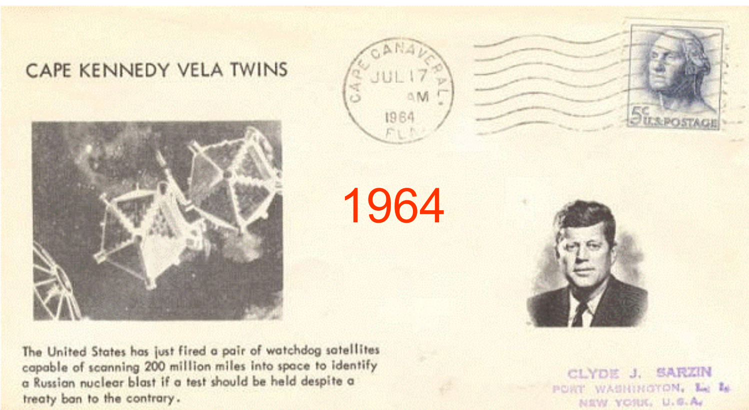
Broad band chirp spectrum of long GRBs

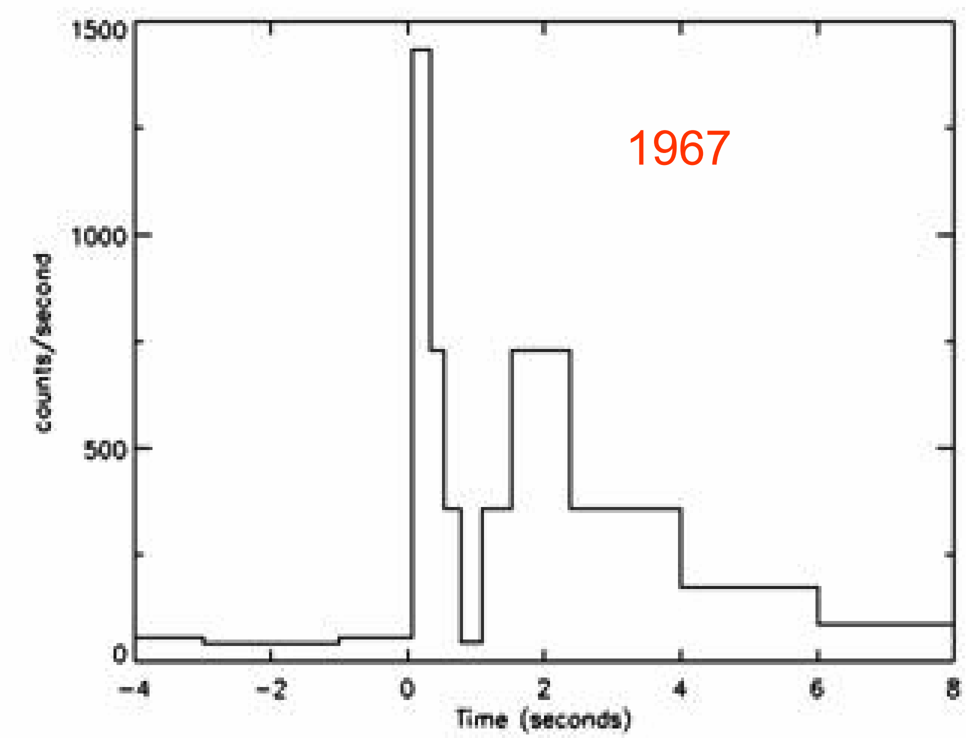
Maurice H.P.M. van Putten

October 2013

Klebesadel, R.W., Strong, I.B., & Olson, R.A., 1973, ApJ, 182, L85

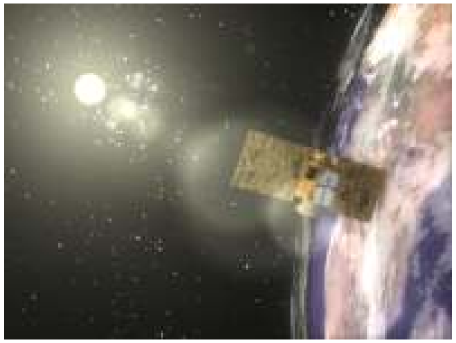
Discovery of mysterious transients





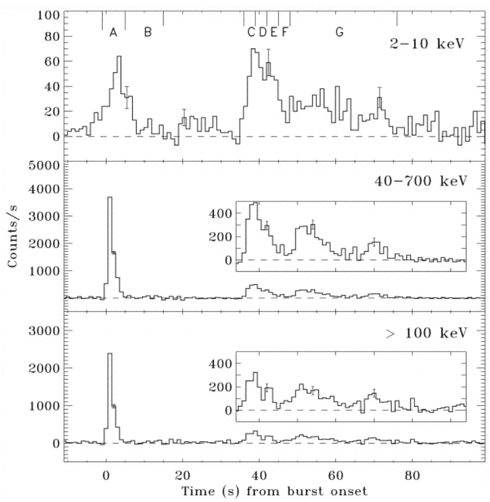
Vela and Konus satellites

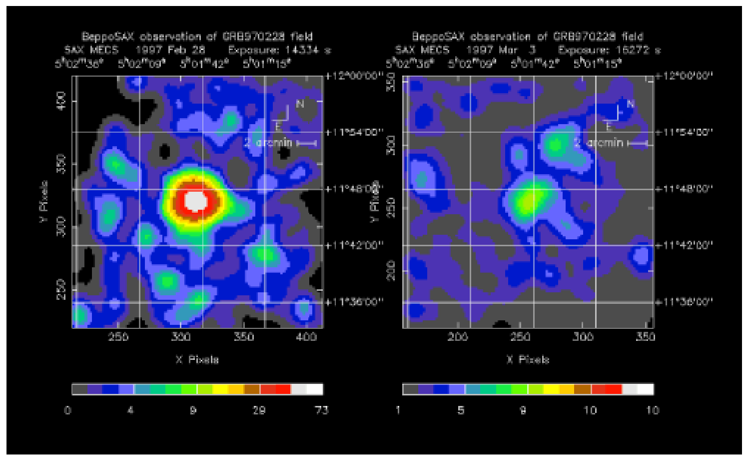
Cosmological origin

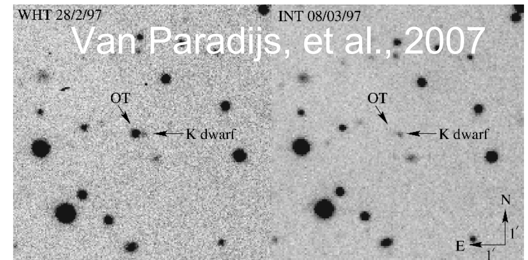


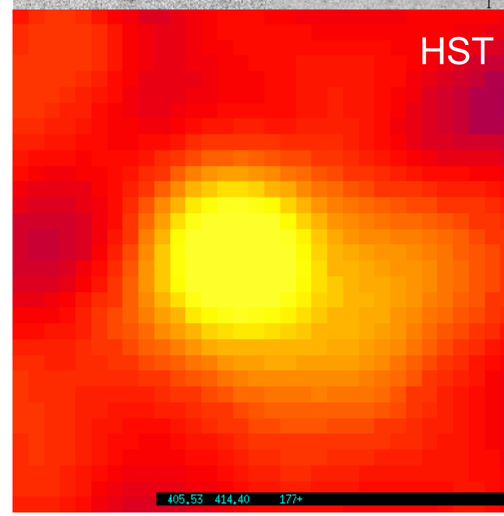
Dutch-Italian BeppoSax satellite

Prompt GRB emission → 1st X-ray afterglow (+ ~ 8 hr) → 1st Optical Transient





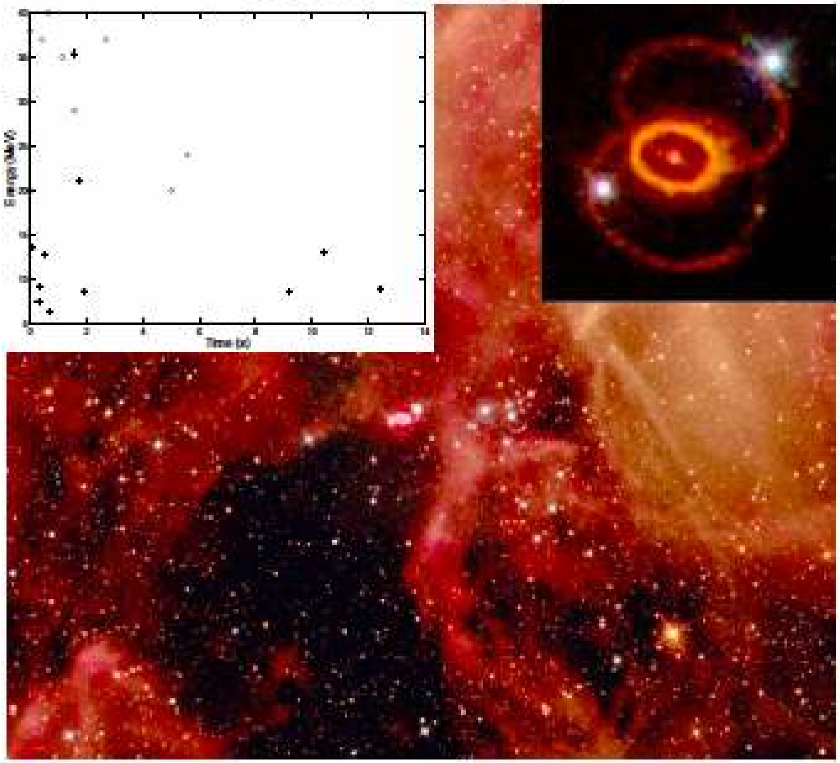




GRB 970228: z=0.695

Association with core-collapse SNe

SN1987A



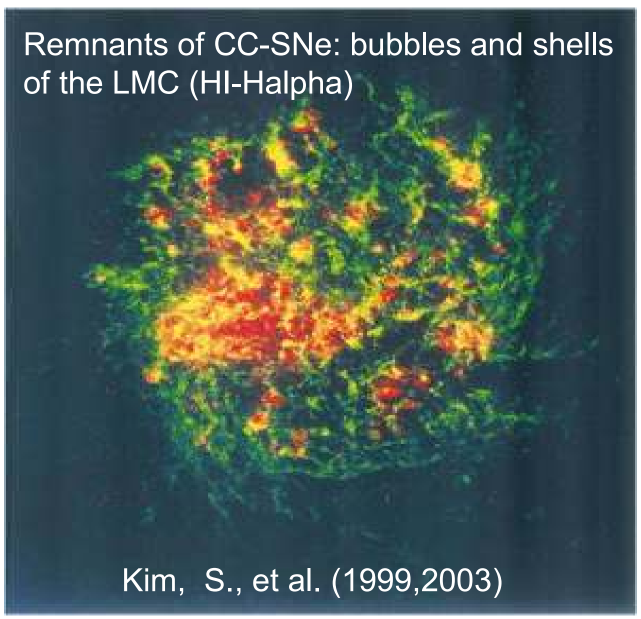
Radio-loud (Turtle et al. 1987) and aspherical, > 10 s > 10 MeV neutrino burst, EK~1e51erg with relativistic jets (Nisenson & Papaliolios 1999) (with BH remnant?)

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)

Van Putten, 2004, ApJ, 611, L81
Guetta & Della Valle 2007, ApJ, 657, L73

GRB-SNe are rare



Branching ratio of SN Ib/c:

~ 0.2-4 %

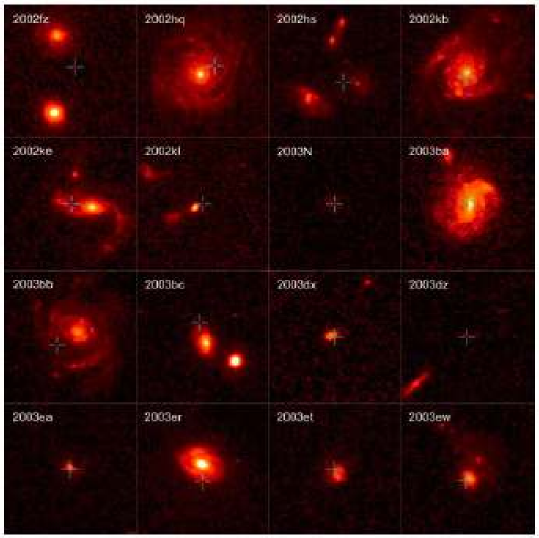
Relative supernova rates:

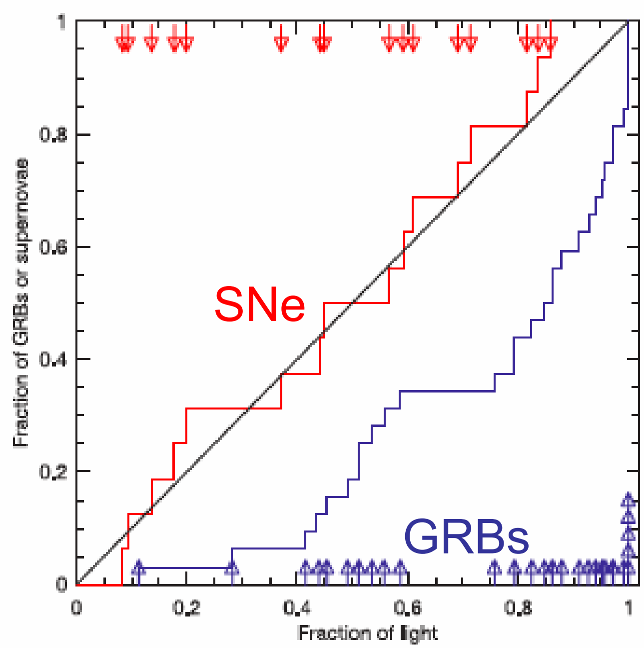
SN Ia :SN II : SN Ib/c ~ 50:50:10

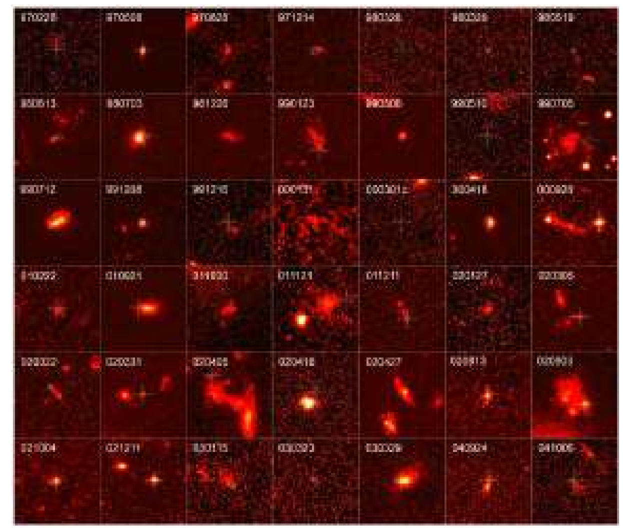
(depends on survey, e.g., 68:22:7 in PTF)

