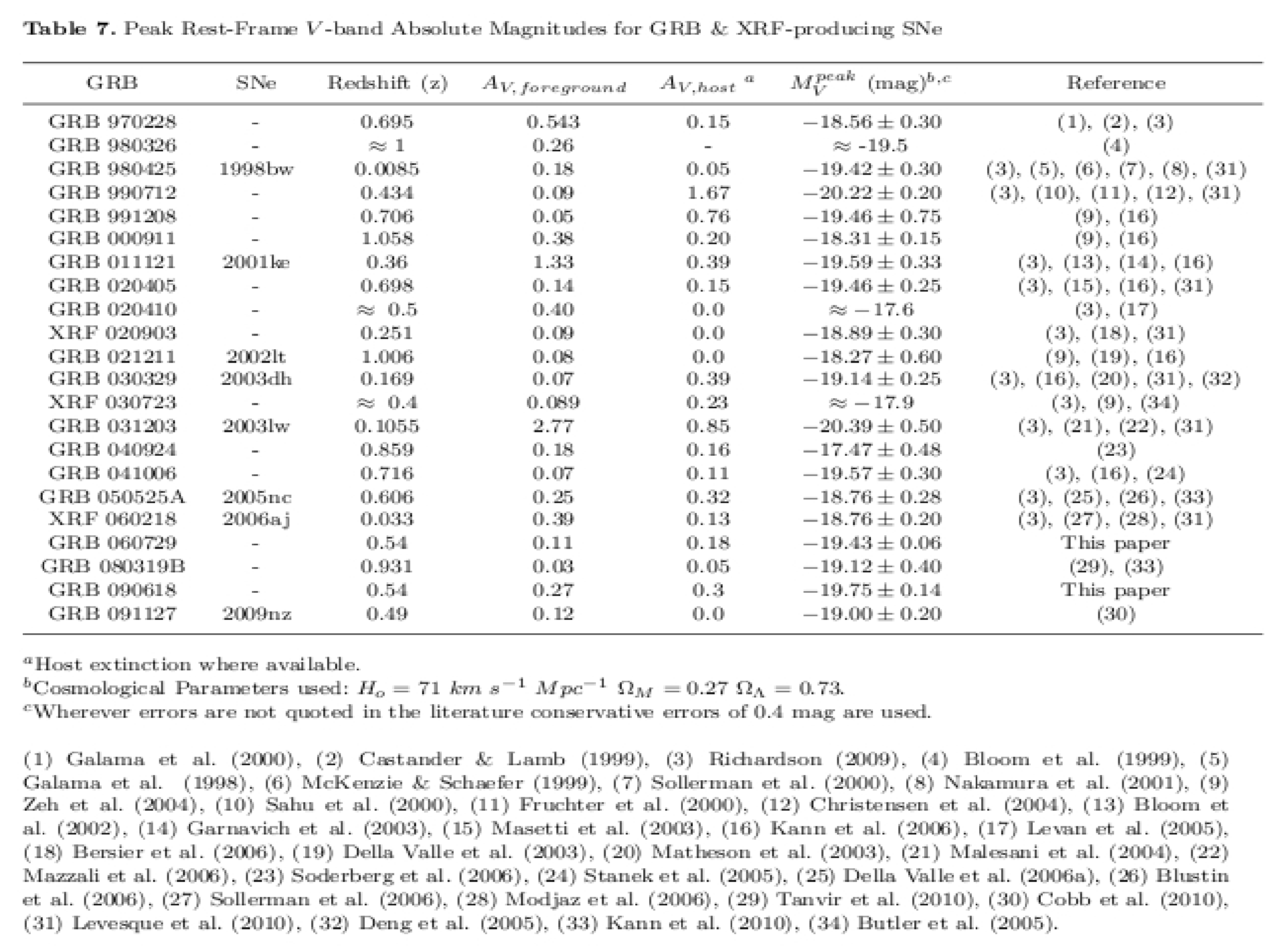


Table 7. Peak Rest-Frame V-band Absolute Magnitudes for GRB & XRF-producing SNe

GRB	SNe	Redshift (z)	$A_{V,foreground}$	$A_{V,host}$ [a]	M_V^{peak} (mag)[b,c]	Reference
GRB 970228	-	0.695	0.543	0.15	-18.56 ± 0.30	(1), (2), (3)
GRB 980326	-	≈ 1	0.26	-	$\approx$ -19.5	(4)
GRB 980425	1998bw	0.0085	0.18	0.05	-19.42 ± 0.30	(3), (5), (6), (7), (8), (31)
GRB 990712	-	0.434	0.09	1.67	-20.22 ± 0.20	(3), (10), (11), (12), (31)
GRB 991208	-	0.706	0.05	0.76	-19.46 ± 0.75	(9), (16)
GRB 000911	-	1.058	0.38	0.20	-18.31 ± 0.15	(9), (16)
GRB 011121	2001ke	0.36	1.33	0.39	-19.59 ± 0.33	(3), (13), (14), (16)
GRB 020405	-	0.698	0.14	0.15	-19.46 ± 0.25	(3), (15), (16), (31)
GRB 020410	-	$\approx$ 0.5	0.40	0.0	≈ -17.6	(3), (17)
XRF 020903	-	0.251	0.09	0.0	-18.89 ± 0.30	(3), (18), (31)
GRB 021211	2002lt	1.006	0.08	0.0	-18.27 ± 0.60	(9), (19), (16)
GRB 030329	2003dh	0.169	0.07	0.39	-19.14 ± 0.25	(3), (16), (20), (31), (32)
XRF 030723	-	$\approx$ 0.4	0.089	0.23	≈ -17.9	(3), (9), (34)
GRB 031203	2003lw	0.1055	2.77	0.85	-20.39 ± 0.50	(3), (21), (22), (31)
GRB 040924	-	0.859	0.18	0.16	-17.47 ± 0.48	(23)
GRB 041006	-	0.716	0.07	0.11	-19.57 ± 0.30	(3), (16), (24)
GRB 050525A	2005nc	0.606	0.25	0.32	-18.76 ± 0.28	(3), (25), (26), (33)
XRF 060218	2006aj	0.033	0.39	0.13	-18.76 ± 0.20	(3), (27), (28), (31)
GRB 060729	-	0.54	0.11	0.18	-19.43 ± 0.06	This paper
GRB 080319B	-	0.931	0.03	0.05	-19.12 ± 0.40	(29), (33)
GRB 090618	-	0.54	0.27	0.3	-19.75 ± 0.14	This paper
GRB 091127	2009nz	0.49	0.12	0.0	-19.00 ± 0.20	(30)

[a] Host extinction where available.

