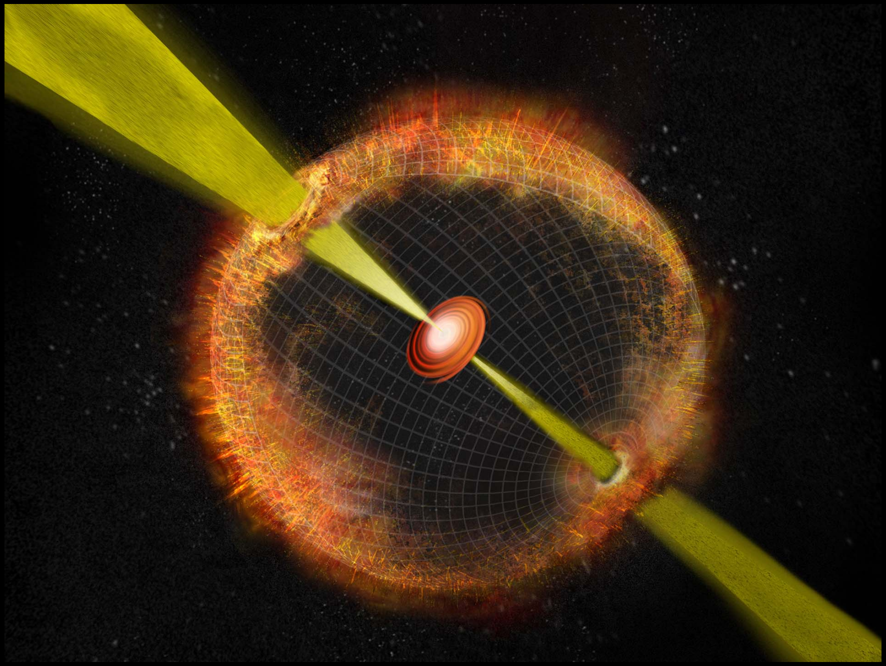
Supernovae shed light on GRBs



Massimo Della Valle
Capodimonte Observatory, INAF-Naples

Summary

1. Supernova Taxonomy
2. GRB-SN properties
3. Progenitors Mass
4. GRB and SN rates
5. GRB populations
6. Conclusions
7. Open Issues

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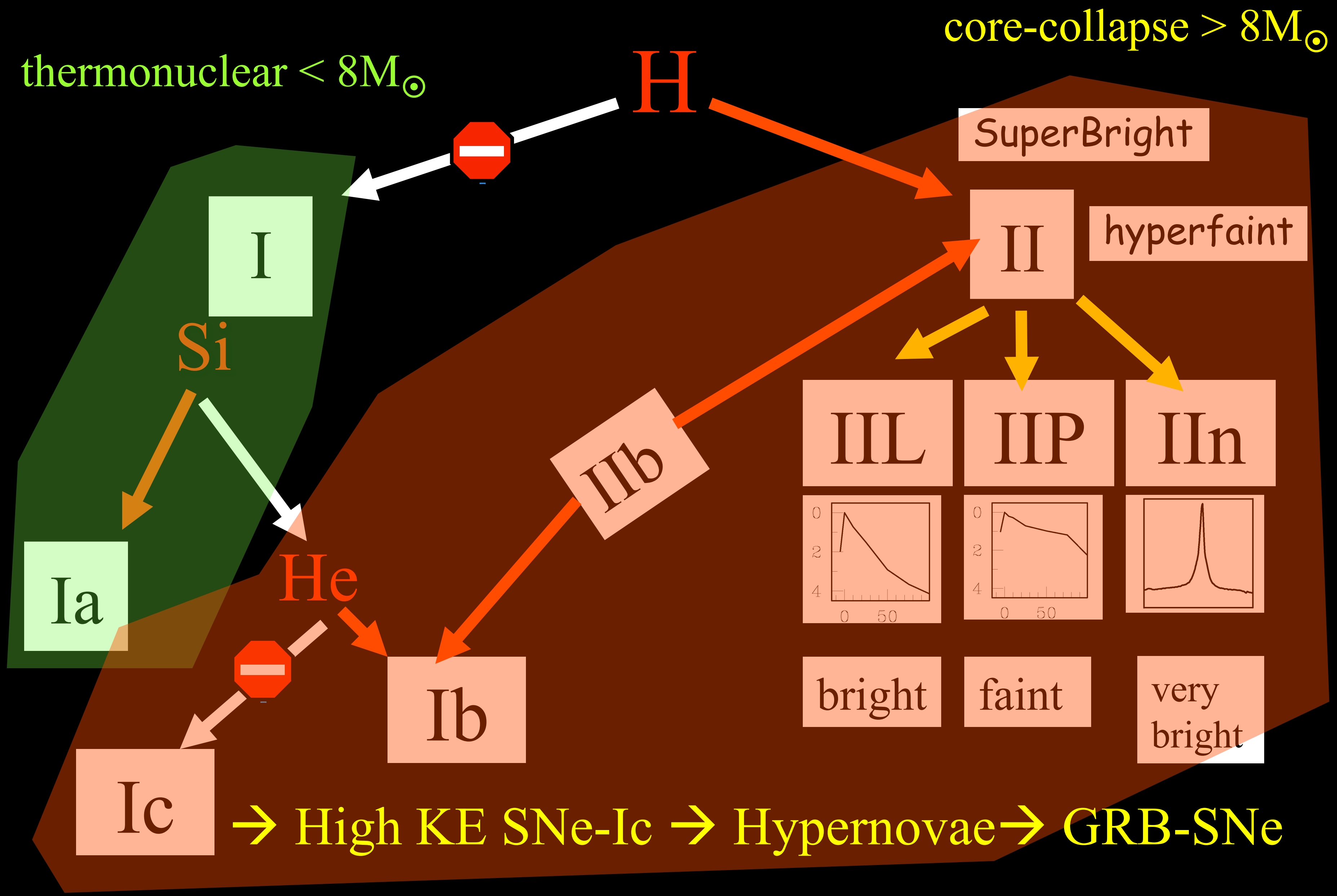
Supernova taxonomy



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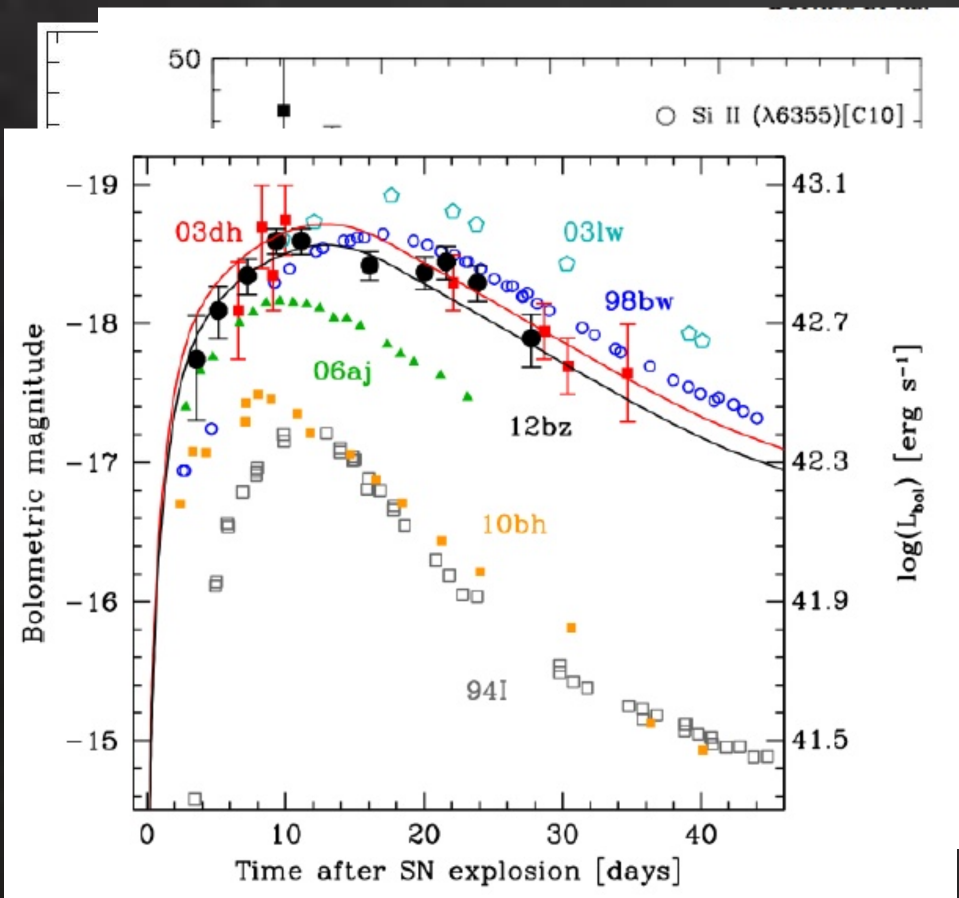
SNe & GRBs at $z < 0.2$

GRB	SN	z	Ref.
GRB 980425	SN 1998bw	0.0085	Galama et al. 1998
GRB 060218	SN 2006aj	0.033	Campana et al. 2006 Pian et al. 2006
GRB 080109	SN 2008D	0.007	Soderberg et al. 2008 Mazzali et al. 2008
GRB 100316D	SN 2010bh	0.06	Bufano et al. 2012 Chornock et al. 2010 Cano et al. 2011 Margutti et al. 2013
GRB 030323	SN 2003dh	0.16	Hjorth et al. 2003 Stanek et al. 2003
GRB 031203	SN 2003lw	0.11	Malesani et al. 2004
GRB 130702A	SN 2013dx	0.15	D'Elia et al. 2014

Properties of GRB-SNe (broad-lined SNe-Ic)



Lack of H and He in the ejecta:
SNe

Very br
expans

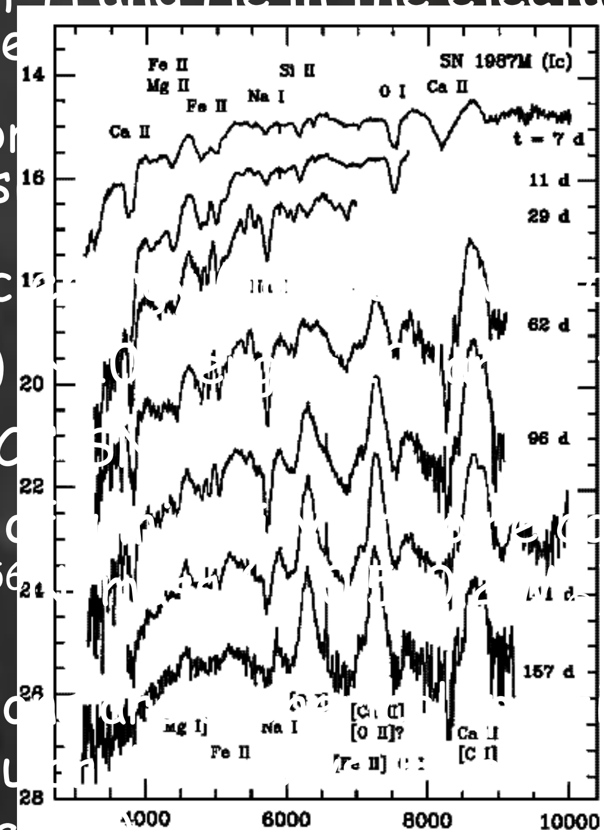
Kinetic

ejecta) than

Usual C

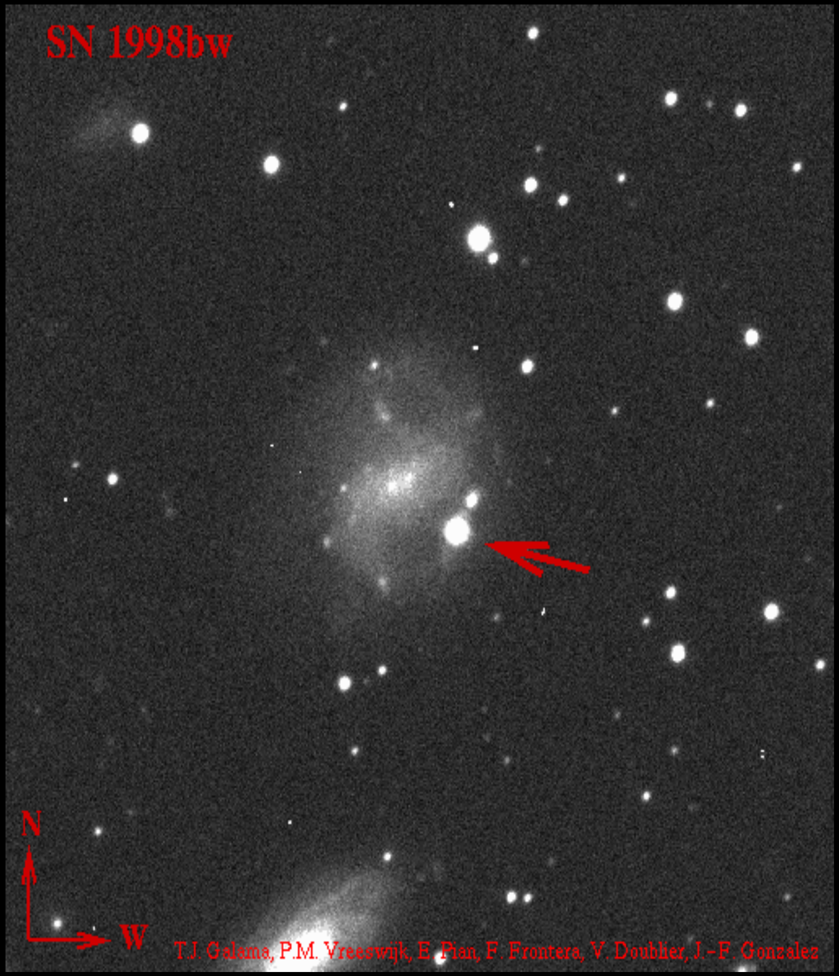
Range o se
large [56]