Fruchter et al. 2006

LGRB relatively central



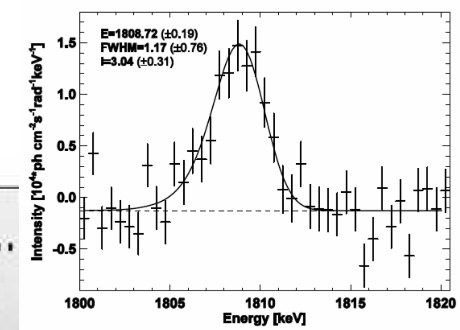


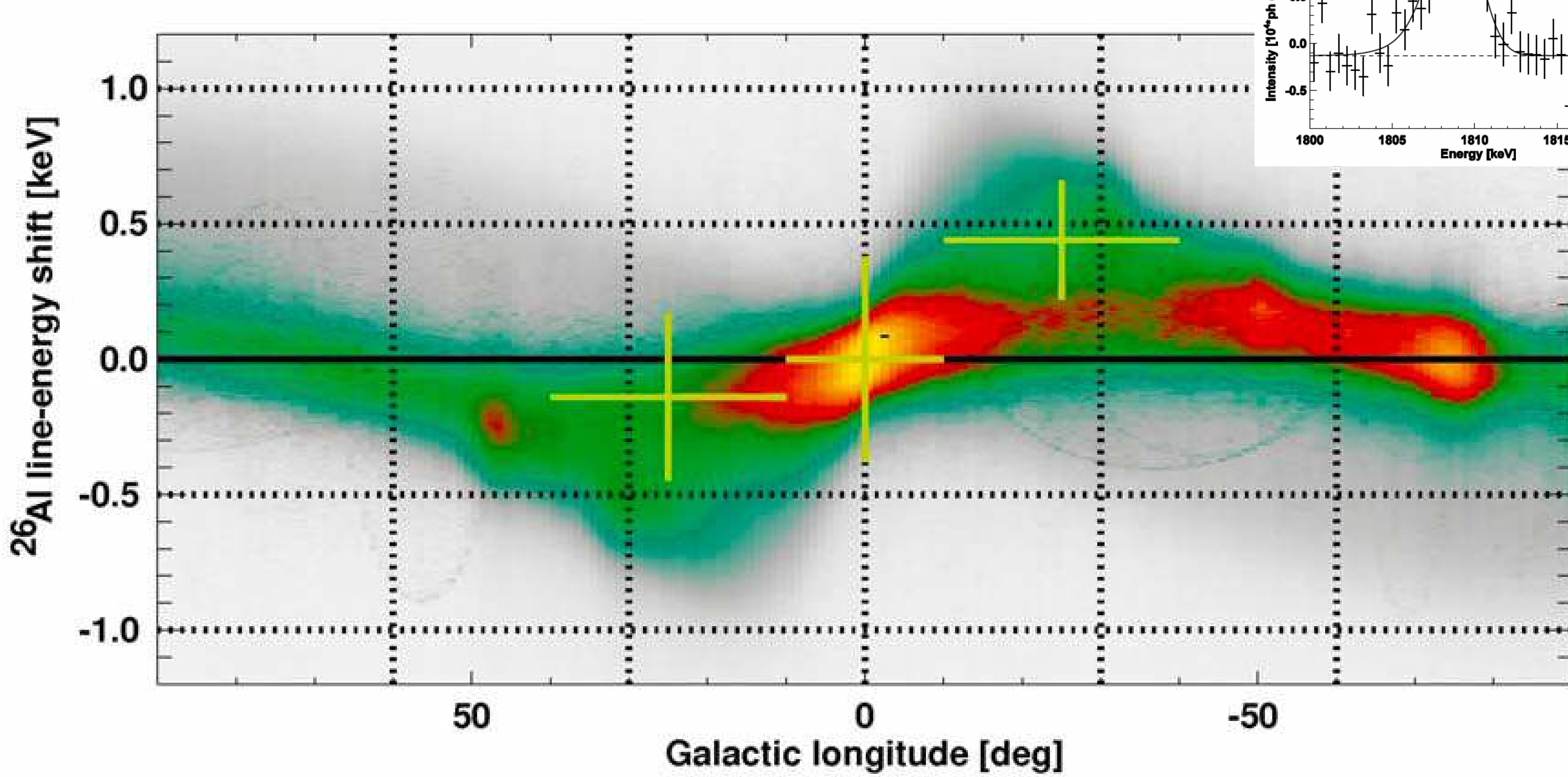


Diehl, R., et al., 2006, Nature, 439, 45

CC-SNe rate in the Milky Way

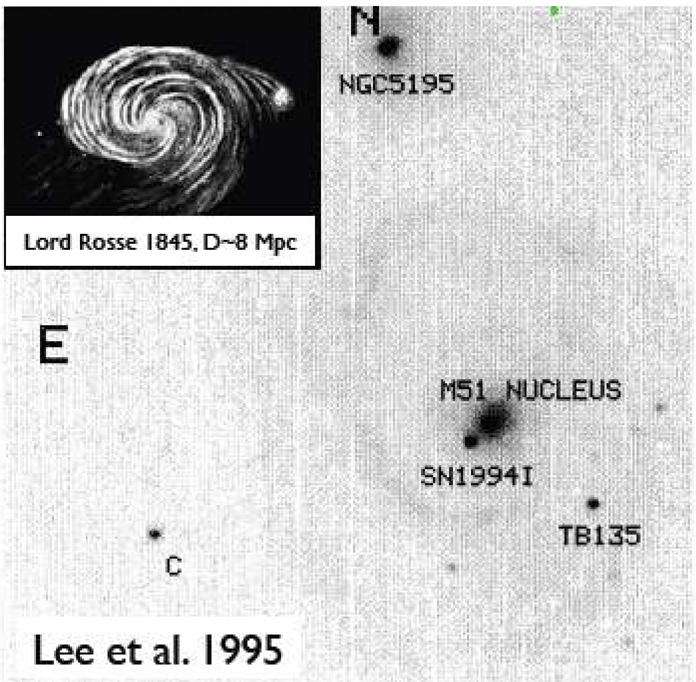
1.809 MeV line





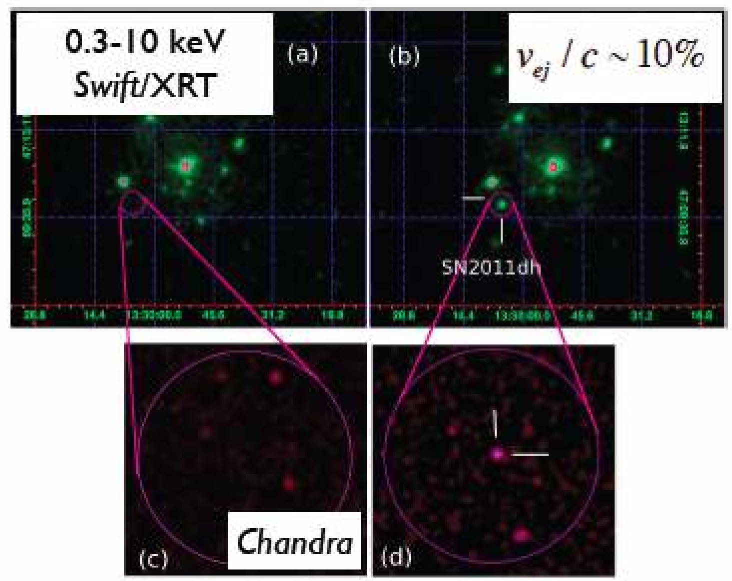
CC-SNe rate: 1.9(+/- 1.1) events / century

M51: a local farm of CC-SNe



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

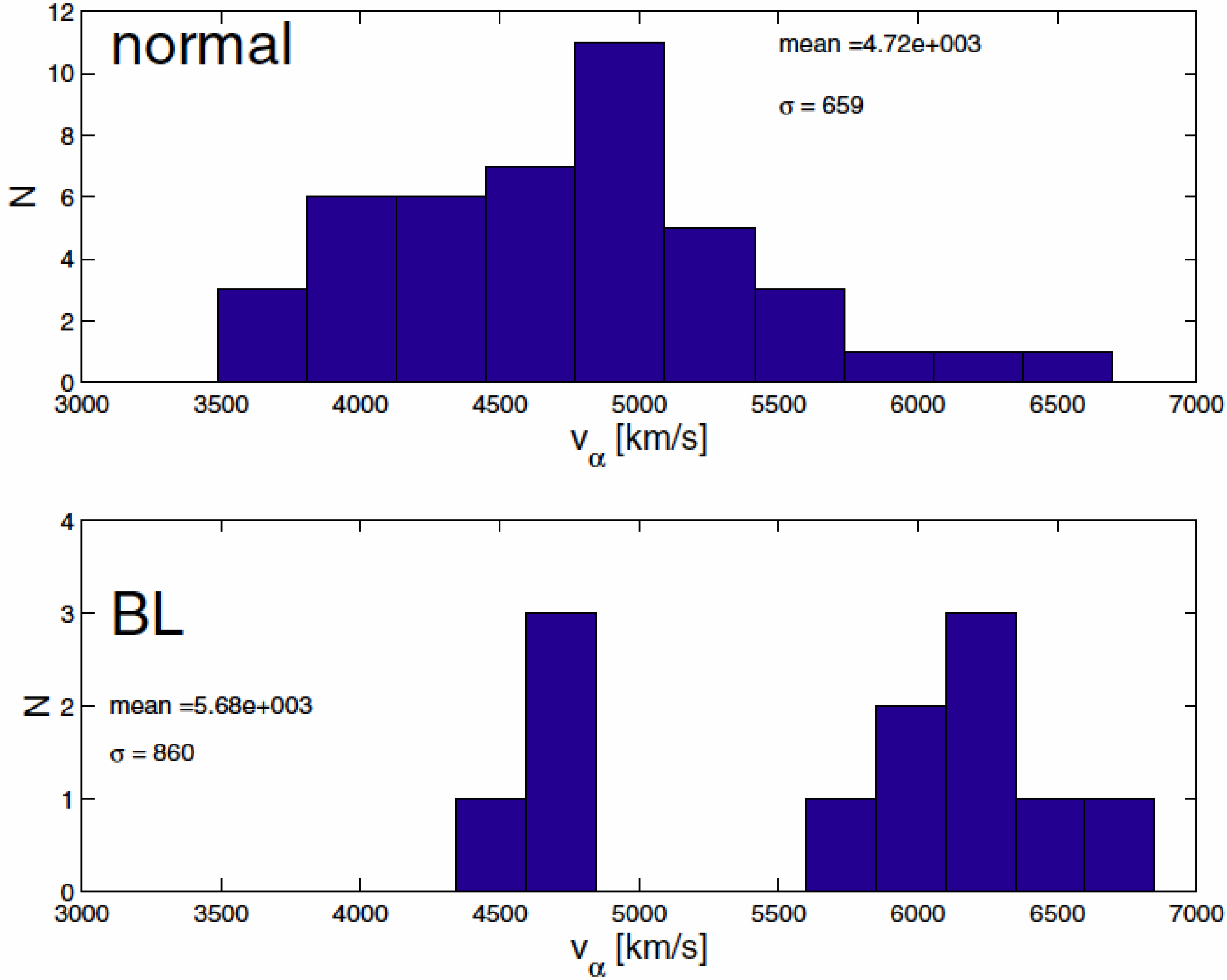
once every ~8.5 years?



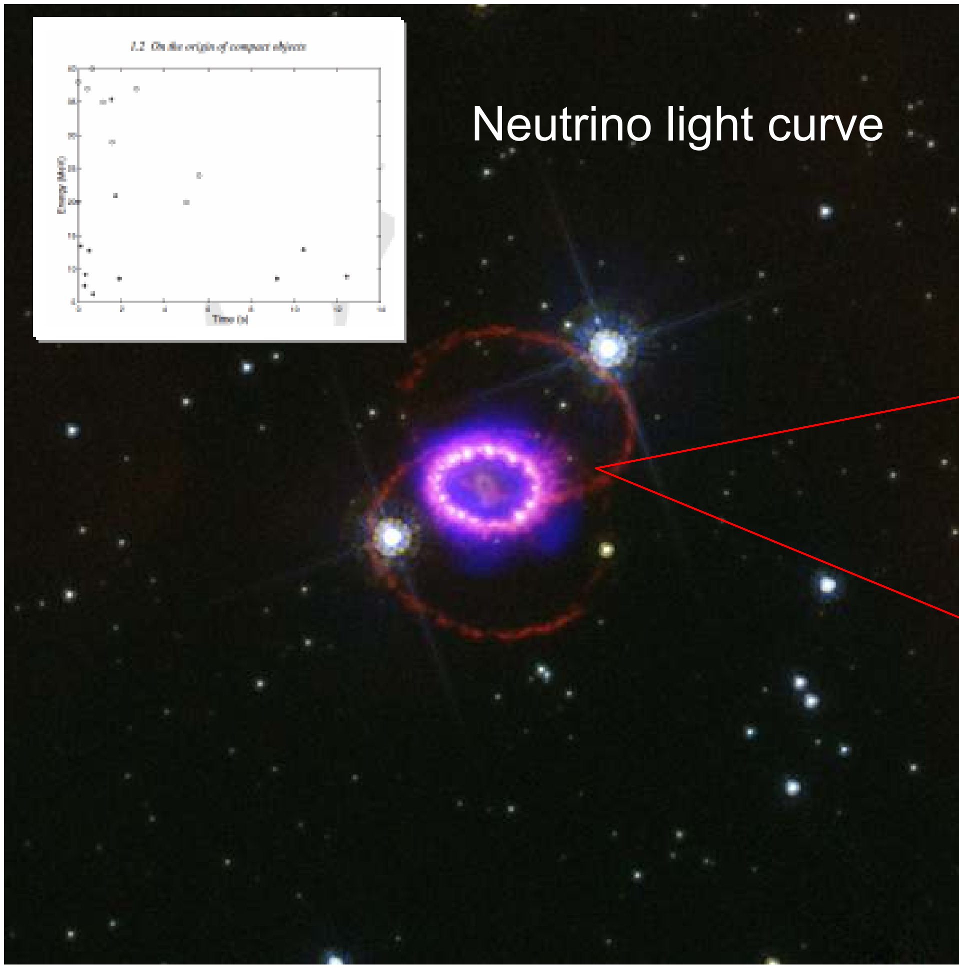
Soderberg, et al., 2011, arXiv:1107.1876

Van Putten, Della Valle & Levinson, 2011, A&A, 536, L6
Maurer et al. 2010, MNRAS, 402, 161

