Electromagnetic priors for black hole spindown in gravitational-wave searches from supernovae and long GRBs

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van Putten, Della Valle & Levinson, A&A Lett., arXiv:1111.0137 (to appear)

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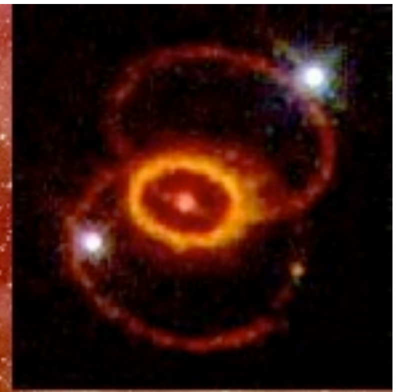
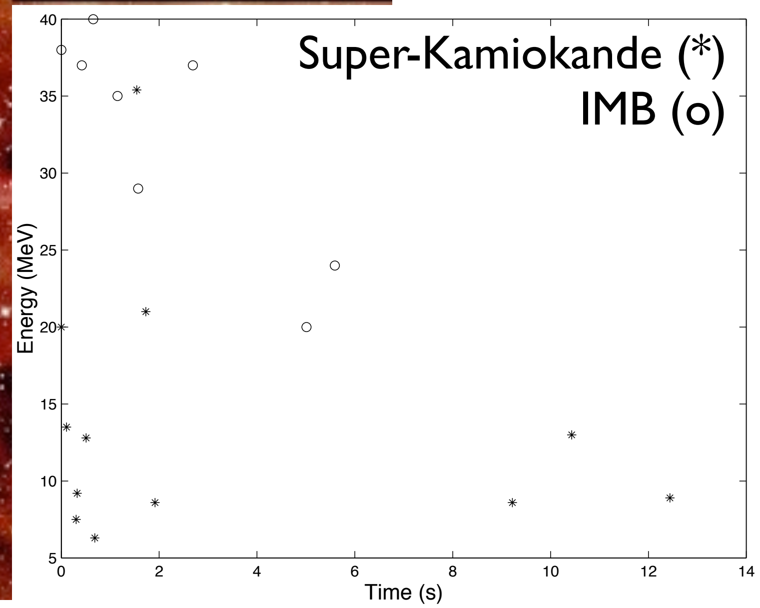




C. Burrows, ESA/STScI and

SN1979C

(Type IIL, M100, D=15.2 Mpc)

Evidence for BH remnant inferred from constant X-ray light curve over 12 years (1995-2007)

(Patnaude, Loeb & Jones, 2010, NewA, 16, 187)

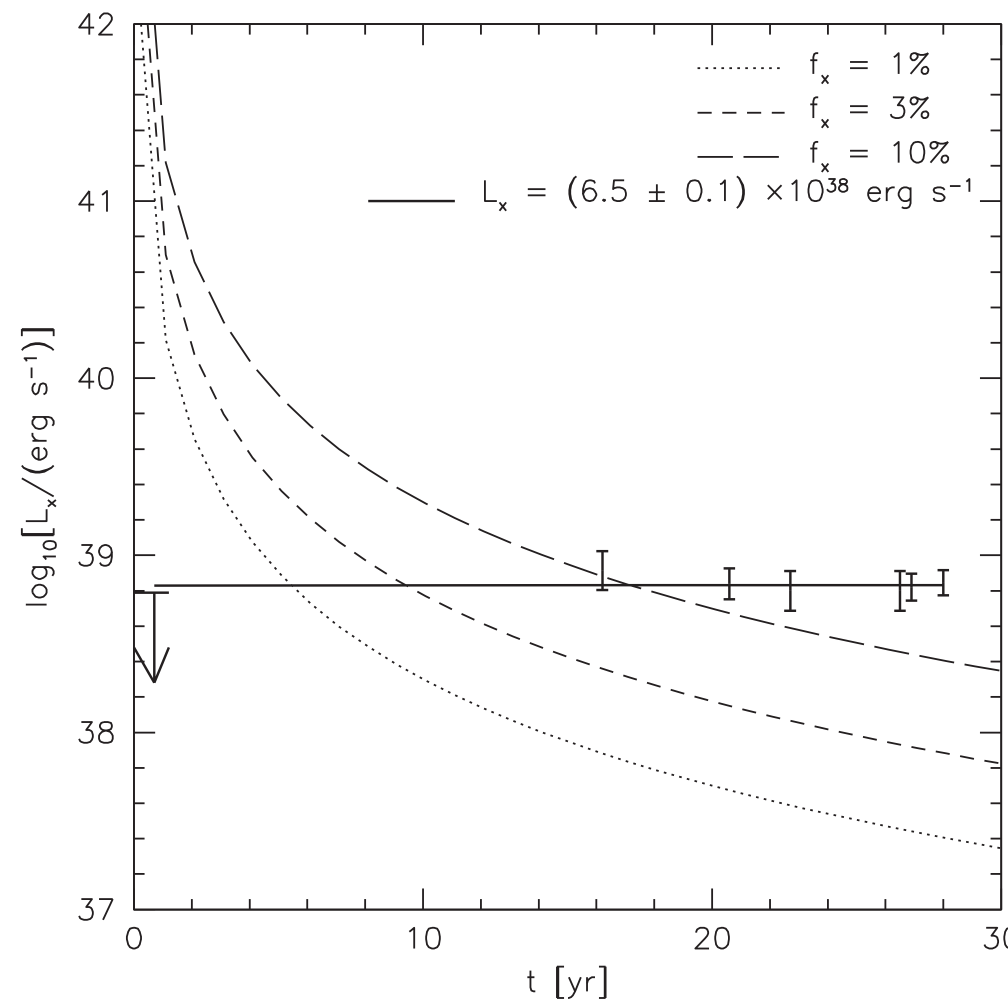
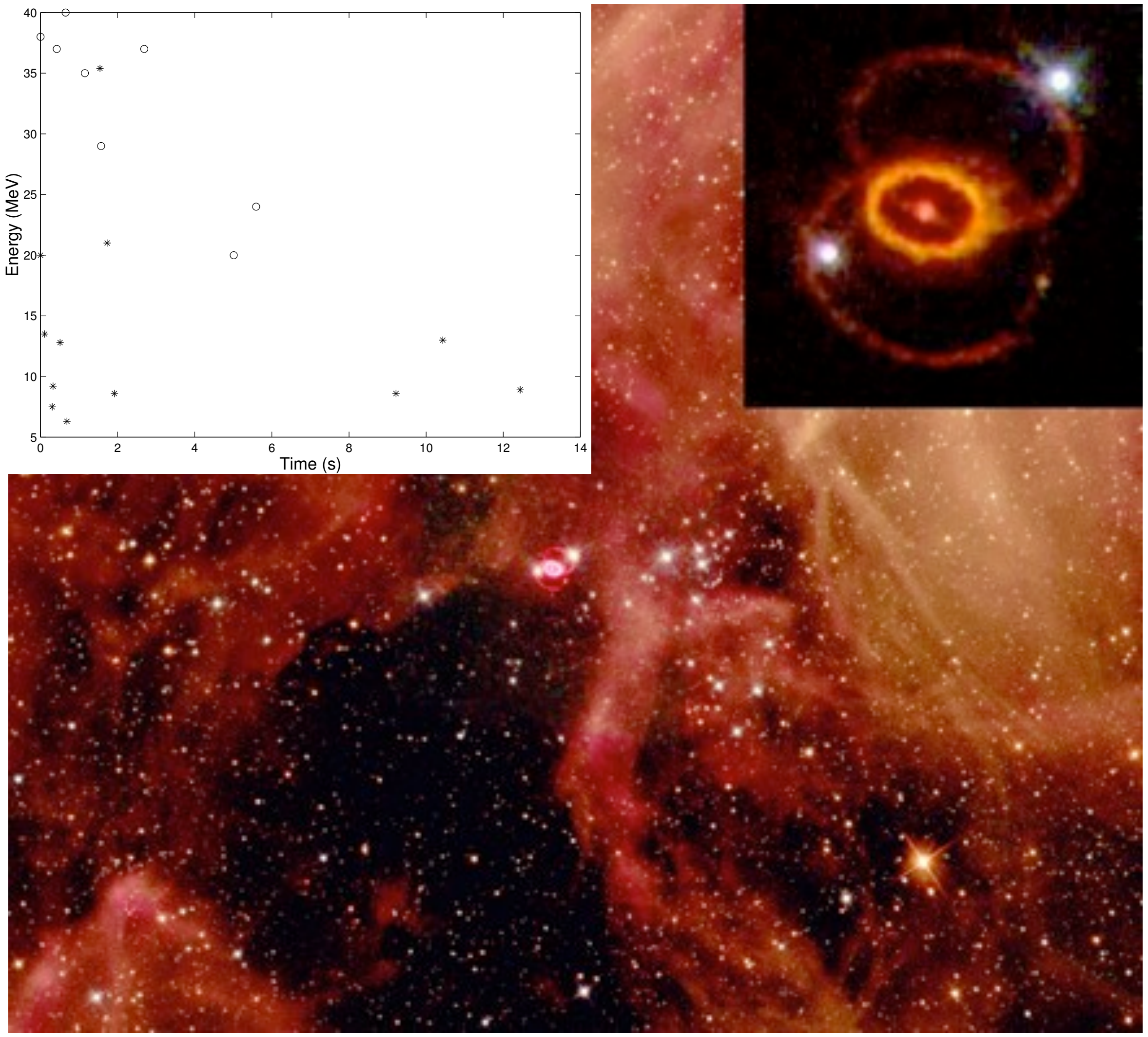