Explosio les
of nebu
Polariza



SN 1998bw

SN 1987A

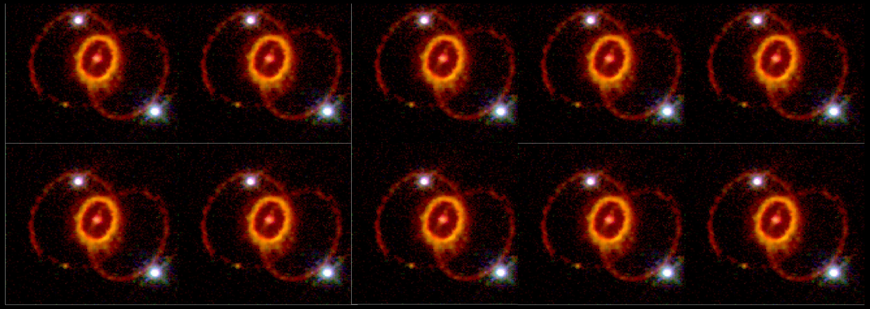


Aspherical explosion

Maeda et al. 2006, 2008

see also Tautenberger et al. 2009

=



$E_K \sim 30 \times 10^{51}$ erg

$E_K \sim 1 \times 10^{51}$ erg

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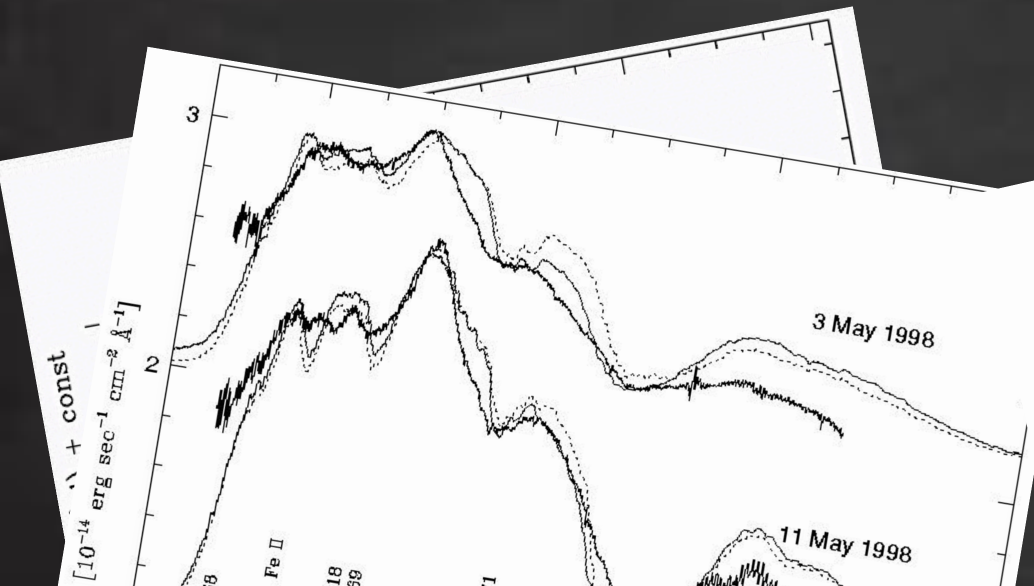
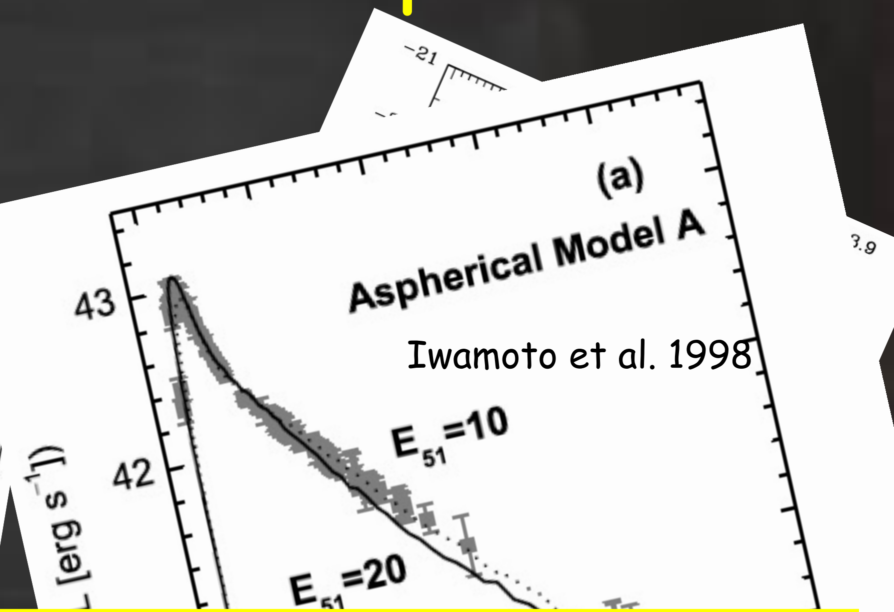
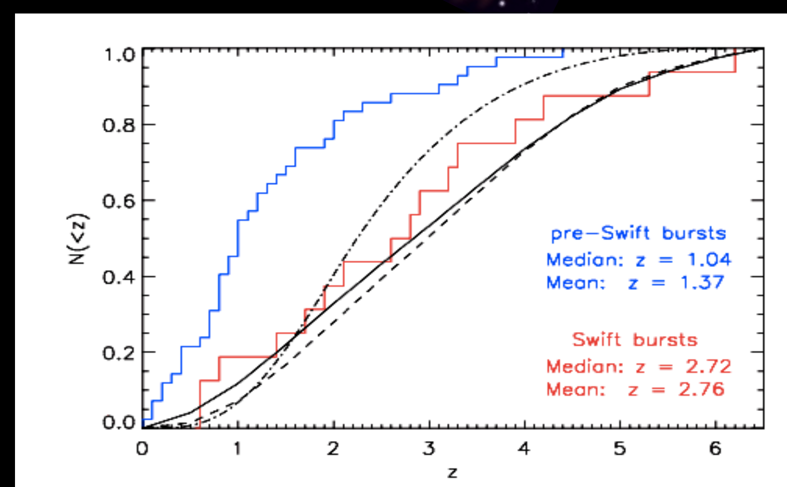
Modeling lightcurves and spectra





1998bw	2003dh	2003lw	2006aj	2008D	2010bh
25-35 $M_\odot$ 40 $M_\odot$	35-40 $M_\odot$	40-50 $M_\odot$	20-25 $M_\odot$	20-30 $M_\odot$	25 $M_\odot$
Woosley 1999; Maeda et al. 2006	Nomoto et al. 2003	Mazzali et al. 2006	Mazzali et al. 2006	Tanaka et al. 2008	Bufano et al. 2012

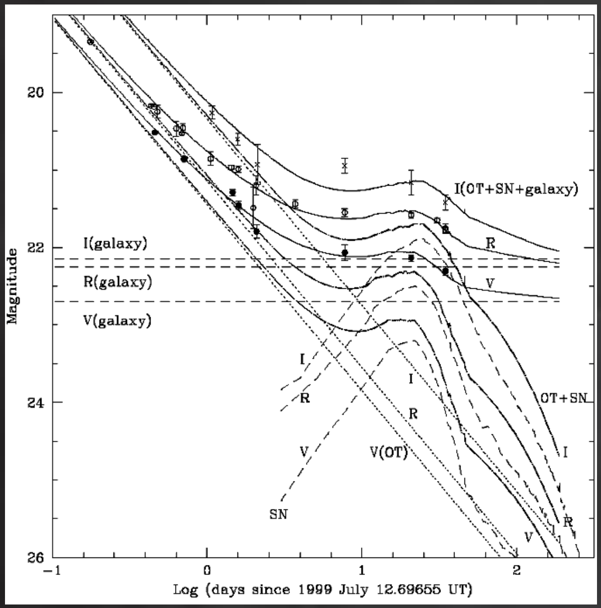
Distant GRB/SNe ?



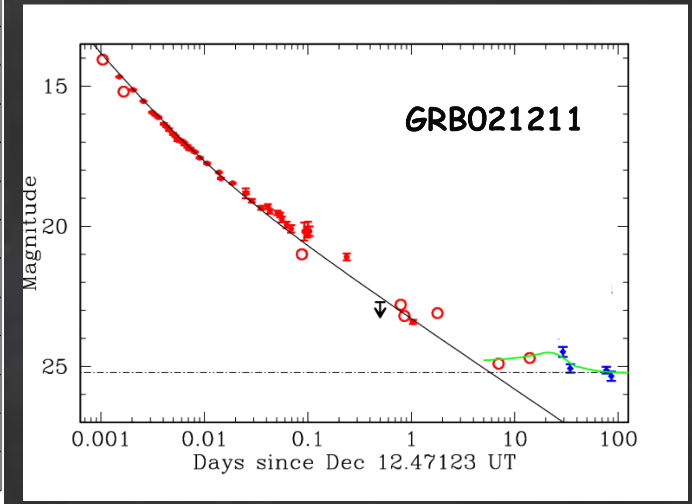
GRB census > 0.2

GRB	SN	z	Ref.
GRB 021202	SN 2002lt	1.002	Della Valle et al. 2003
GRB 050525A	SN 2005nc	0.606	Della Valle et al. 2006
GRB 101219B	SN 2010ma	0.55	Sparre et al. 2011
GRB 060729	SN no name	0.54	Cano et al. 2011
GRB 090618	SN no name	0.54	Cano et al. 2011
GRB 081007	SN 2008hw	0.53	Della Valle et al. 2008 Zhi-ping et al. 2008
GRB 091127	SN 2009nz	0.49	Cobb et al. 2010 Berger et al. 2011
GRB120714B	SN 2012eb	0.40	Klose et al. 2012
GRB 130427A	SN 2013cq	0.34	Melandri et al. 2014 Xu et al. 2013
GRB 120422A	SN 2012bz	0.28	Melandri et al. 2012
GRB 120729A; 130215A; GRB 130831A	?; SN2013ez , SN2013fu	0.8;0.6;0.48	Cano et al. 2014