CC-SNe are diverse



Diversity from M and NS/BH remnants

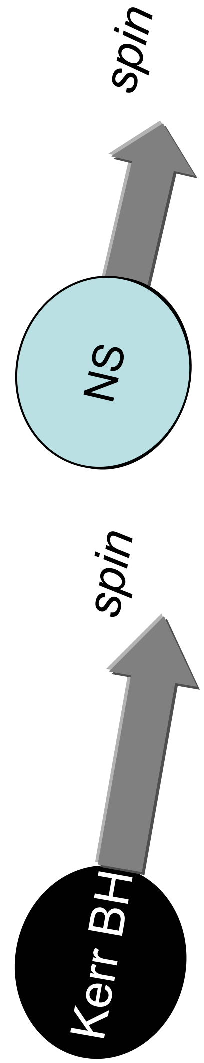


3×10^{52} erg (maximal spin, $1.5M_{Sun}$)

$1\%Mc^2$

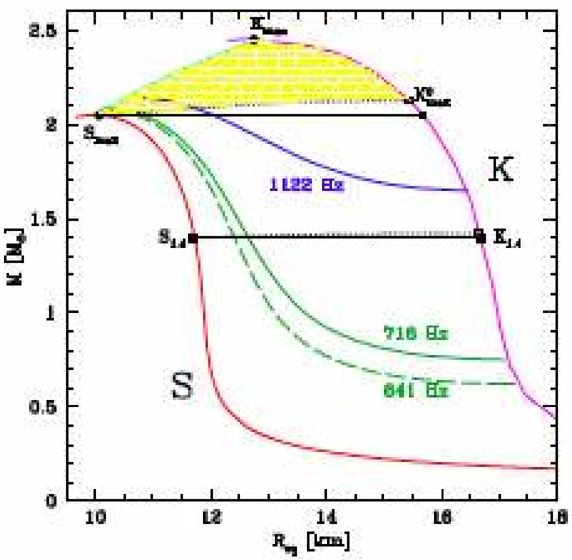
6×10^{54} erg (maximal spin, $10M_{Sun}$)

$30\%Mc^2$

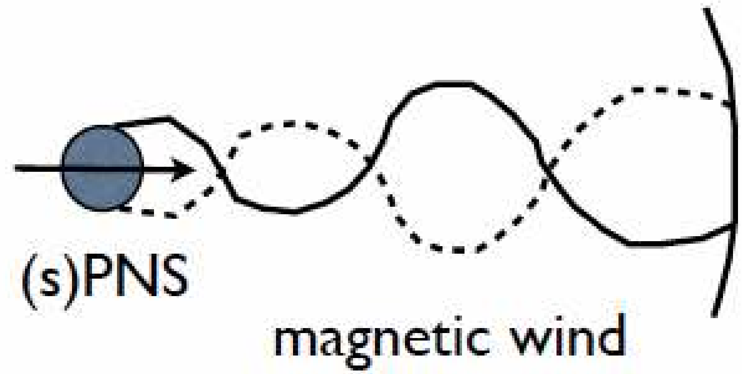


Producing SNe from spindown of a proto-neutron star (PNS)

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



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



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

remnant stellar envelope

Efficiency in expelling stellar envelope by magnetic winds:

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

(baryon-poor to baryon-rich winds)

$$E_c = \begin{cases} 3\times10^{52} \text{ erg (PNS)} \\ 7.5\times10^{52} \text{ erg (sPNS)} \end{cases}$$

(supramassive PNS)

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

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

Van Putten, Della Valle & Levinson (2011)

Pushing the energy envelope

M. H. P. M. van Putten et al.: Electromagnetic priors for black hole spindown in searches

Table 1. References refer to SNe except for GRB 070125.

GRB	Supernova	Redshift z	E_γ	E_{tot}	E_{SN}	η	E_{rot}/E_c	Prior	Ref.
	SN2005ap	0.283			>10	1	>0.3	indet	1
	SN2007bi	0.1279			>10	1	>0.3	indet	1
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		2.607		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

Notes. Energies are in units of 10^{51} erg.

Rapidly rotating NS are unlikely a universal inner engine

Van Putten et al., 2011, PRD, 83, 044046

"Orphan long GRBs?"

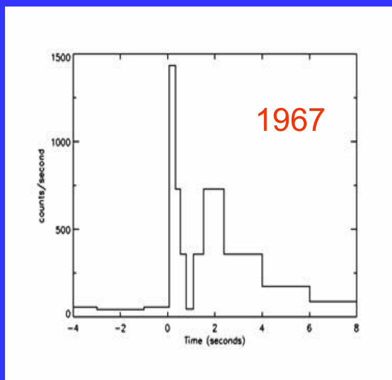
TABLE I. Proposed core-collapse and merger progenitors to a Swift sample of long GRBs.

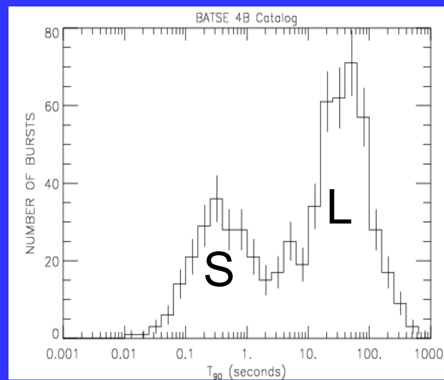
GRB	Redshift	Duration(s)	Host	Constraint[a]	Type
050820A [37,38]	1.71	13 ± 2	UVOT < 1 arcsec	ISM-like [17]	Merger
050904 [39–41]	6.29	225 ± 10	Unseen low star-forming region	Dense molecular cloud [57]	CC-SN
050911	0.165	16	Cluster Edinburgh-Durham Galaxy Catalogue 493	No x-ray afterglow [42]	Merger [58,16]
060418 [43–46]	1.490	(52 ± 1)	ISM spectrum	γ-ray efficiency [17]	Merger
060505 [47]	0.09	4	Spiral, ionized atomic hydrogen	No SN [c]	Merger
060614 [47,50][b,c]	0.13	102	Faint star-forming region	No SN[b,c]	Merger [14,15]
070125 [51–53]	1.55	>200	Halo	ISM-like [53]	Merger
080319B [54–56]	0.937	50	Faint dwarf galaxy	Wind [17]	CC-SN

[a]"ISM-like" refers to a constant host density; wind refers to a r^{-2} density profile associated with a massive progenitor [35,36].
[b]Observed with an 8.2 m telescope, [48].
[c]Observed with a 1.5 m telescope, [49].

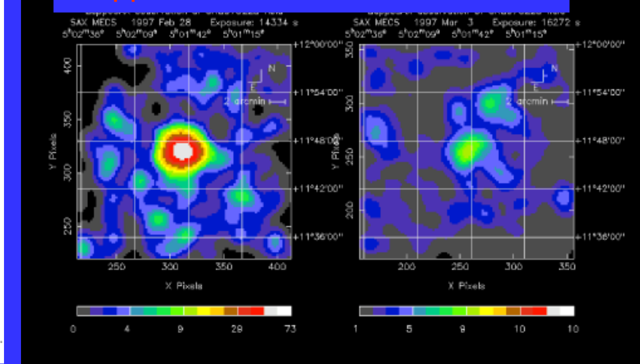
Some long GRBs appear to have no massive stars progenitor

Thumbnail overview…

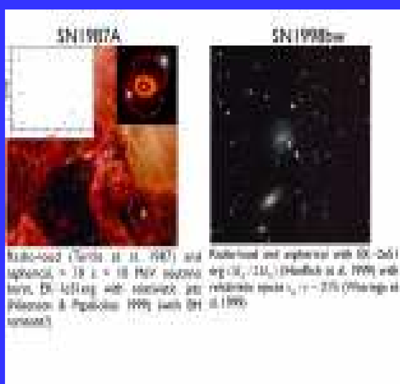


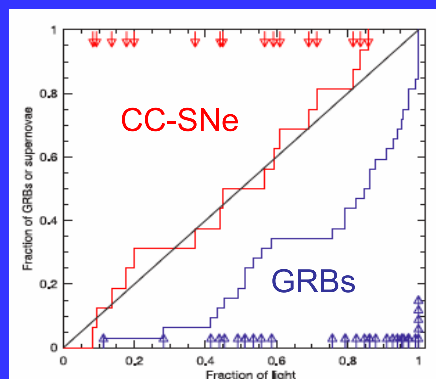


BeppoSax GRB 970228: Z-0.695

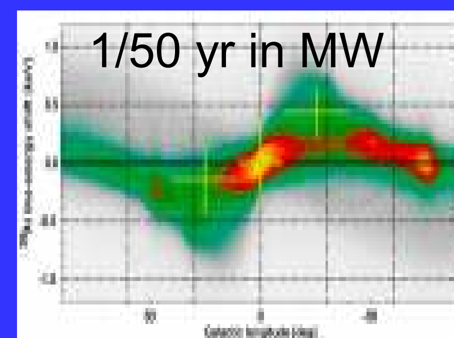


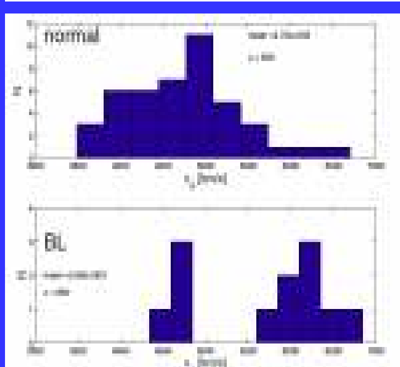
Swift, HETE II: X-ray afterglows also to short GRBs 050509B, 050709,…





GRB-SNe are rare making up < 1% of all SN Ib/c and < 0.2% of all CC-SNe





CC-SNe are diverse and produce NS and BH remnants

Hyper energetic events GRB 031203/SN2003lw GRB030329/SN2003dh defy max Erot of NS

Swift Era LGRBs with no association to massive stars: GRB 059820A, 050911, 060418, 060505, 060614, 070125

Outline

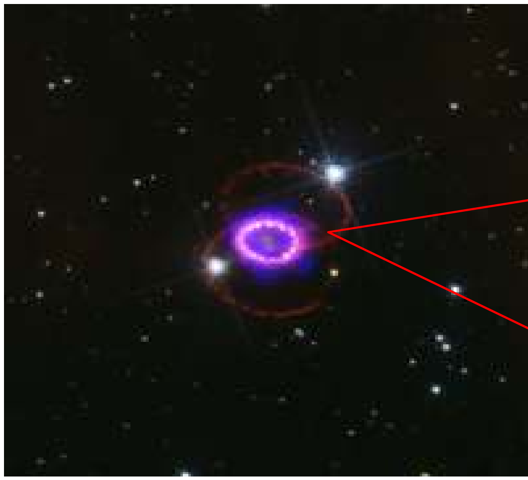
1. Progenitors of GRBs from rotating black holes

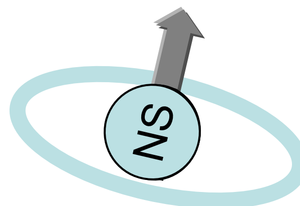
2. Radiation processes from frame dragging

3. Probe the inner engine by time domain analysis

4. Outlook on long duration chirps from GRBs and CC-SNe

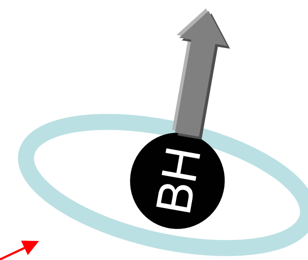
Astronomical origin of LGRBs





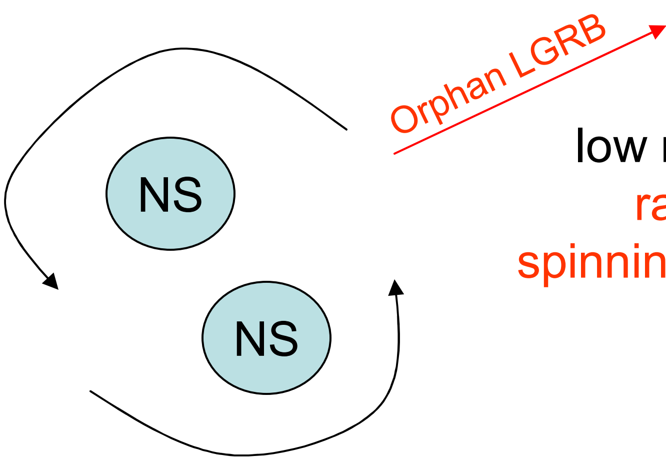
3×10^{52} erg (maximal spin, $1.5\,M_{Sun}$)

$1\%\,Mc^2$



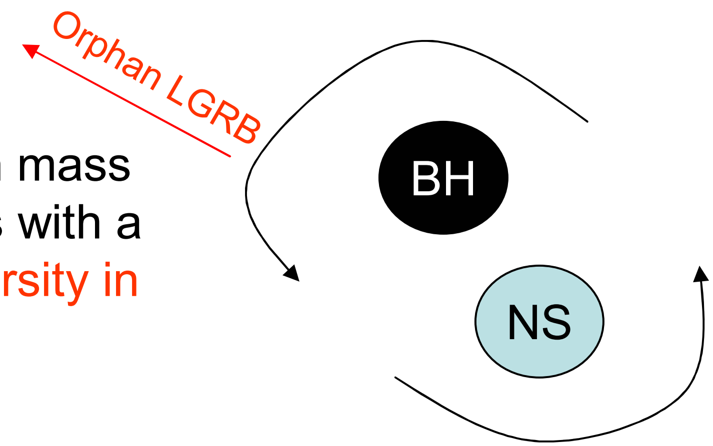
6×10^{54} erg (maximal spin, $10\,M_{Sun}$)

$30\%\,Mc^2$



low mass rapidly spinning BH

high mass BHs with a diversity in spin



Van Putten, 2012, Vulcano Meeting; astro-ph/1301.0964
Van Putten, 1999, Science, 294, 115; Baiotti et al., 2008, PRD, 78, 084033

Rapidly rotating BHs from NS-NS mergers

Radiation driven coalescence NS-NS→

PNS in merger →

conservative prompt collapse

NS+NS → PNS → BH
$$\left\{\begin{array}{l} M + M \rightarrow 2M \rightarrow 2M \\ J_{orbit} \downarrow J_{\max}^{PNS} \rightarrow J_{\max}^{PNS} \end{array}\right.$$

$$M_{PNS} \cong 3M_{Sun}, R \cong 14\text{km}:$$

$$E_{rot} \cong 2M \sin^2\left(\frac{1}{4}\arcsin\left[\frac{2}{5}\sqrt{\frac{R}{R_g}}\bigg|_{PNS}\right]\right) \cong 0.4 M_{Sun} c^2$$