Fig. 1. Evolution of the X-ray luminosity of SN 1979C. The dotted, dashed, and long-dashed diagonal lines correspond to the evolution of the SN luminosity if it were powered by the magnetic dipole spindown of a central magnetar for various X-ray efficiencies, f_x. The data points correspond to the 0.3–2.0 keV X-ray luminosities with $1-\sigma$ uncertainties, assuming a distance of 15.2 Mpc. The upper limit from the *Einstein* observatory is depicted as an arrow. The heavy solid line corresponds to our best fit value of a nearly constant X-ray luminosity.

SN1987A

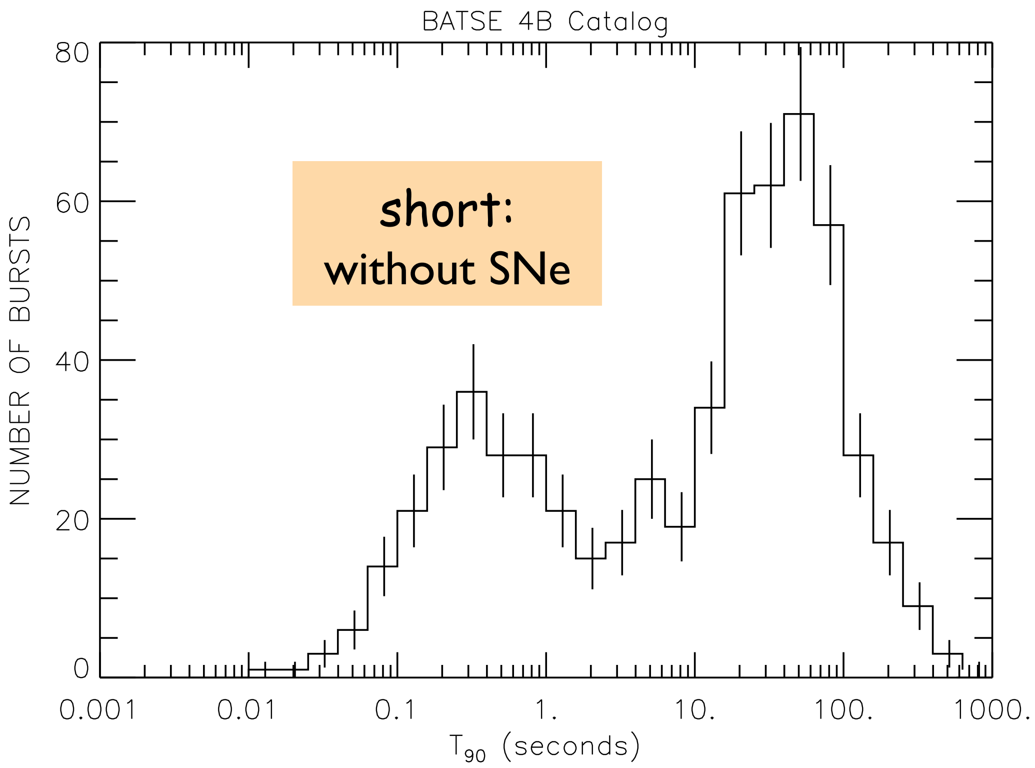


Radio-loud (Turtle et al. 1987) and aspherical, > 10 s > 10 MeV neutrino burst, EK~1e51erg with relativistic jets (Nisenson & Papaliolios 1999) (with BH remnant?)