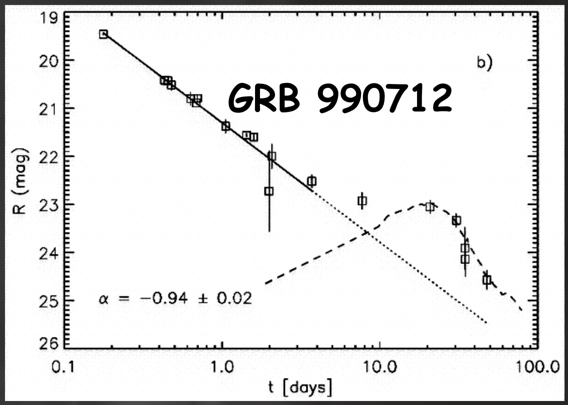
up to $z \sim 1$



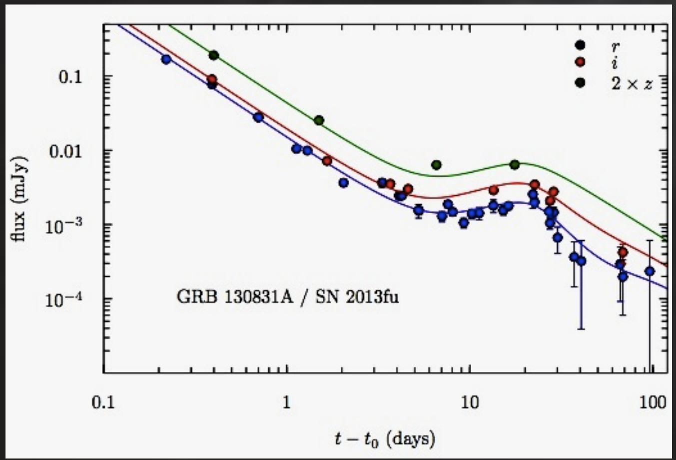
Sahu et al. 2000



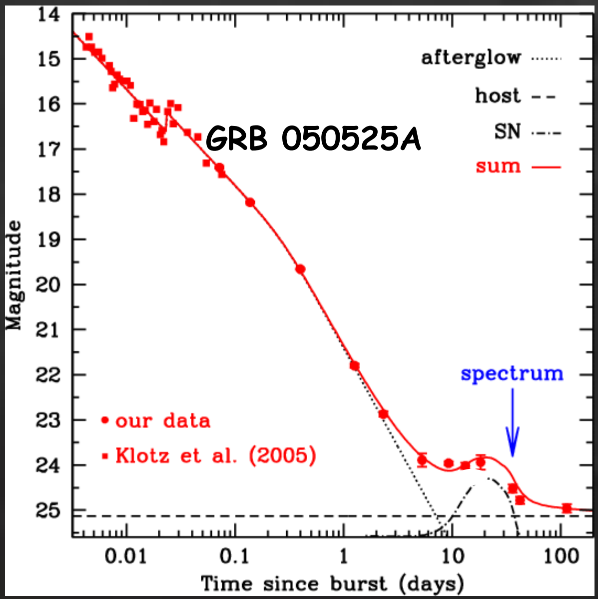
Della Valle et al. 2003



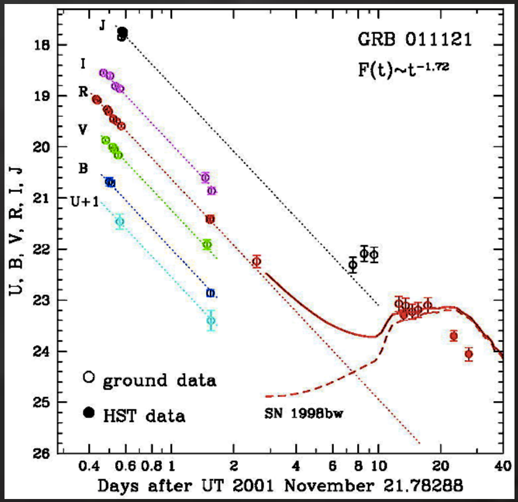
Bjornsson et al. 2001



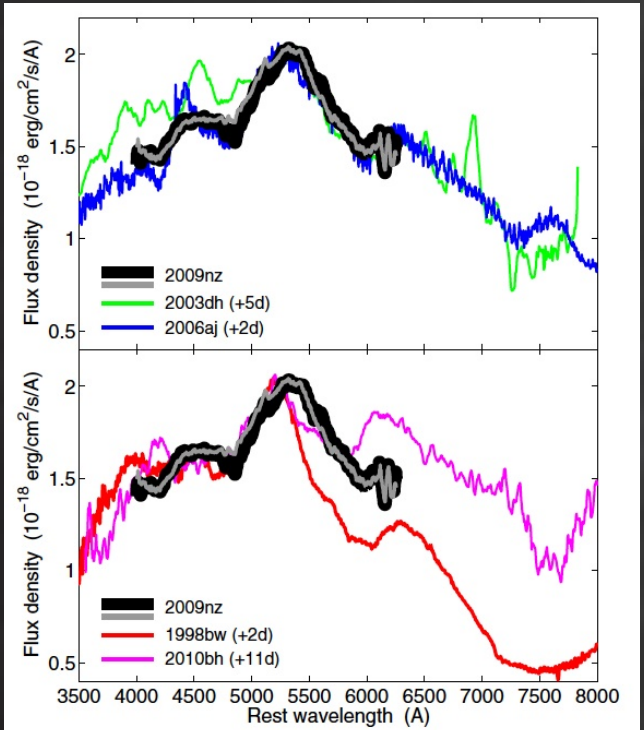
Cano et al. 2014

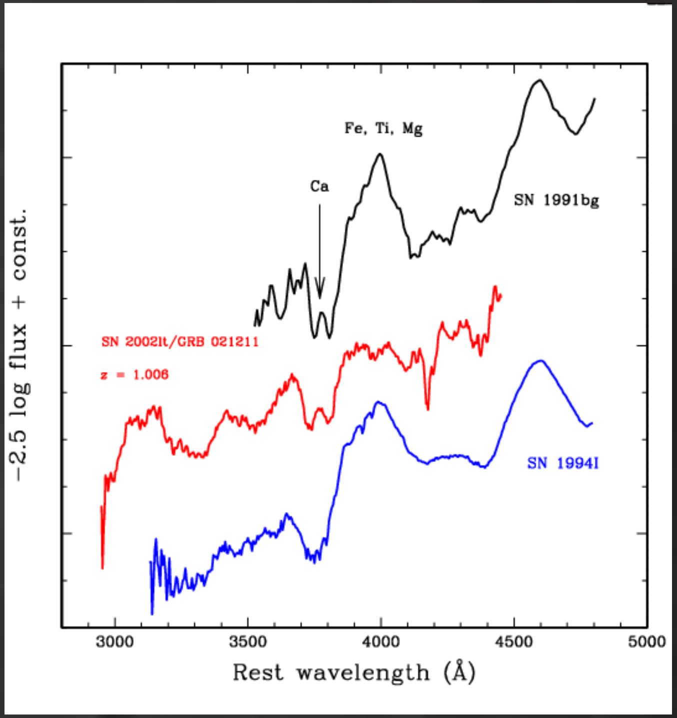


Della Valle et al. 2006



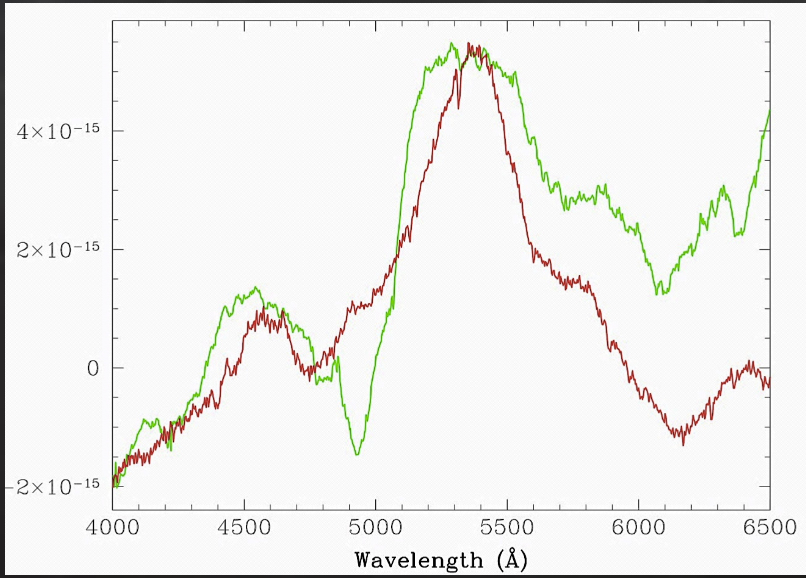
Garnavich et al. 2003





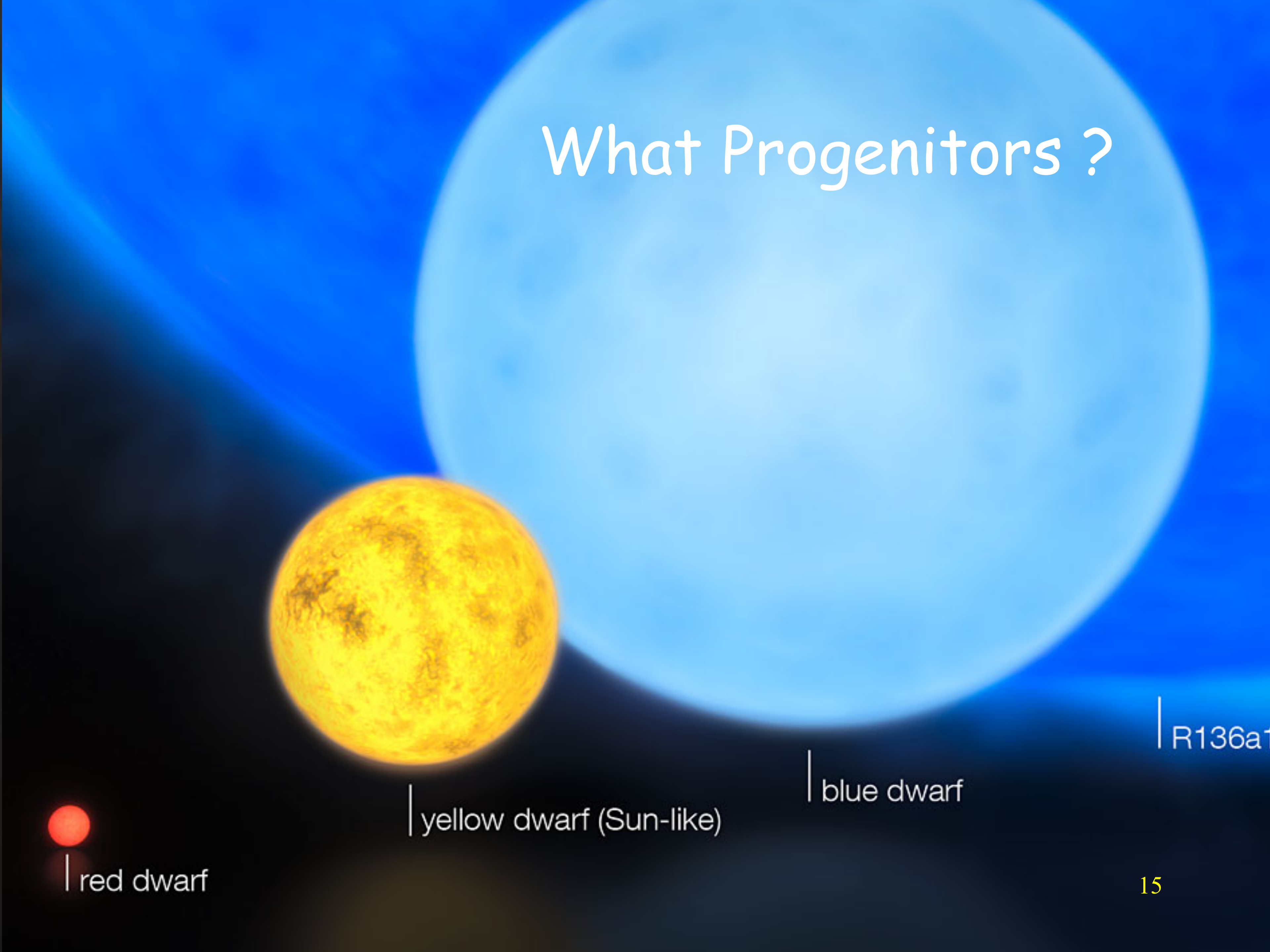
Berger et al. 2011
SN 2009nz @ z=0.49

Della Valle et al. 2003
SN 2002lt @ z=1

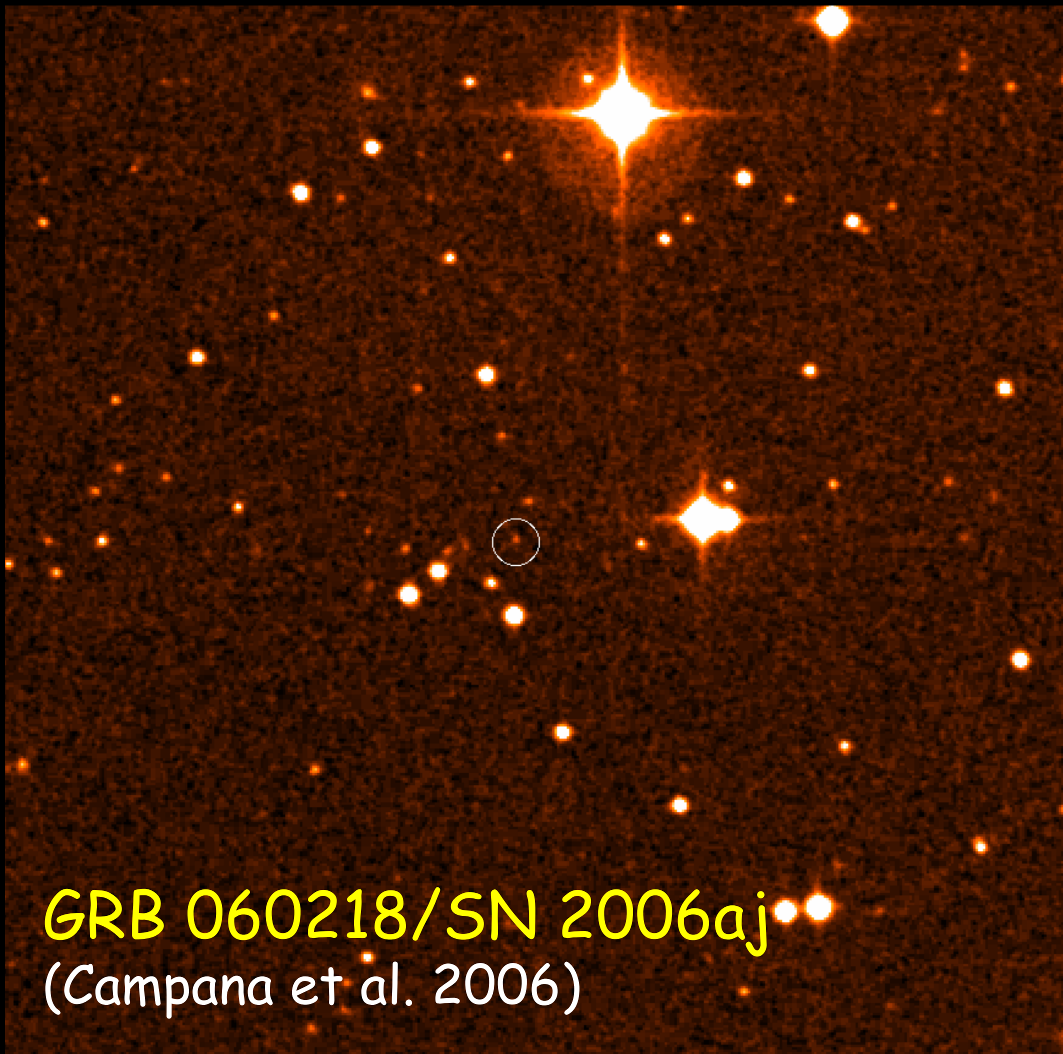


Zhi-Ping et al. 2013
SN 2008hw @ z=0.53

What Progenitors ?



What Stars are GRB Progenitors ?



GRB 060218/SN 2006aj
(Campana et al. 2006)