NS-NS mergers are factories of low mass rapidly rotating BHs

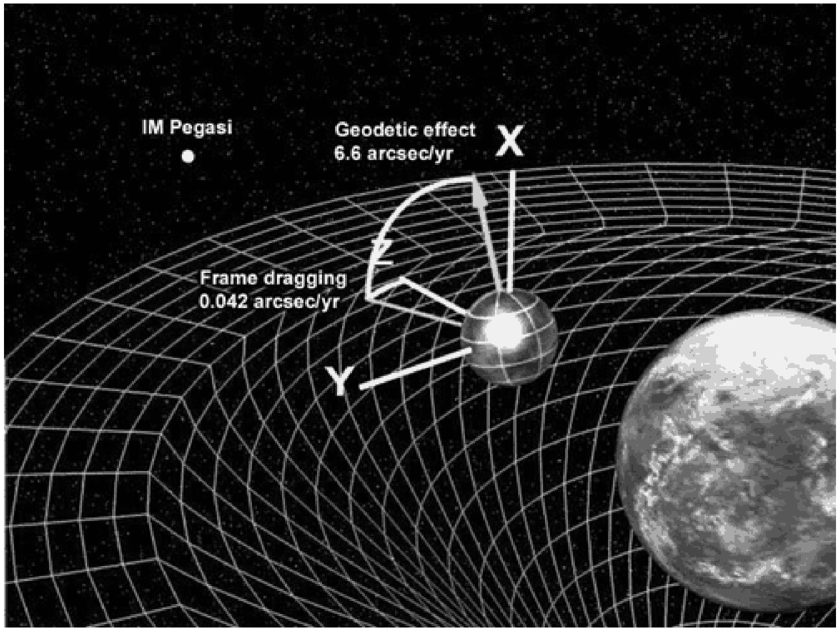
Precession by frame dragging

Measures *J* induced rotation of surrounding spacetime

Perpendicular to GP for a polar orbit (normal to *J*)

Frame dragging in GP-B orbit (642 km):

$\omega =$ **-39 marcs/yr**

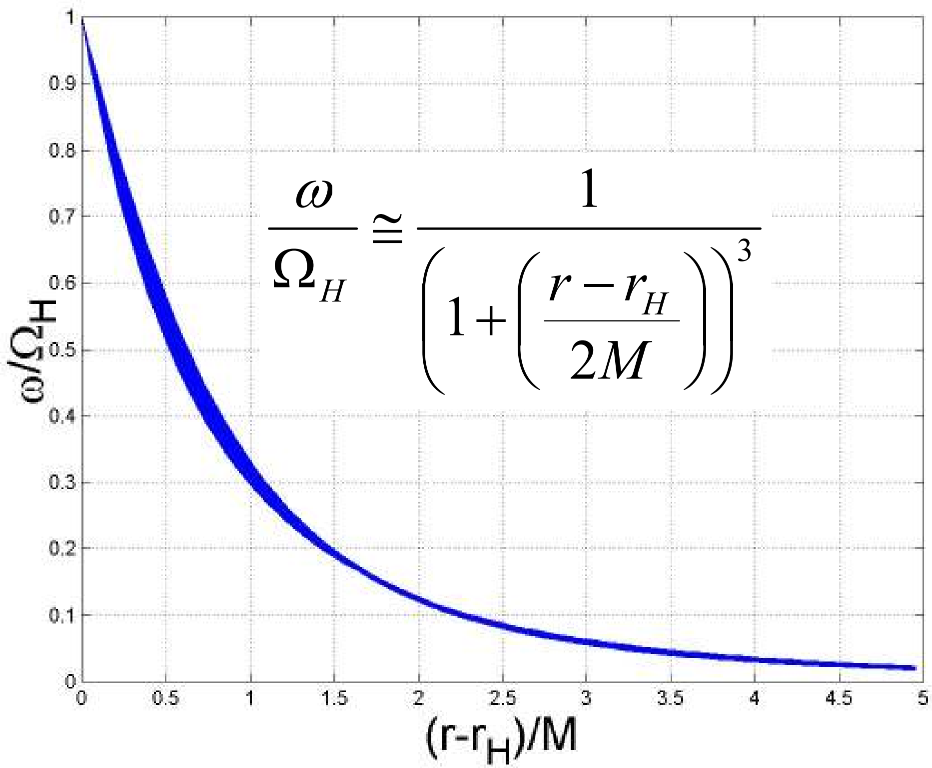


Two complementary experiments:

Everitt, F., et al., 2011, PRL, 106, 221101
Ciufollii, I. & Pavils, E.C., 2004, Nature, 431, 958

Van Putten, 2012,
MG13 Meeting

Relativistic frame dragging nearby BHs

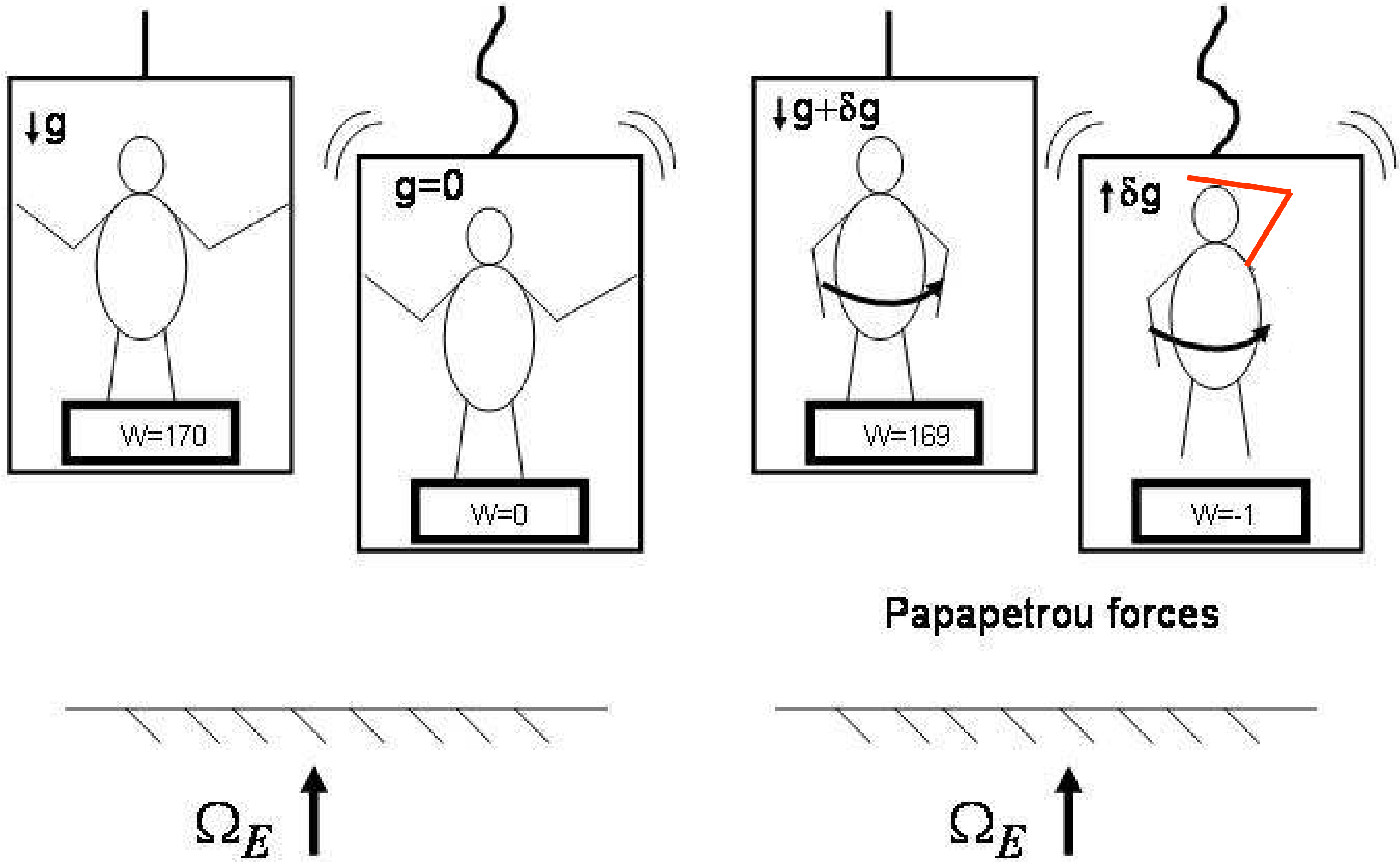


$$\frac{\omega}{\Omega_H} \cong \frac{1}{\left(1+\left(\frac{r-r_H}{2M}\right)\right)^3}$$

Variations with spin: 7.25%
Variations with poloidal angle: 1.67%

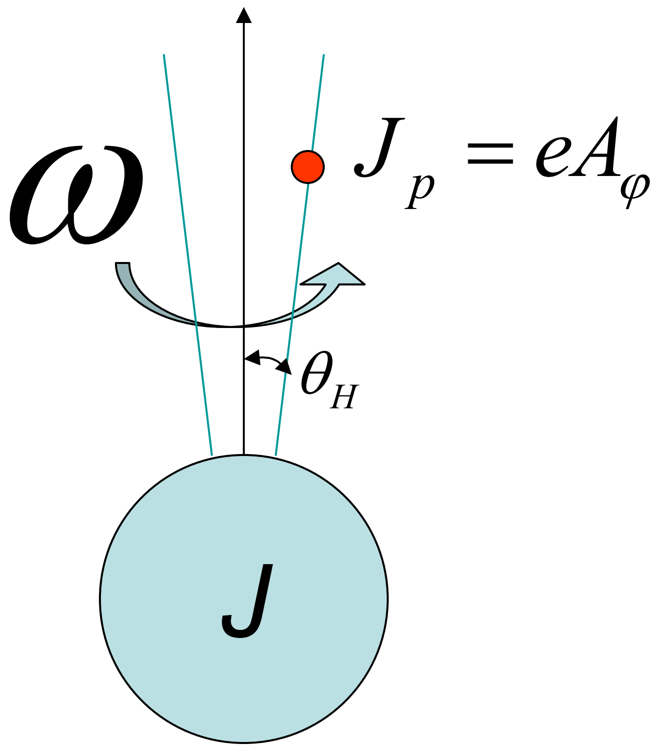
Van Putten & Levinson, 2012,
Cambridge University Press

Frame dragging induced forces



Van Putten, 2001, Phys. Rev. Lett., 84, 3752; Nuov. Cim. 2005, 28, 597; 2008, ApJ, 685, L63

Energy induced by frame dragging

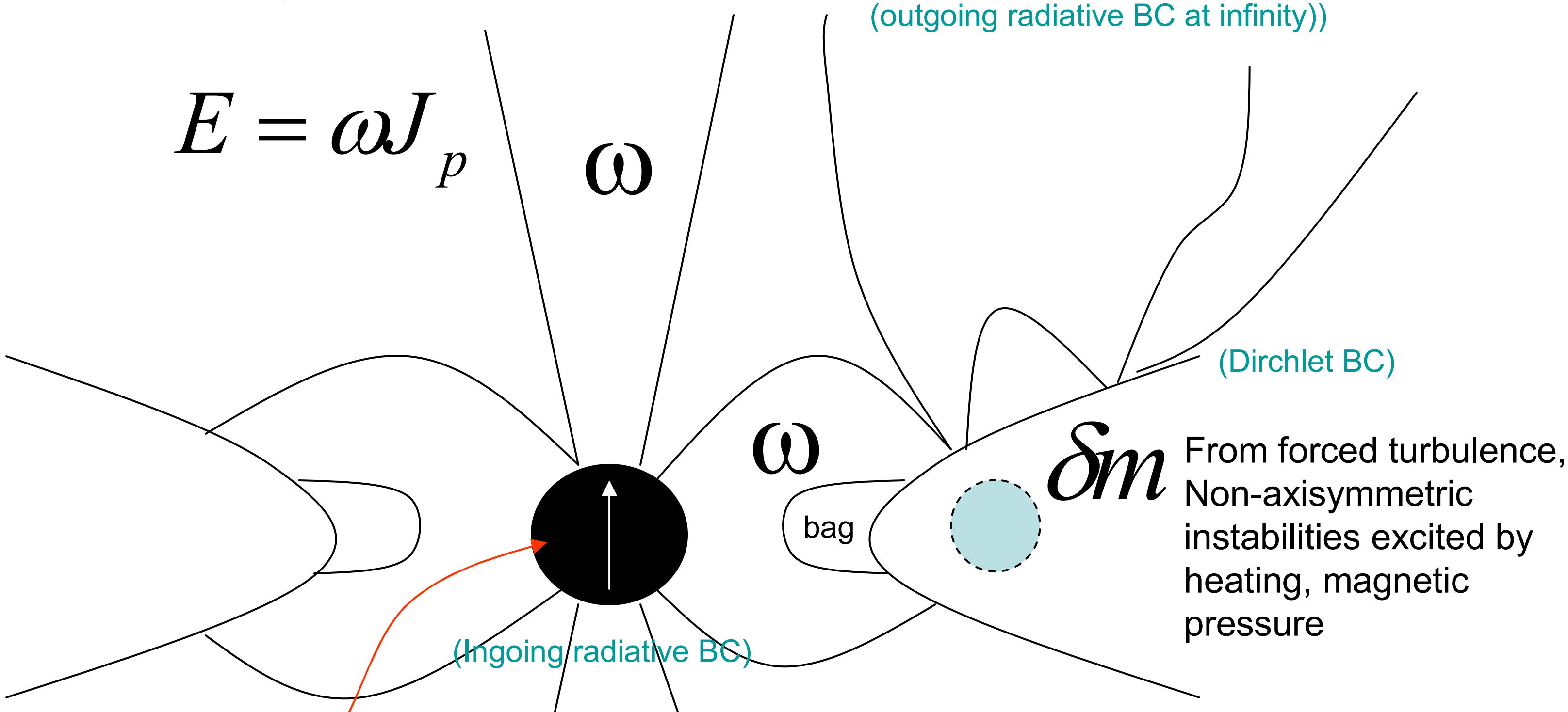


Exact geometric result

$$E = \omega J_p$$

van Putten, 1999, Science, 284, 115, van Putten, 2001, Phys. Rev. Lett., 84, 091101; van Putten & Levinson, 2002, Science, 295, 1874; van Putten, 2002, ApJ, 575, L71; Bromberg, Levinson, van Putten, 2006, NewA, 11, 619; van Putten, 2012, Prog. Theor. Phys., 127,331 van Putten, 2008, ApJ, 684, L91

Relativistic frame dragging induced interactions



Magnetic moment in lowest energy state

$$\text{catalytic conversion}: \begin{cases} \dfrac{dM}{dt} \propto -\sigma_{B_p}^2 (\Omega_H - \Omega_T)\Omega_T \\ \dfrac{dJ}{dt} \propto -\sigma_{B_p}^2 (\Omega_H - \Omega_T) \end{cases}$$