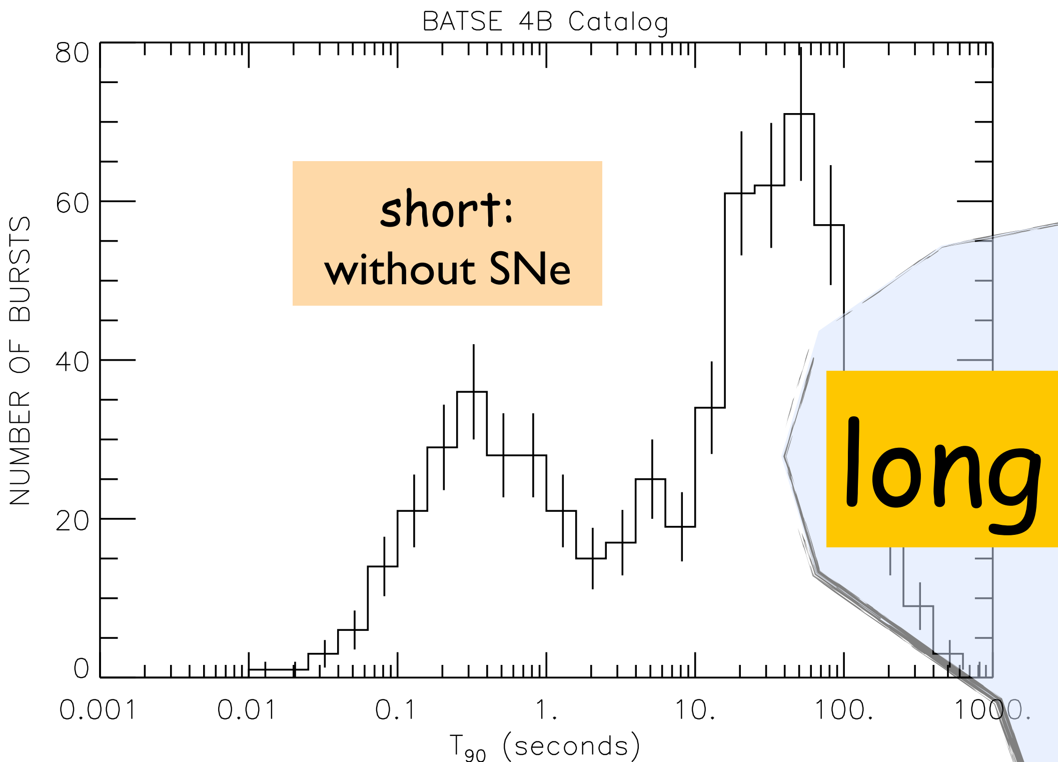
SN1998bw

Radio-loud and aspherical with EK~2e51 erg $(M_{ej}/2M_{\odot})$ (Hoeflich at al. 1999) with relativistic ejecta $v_{ej}/c \sim 20\%$ (Wieringa et al. 1999)

GRB classification



GRB classification



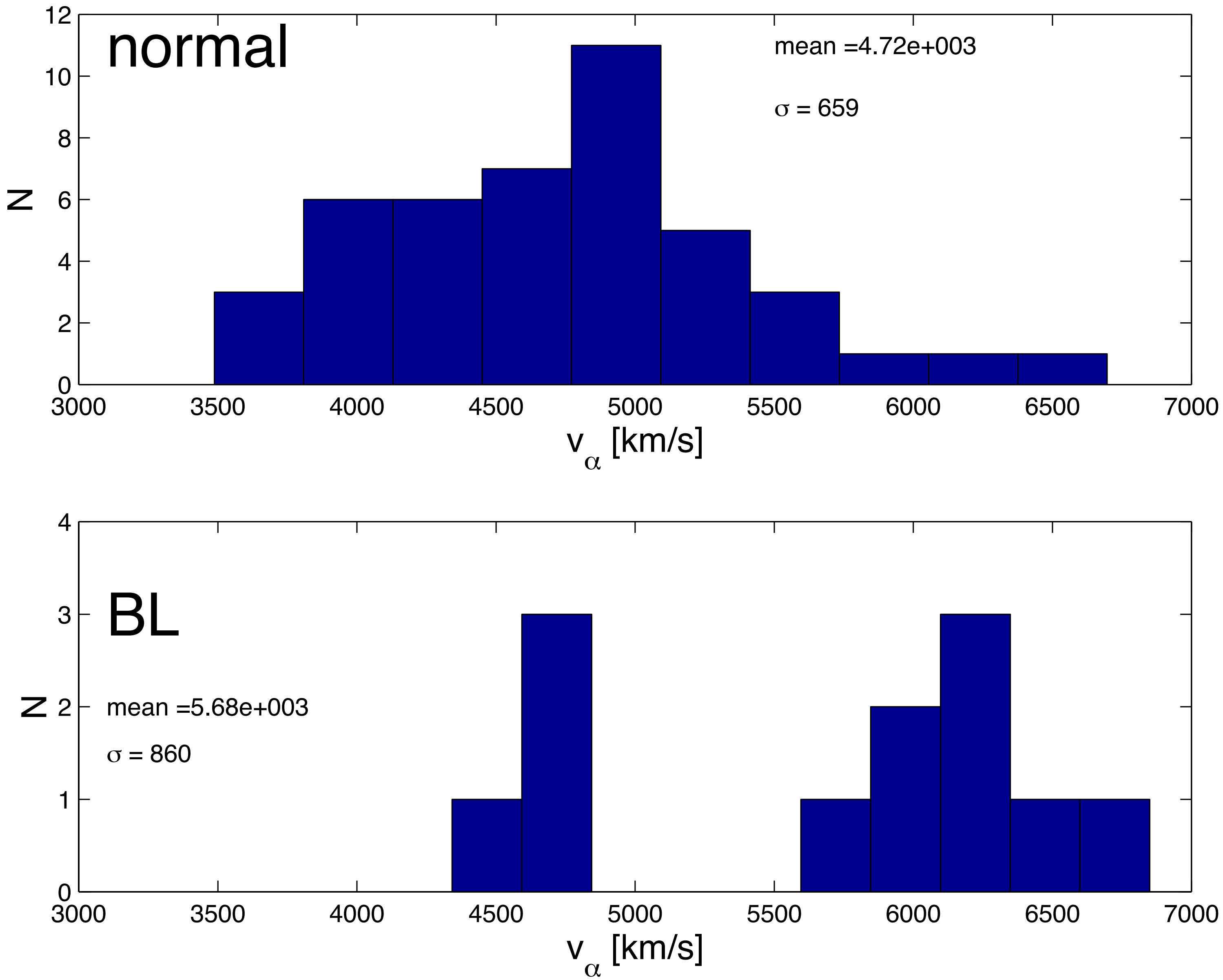
“with”

GRB 970228/SN
GRB 980425/SN1998bw
GRB 011121/SN2001ke
GRB 021202/SN2002lt
GRB 030329/SN2003dh
GRB 050525A/SN2005nc
GRB 050824/SN
GRB 050904/SN
GRB 060218/SN2006aj
GRB 070419A/SN
GRB 080319B/SN
GRB 081007/SN2008hw
GRB 090618/SN
GRB 091127/SN2009nz
GRB 100316D/SN2010bh
GRB 101219B/SN2010ma

“without”

GRB 050820A	ISM-like (constant density)
GRB 050911	no X-ray afterglow
GRB 060505	no SN
GRB 060614	no SN
GRB 070125	halo, ISM-like