$z = 0.033$

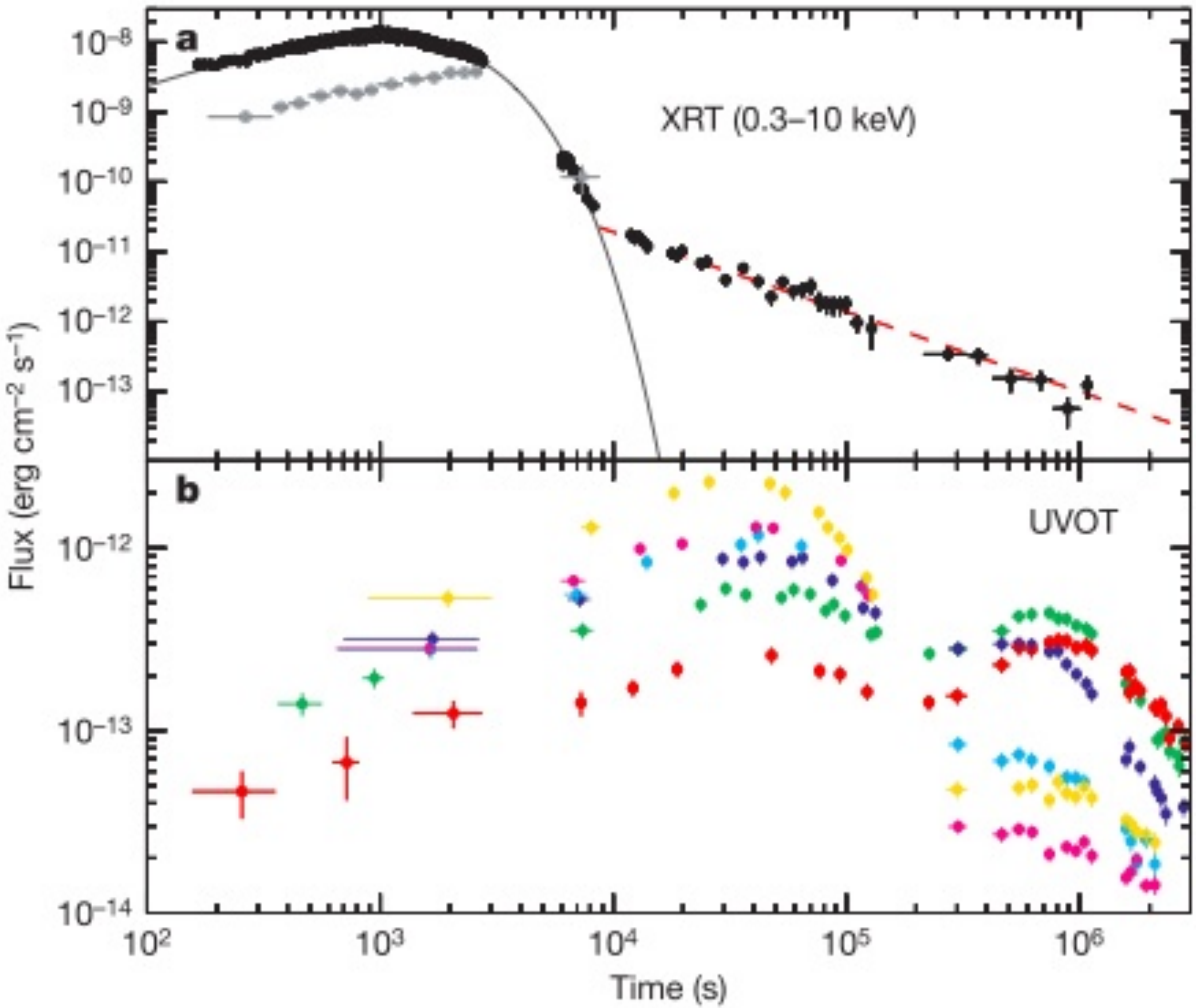
faint: $E_\gamma \sim 10^{49}$ erg

M_V (host) = -16

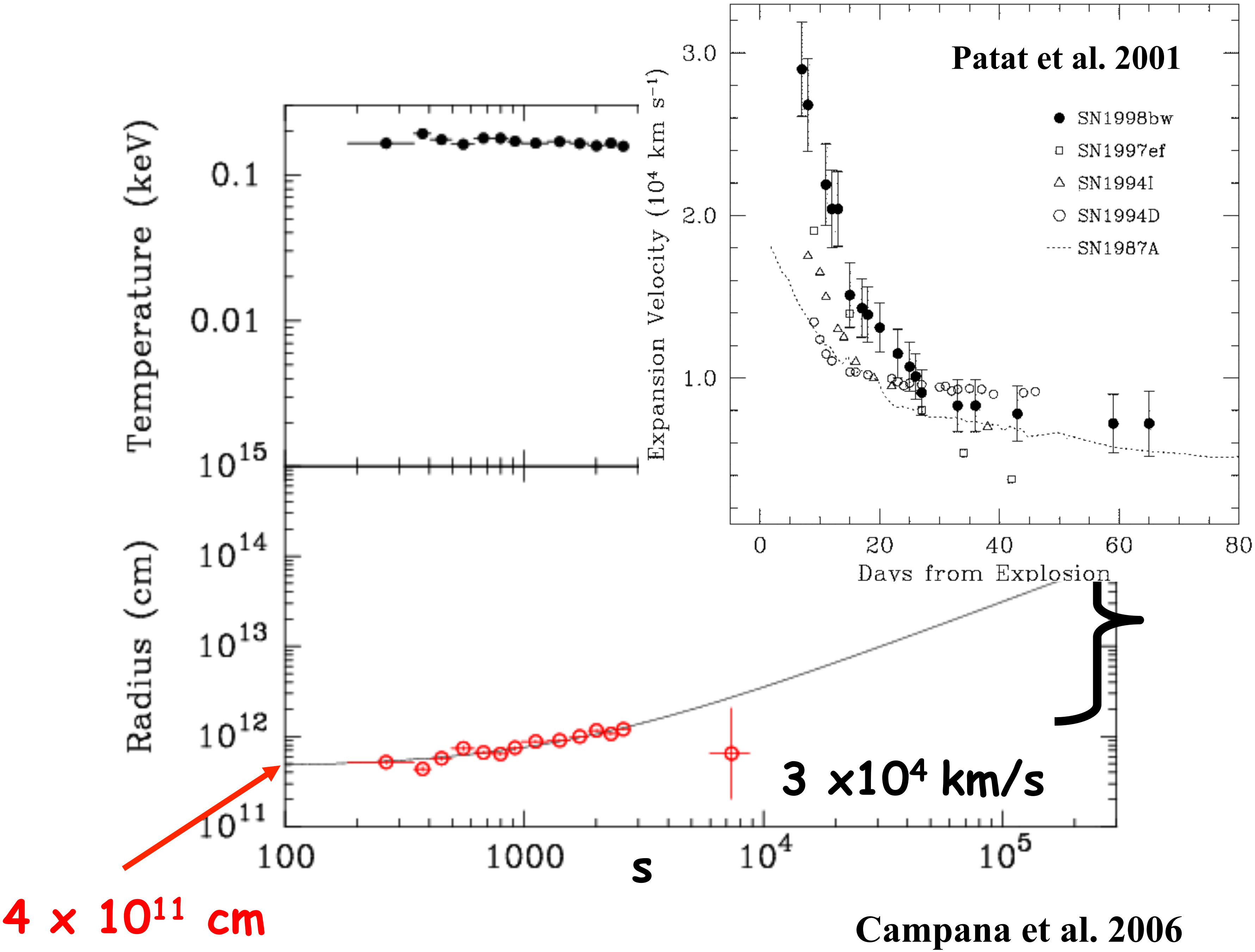
Host has brightness
Similar to SMC

$Z/Z_\odot \sim 0.3$

2006aj = SN-Ic

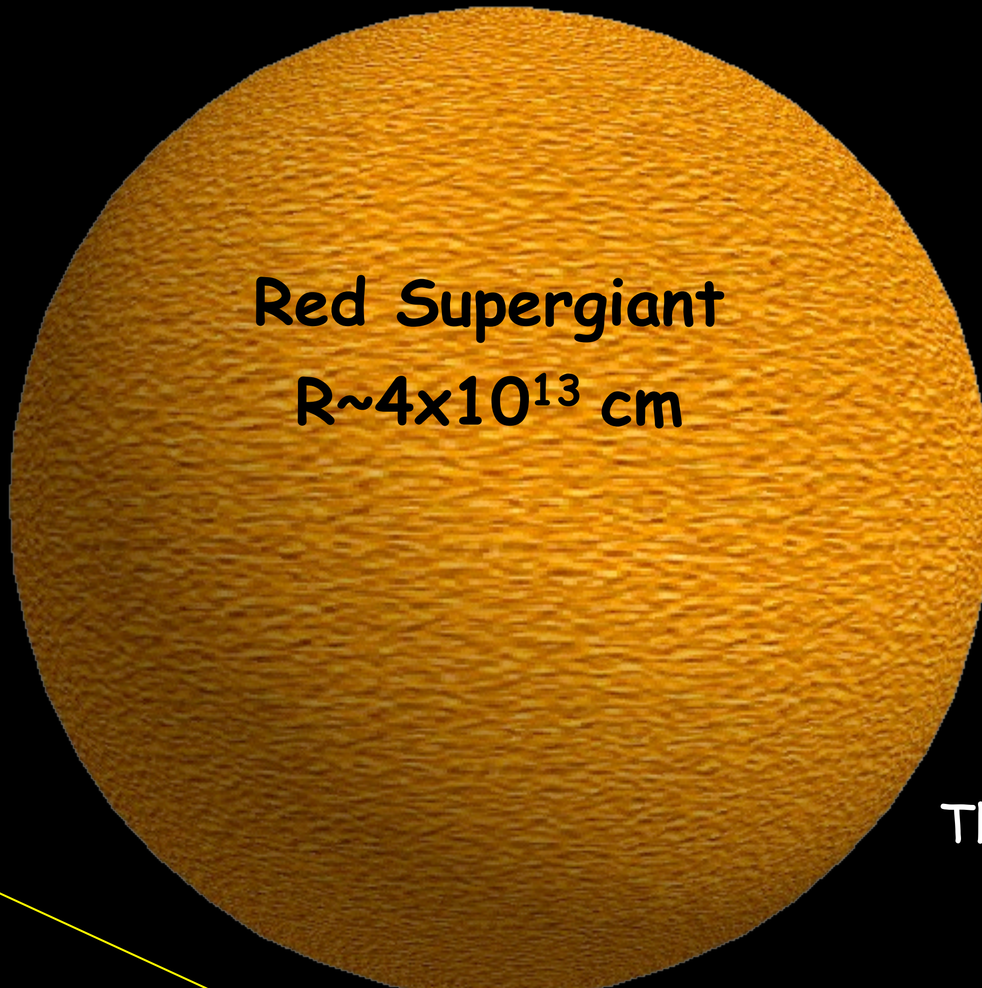


Campana et al. 2006



Temperature (keV)
0.1
0.01
Radius (cm)
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
100
1000
10^4
10^5
s
4×10^{11} cm
3×10^4 km/s
Campana et al. 2006
Patat et al. 2001
Expansion Velocity (10^4 km s^{-1})
3.0
2.0
1.0
0
20
40
60
80
Days from Explosion
SN1998bw
SN1997ef
SN1994I
SN1994D
SN1987A

SNe-CC size progenitors



Blue Supergiant

$R \sim 4 \times 10^{12}$ cm

The radius of the progenitor

W-R Star

$R \sim 4 \times 10^{11}$ cm

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What is the rate of SNe-Ib/c ?

Asiago Survey (Cappellaro et al. 1999)

galaxy type	N. SNe*			rate [SNu]		
	Ia	Ib/c	II	Ia	Ib/c	II
E-S0	22.0			0.18 ± 0.06	< 0.01	< 0.02
S0a-Sb	18.5	5.5	16.0	0.18 ± 0.07	0.11 ± 0.06	0.42 ± 0.19
Sbc-Sd	22.4	7.1	31.5	0.21 ± 0.08	0.14 ± 0.07	0.86 ± 0.35
Others#	6.8	2.2	5.0	0.40 ± 0.16	0.22 ± 0.16	0.65 ± 0.39
All	69.6	14.9	52.5	0.20 ± 0.06	0.08 ± 0.04	0.40 ± 0.19

Rate for Ib/c: 0.152 ± 0.064 SNu

Guetta & DV 2007

1.8×10^4 SNe-Ibc $Gpc^{-3}\ yr^{-1}$ → **1.1×10^4 up to 2.6×10^4**

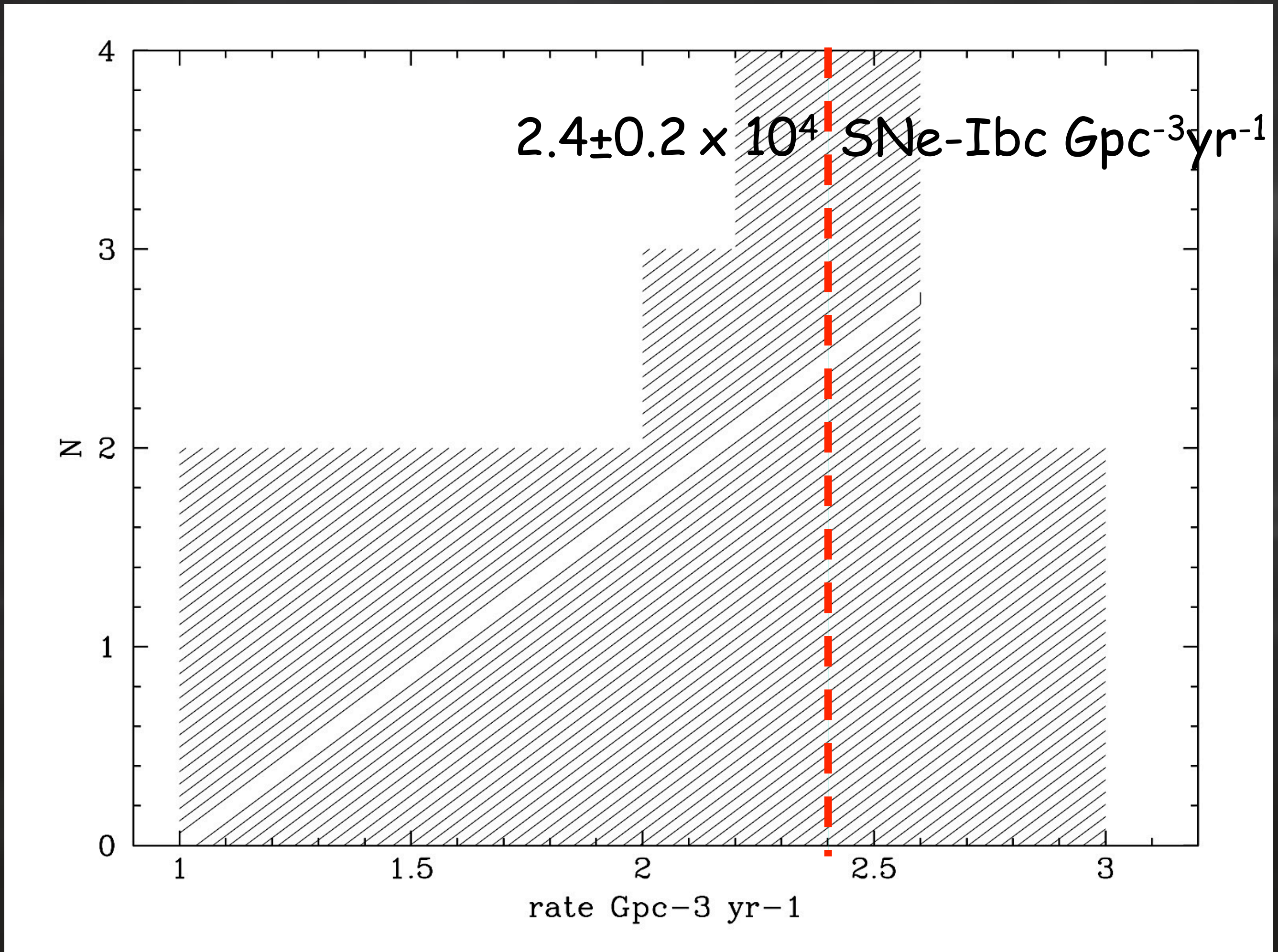
What is the rate of SNe-Ib/c ?

Lick Survey (Li et al. 2011)

Rate	SN Ia	SN Ibc	SN II
Early(fiducial; SNuK)	$0.064^{+0.008}_{-0.007}(^{+0.013}_{-0.013})$	$0.008^{+0.006}_{-0.004}(^{+0.002}_{-0.002})$	$0.004^{+0.003}_{-0.002}(^{+0.001}_{-0.001})$
Late(fiducial; SNuK)	$0.074^{+0.006}_{-0.006}(^{+0.012}_{-0.012})$	$0.096^{+0.010}_{-0.009}(^{+0.018}_{-0.018})$	$0.172^{+0.011}_{-0.011}(^{+0.045}_{-0.036})$
Early(LF-average; SNuK)	$0.048^{+0.006}_{-0.005}(^{+0.010}_{-0.010})$	$0.006^{+0.004}_{-0.003}(^{+0.002}_{-0.002})$	$0.003^{+0.002}_{-0.001}(^{+0.001}_{-0.001})$
Late(LF-average; SNuK)	$0.065^{+0.006}_{-0.005}(^{+0.010}_{-0.010})$	$0.083^{+0.009}_{-0.008}(^{+0.016}_{-0.016})$	$0.149^{+0.010}_{-0.009}(^{+0.039}_{-0.031})$
Vol-rate (10^{-4} SN Mpc^{-3} yr^{-1})	$0.301^{+0.038}_{-0.037}(^{+0.049}_{-0.049})$	$0.258^{+0.044}_{-0.042}(^{+0.058}_{-0.058})$	$0.447^{+0.068}_{-0.068}(^{+0.131}_{-0.111})$

Rate for Ib/c: 2.6×10^4 SNe-Ibc Gpc^{-3} yr^{-1}

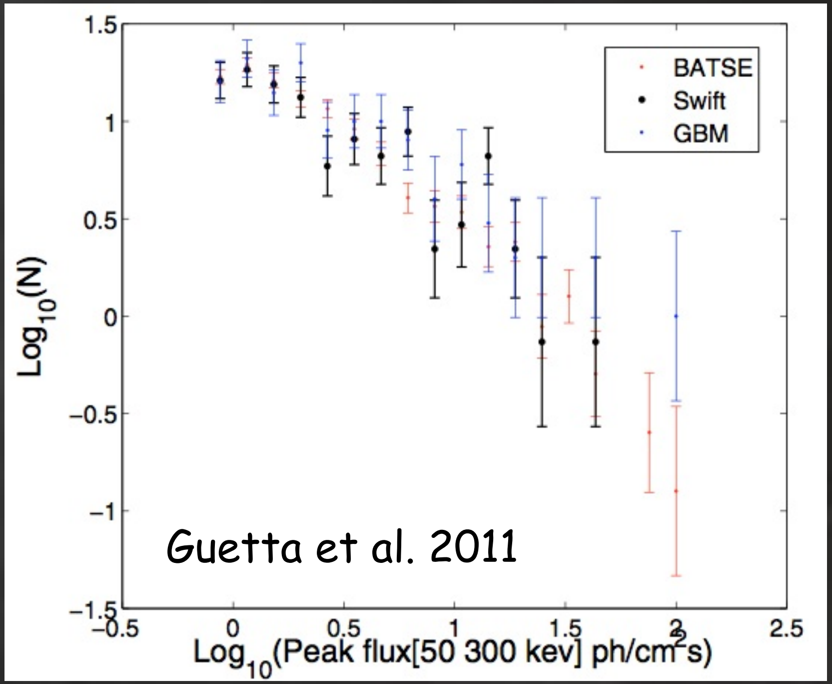
$2.2 \times 10^4 \rightarrow 3 \times 10^4$ SNe-Ibc Gpc^{-3} yr^{-1}


2.4±0.2 x 10^4 SNe-Ibc Gpc^-3yr^-1
N
0
1
2
3
4
1
1.5
2
2.5
3
rate Gpc−3 yr−1

What is the rate of (long) GRBs ?