[b] Cosmological Parameters used: $H_o = 71\ km\ s^{-1}\ Mpc^{-1}\ \Omega_M = 0.27\ \Omega_\Lambda = 0.73$.

[c] Wherever errors are not quoted in the literature conservative errors of 0.4 mag are used.

(1) Galama et al. (2000), (2) Castander & Lamb (1999), (3) Richardson (2009), (4) Bloom et al. (1999), (5) Galama et al. (1998), (6) McKenzie & Schaefer (1999), (7) Sollerman et al. (2000), (8) Nakamura et al. (2001), (9) Zeh et al. (2004), (10) Sahu et al. (2000), (11) Fruchter et al. (2000), (12) Christensen et al. (2004), (13) Bloom et al. (2002), (14) Garnavich et al. (2003), (15) Masetti et al. (2003), (16) Kann et al. (2006), (17) Levan et al. (2005), (18) Bersier et al. (2006), (19) Della Valle et al. (2003), (20) Matheson et al. (2003), (21) Malesani et al. (2004), (22) Mazzali et al. (2006), (23) Soderberg et al. (2006), (24) Stanek et al. (2005), (25) Della Valle et al. (2006a), (26) Blustin et al. (2006), (27) Sollerman et al. (2006), (28) Modjaz et al. (2006), (29) Tanvir et al. (2010), (30) Cobb et al. (2010), (31) Levesque et al. (2010), (32) Deng et al. (2005), (33) Kann et al. (2010), (34) Butler et al. (2005).