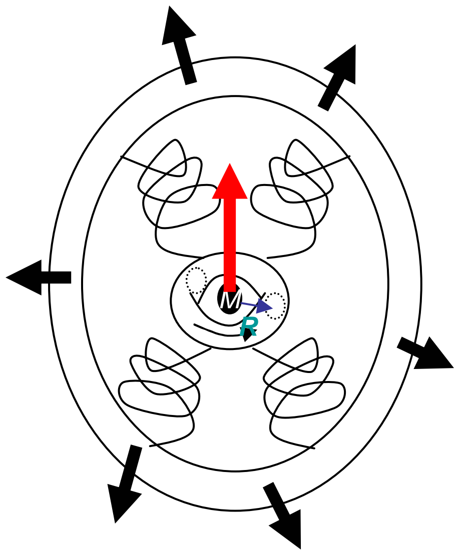
⇒ radiation

$$L_{GW} = 2 \times 10^{51} \left(\frac{M}{4R}\right)^5 \left(\frac{M_D}{0.01 M_H}\right)^2 \left(\frac{\delta m}{0.1 M_D}\right)^2 \text{ erg s}^{-1}$$

Bisnovatyi-Kogan, 1970, Astron. Zh., 47, 813
Van Putten, Della Valle & Levinson, 2011, A&A, 536, L6
Van Putten & Gupta, 2009, MNRAS, 394, 2238
Van Putten & Levinson, 2003, ApJ, 584, 937
Van Putten, 2003, 583, 374

T_{90} duration: lifetime of rapid spin of BH

Aspherical explosion mechanism



$$\frac{T_{90}}{20\text{ s}} \cong \left(\frac{0.1M_{Sun}}{M_D}\right)\left(\frac{M}{7M_{Sun}}\right)^2\left(\frac{R_D}{6R_g}\right)^4$$

M_D/M ~ const. implies a positive correlation between E_k in the SN and $E\gamma$ in prompt GRB emission

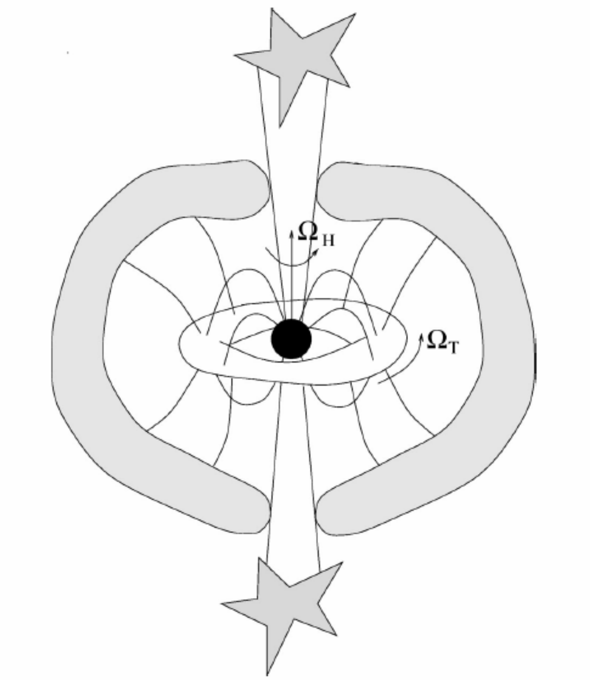
Low $M_D < 0.01\ M_{Sun}$ and high $M > 30\ M_{Solar}$ (from > 100 M_{Solar} progenitor?) implies T_{90} > hour van Putten & Levinson, 2003, ApJ, 584, 937; van Putten, 2008, ApJ, 685, L63

Spectral energy correlation (HETE-II & Swift)

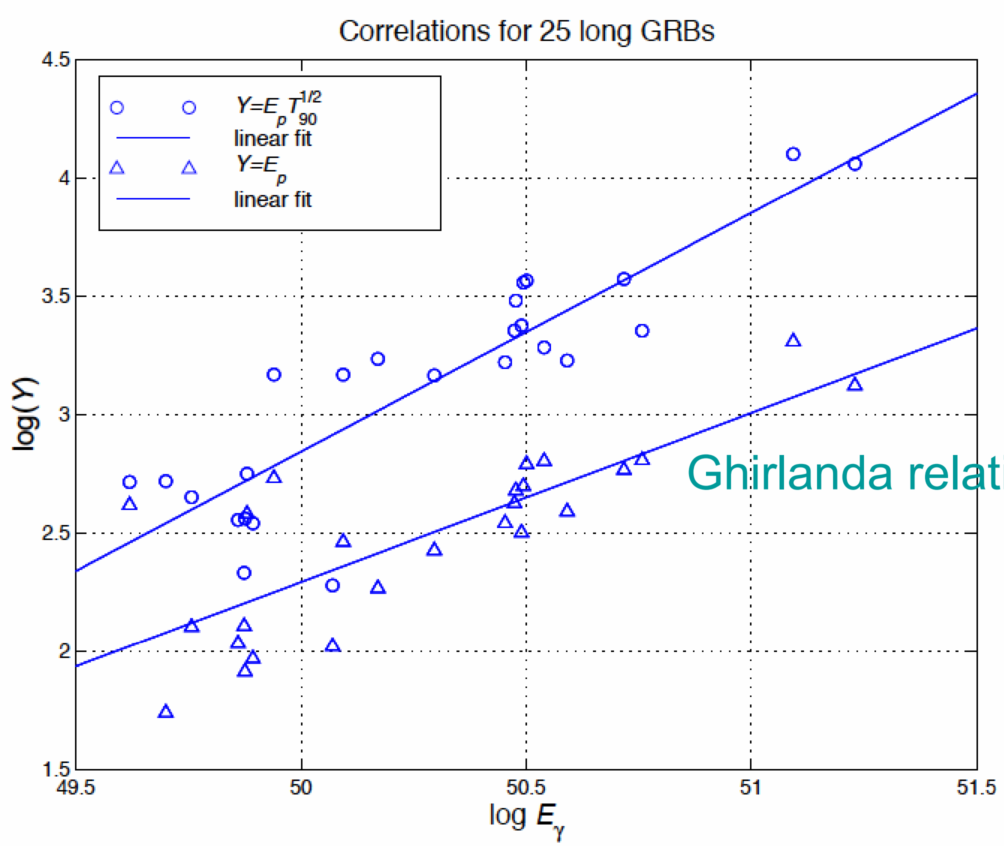
$$E = \omega J_p$$

→ Relativistic capillary effect launching BPJ with particle acceleration beyond outgoing Alfven surfaces at attenuated luminosities $L_H \propto \theta_H^4$ with

$$E_p T_{90}^{1/2} \propto E_\gamma$$



T_{90} = lifetime of black hole spin



Bisnovatyi-Kogan, 1970, Astron. Zh., 47, 813
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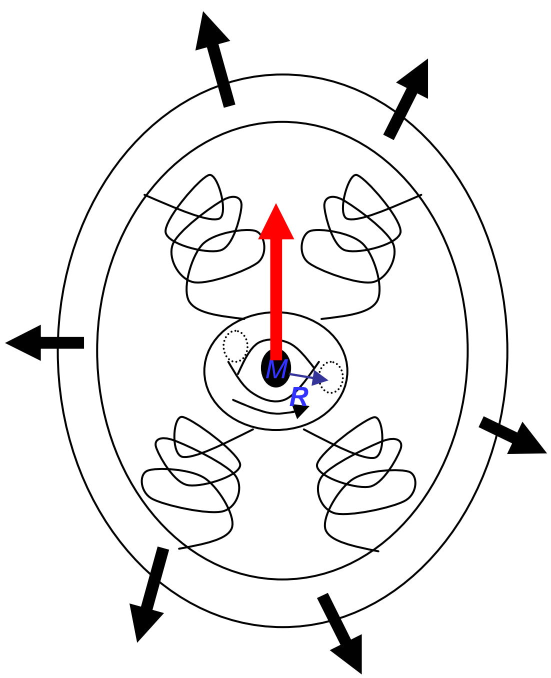
Van Putten & Levinson, 2003, ApJ, 584, 937
Van Putten, 2003, 583, 374

Comparing BH vs NS inner engines

Aspherical explosion mechanism



Spindown of rotating BH-torus system

SN from baryon rich torus wind,
GRB from baryon-poor jet.
Reservoir: E_{rot}[BH]

→ Successful GRB and SN

Spindown of a (proto-)NS:

SN *and* GRB from one magnetic wind (one choice of baryon loading).
Reservoir: E_{rot}[NS]

→ Either successful GRB or SN

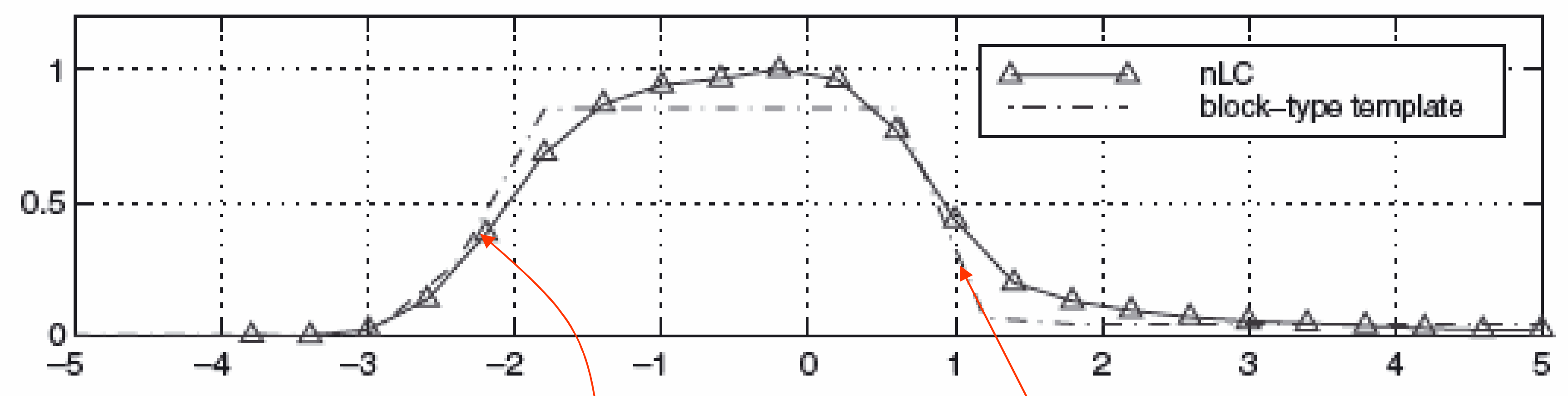
Van Putten & Gupta, 2009, MNRAS, 394, 2238; Van Putten, 2012, Prog. Theor. Phys., 127, 331

Observational test in time domain - I

Black hole spindown over ~ T_{90}

Van Putten & Gupta, 2009, MNRAS, 394, 2238

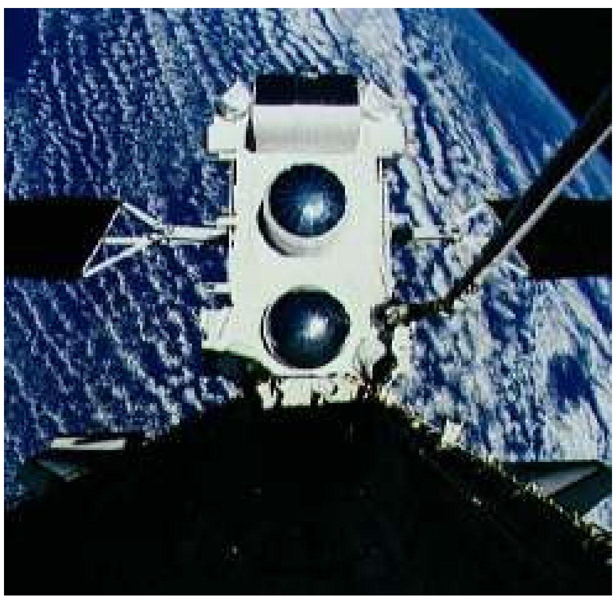
Extracting normalized lc by matched filtering



normalized light curve

A choice of model light curve

(nLC depends only weakly on choice of template)

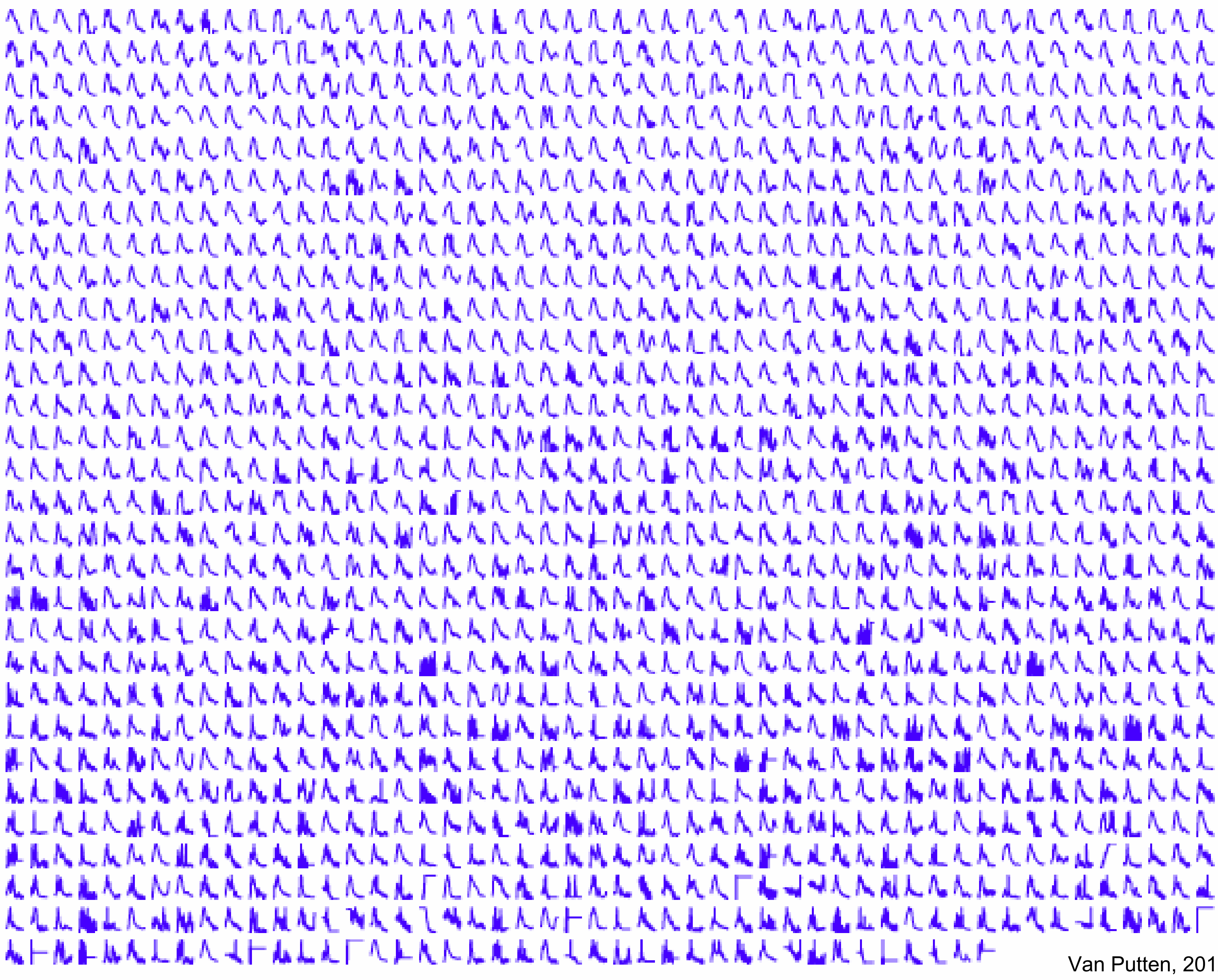


4 parameter matched filtering: scaling in count rate and time with arbitrary shifts (subtraction base line count and offset in time)