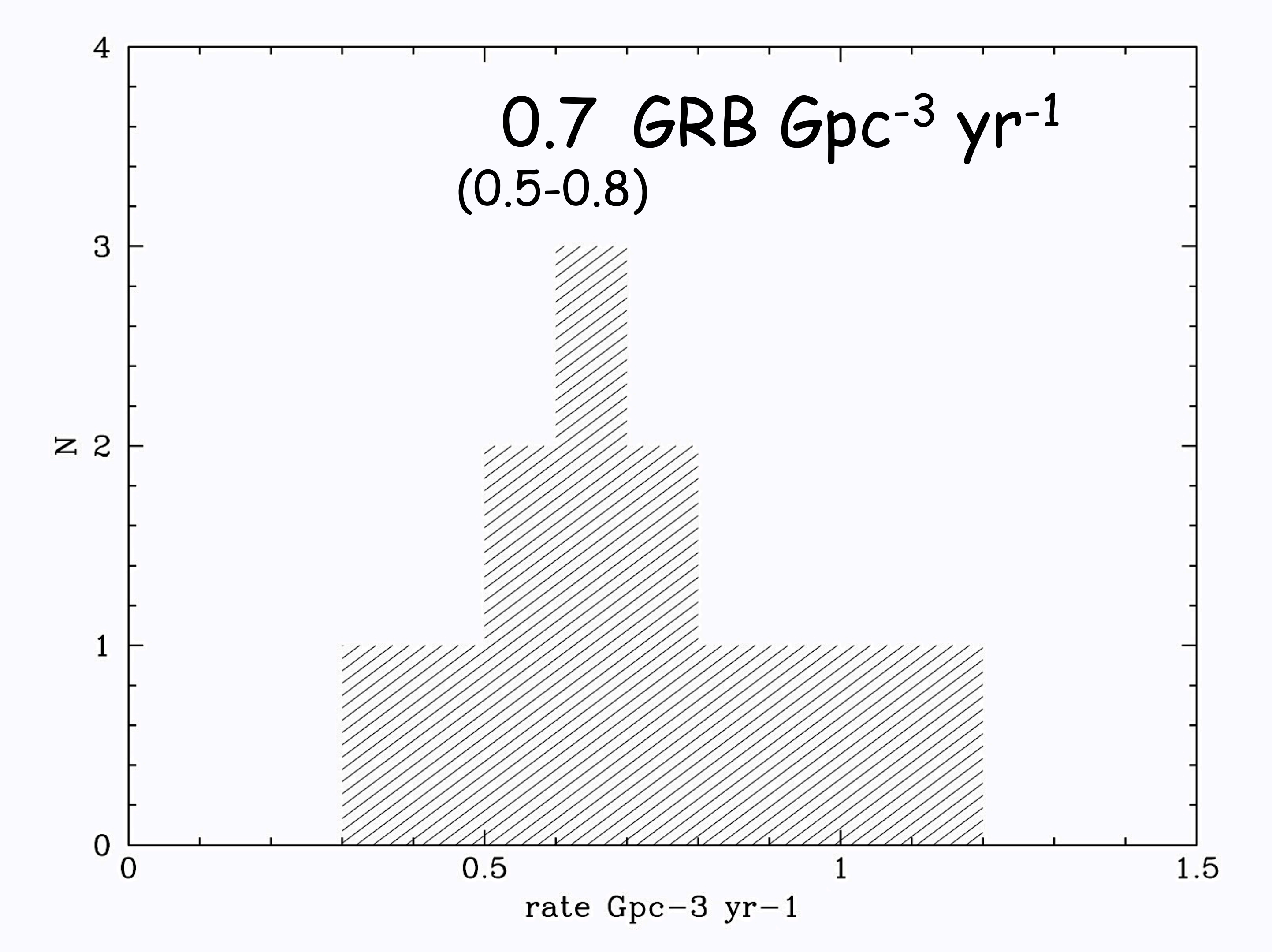
GRB $Gpc^{-3}\ yr^{-1}$

1.5	Schmidt 1999
0.15	Schmidt 2001
0.5	Guetta et al. 2005
1.1	Guetta & Della Valle 2007
1.1	Liang et al. 2007
> 0.5	Pelangeon et al. 2008
1.3	Wanderman and Piran



Sample	Rate ($z = 0$)[1] $Gpc^{-3}\ yr^{-1}$	L^* [50–300] keV 10^{51} erg/s	a_1	a_2	χ^2/d.o.f.[3]
GBM	$0.5^{+0.3}_{-0.2}$	$5.5^{+1.5}_{-2}$	$0.3^{+0.1}_{-0.5}$	$2.3^{+0.6}_{-0.3}$	1.1
BATSE	$1.0^{+0.2}_{-0.4}$	$4^{+2}_{-1.5}$	$0.1^{+0.3}_{-0.1}$	$2.6^{+0.9}_{-0.5}$	1.1
Swift	$0.6^{+0.3}_{-0.1}$	$3.3^{+2.5}_{-0.5}$	$0.1^{+0.3}_{-0.1}$	$2.7^{+1}_{-0.4}$	0.95

What is the local rate of (long) GRBs ?

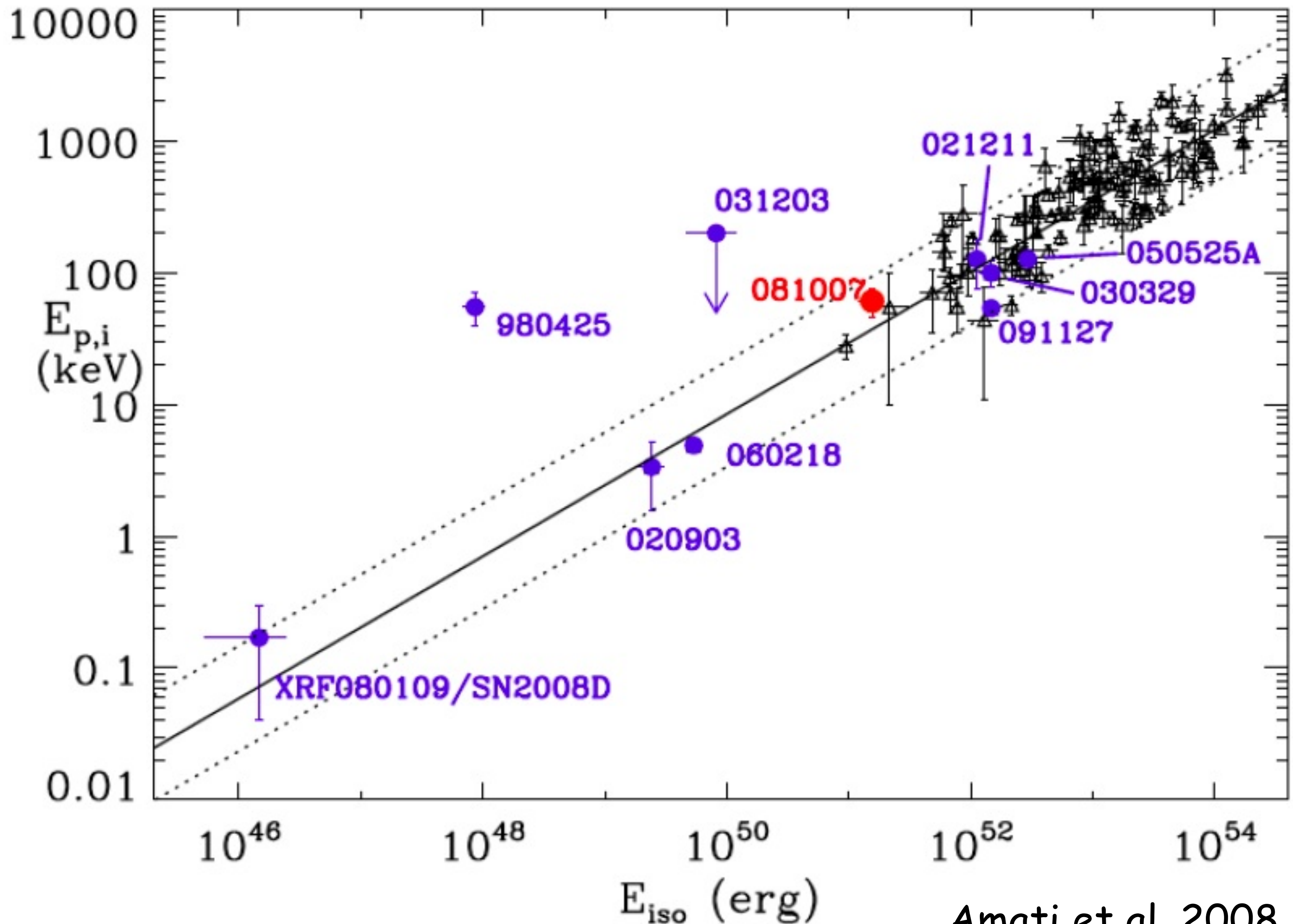


What is the fraction of SNe-Ib/c which produces (long)GRBs ?

Rate for Ibc: 2.4×10^4 SNe-Ibc $Gpc^{-3}\ yr^{-1}$

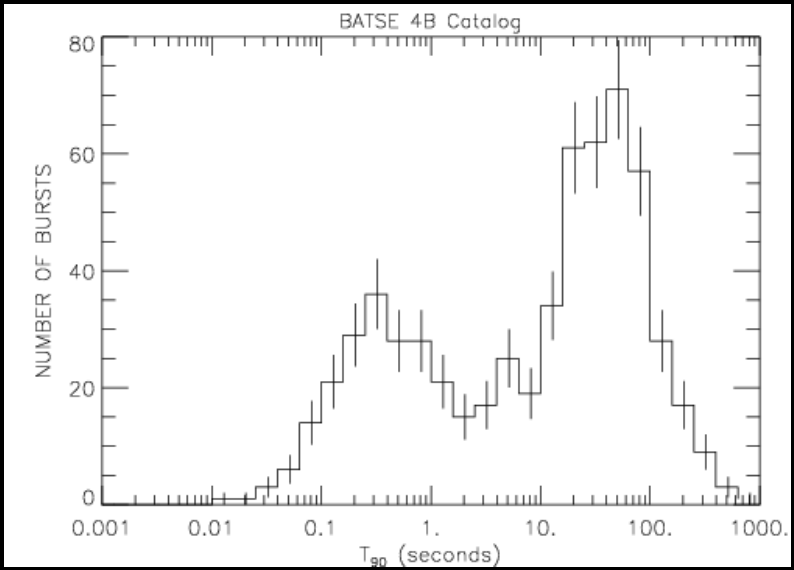
GRB rate: 0.7 GRB $Gpc^{-3}\ yr^{-1}$

To BE*am* or not to BE*am*



Amati et al. 2008

Energy Crisis



Fluence : $10^{-7} \div 10^{-5}$ erg cm^{-2}

Distanza: up to $z \sim 10$

Energy : E_{iso} up to ~ few x 10^{54} erg

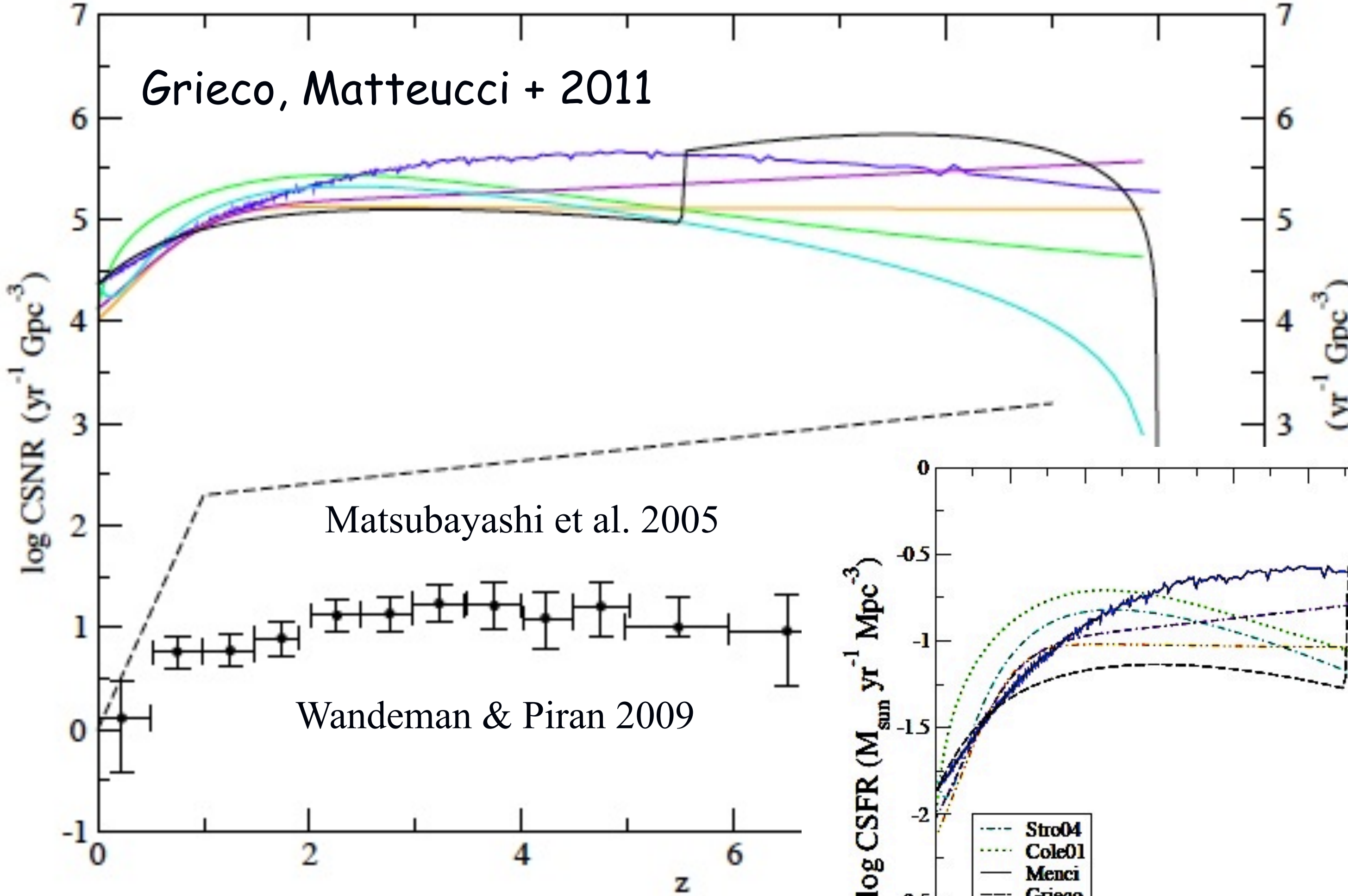
10^{54} erg ~ 1 $M_{\odot}$ ~ x 10

What is the fraction of SNe-Ib/c which produces (long)GRBs ?