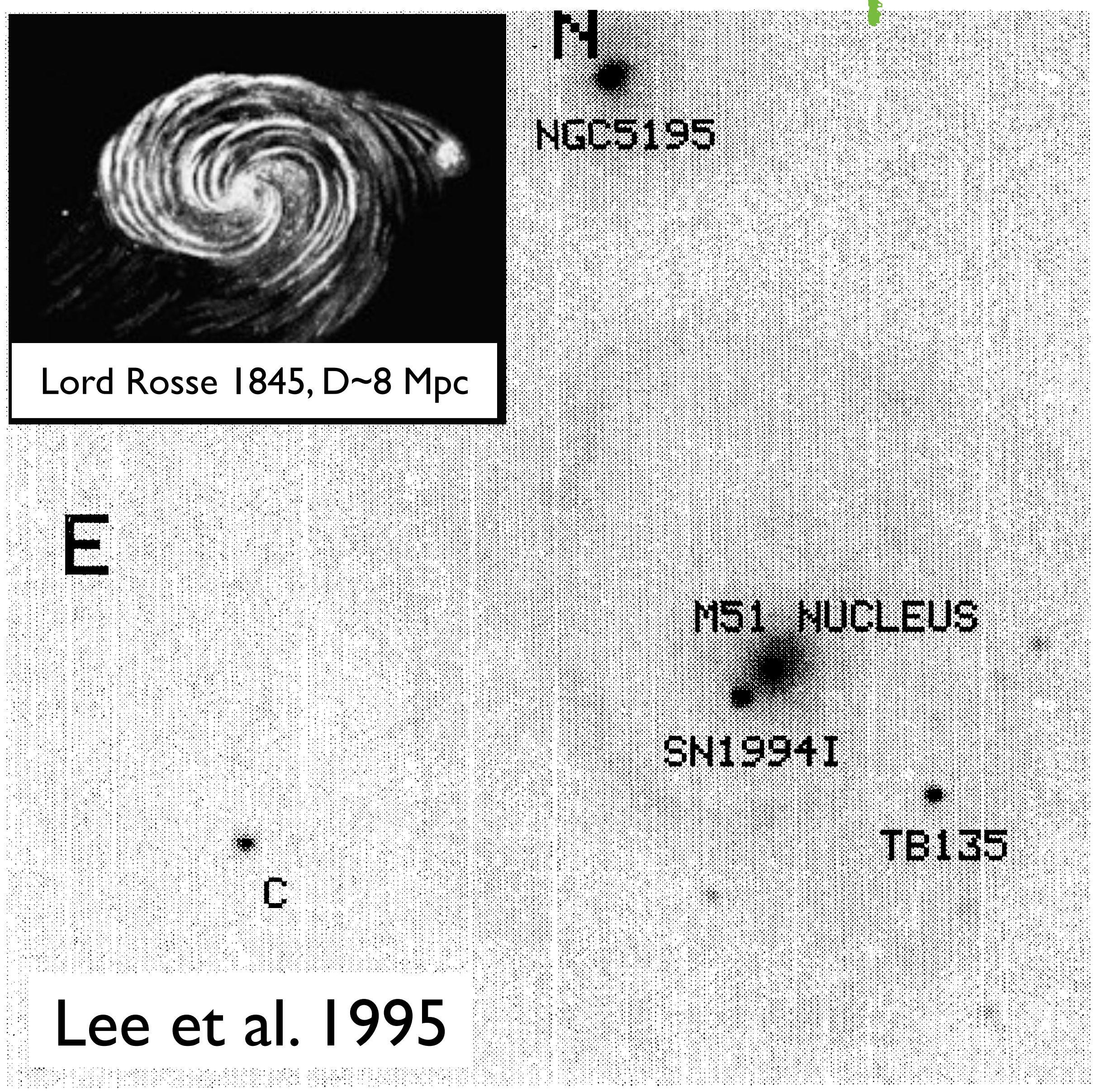
Observational evidence for a class of relativistic CC-SNe

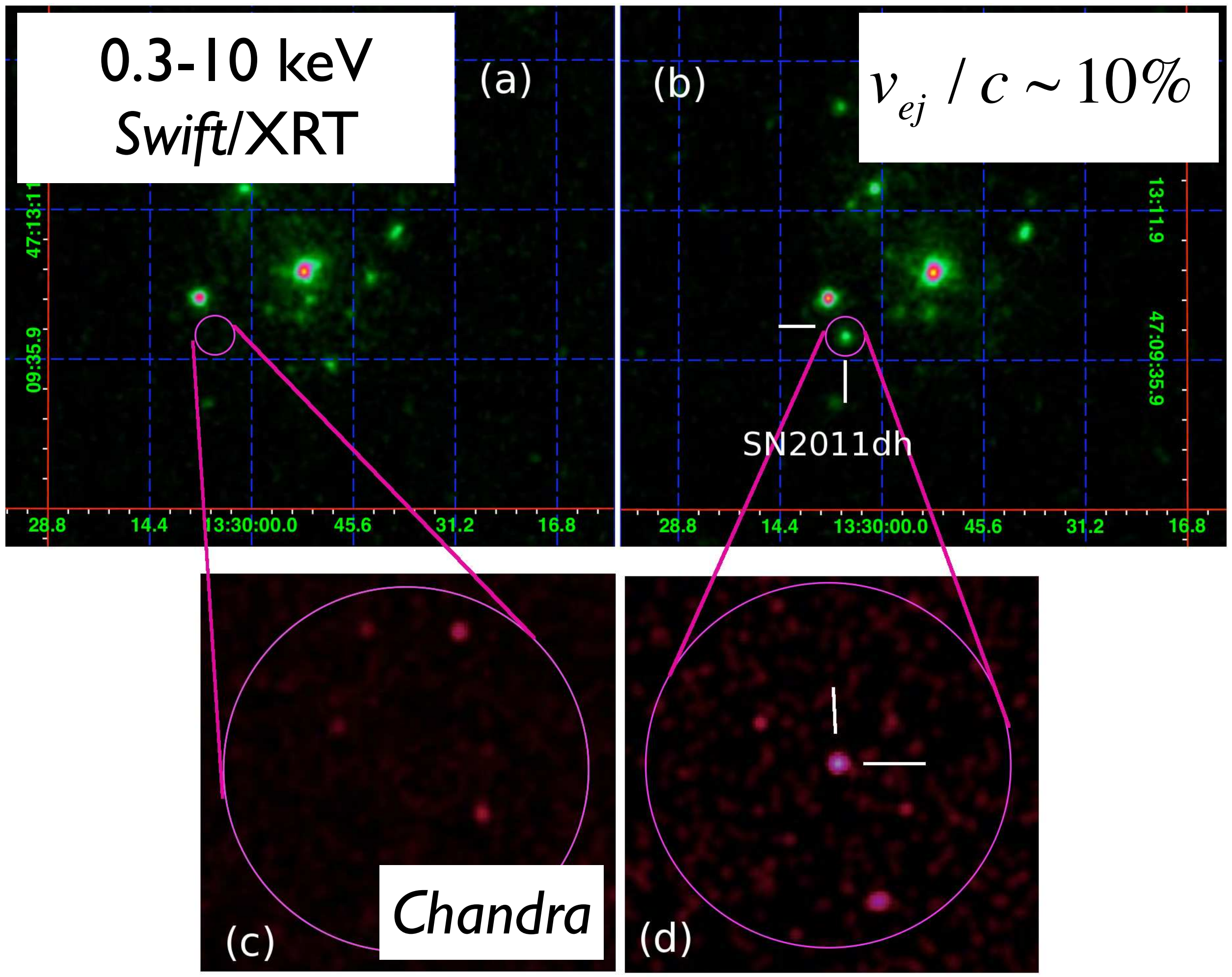


$$\beta_{ej} = \begin{cases} 4.7\% \text{ (typical)} \\ 5.7\% \text{ (anomalous)} \end{cases}$$

Data from Maurer et al., 2010, MNRAS, 402, 161

M51: farm of CC-SNe at 8 Mpc





Soderberg, et al., 2011, arXiv:1107.1876

SN1994i: Type Ic, M~12-30 solar
SN2005cs: Type II, M~18.1 solar
SN2011dh: Type II-P, M~13 solar

once every ~8.5 years?

Rotationally powered aspherical relativistic SNe

Bisnovatyi-Kogan 1970, LeBlanc & Wilson 1970
Ostriker & Gunn 1971, Paczynski 1991

proto-neutron star (PNS)

$$E_{sp} \approx 3\times 10^{52}\ \text{erg}$$

$$E_{sp} \leq 7.5\times 10^{52}\ \text{erg}$$ (supramassive)

(e.g. Haensel et al., 2009, A&A, 502, 605)

Formation with superstrong magnetic fields?

(e.g. Heger, Woosley & Spruit, 2005, ApJ, 626, 350)

Production GRBs from baryon-poor jets?