Apply to the complete BATSE catalogue of 1491 long GRBs…

BATSE Catalogue of 1491 long GRBs

(smoothed, scaled and ordered by T90)



Van Putten, 2012, Prog. Theor. Phys., 227, 331

Van Putten, 2001, Phys. Rev. Lett., 87, 091101; Prog. Theor. Phys., 127, 331

Spin down of black holes and proto-neutron stars

Black hole spindown from equations of suspended accretion: balance between input from BH and radiation output in GWs, MeV neutrinos and magnetic winds from the torus:

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

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

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

C: spindown of PNS

Overview of spindown in BATSE

Van Putten, 2012, Prog. Theor. Phys., 127, 331

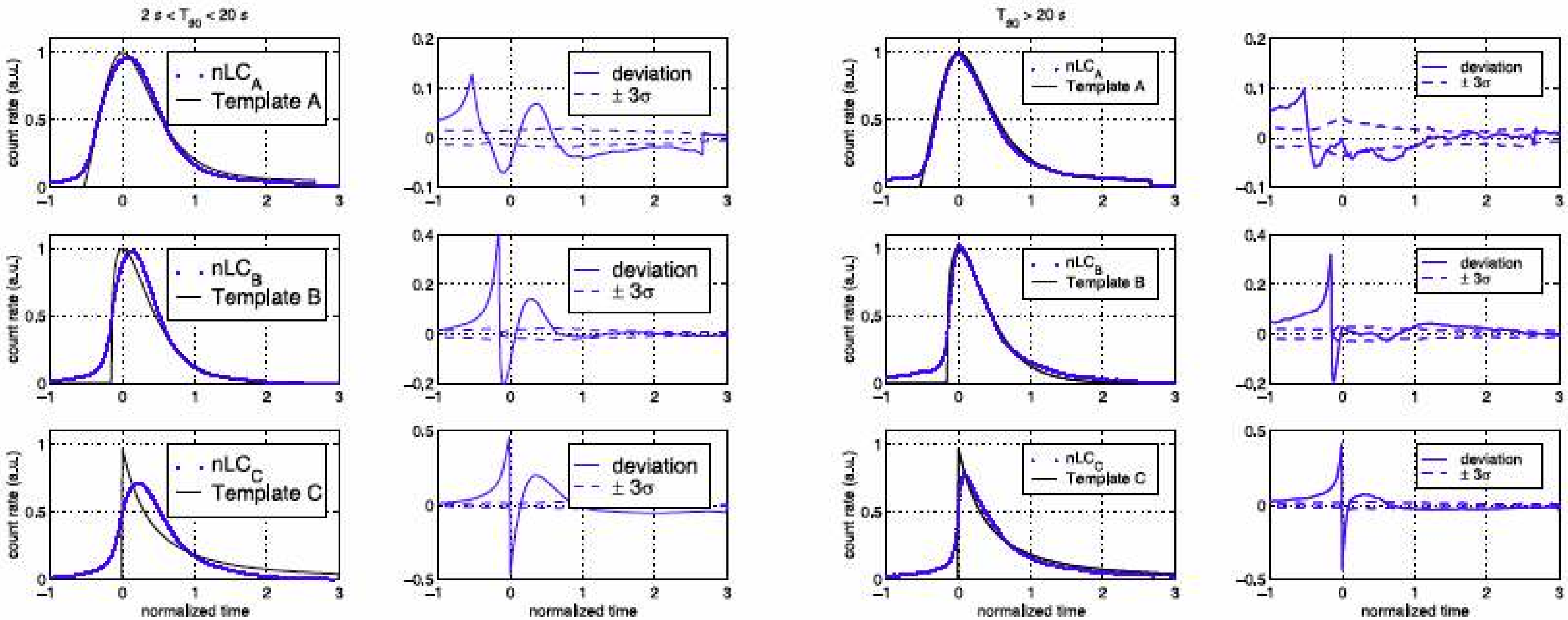


Fig. 6. Shown are the nLC (*circles*) generated by model templates A–C (*lines*) for the ensemble of 531 long duration bursts with 2 s $< T_{90} <$ 20 s (*left*) and the ensemble of 960 long bursts with T_{90} >20 s (*right*) and the associated deviations for Templates A–C. Here, the standard deviation σ is calculated from the square root of the variance of the photon count rates in the ensemble of individually normalized light curves as a function of normalized time.

Piran & Sari, 1977, astro-ph/9702093v1
Van Putten, 2012, Prog. Theor. Phys., 127, 331

Observational test in time domain - II

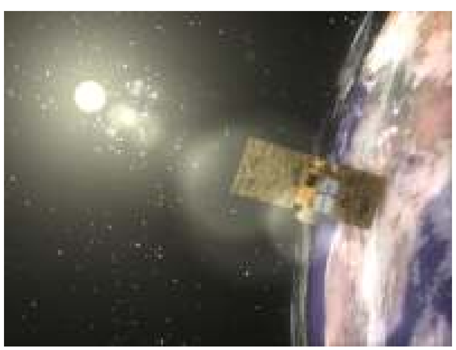
Correlation intermittency at source and GRB light curve

$$L_H \propto \sigma_B^2 M^2 (\Omega_H - \Omega_T)\Omega_T$$

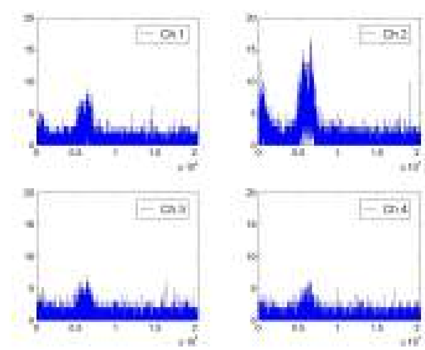
GRB lc

Short time scale intermittencies in, e.g., forced turbulence in disk or (superradiant) instabilities in the inner torus magnetosphere

Broad band modulations by unsteady collimating disk winds

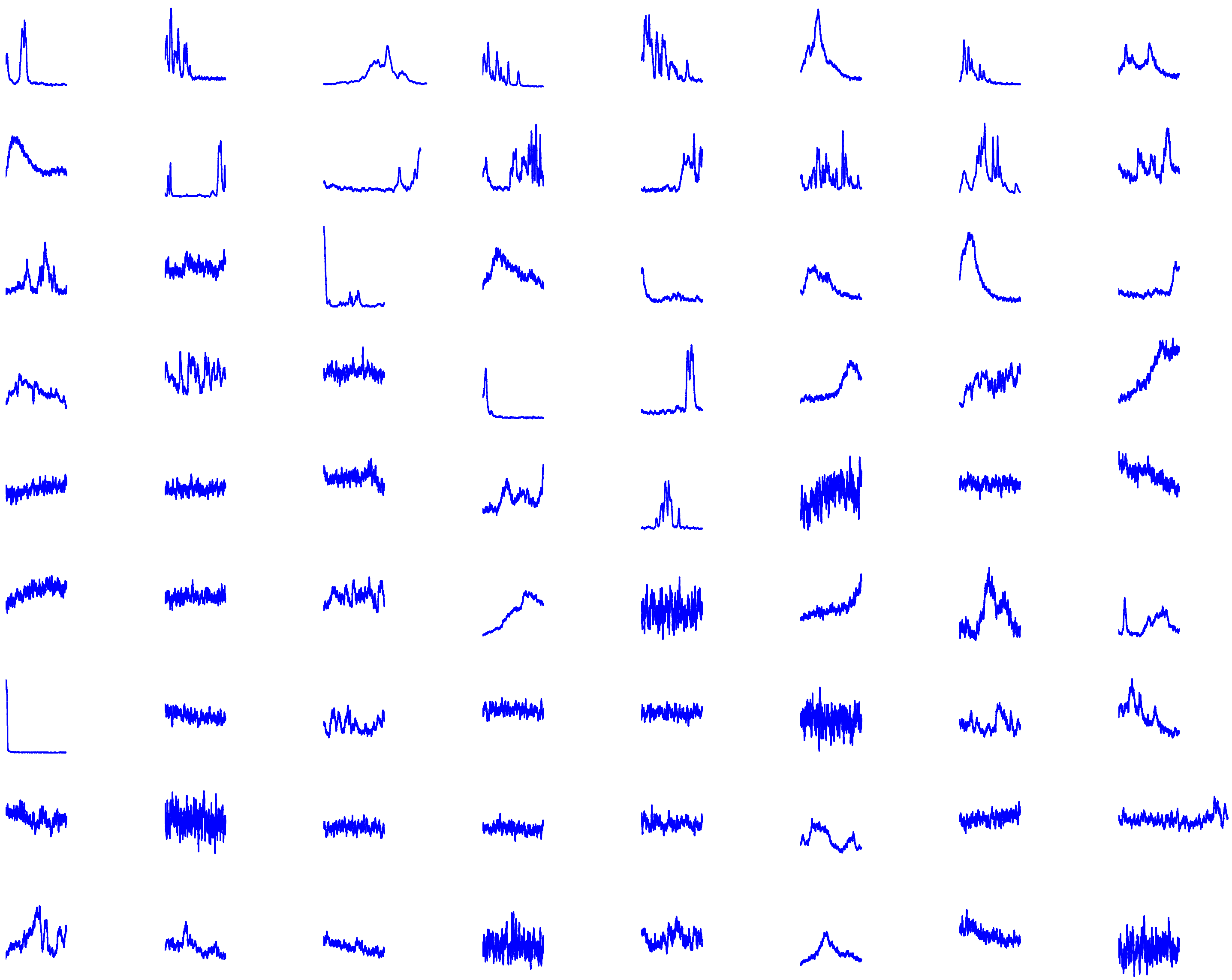


Apply to the BeppoSax catalogue of 2 kHz sampled light curves of long GRBs…



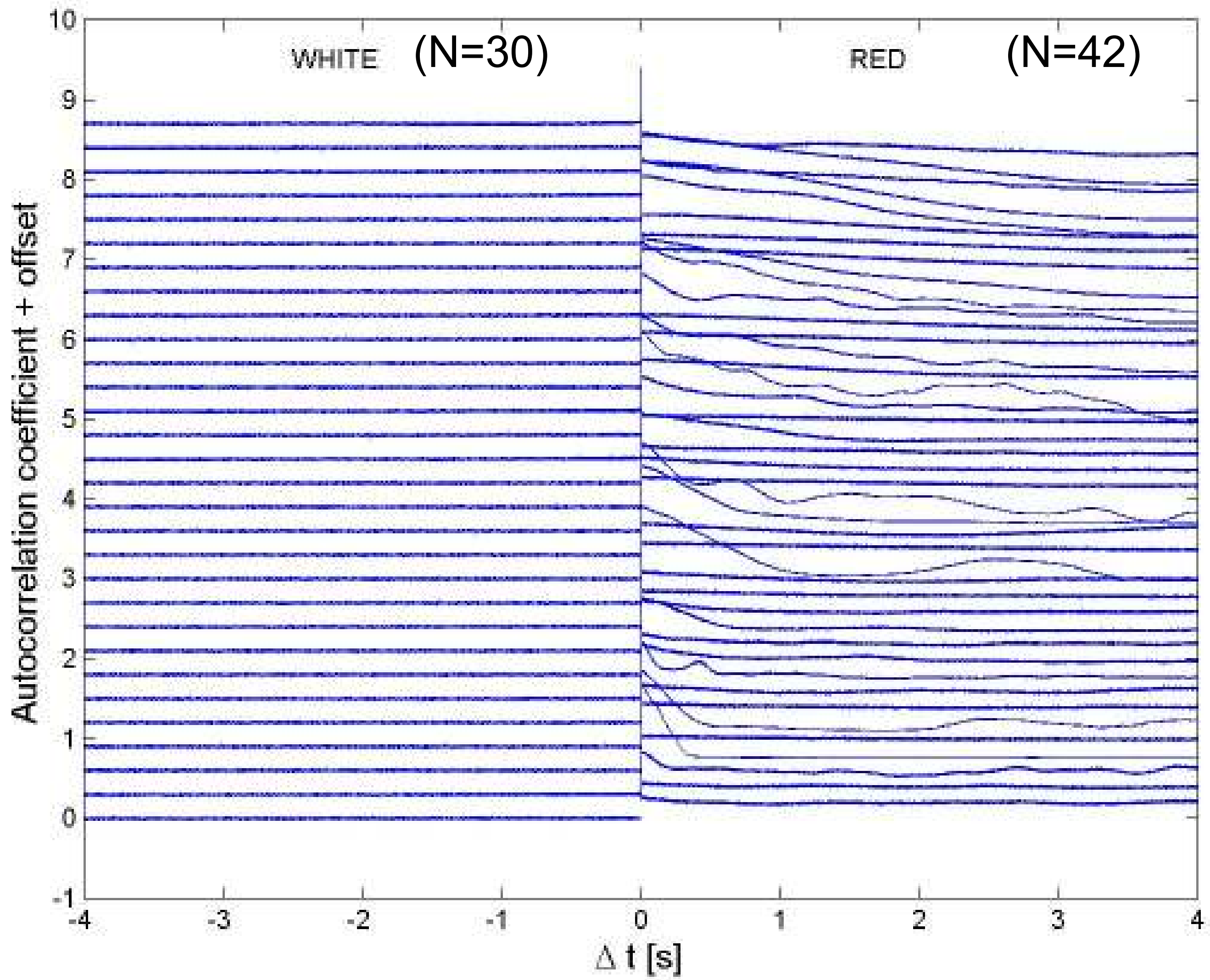
BeppoSax Catalogue of long GRBs: 72 bright events