Rate for Ibc: 2.4×10^4 SNe-Ibc $Gpc^{-3}\ yr^{-1}$

GRB rate: 0.7 GRB $Gpc^{-3}\ yr^{-1}$

$\langle fb^{-1} \rangle \sim 500$	(Frail et al. 2001)	$(\vartheta \sim 4°)$
$\langle fb^{-1} \rangle \sim 75$	(Guetta, Piran & Waxman 2004)	$(\vartheta \sim 9°)$
$\langle fb^{-1} \rangle < 10$	(Guetta & DellaValle 2007)	$(\vartheta > 25°)$ for sub-lum GRBs
$\langle fb^{-1} \rangle \sim 1$	(Ruffini et al. 2006)	$(\vartheta \sim 4\,\pi)$



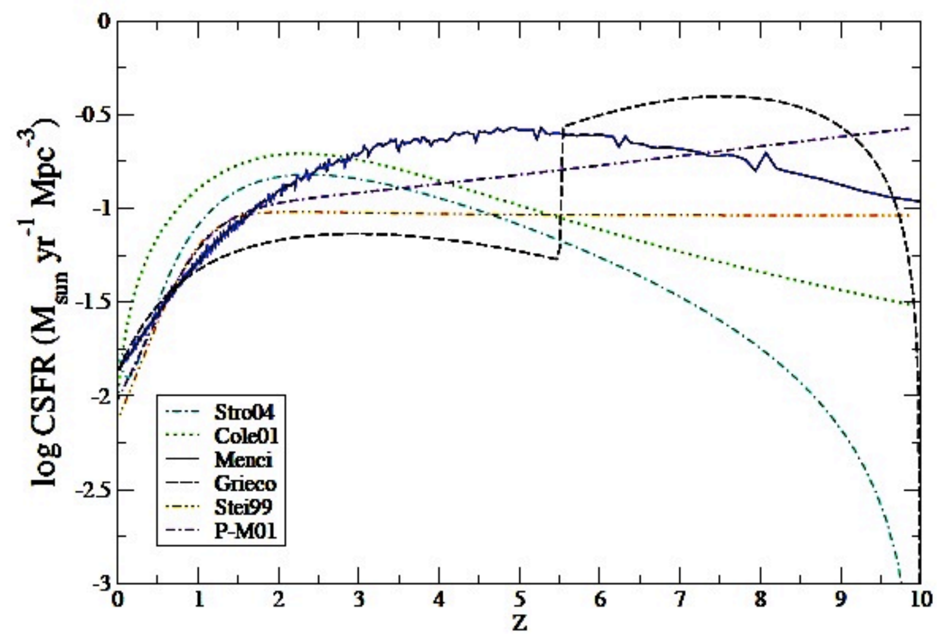


Figure 6. Evolution of different cosmic star formation rates with redshift: Menci, private communication (blue solid line), our model (black long-dashed line), Strolger 2004 (turquoise dashed-dotted line), Steidel 1999 (orange double dotted-dashed line), Porciani & Madau 2001 (violet double dashed-dotted line). The green dotted line is the fit (Cole et al. 2001) of the data collected by Hopkins (2004).

GRB/SNeIbc →0.1-0.01%

θ ~ 13°-40°

What is the fraction of SNe-Ib/c which produces (long)GRBs ?

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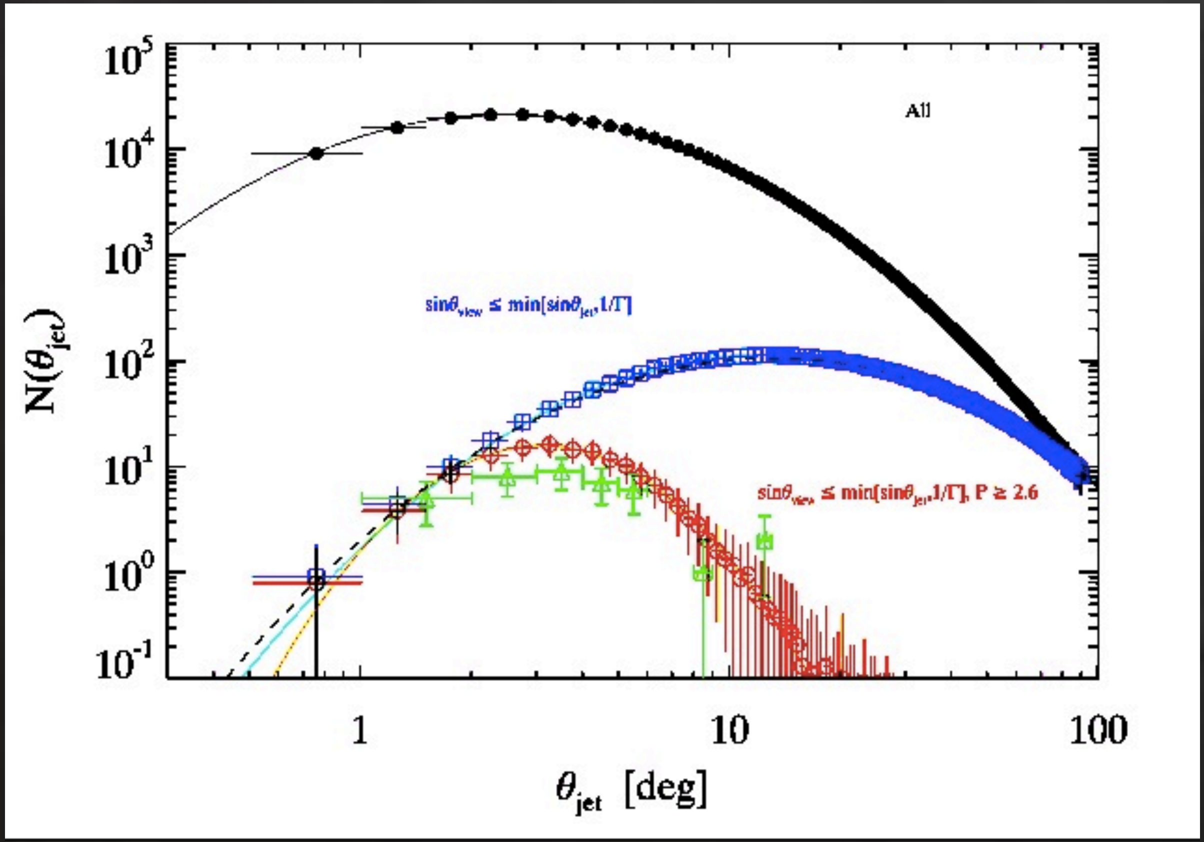
$\langle fb^{-1} \rangle \sim 1$	(Ruffini et al. 2006)	($\vartheta \sim 4\,\pi$)

The faster the narrower: characteristic bulk velocities and jet opening angles of Gamma Ray Bursts

G. Ghirlanda[1*], G. Ghisellini[1], R. Salvaterra[2], L. Nava[3], D. Burlon[4], G. Tagliaferri[1], S. Campana[1], P. D'Avanzo[1], A. Melandri[1] (2013)



> $1° < \vartheta < 100°$

$\vartheta_{peak} \sim 4°$

What is the fraction of SNe-Ib/c which produces (long)GRBs ?

Rate for Ibc: 2.4×10^4 SNe-Ibc $Gpc^{-3}\ yr^{-1}$

GRB rate: 0.7 GRB $Gpc^{-3}\ yr^{-1}$

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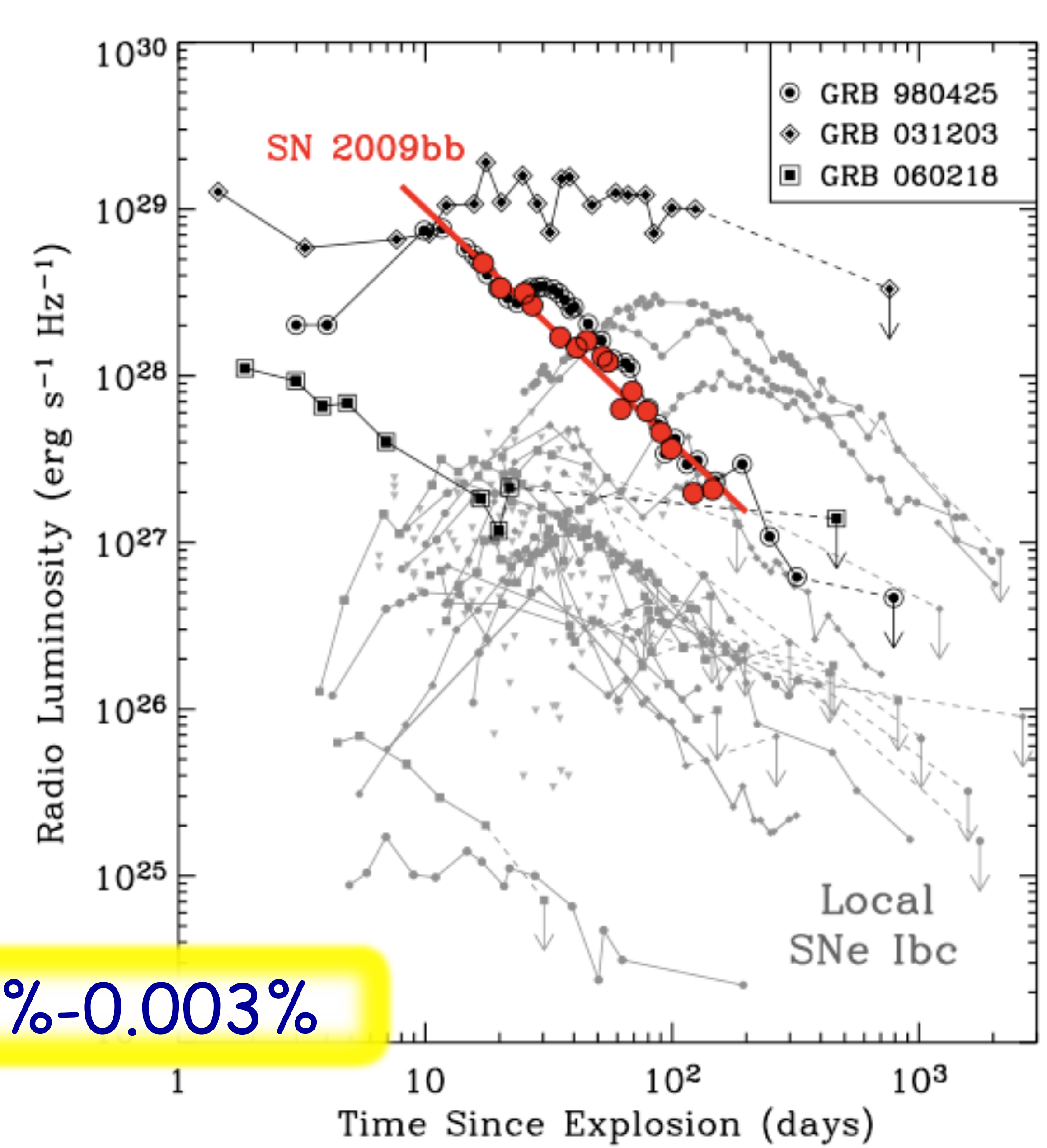
$\langle fb^{-1} \rangle \sim 1$	(Ruffini et al. 2006)	($\vartheta \sim 4\ \pi$)

GRB/SNe-Ibc: 1.5%-0.003%

Discovery of a Relati
Gamma-ray Trigger

A. M. Soderberg[1], S.
R. A. Chevalier[4], P. Chandra[5],
V. Chaplin[7], V. Connaughton[7],
N. Chugai[11], M. D. Stritzinger[12],
E. M. Levesque[1,15], J. E. Grindlay
P. A. Milne[16], M. A. P. Torres[1]



GRB/SNe-Ibc ~ 1/146

GRB/SNe-Ibc ~ 0.7%

< 5% at 99%

GRB/SNe-Ibc: 1.5%-0.003%

+

HNe/SNe-Ibc: ~ 7%

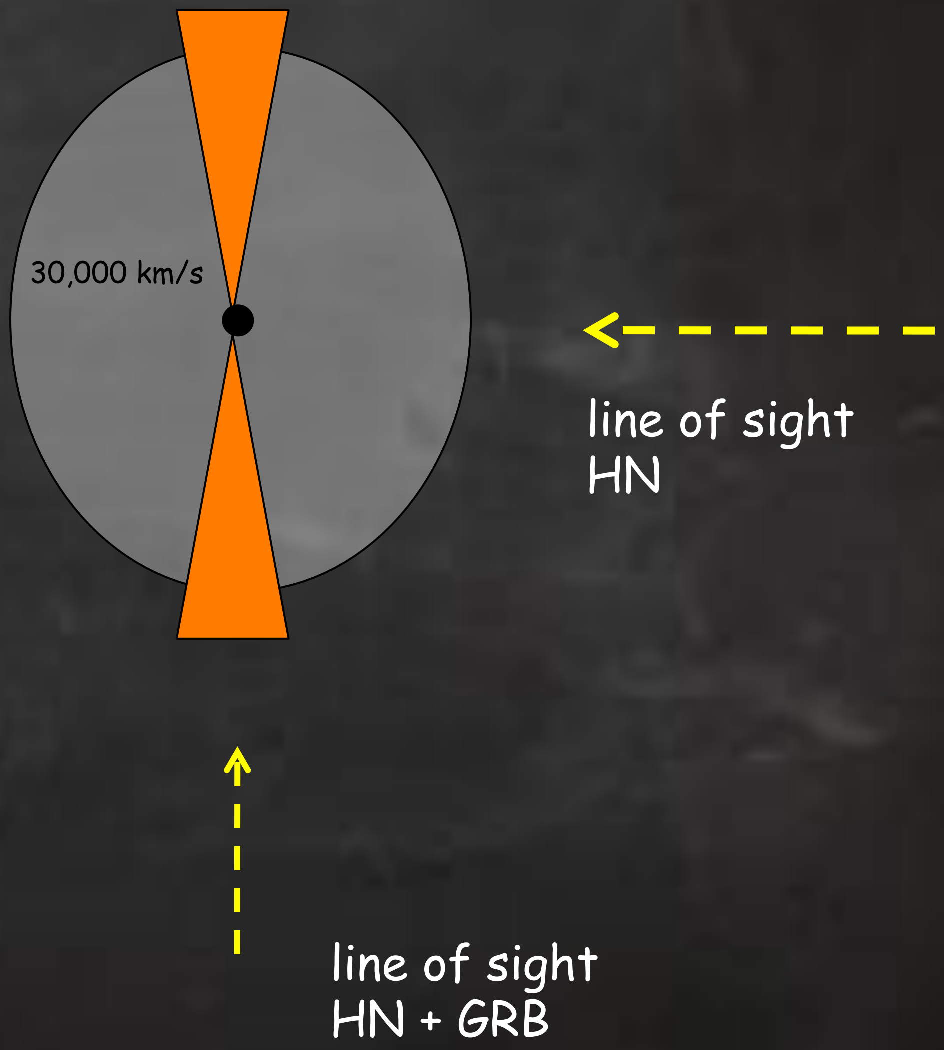
GRB/SNe-Ibc: ~ 1.5%

GRB/HNe: ~ 20%

A simplified Scheme for a GRB-SN event

-an almost isotropic component carrying most energy 10^{52} erg and mass ($\sim$5-10$M_\odot$)