(Dessart, et al., 2007, ApJ, 669, 585; 2008, ApJ, 673, L43)

Kerr black hole

$$E_{sp} \approx 6\times 10^{54}\left(\frac{M}{10M_\odot}\right)\text{erg}$$

Natural outcome of massive progenitors in intra-day binaries (e.g. Woosley 2003, Paczynski 1998)

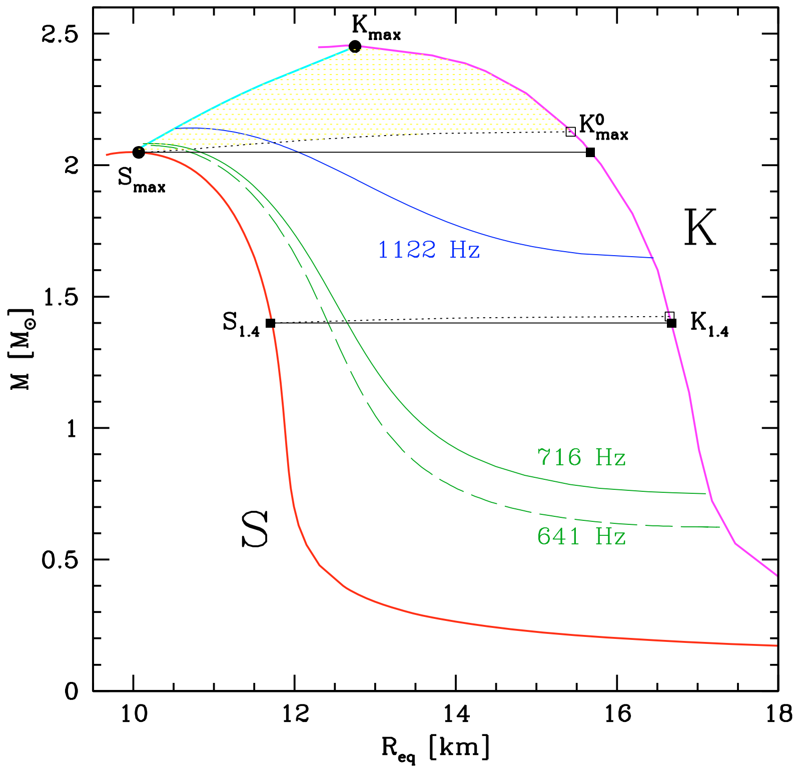
$$E_{BPJ} = 4\times 10^{52}\left(\frac{M}{10M_\odot}\right)\left(\frac{\theta_H}{0.5}\right)^4 \text{erg}$$

$$E_w = 4\times 10^{53}\left(\frac{M}{10M_\odot}\right)\text{erg}$$

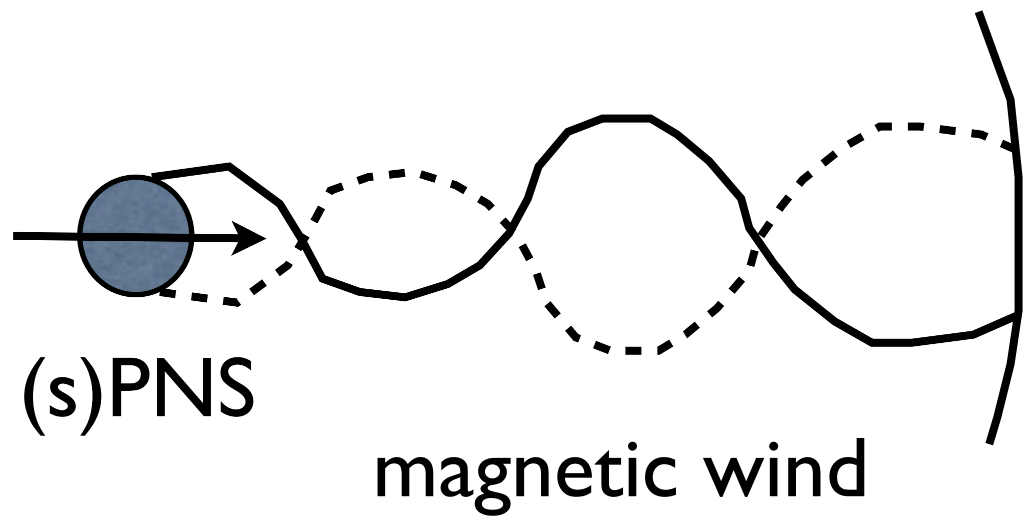
(van Putten & Levinson, 2003, ApJ, 584,937)

Producing SNe from spindown of a proto-neutron star (PNS)

Bisnovatyi-Kogan, G.S., 1970, Astron. Zh., 47, 813



Haensel et al., 2009, A&A, 502, 605



$$\beta_{ej} = \begin{cases} 4.5\% \text{ (typical)} \\ 5.7\% \text{ (relativistic)} \end{cases}$$

$$E_c = \begin{cases} 3\times 10^{52} \text{ erg (PNS)} \\ 7.5\times 10^{52} \text{ erg (sPNS)} \end{cases}$$

(supramassive PNS)

Efficiency in expelling stellar envelope by magnetic winds:

$$\frac{1}{2}\beta_{ej} < \eta < 1$$

(baryon-poor to baryon-rich winds)

$$E_w = \eta^{-1} E_{SN} \le E_c$$

(van Putten, Della Valle & Levinson, 2011, A&A Lett., to appear arXiv:1111.0137)

Sample of hyper-energetic CC-SNe and long GRBs

GRB	Supernova	Redshift z	E_γ	E_{tot}	E_{SN}	η	E_{rot}/E_c
	SN2005ap	0.283			> 10	1	> 0.3
	SN2007bi	0.1279			> 10	1	> 0.3
GRB 980425	Sn1998bw	0.008	< 0.001		50	1	1.7
GRB 031203	SN2003lw	0.1055	< 0.17		60	0.25	10
GRB 060218	SN2006aj	0.033	< 0.04		2	0.25	0.25
GRB 100316D	SN2006aj	0.0591	0.037-0.06		10	0.25	1.3
GRB 030329	SN2003dh	0.1685	0.07-0.46		40	0.25	5.3
GRB 050820A		1.71		42			1.4
GRB 050904		6.295		12.9			0.43
GRB 070125		1.55		25.3			0.84
GRB 080319B		0.937		30			1.0
GRB 080916C		4.25		10.2			0.34
GRB 090926A		2.1062		14.5			0.48
GRB 070125	(halo event)	1.55		25.3			0.84

$$E_{tot} = E_\gamma + E_k$$

E_k : from calorimetry on afterglow emissions and/or accompanying SN (if present, and observationally limited to 0.17 z)

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black holes?