(smoothed, scaled and ordered by T90)



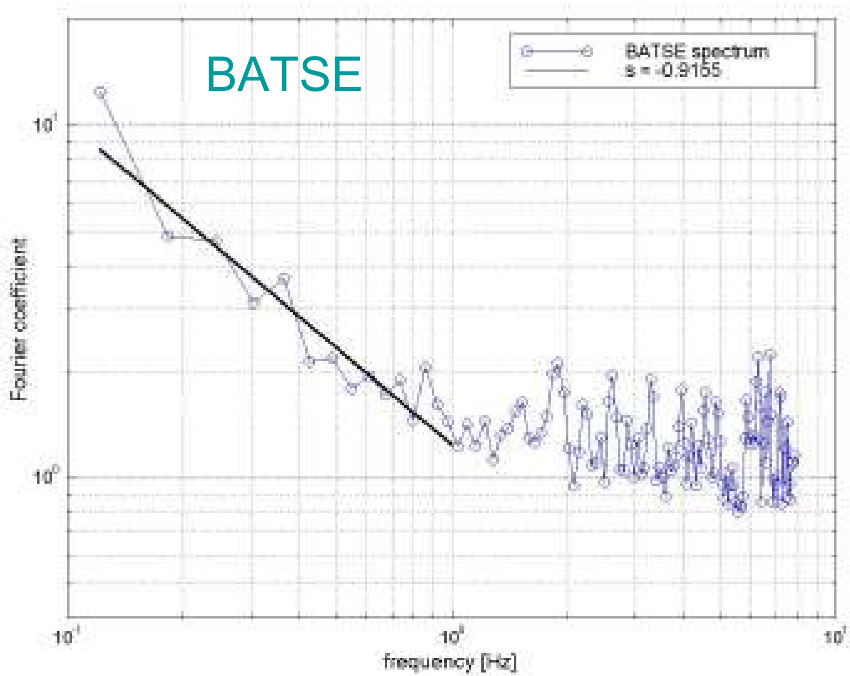
Van Putten, 2013, astro-ph/1309.0101

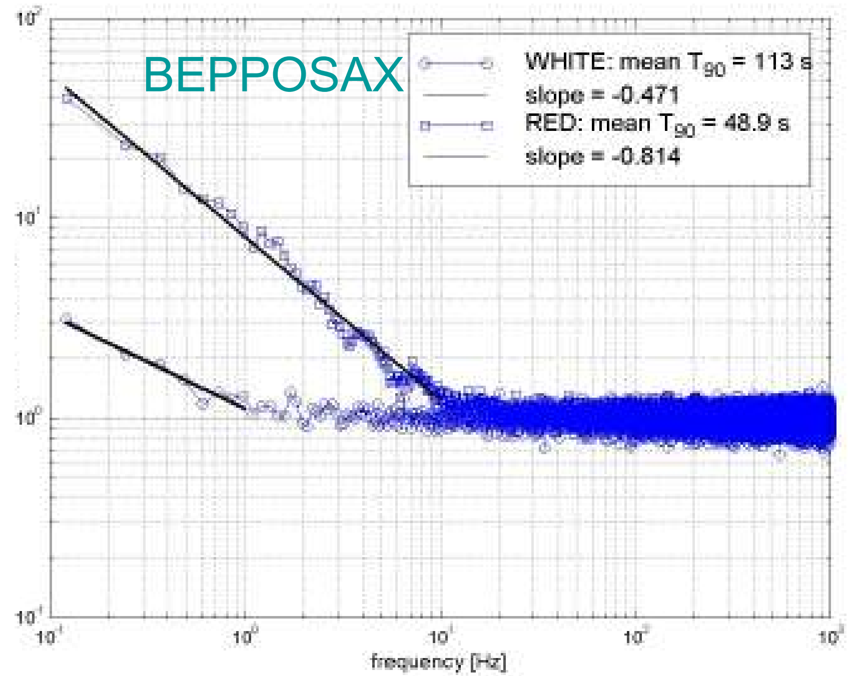
Two color autocorrelation functions



Van Putten, 2013, astro-ph/1309.0101
Cf. BATSE: Beloborodov, A.M., Stern, B.E., & Svensson, R., 1998, ApJ, 508, L25; ibid., 2000, ApJ, 535, 158

Fourier spectra

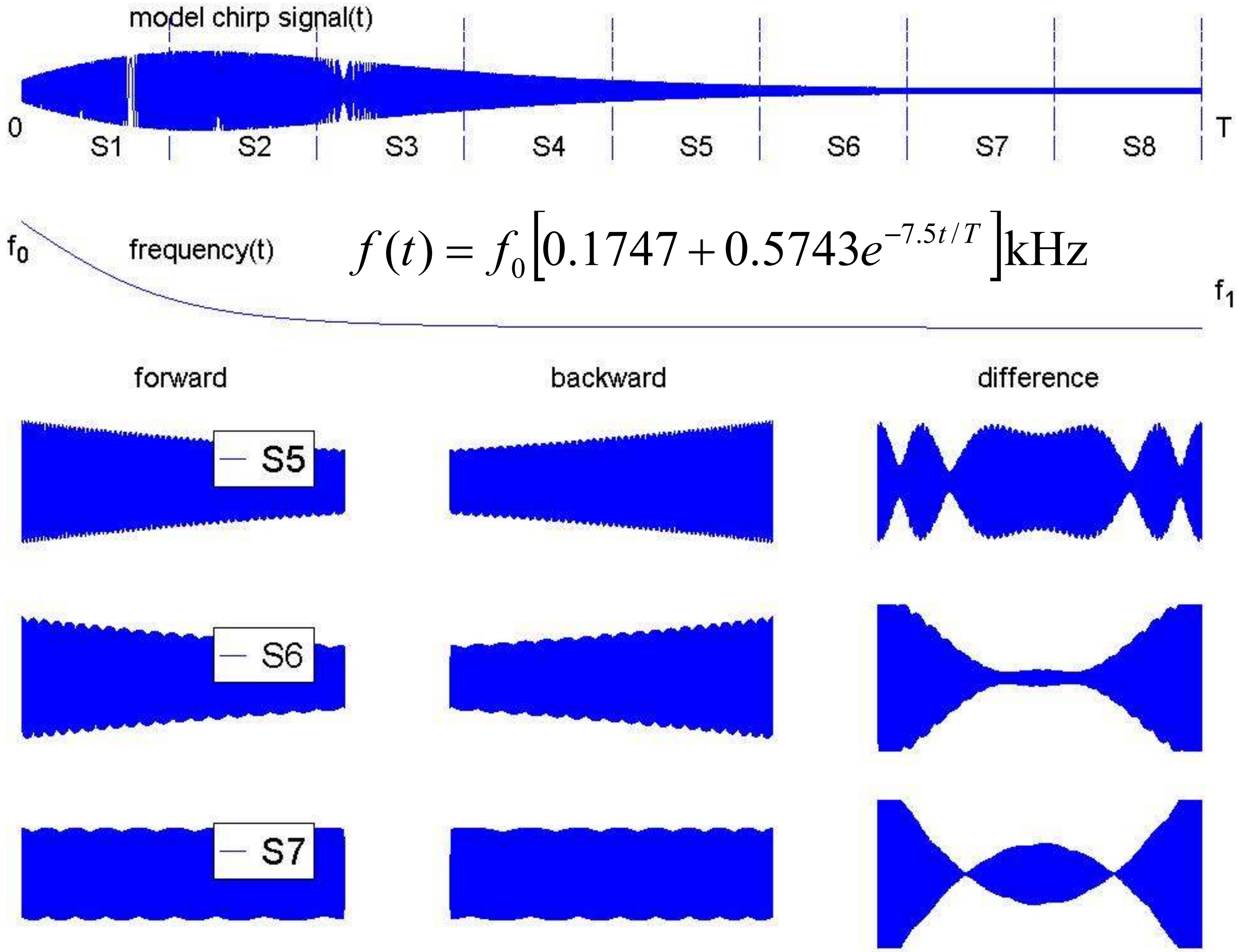




A view limit to about 10 Hz…

van Putten, Kanda, Tagoshi, Tatsumi, Masa-Katsu, & Della Valle, Phys. Rev. D, 83, 044046 (2011); Van Putten et al., 2013, in prep.

Time Sliced Matched Filtering (TSMF)



Negative chirp

positive chirp

differential chirp

Van Putten et al., 2013, in prep.

Chirp search by differential TSMF

Calculate

Sample Correlation Coefficients (SCC) between chirp templates and (the first 8 second) 2 kHz BeppoSax light curves

Maxima $R(M,T_{90})$ of SCC across a broad range of model parameters: the mass M of an initially maximally rotating BH and T_{90}

Controls: R_c from time-randomized BeppoSax light curves and light curves from a random number generator (gives practically same results)

Extract spectra from $\Delta = \frac{R - R_c}{R_c}$

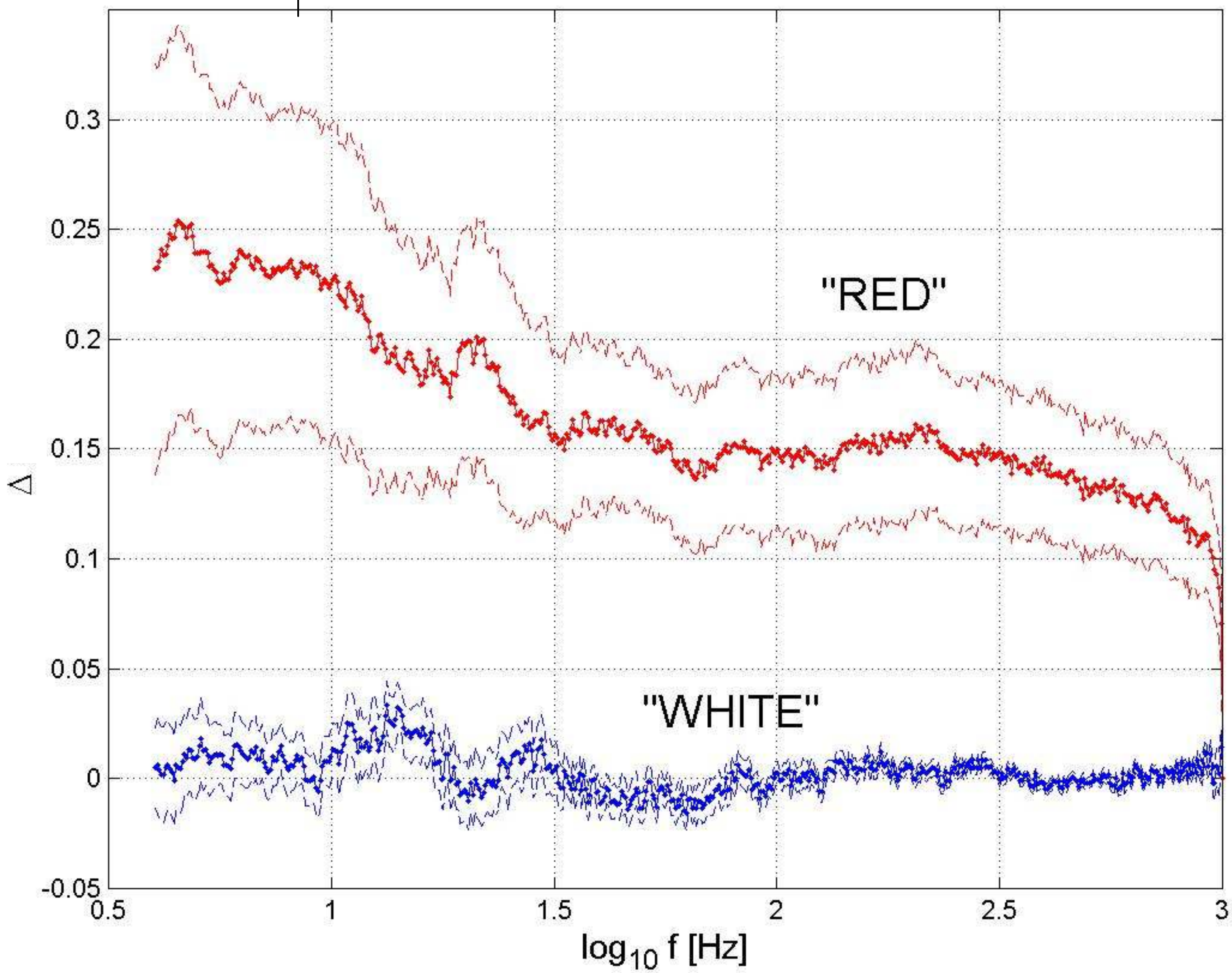
Averages of the spectra for White and Red events

Run this on a supercomputer for 35 million chirp templates over 72 BeppoSax lc's

Van Putten, 2013, arXiv:1309.0101

Chirp spectrum

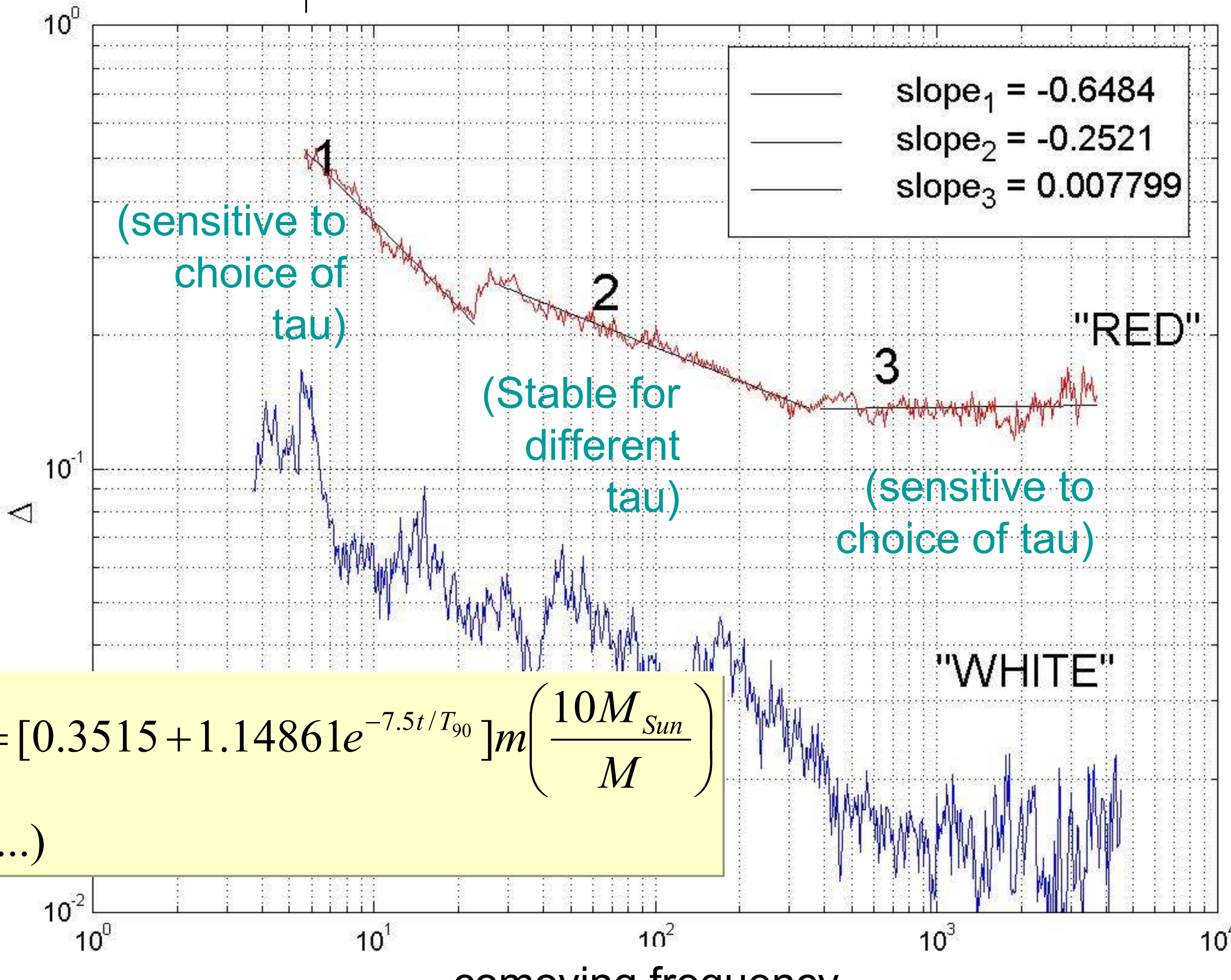
$\tau = 1\,\mathrm{s}$



Van Putten, et al., 2013, in prep.