-highly collimated component 4°-10° for HL-GRBs containing a tiny fraction of the mass ($10^{-4/-5}$ $M_\odot$) moving at $\Gamma \sim \times 10^{2-3}$



GRB/HNe: ~ 20%

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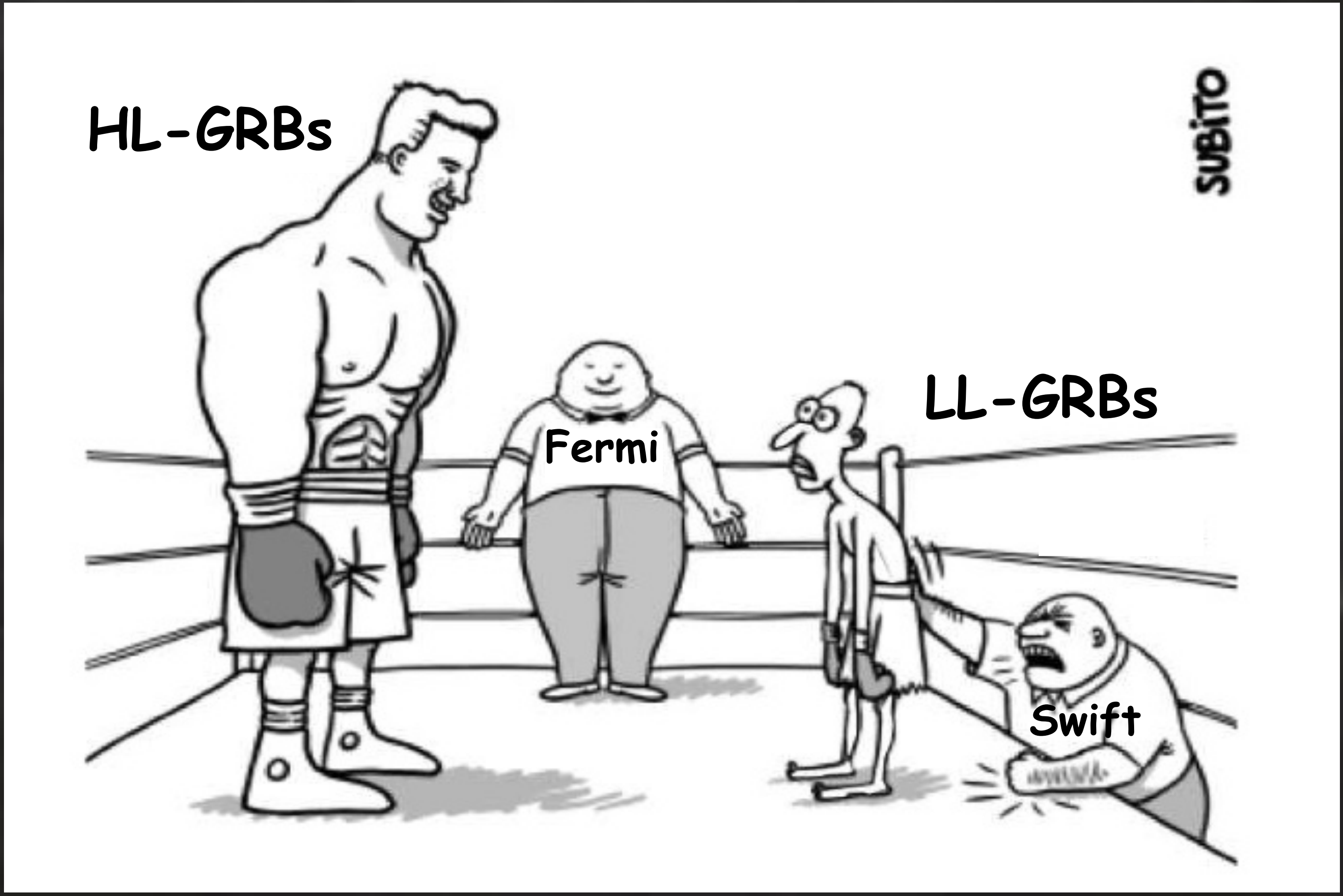
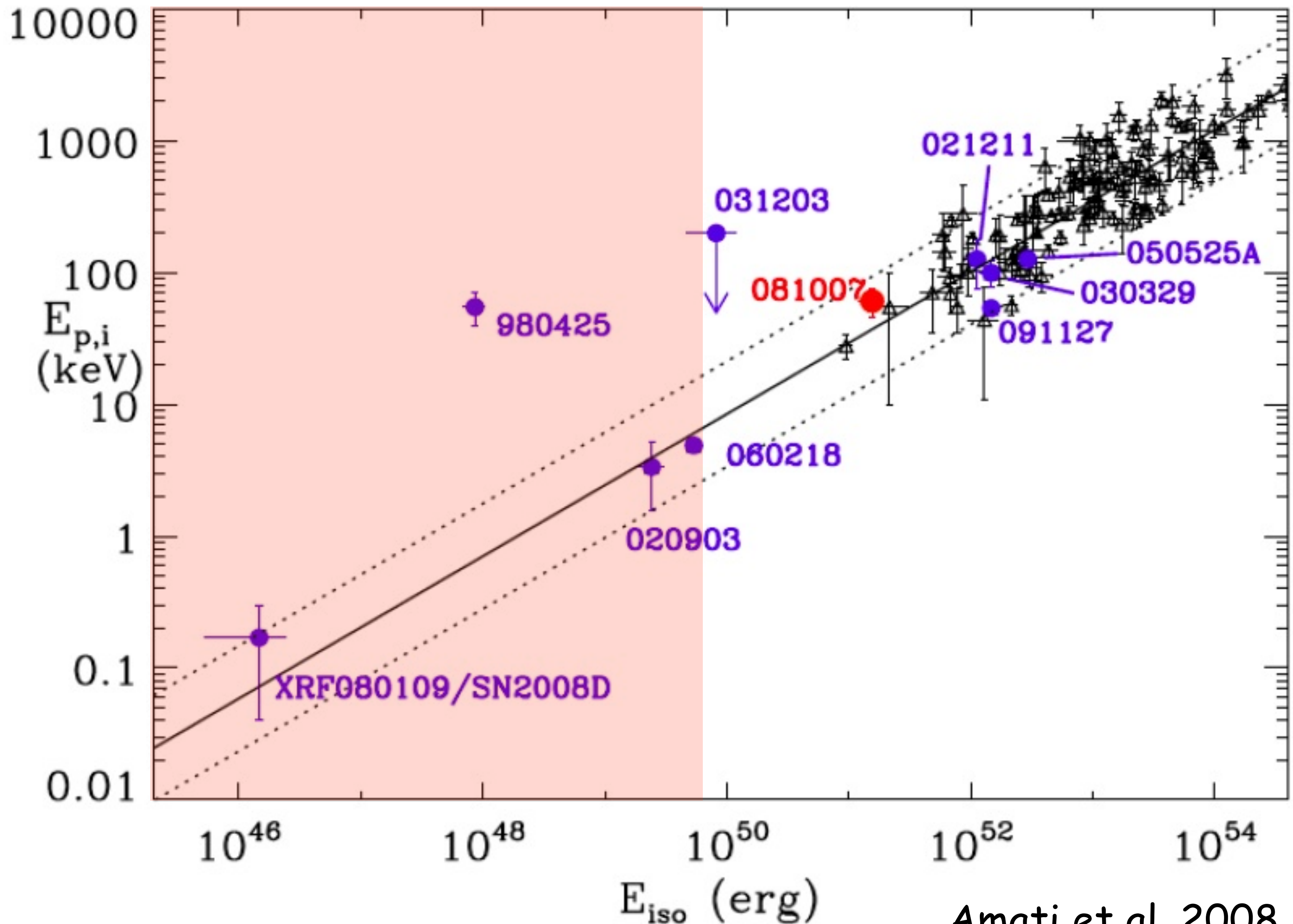
HL-GRBs vs. LL-GRBs





Amati et al. 2008

SNe & GRBs at z < 0.1

GRB	SN	z	E_{iso} (erg)
GRB 980425	SN 1998bw	0.0085	$\sim 10^{48}$
GRB 060218	SN 2006aj	0.033	$\sim 10^{50}$
GRB 080109	SN 2008D	0.007	$\sim 10^{46}$
GRB 100316D	SN 2010bh	0.06	$\sim 10^{50}$

LL-GRBs sample a volume $\sim 10^6$ smaller →
Rate: up to x 10^3 Gpc^{-3} yr^{-1}
(Della Valle 2005, Pian et al. 2006, Cobb et al. 2006, Soderberg et al. 2006, Liang et al. 2006, Guetta & Della Valle 2007, Amati et al. 2007)

LL vs. HL Rates

LL-GRBs ~ 71 x (1 ÷ 10) ~ 70 ÷ 700 LL-GRBs $Gpc^{-3}\ yr^{-1}$

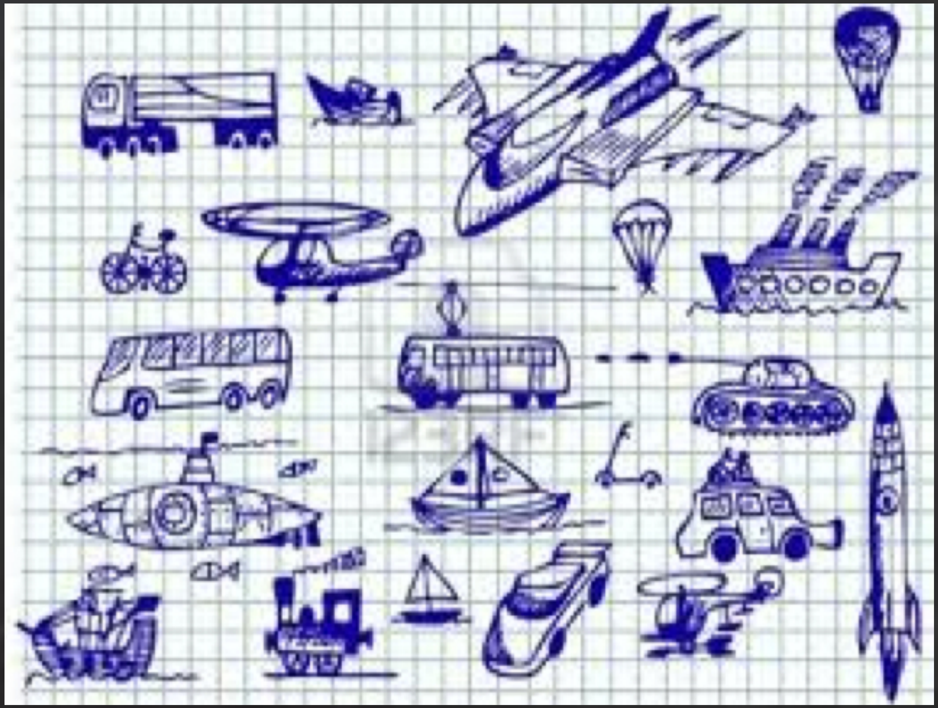
<fb-1> < 10 (Guetta & DellaValle 2007) (ϑ > 25°) for sub-lum GRBs

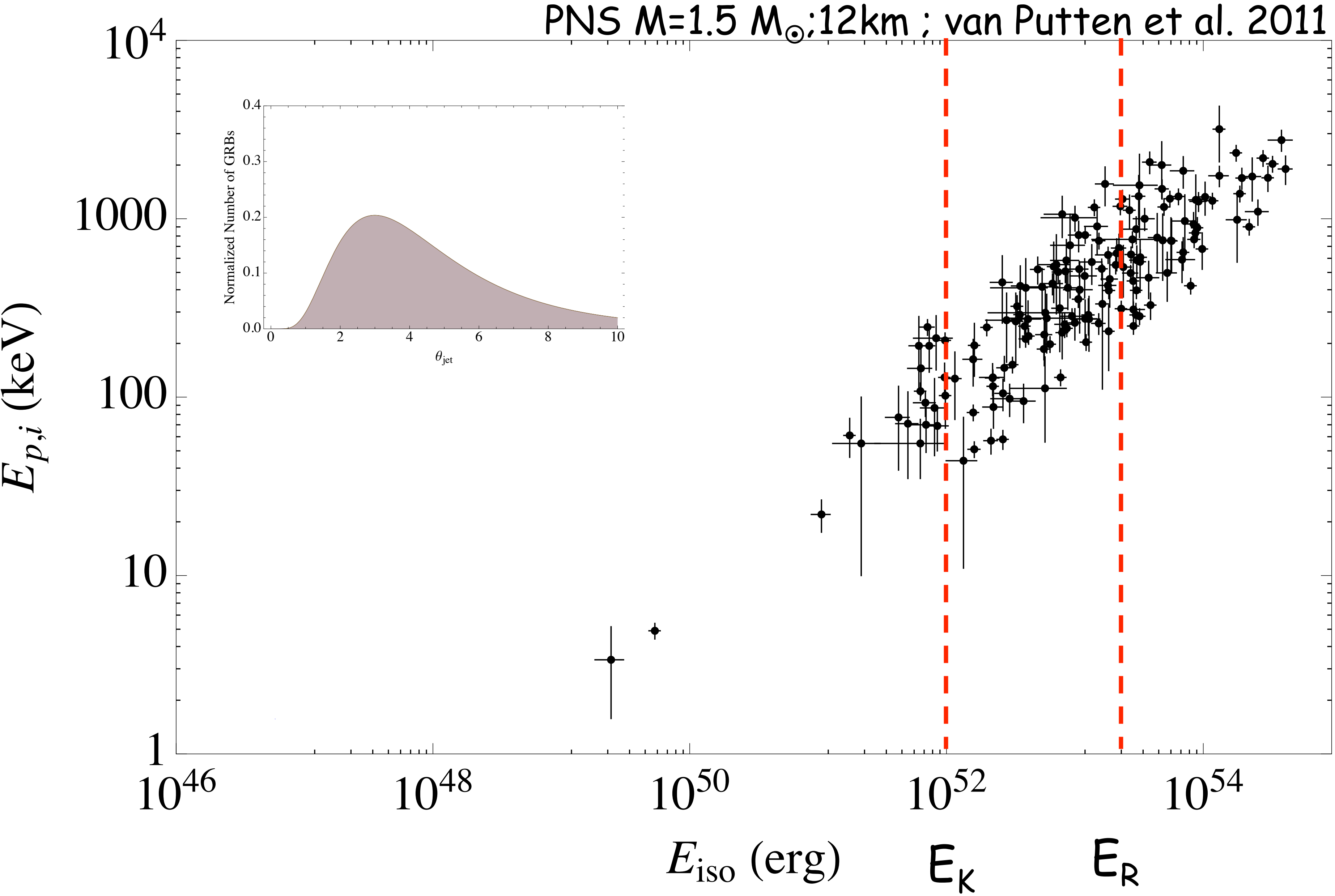
$\langle fb^{-1}\rangle_{HL\text{-}GRBs}$ ~ 75 ÷ 500