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GRB-SNe vs Local Ibc SNe

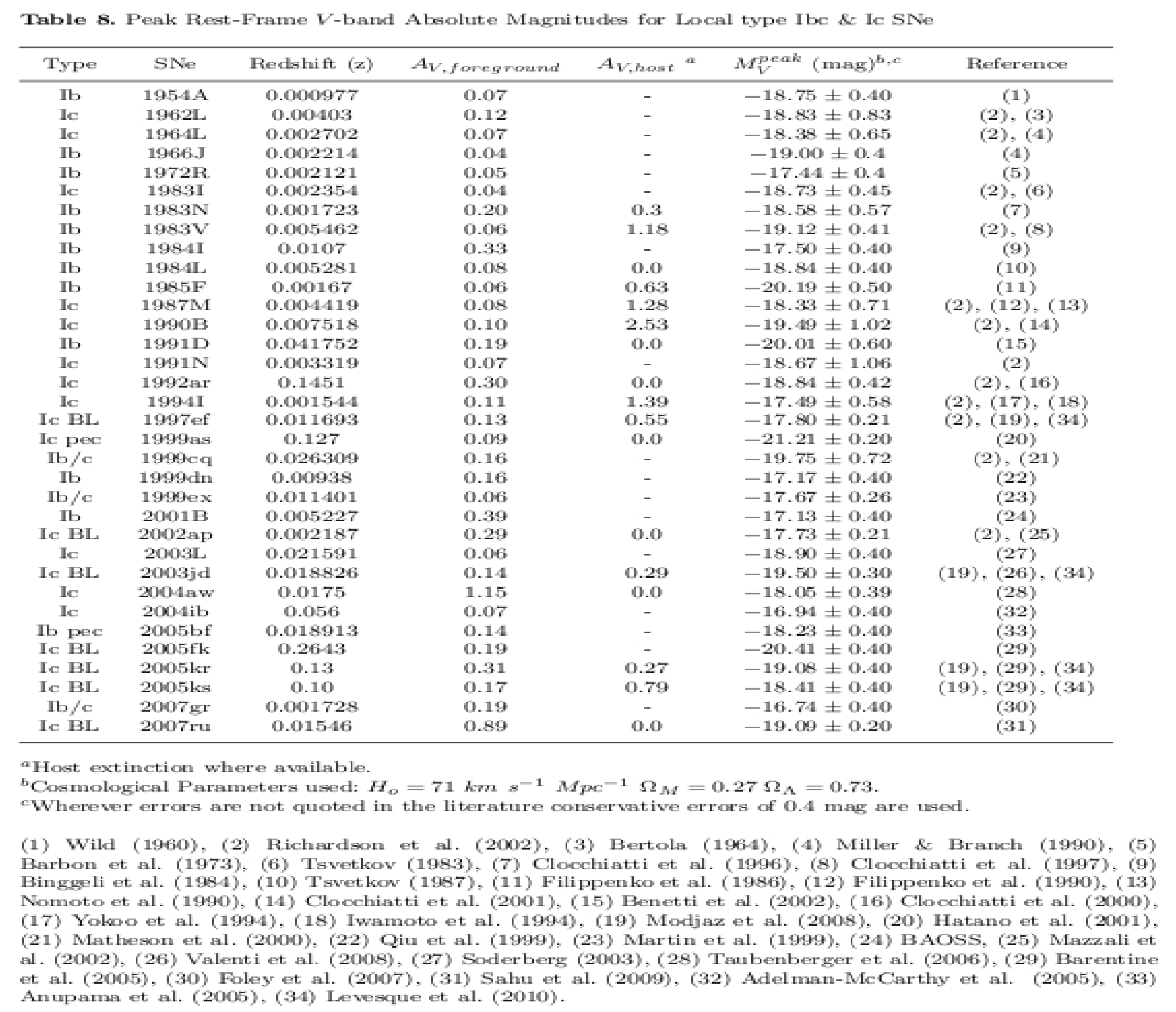

Table 8. Peak Rest-Frame V-band Absolute Magnitudes for Local type Ibc & Ic SNe

Type	SNe	Redshift (z)	$A_{V,foreground}$	$A_{V,host}$ [a]	M_V^{peak} (mag)[b,c]	Reference
Ib	1954A	0.000977	0.07	-	-18.75 ± 0.40	(1)
Ic	1962L	0.00403	0.12	-	-18.83 ± 0.83	(2), (3)
Ic	1964L	0.002702	0.07	-	-18.38 ± 0.65	(2), (4)
Ib	1966J	0.002214	0.04	-	-19.00 ± 0.4	(4)
Ib	1972R	0.002121	0.05	-	-17.44 ± 0.4	(5)
Ic	1983I	0.002354	0.04	-	-18.73 ± 0.45	(2), (6)
Ib	1983N	0.001723	0.20	0.3	-18.58 ± 0.57	(7)
Ib	1983V	0.005462	0.06	1.18	-19.12 ± 0.41	(2), (8)
Ib	1984I	0.0107	0.33	-	-17.50 ± 0.40	(9)
Ib	1984L	0.005281	0.08	0.0	-18.84 ± 0.40	(10)
Ib	1985F	0.00167	0.06	0.63	-20.19 ± 0.50	(11)
Ic	1987M	0.004419	0.08	1.28	-18.33 ± 0.71	(2), (12), (13)
Ic	1990B	0.007518	0.10	2.53	-19.49 ± 1.02	(2), (14)
Ib	1991D	0.041752	0.19	0.0	-20.01 ± 0.60	(15)
Ic	1991N	0.003319	0.07	-	-18.67 ± 1.06	(2)
Ic	1992ar	0.1451	0.30	0.0	-18.84 ± 0.42	(2), (16)
Ic	1994I	0.001544	0.11	1.39	-17.49 ± 0.58	(2), (17), (18)
Ic BL	1997ef	0.011693	0.13	0.55	-17.80 ± 0.21	(2), (19), (34)
Ic pec	1999as	0.127	0.09	0.0	-21.21 ± 0.20	(20)
Ib/c	1999cq	0.026309	0.16	-	-19.75 ± 0.72	(2), (21)
Ib	1999dn	0.00938	0.16	-	-17.17 ± 0.40	(22)
Ib/c	1999ex	0.011401	0.06	-	-17.67 ± 0.26	(23)
Ib	2001B	0.005227	0.39	-	-17.13 ± 0.40	(24)
Ic BL	2002ap	0.002187	0.29	0.0	-17.73 ± 0.21	(2), (25)
Ic	2003L	0.021591	0.06	-	-18.90 ± 0.40	(27)
Ic BL	2003jd	0.018826	0.14	0.29	-19.50 ± 0.30	(19), (26), (34)
Ic	2004aw	0.0175	1.15	0.0	-18.05 ± 0.39	(28)
Ic	2004ib	0.056	0.07	-	-16.94 ± 0.40	(32)
Ib pec	2005bf	0.018913	0.14	-	-18.23 ± 0.40	(33)
Ic BL	2005fk	0.2643	0.19	-	-20.41 ± 0.40	(29)
Ic BL	2005kr	0.13	0.31	0.27	-19.08 ± 0.40	(19), (29), (34)
Ic BL	2005ks	0.10	0.17	0.79	-18.41 ± 0.40	(19), (29), (34)
Ib/c	2007gr	0.001728	0.19	-	-16.74 ± 0.40	(30)
Ic BL	2007ru	0.01546	0.89	0.0	-19.09 ± 0.20	(31)

[a] Host extinction where available.
[b] Cosmological Parameters used: $H_o = 71\ km\ s^{-1}\ Mpc^{-1}$ $\Omega_M = 0.27$ $\Omega_\Lambda = 0.73$.
[c] Wherever errors are not quoted in the literature conservative errors of 0.4 mag are used.

(1) Wild (1960), (2) Richardson et al. (2002), (3) Bertola (1964), (4) Miller & Branch (1990), (5) Barbon et al. (1973), (6) Tsvetkov (1983), (7) Clocchiatti et al. (1996), (8) Clocchiatti et al. (1997), (9) Binggeli et al. (1984), (10) Tsvetkov (1987), (11) Filippenko et al. (1986), (12) Filippenko et al. (1990), (13) Nomoto et al. (1990), (14) Clocchiatti et al. (2001), (15) Benetti et al. (2002), (16) Clocchiatti et al. (2000), (17) Yokoo et al. (1994), (18) Iwamoto et al. (1994), (19) Modjaz et al. (2008), (20) Hatano et al. (2001), (21) Matheson et al. (2000), (22) Qiu et al. (1999), (23) Martin et al. (1999), (24) BAOSS, (25) Mazzali et al. (2002), (26) Valenti et al. (2008), (27) Soderberg (2003), (28) Taubenberger et al. (2006), (29) Barentine et al. (2005), (30) Foley et al. (2007), (31) Sahu et al. (2009), (32) Adelman-McCarthy et al. (2005), (33) Anupama et al. (2005), (34) Levesque et al. (2010).

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GRB-SNe vs Local Ibc SNe

When comparing these two samples of SNe we are attempting to answer the following question:

"Are the progenitors of GRB/XRF associated SNe the same as those of local type Ibc SNe without an accompanying GRB/XRF trigger?"

by testing if the distribution of the peak magnitudes are the two SNe are the different.

To do this we performed a Kolomogorov-Smirnov (KS) test on the two samples:

(1) GRB/XRF-SNe (N=22)
(2) Local Ibc SNe (N=34)
(3) Local Ic SNe (N=19)

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GRB-SNe vs Local Ibc SNe

We performed the KS test twice:

(1) Considering all events

(2) Considering only those events where the host extinction is known.