$$E_{tot} = E_\gamma + E_k$$

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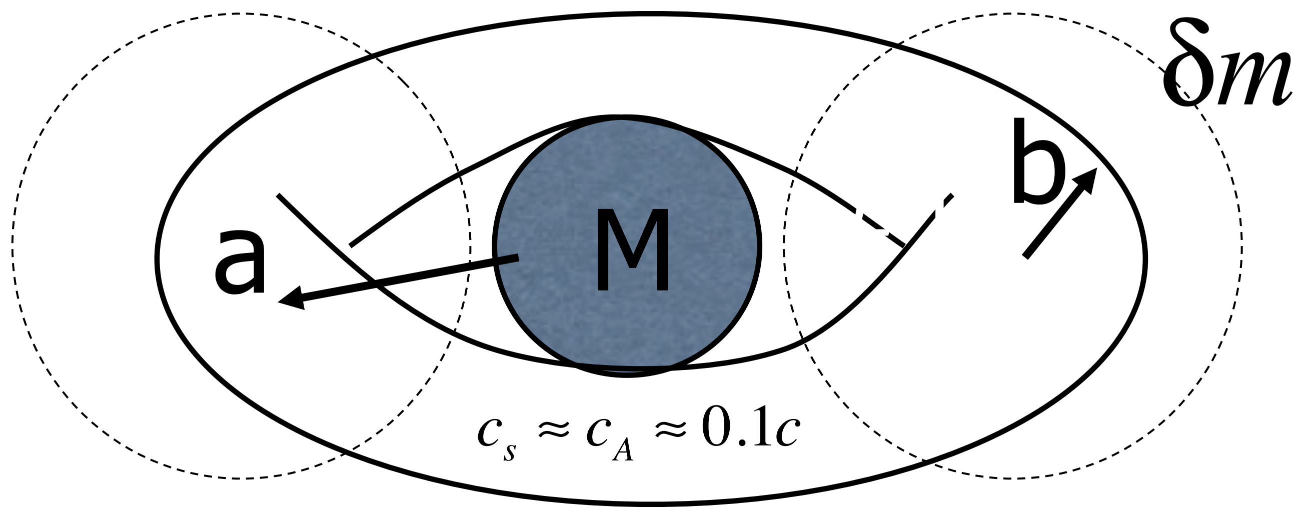
Multimessenger emissions

(GWs, MeV neutrinos and magnetic winds)



Thermal and magnetic pressure-induced Papaloizou-Pringle instability

van Putten 2002, van Putten & Levinson 2003

or magnetic-pressure type instabilities

(Bromberg et al. 2006)

Study spindown in light curve in gamma-rays by matched filtering

Spin down of black holes and proto-neutron stars

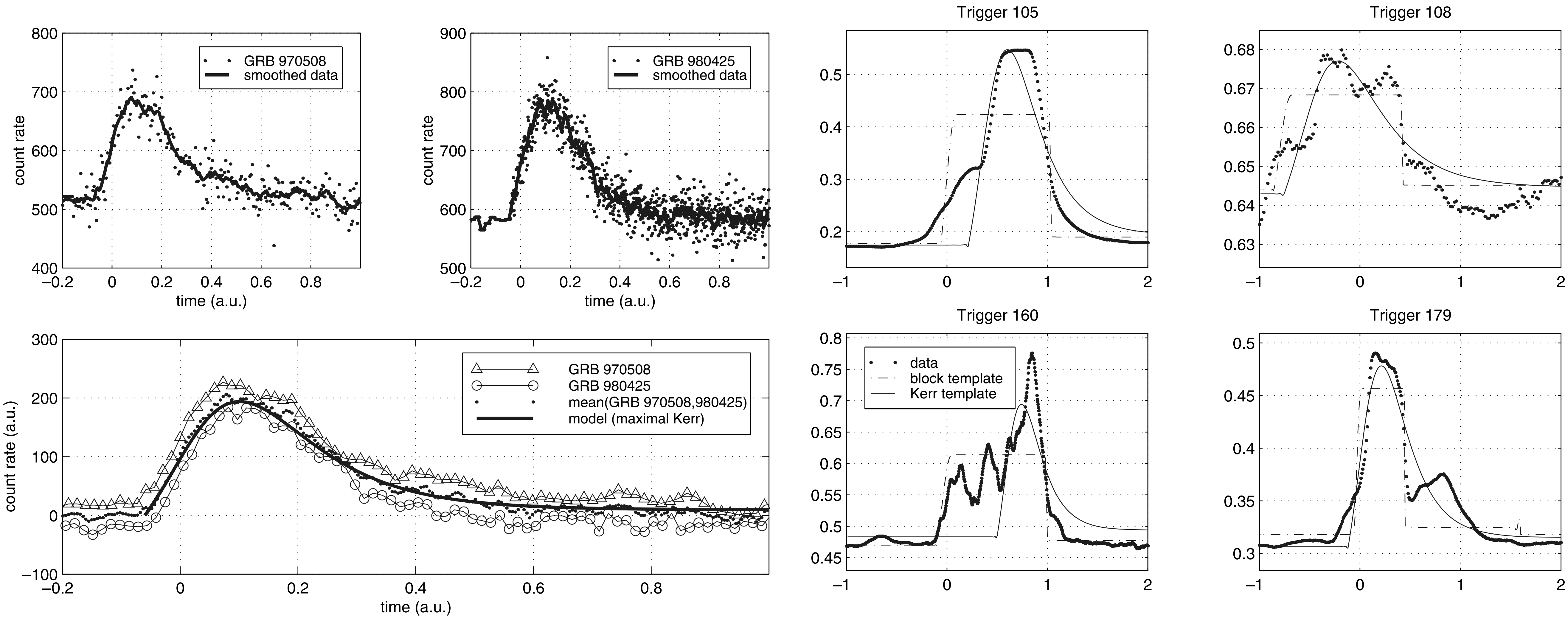
$$\tau_+ = \tau_- + \tau_{GW} + \tau_\nu, \quad \Omega_+ \tau_+ = \Omega_- \tau_- + \Omega_T \tau_{GW} + P_\nu,$$

$A: \quad \Omega_T = \Omega_{ISCO}$ matter at ISCO with GW emissions

$B: \quad \Omega_T = \frac{1}{2}\Omega_H.$ matter further out with no GW emissions