Chirp spectrum in comoving frame (preliminary result)

$\tau = 1\,\mathrm{s}$

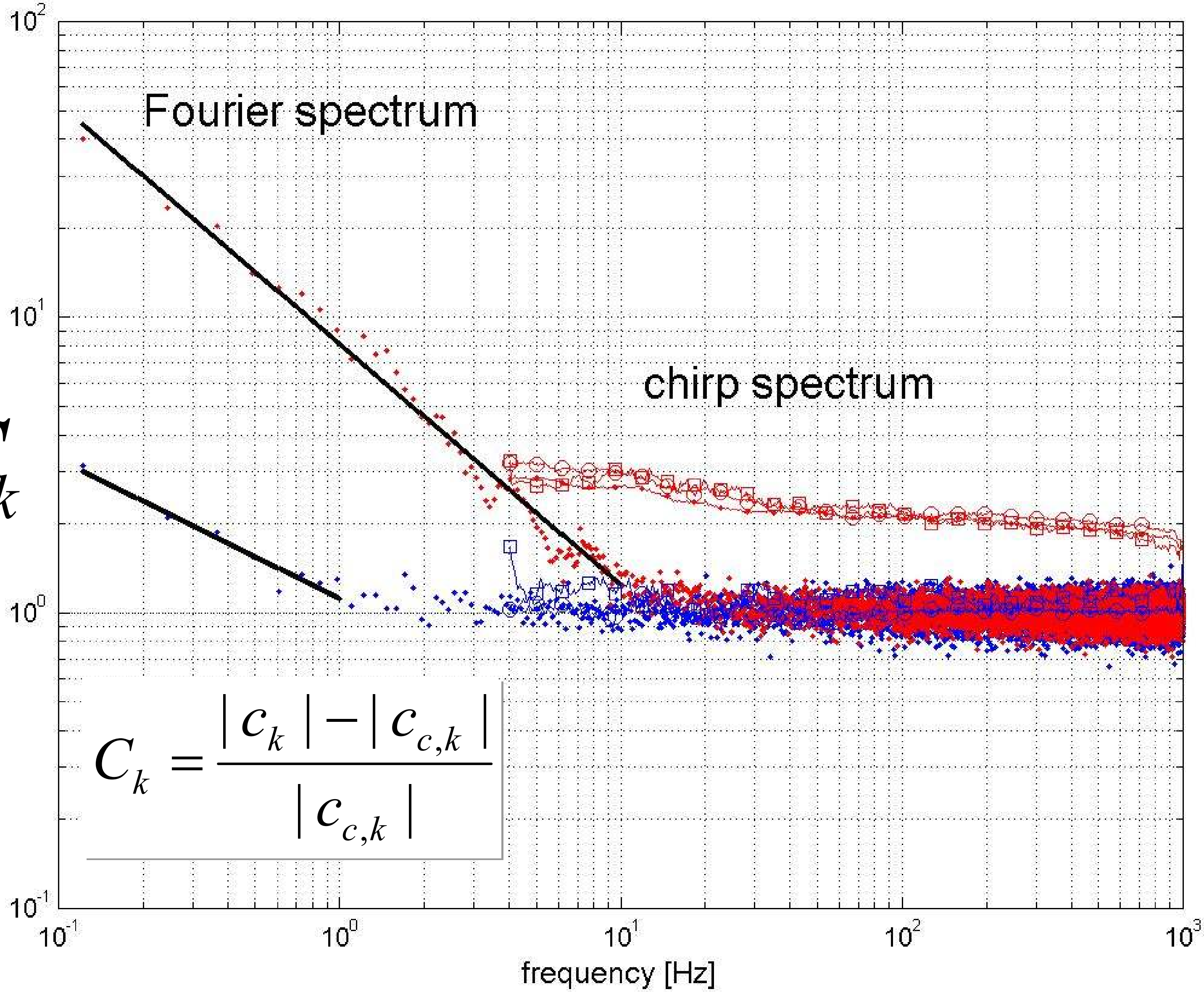


$$f_{chirp}^{\delta m}(t) = [0.3515 + 1.14861 e^{-7.5t/T_{90}}]\, m \left(\frac{10 M_{Sun}}{M}\right)$$

$(m = 1,2,\ldots)$

Van Putten, at al. 2013, in prep.

Blended Fourier-chirp spectrum



C_k

10Δ

$$C_k = \frac{|c_k| - |c_{c,k}|}{|c_{c,k}|}$$

Conclusion

Long GRBs: telltales of GR frame dragging playing itself out around rotating black holes surrounded by hot high density matter

$$\omega \approx \Omega_H \left(\frac{R_g}{r} \right)^3$$

Relativistic frame dragging around black holes

$$T_{90} =$$

Lifetime of BH spin (typically tens of seconds, up to hours), LGRBs involve rapidly rotating BHs from CC-SNe and mergers, including NS-NS mergers

$$E = \omega J_p$$

High energy emission in prompt GRB

$$E_{GW} \sim 0.1 Mc^2 \left(\frac{M}{10 M_{Sun}} \right)$$

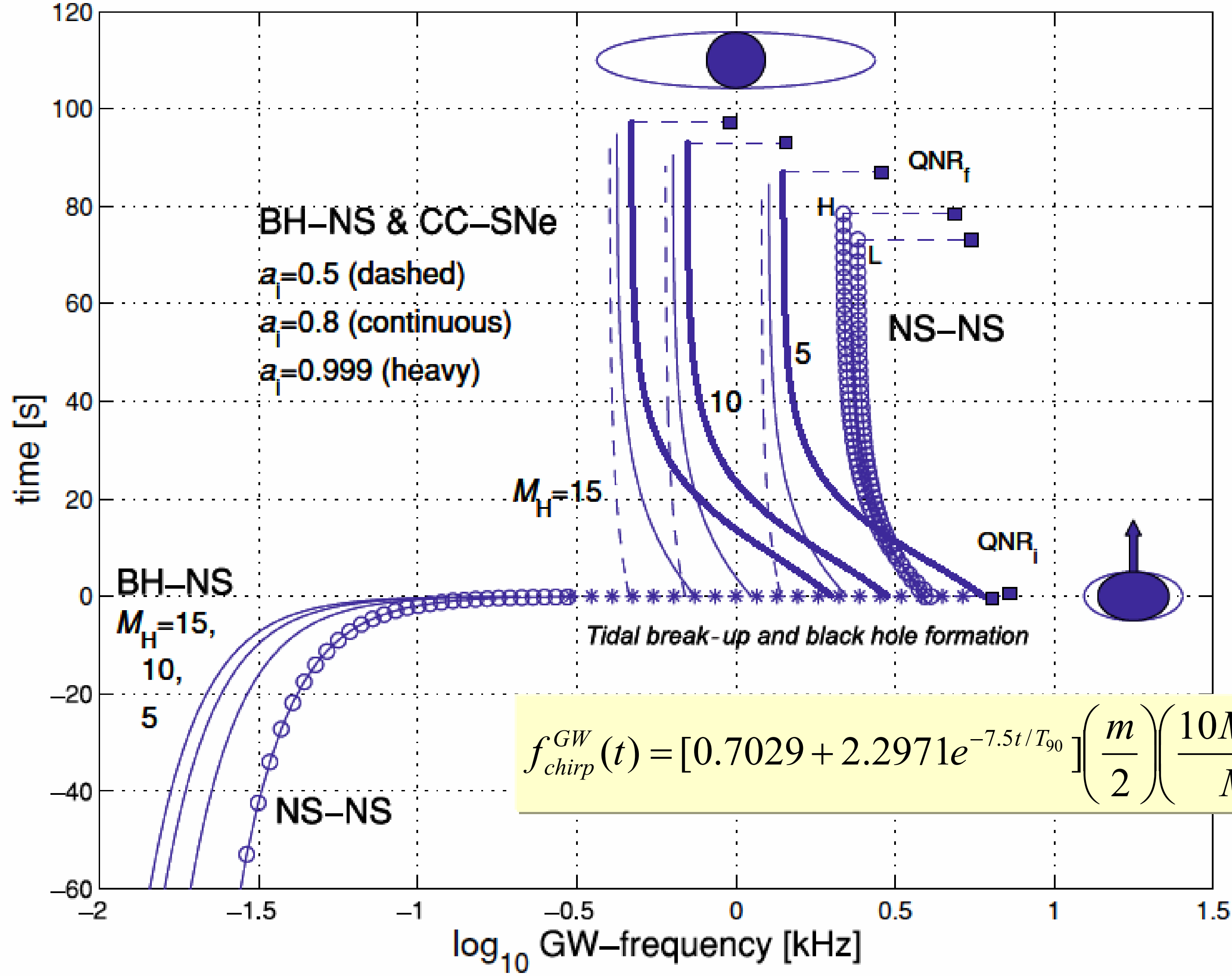
also from a broader group of BL CC-SNe ("failed GRBs", Low Luminosity GRBs)

$$D_{LIGO-Virgo,KAGRA} \cong 35\,\mathrm{Mpc}$$

for detection of negative chirp

Van Putten, 2009, MNRAS, 396, L81

Chirp diagram

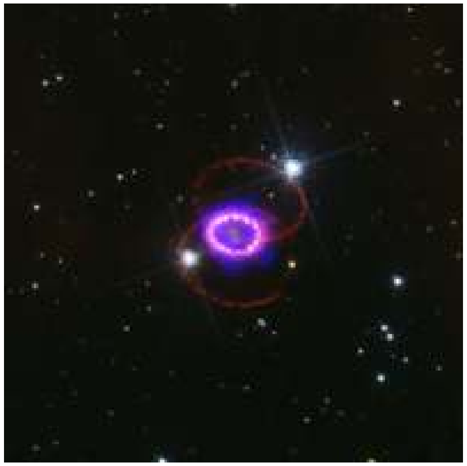


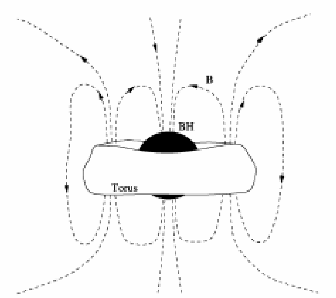
$$f_{chirp}^{GW}(t) = [0.7029 + 2.2971 e^{-7.5t/T_{90}}]\left(\frac{m}{2}\right)\left(\frac{10M_{Sun}}{M}\right)$$

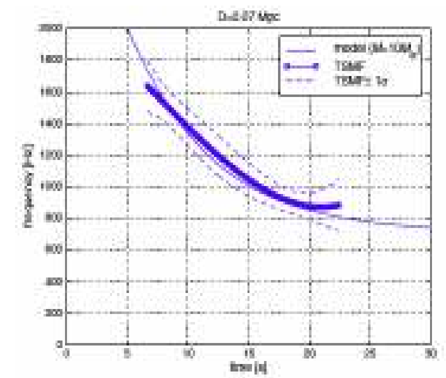
Outlook

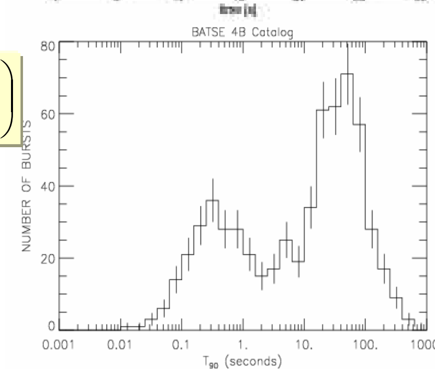
Multimessenger chirp search

Complete optical-radio surveys of nearby CC-SNe



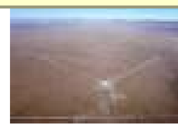


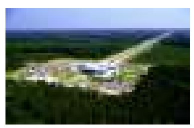


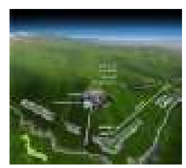


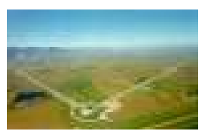
Chirp search in GW data by massively parallel computing

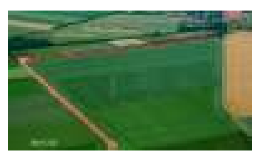
$$f_{chirp}^{GW}(t) = [0.7029 + 2.2971 e^{-7.5t/T_{90}}]\left(\frac{m}{2}\right)\left(\frac{10 M_{Sun}}{M}\right)$$











$$T_{90} = \frac{T_{90}[\mathrm{GRB}]}{1+z}$$

Duration in GWB in nearby relativistic SNe, failed GRBs

van Putten, Kanda, Tagoshi, Tatsumi, Masa-Katsu, & Della Valle, Phys. Rev. D, 83, 044046 (2011)
Aasi et al., 2013 (LIGO Collaboration) A search for long-lived gravitational-wave transients coincident with long gamma-ray bursts, arXiv:1309.6160
Also: Adrian-Martinez et al., LIGO-Virgo+ANTARES search for coincident GW and HE neutrinos, arXiv:1205.3018v3