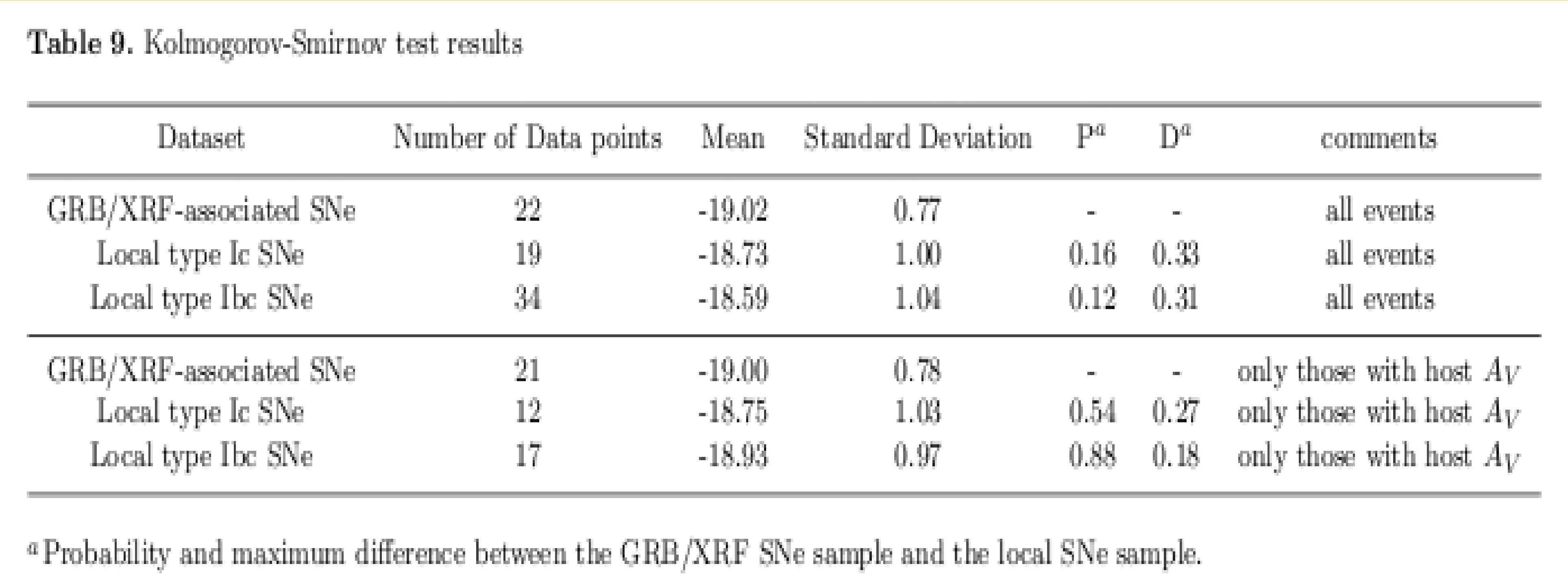

Table 9. Kolmogorov-Smirnov test results

Dataset	Number of Data points	Mean	Standard Deviation	P^a	D^a	comments
GRB/XRF-associated SNe	22	-19.02	0.77	-	-	all events
Local type Ic SNe	19	-18.73	1.00	0.16	0.33	all events
Local type Ibc SNe	34	-18.59	1.04	0.12	0.31	all events
GRB/XRF-associated SNe	21	-19.00	0.78	-	-	only those with host A_V
Local type Ic SNe	12	-18.75	1.03	0.54	0.27	only those with host A_V
Local type Ibc SNe	17	-18.93	0.97	0.88	0.18	only those with host A_V

[a] Probability and maximum difference between the GRB/XRF SNe sample and the local SNe sample.

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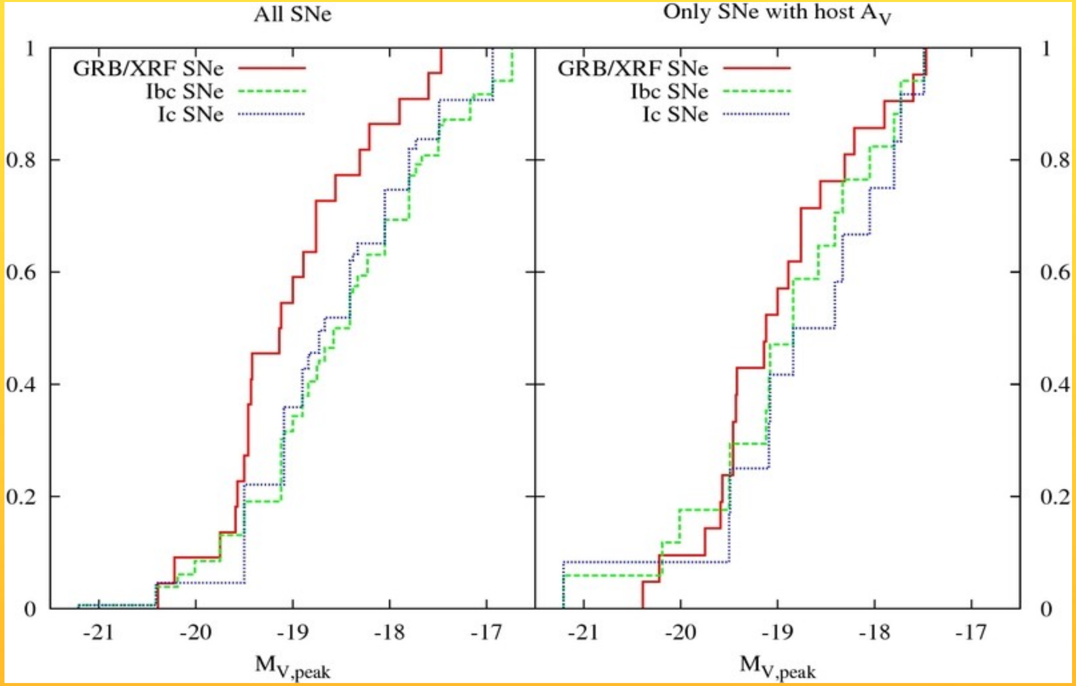
GRB-SNe vs Local Ibc SNe



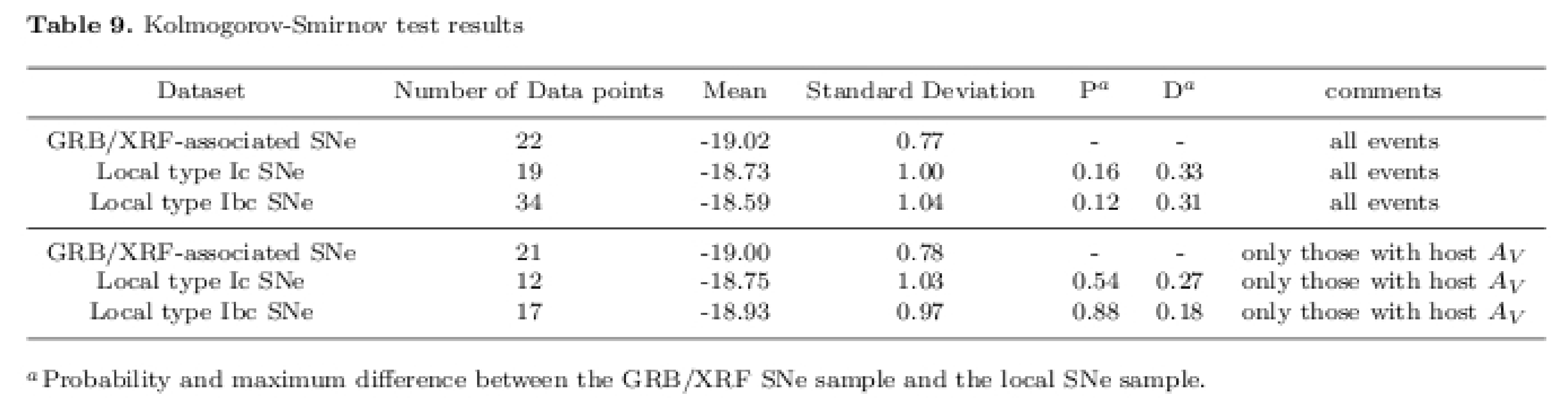


Table 9. Kolmogorov-Smirnov test results

Dataset	Number of Data points	Mean	Standard Deviation	P^a	D^a	comments
GRB/XRF-associated SNe	22	-19.02	0.77	-	-	all events
Local type Ic SNe	19	-18.73	1.00	0.16	0.33	all events
Local type Ibc SNe	34	-18.59	1.04	0.12	0.31	all events
GRB/XRF-associated SNe	21	-19.00	0.78	-	-	only those with host A_V
Local type Ic SNe	12	-18.75	1.03	0.54	0.27	only those with host A_V
Local type Ibc SNe	17	-18.93	0.97	0.88	0.18	only those with host A_V

[a] Probability and maximum difference between the GRB/XRF SNe sample and the local SNe sample.