Model C: **spindown of PNS**

Individually normalized GRB light curves



Van Putten & Gupta, 2009, MNRAS

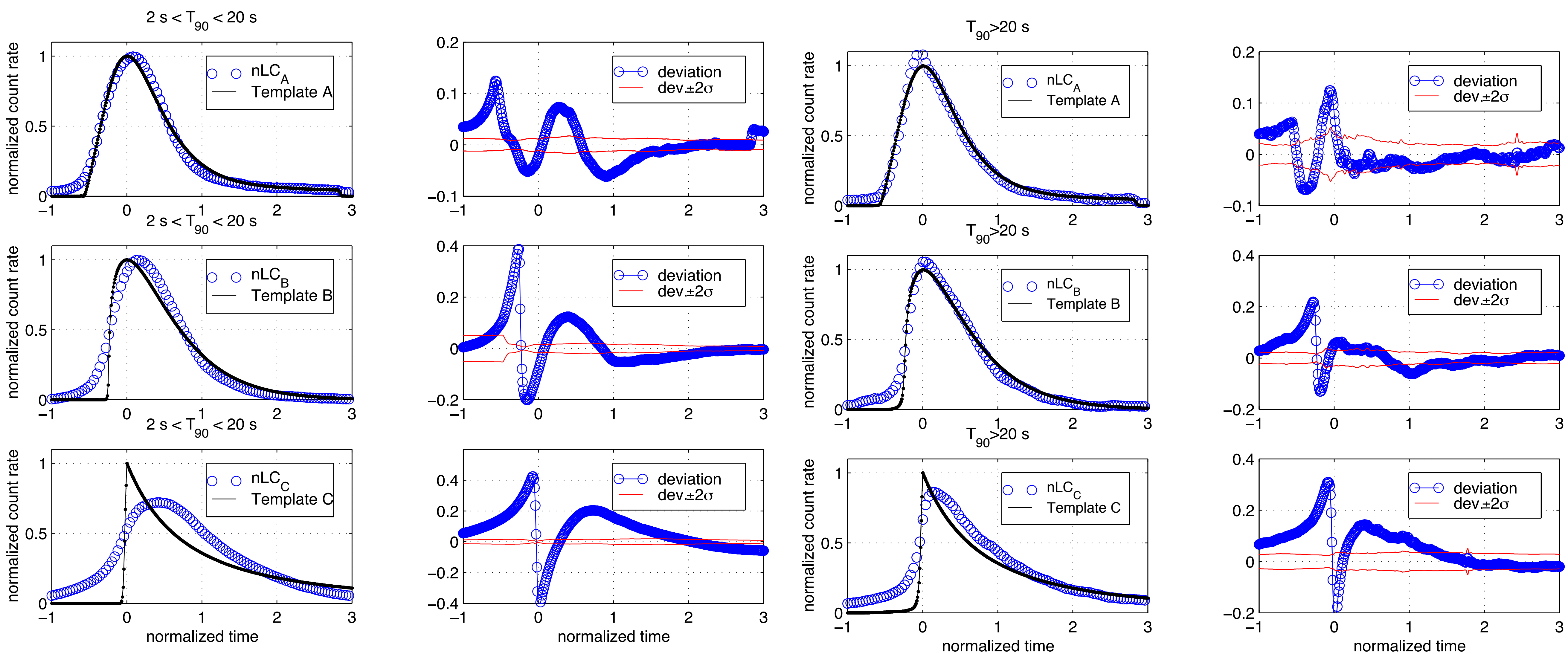
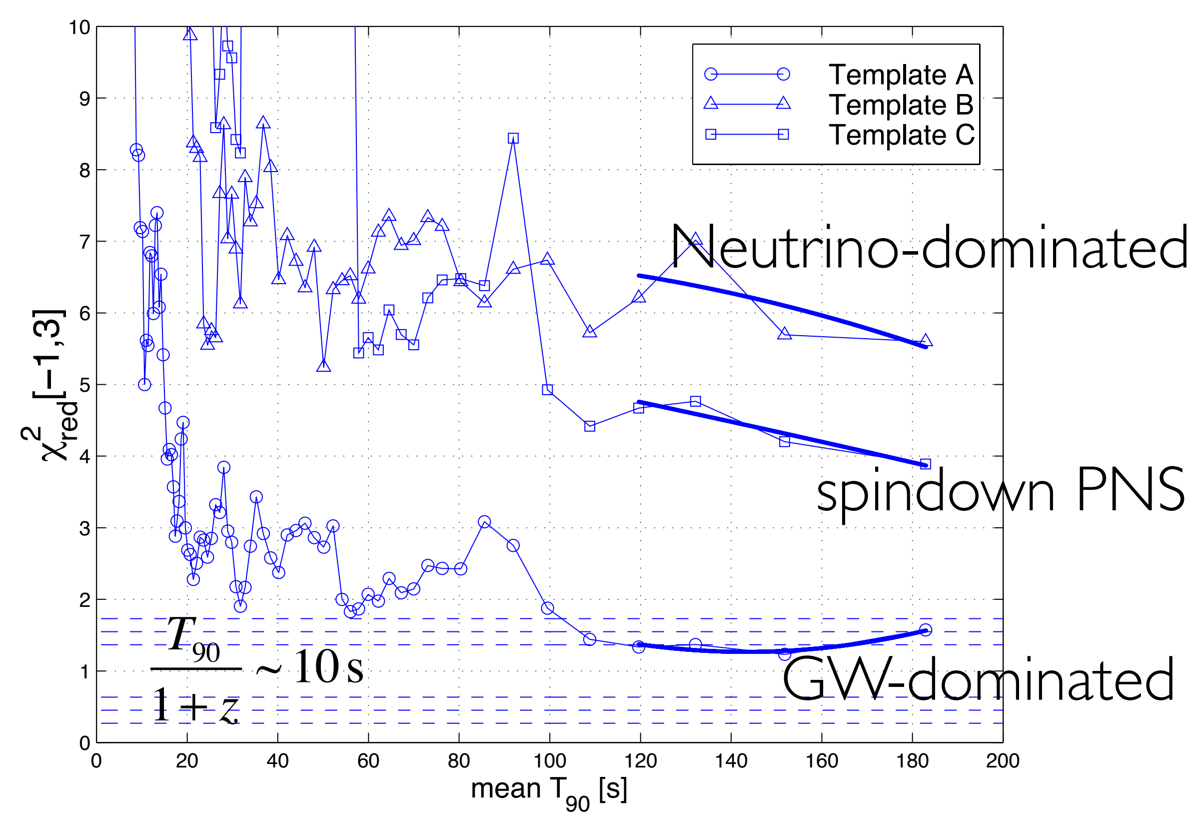


TABLE I. Summary on the nLC over $t_k\epsilon[-1,3]$ ($k = 1, 2, \cdots, \nu = 400$) of two ensembles of $N = 300$ long GRBs to templates derived from spindown of black holes (14) and PNS (17).

Quantity	Symbol	$2\text{ s} < T_{90} < 20\text{ s}$	$T_{90} > 20\text{ s}$	$\langle T_{90}\rangle \geq 120\text{ s}$
mean duration	T_{90}[s]	9.8	72	119.6-182.9
ensemble size	N	300	300	60
(sub-)interval	I	[-3,1], [-1,0], [0,3]	[-3,1], [-1,0], [0,3]	[-3,1]
convergence nLC	σ_A[%]	0.98, 0.65, 0.11	1.2, 1.3, 1.2	
	σ_B[%]	0.67, 0.94, 0.19	1.2, 1.1, 1.2	
	σ_C[%]	0.15, 0.12, 0.15	1.6, 1.4, 1.7	
deviation δ	Σ_A[%]	4.0, 5.0, 3.3	3.5, 5.4, 1.4	
	Σ_B[%]	8.7, 14, 5.2	5.6, 7.9, 2.9	
	Σ_C[%]	13, 12, 12	8.3, 7.9, 6.7	
goodness-of-fit	$\chi^2_{red,A}$			1.38
	$\chi^2_{red,B}$			3.50
	$\chi^2_{red,C}$			4.38