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GRB-SNe vs Local Ibc SNe

We find:

(1) Considering all events

Modest probability that the GRB/XRF progenitors are drawn from the same parent population as all of the local Ibc SNe (P=0.16), and the local Ic SNe (P=0.19).

(2) Considering only those events where the host extinction is known.

Increased probability that the GRB/XRF progenitors are drawn from the same parent populations as the local Ibc SNe (P=0.88), and the local Ic SNe (P=0.60)

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GRB-SNe vs Local Ibc SNe

General Conclusion:

The GRB/XRF associated SNe are generally brighter than the local Ibc SNe.

However:

The samples of local Ibc SNe are not complete, they include only those events where a measurement of the peak brightness has been made.

This test only addresses the SNe brightness, it does not address factors such as host and progenitor metallicity and typical outflow velocities.

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Future Research

(1) XRF 100316D / SN 2010bh

BVRi LCs (HST & FTS) - pseudo Bolometric LC

(2) GRB 030329 / SN 2003dh

Afterglow-subtracted BVRI LCs of SN 2003dh - pseudo Bolometric LC

XRF 100316D - SN 2010 bh

Discovered by Swift on March 16, 2010 (Stamatikos et al. 2010) in a near-by disturbed galaxy ($z = 0.059$; Vergani et al. 2010)

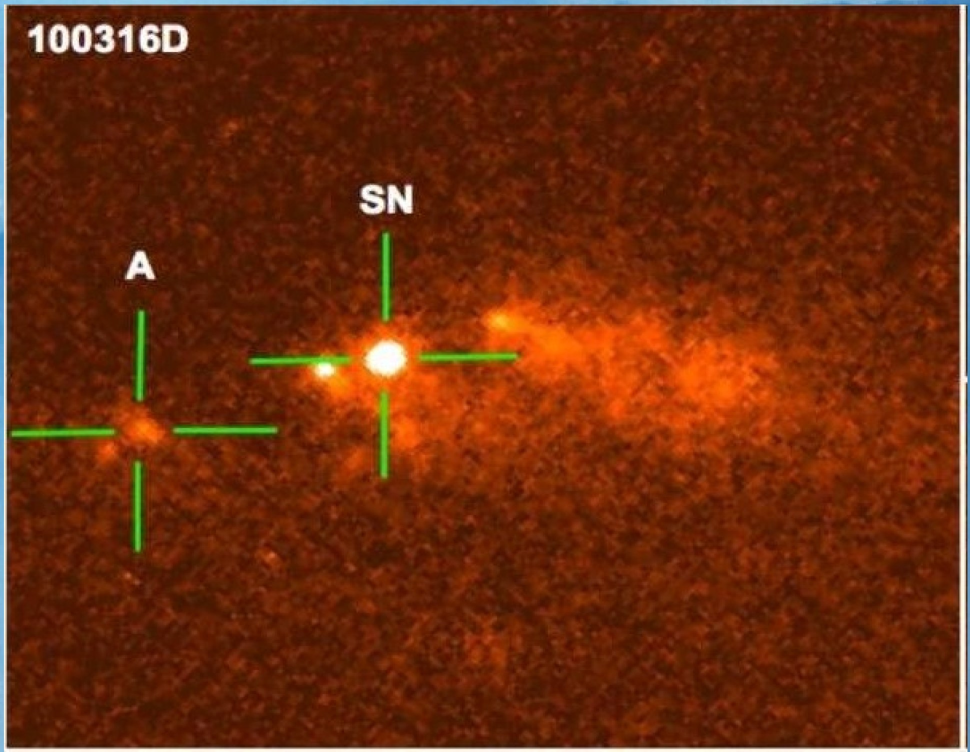
X-ray LC similar to XRF 060218, as well as similarly low energy budget:

$E_{iso} = 4 \times 10^{49}$ ergs

(Starling et al. 2010)

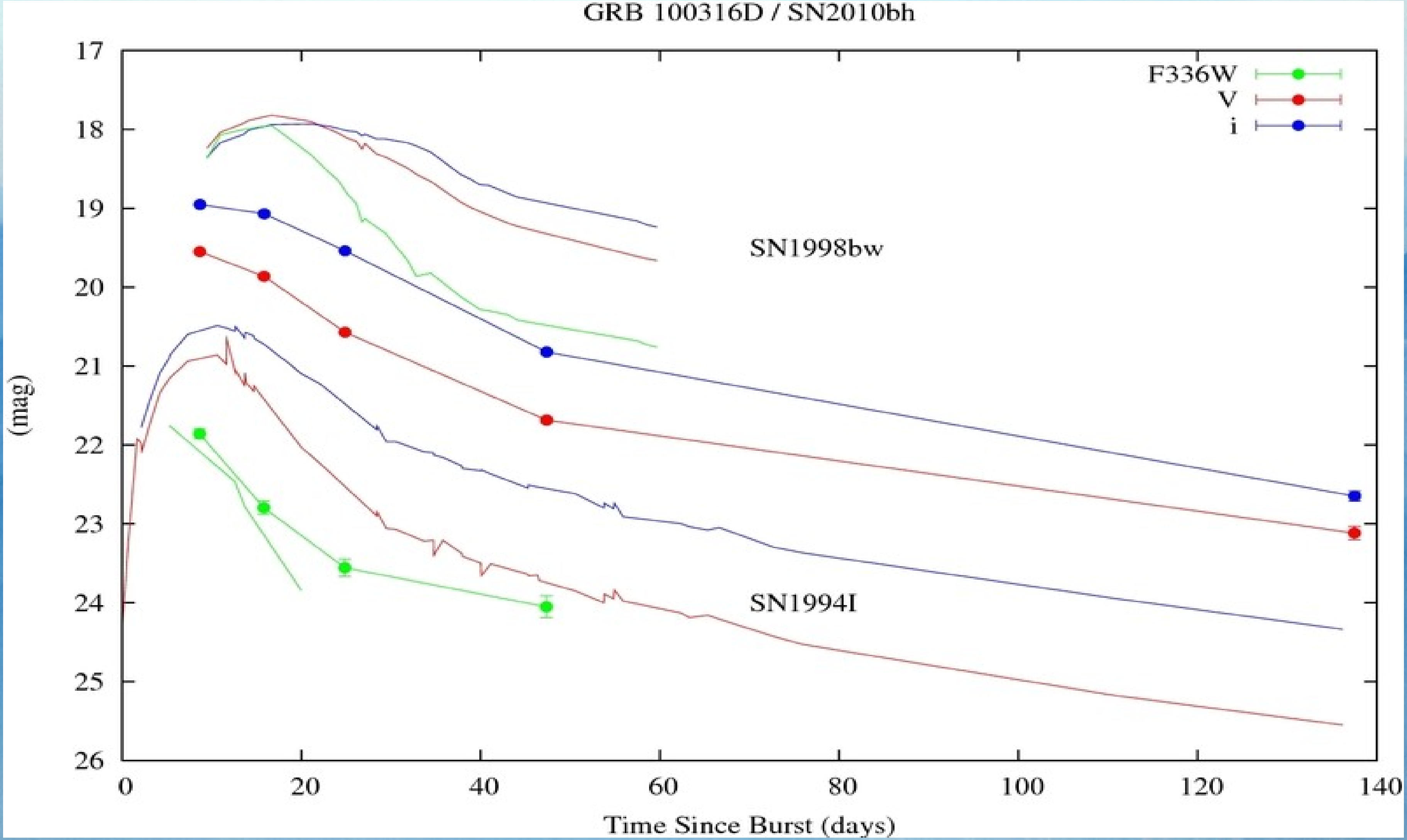
Spectroscopic confirmation of type Ic SNe: 2010 bh