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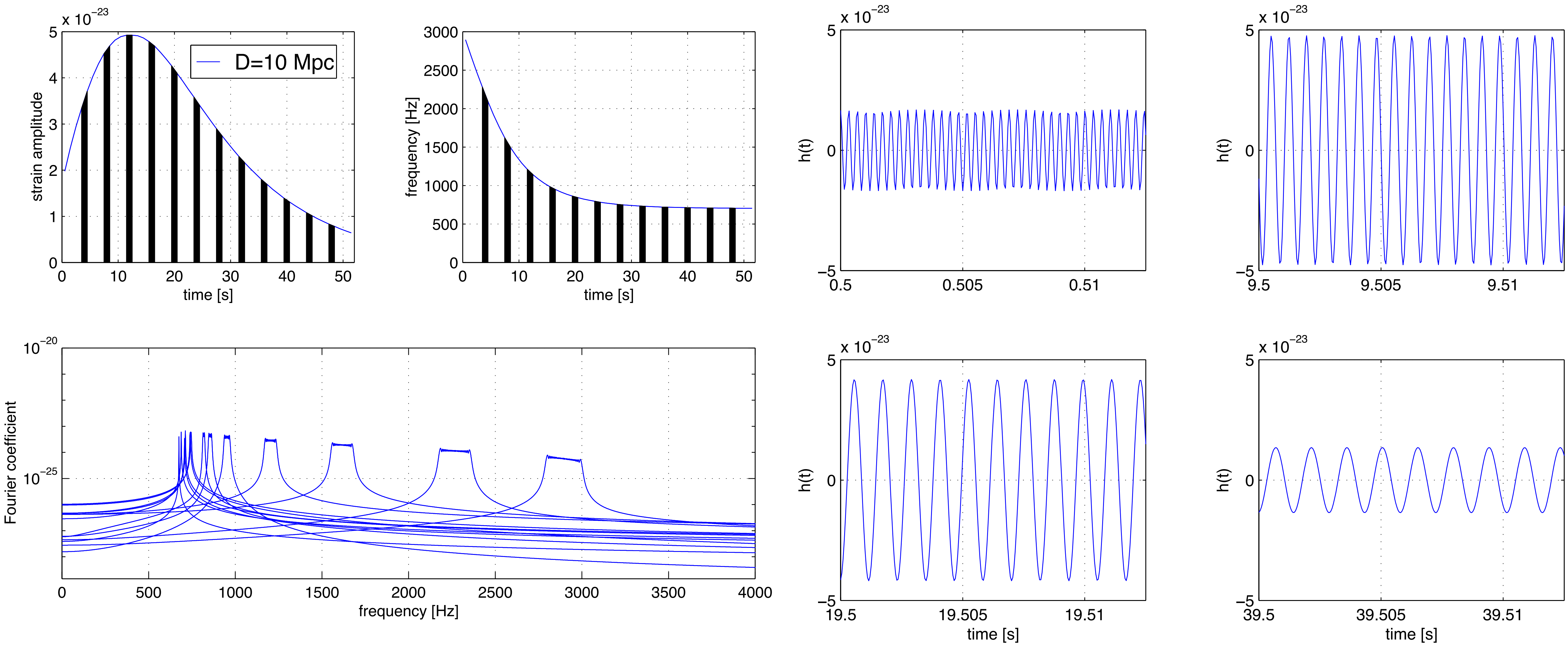
GRB 980425	Sn1998bw	0.008	< 0.001		50	1	1.7	BH	2
GRB 031203	SN2003lw	0.1055	< 0.17		60	0.25	10	BH	3
GRB 060218	SN2006aj	0.033	< 0.04		2	0.25	0.25	indet	4
GRB 100316D	SN2006aj	0.0591	0.037-0.06		10	0.25	1.3	BH	5
GRB 030329	SN2003dh	0.1685	0.07-0.46		40	0.25	5.3	BH	6
GRB 050820A		1.71		42			1.4	BH	7
GRB 050904		6.295		12.9			0.43	indet	7
GRB 070125		1.55		25.3			0.84	indet	7
GRB 080319B		0.937		30			1.0	BH	7
GRB 080916C		4.25		10.2			0.34	indet	7
GRB 090926A		2.1062		14.5			0.48	indet	8
GRB 070125	(halo event)	1.55		25.3			0.84	indet	9

$$E_{tot} = E_\gamma + E_k$$

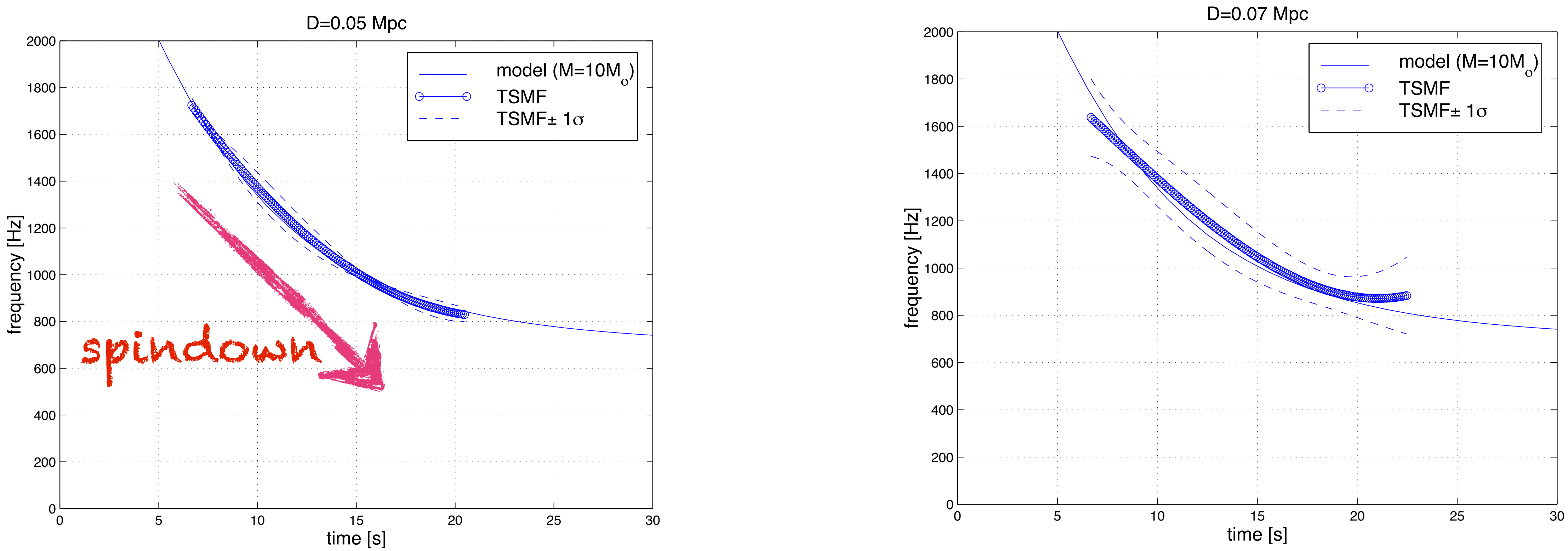
E_k : from calorimetry on afterglow emissions and/or accompanying SN (if present, and observationally limited to 0.17 z)

Gravitational-wave form templates



$$f_{GW} = 595 - 704\,\mathrm{Hz}\left(\frac{10\,M_{\odot}}{M}\right)$$

Estimated sensitivity distances



Advanced detectors (LIGO-Virgo, LCGT): h~2e-24@1000Hz

$$D \approx 35 \text{ Mpc}$$

van Putten, Kanda, Tagoshi, Tatsumi, Masa-Katsu & Della Valle, 2011, PRD, 83, 044046

Conclusions

Some nearby galaxies (M51, M82) show frequent CC-SNe (1/10 years)

Long GRBs from prolonged BH spindown in CC-SNe and mergers

Accompanying magnetic torus winds may power hyper-energetic SNe

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Collaboration with observers

Develop a catalogue of nearby galaxies producing frequent CC-SNe

Downselect radio-loud hyper-energetic events and search for GWBs:

- needs dedicated optical survey
- LCGT pipeline for long bursts, manycore-GPU?
  (presently 1000 hr/1hr TAMA data)