(Wiersema et al. 2010)



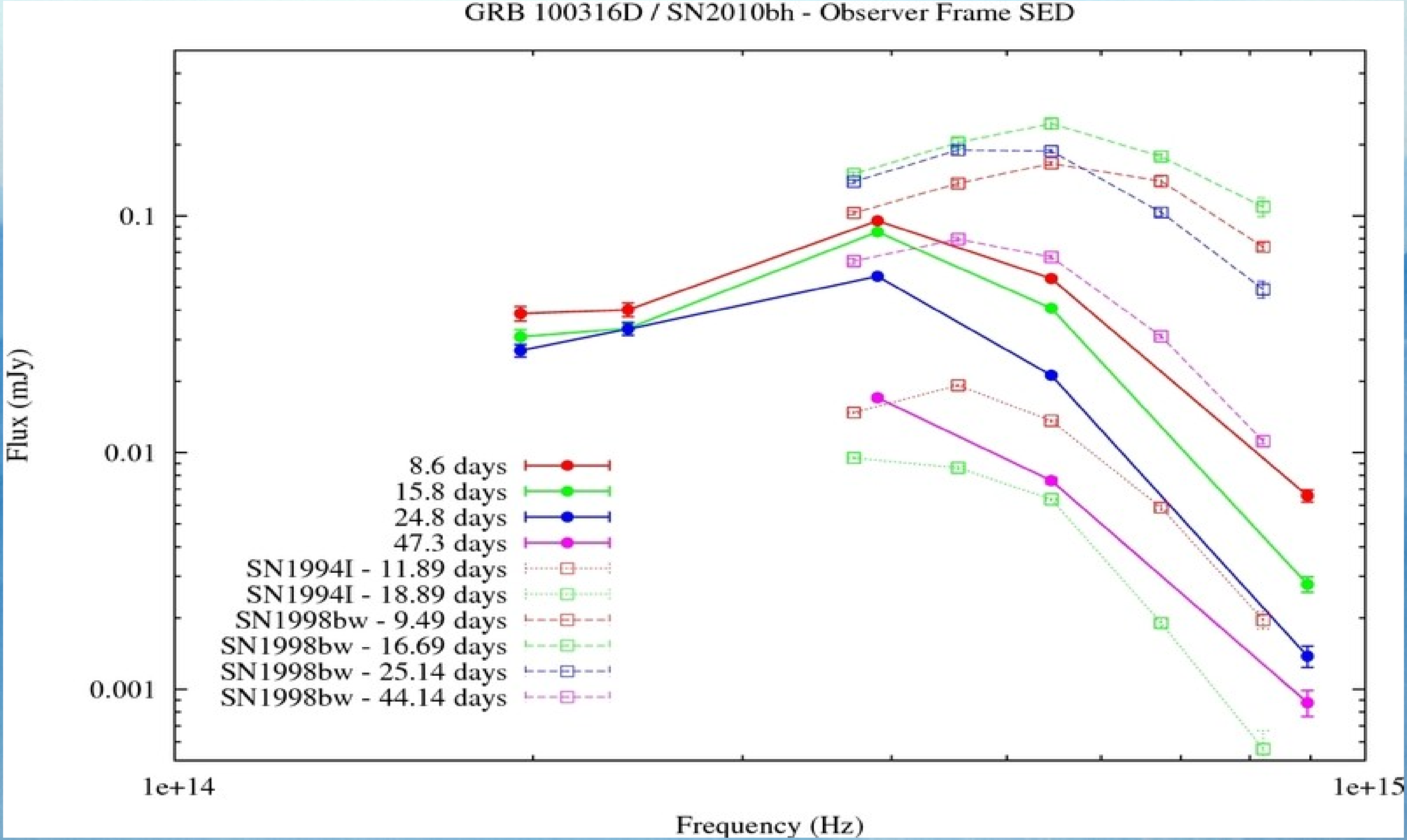
XRF 100316D – SN 2010 bh

HST photometry

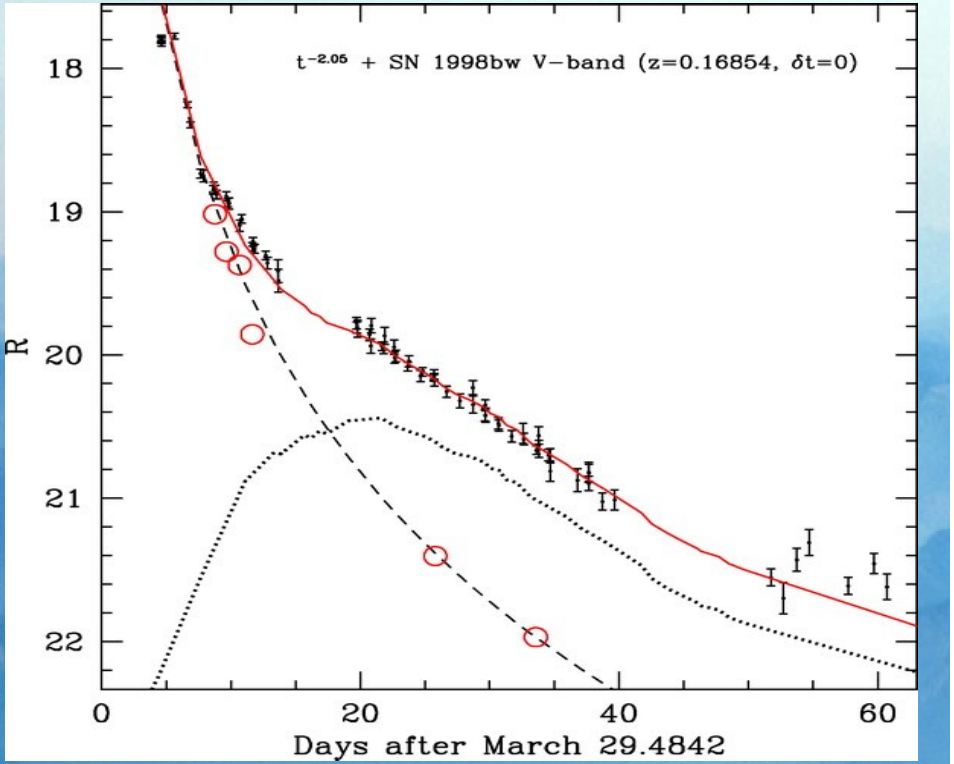


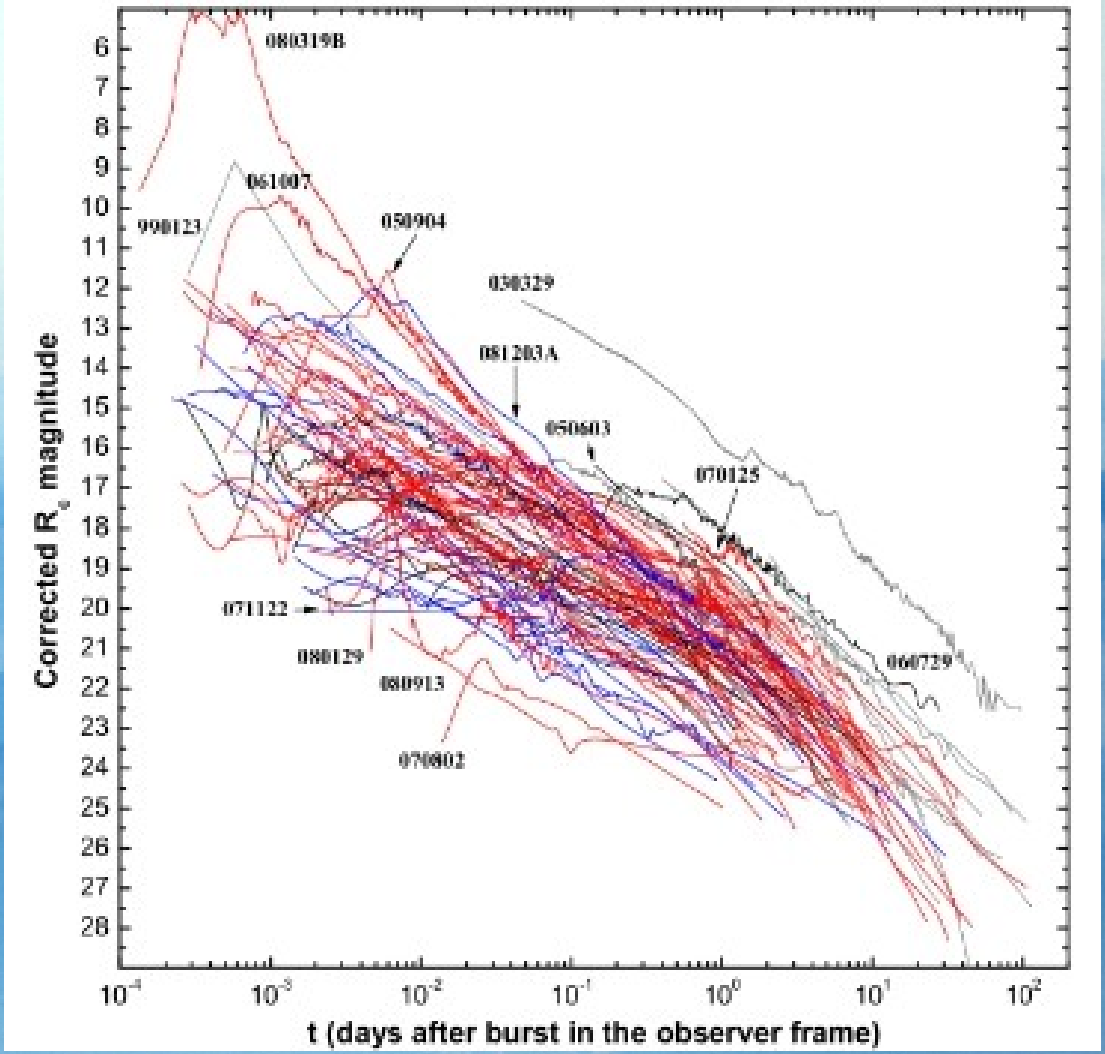
XRF 100316D - SN 2010 bh

HST photometry



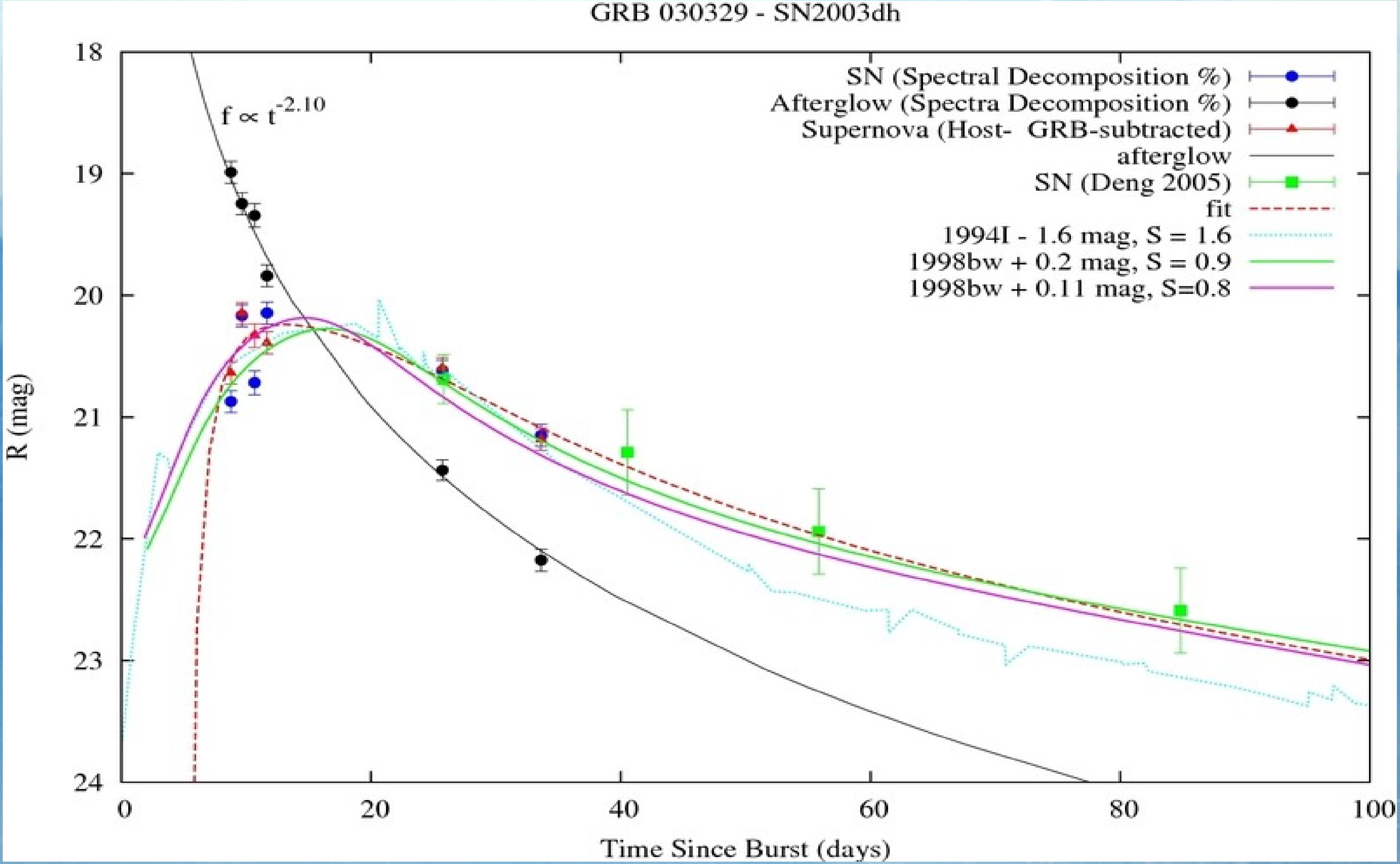
GRB 030329 – SN 2003 dh





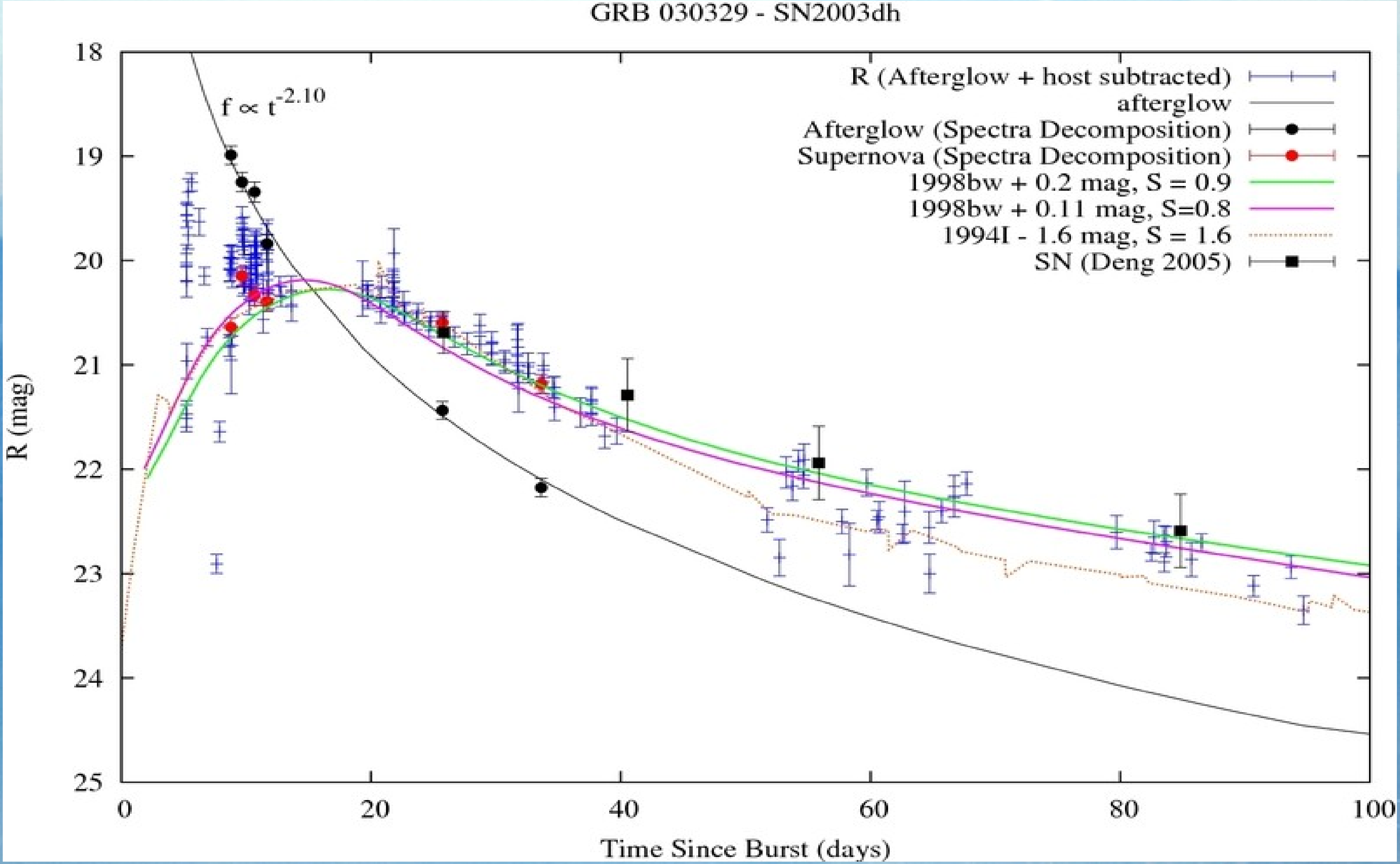
GRB 030329 - SN 2003 dh

Spectra & photometry from Matheson et al. 2003



GRB 030329 - SN 2003 dh

Photometry from Matheson et al. 2003, Lipkin et al. 2004



Concluding Remarks

Work to date:

Two case-studies of GRB-SNe, similar in peak brightness and temporal evolution as SN 1998bw.

Included these two GRB-SNe with the complete GRB/XRF-SNe sample and compared them to local Ibc SNe (without a GRB-trigger), concluding that GRB/XRF SNe are generally brighter.

Concluding Remarks

Work to do:

XRF 100316D:

Obtain template images for image subtraction on FTS images; create BVRi LCs and create pseudo-Bolometric LC

GRB 030329:

Model afterglow & subtract from the host-subtracted LCs to create "SN" LCs.