HL-GRBs ~ 0.7 x $\langle fb^{-1}\rangle$ ~ 50 ÷ 350 $Gpc^{-3}\ yr^{-1}$

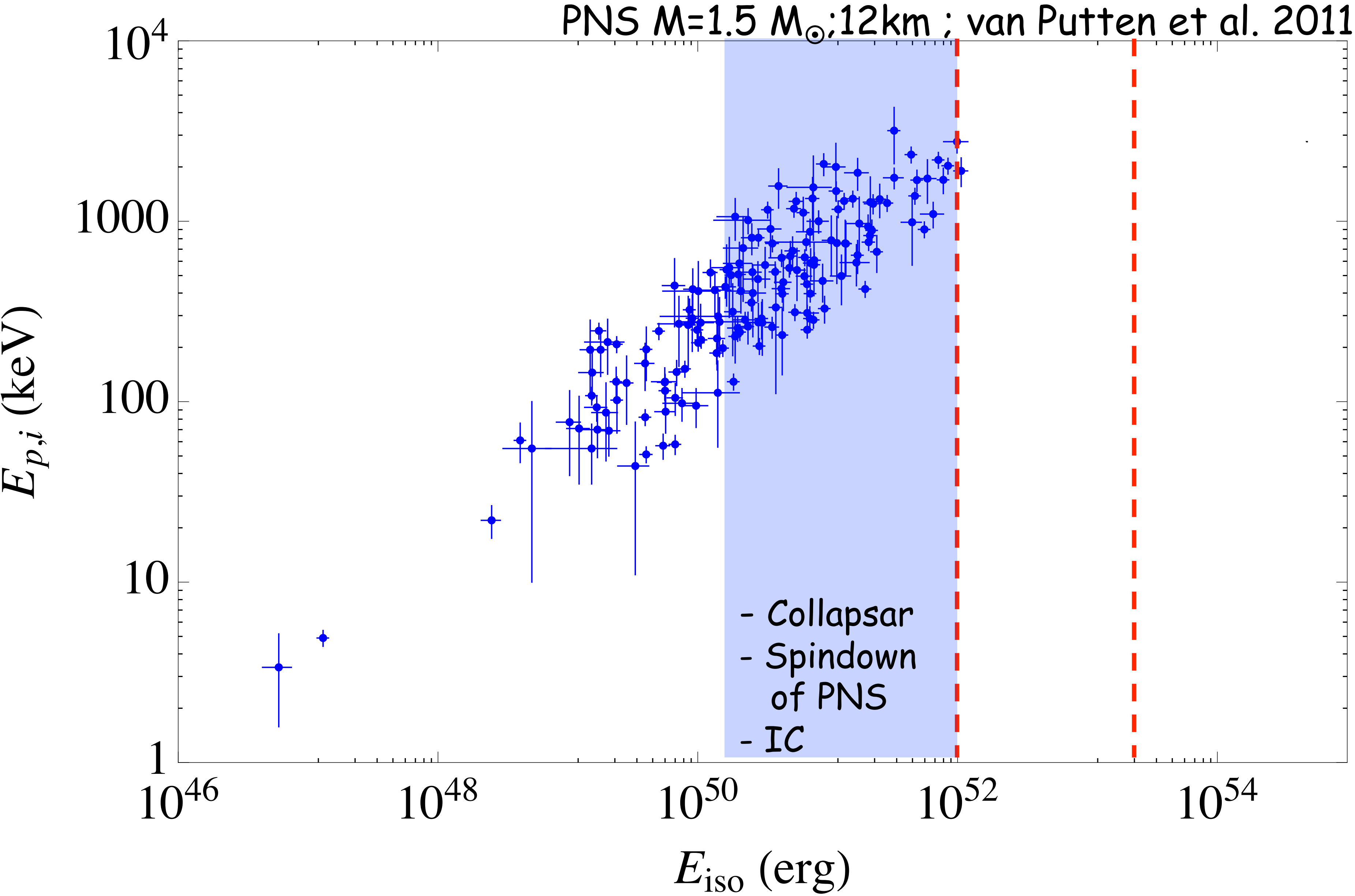
LL-GRB/*HL*-GRB < ~ 20

LL vs. HL GRBs
Clues to different central engines?

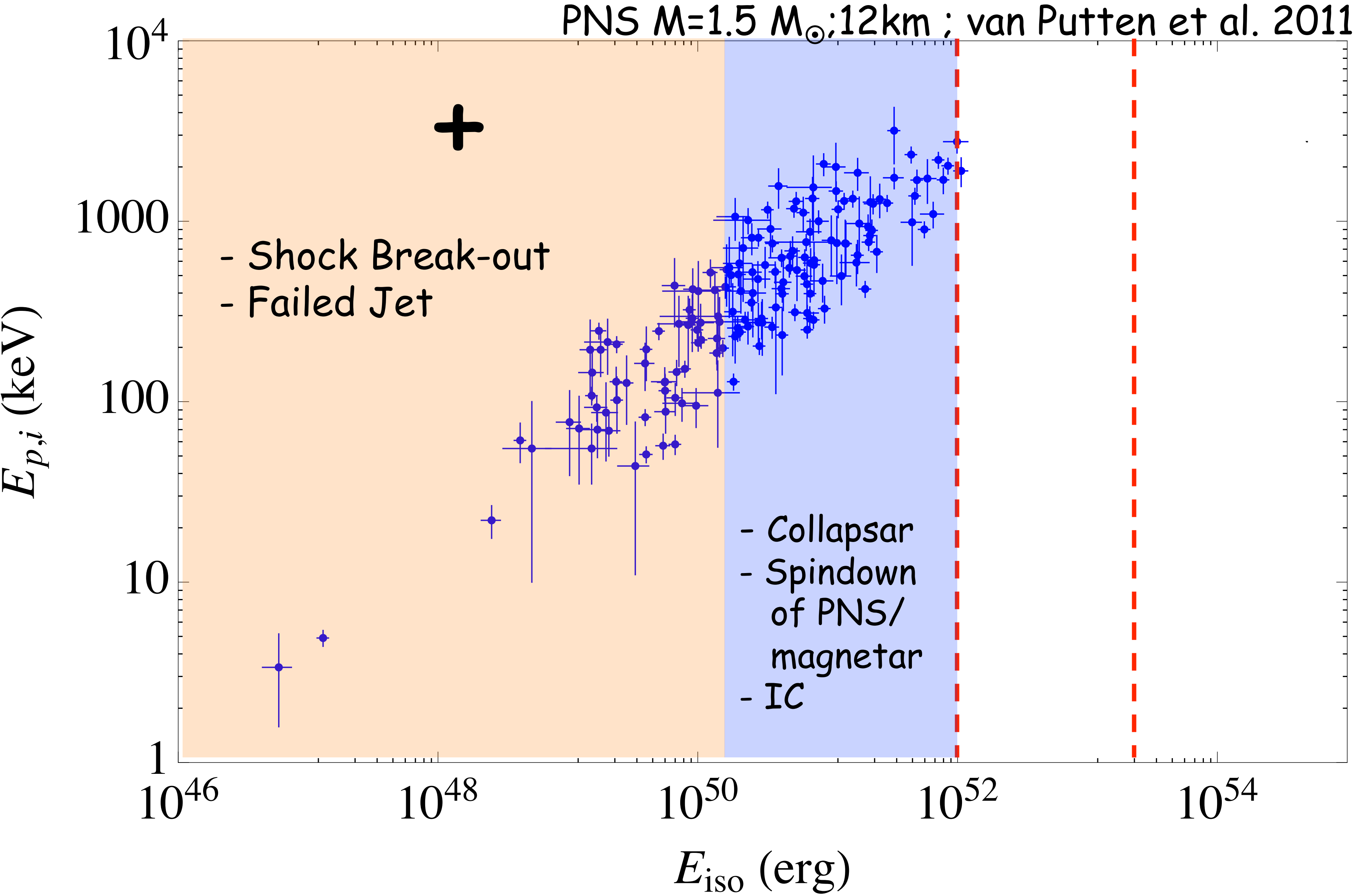




PNS M=1.5 M☉;12km ; van Putten et al. 2011
10^4
1000
100
10
1
$E_{p,i}$ (keV)
10^{46}
10^{48}
10^{50}
10^{52}
10^{54}
E_{iso} (erg)
E_K
E_R
Normalized Number of GRBs
0.4
0.3
0.2
0.1
0.0
0
2
4
6
8
10
θ_{jet}



van Putten et al. 2011; Lazzati et al. 2012, Fan et al. 2013; MacFadyen & Woosley 1999; Woosley 1993, Fryer, Ruffini & Rueda 2014

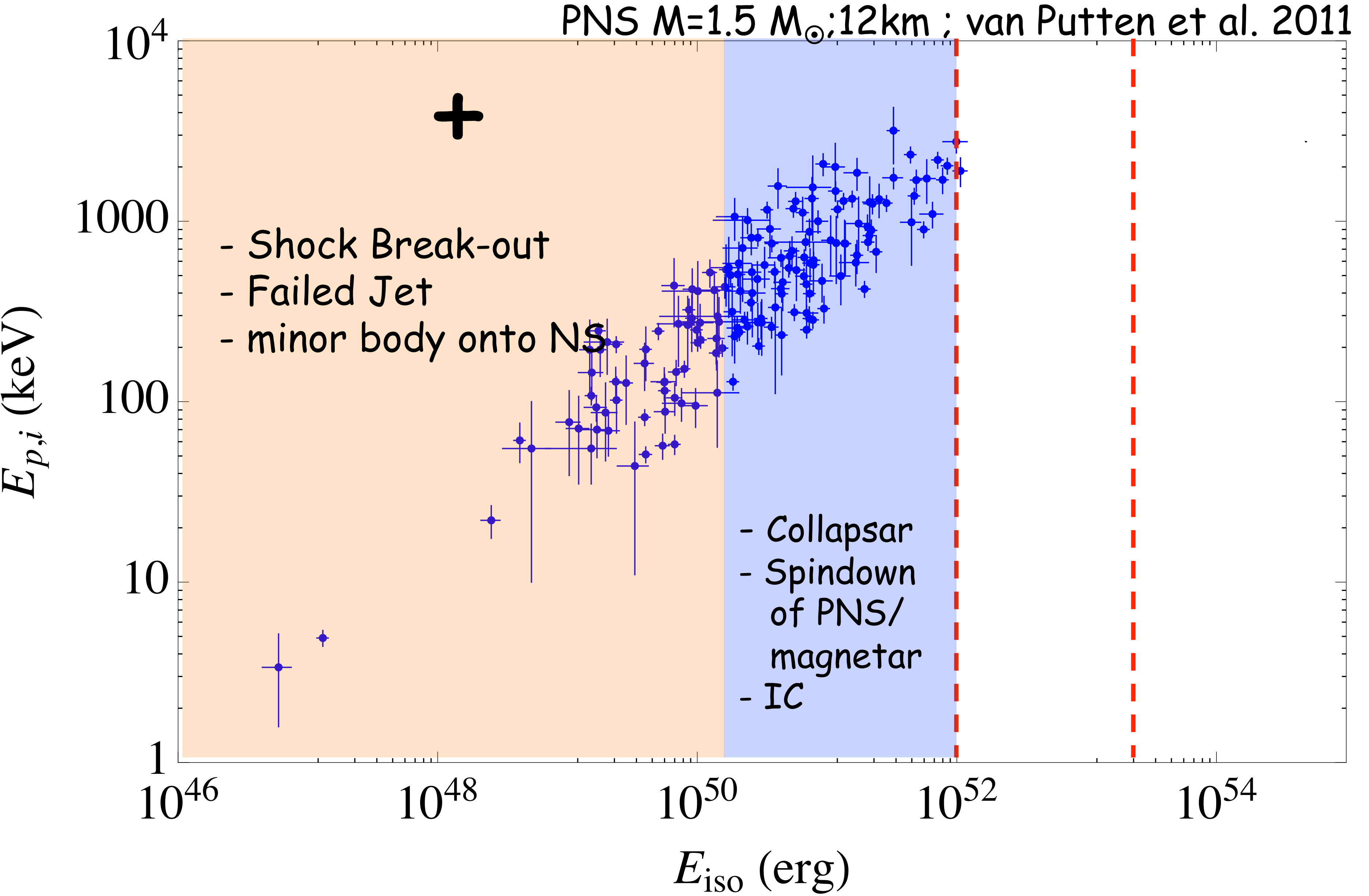

PNS M=1.5 M$_\odot$;12km ; van Putten et al. 2011
- Shock Break-out
- Failed Jet
- Collapsar
- Spindown of PNS/ magnetar
- IC
$E_{p,i}$ (keV)
E_{iso} (erg)
10^4
1000
100
10
1
10^{46}
10^{48}
10^{50}
10^{52}
10^{54}

LETTER

doi:10.1038/nature10592

The unusual gamma-ray burst GRB 101225A explained as a minor body falling onto a neutron star

S. Campana[1], G. Lodato[2], P. D'Avanzo[1], N. Panagia[3,4,5], E. M. Rossi[6], M. Della Valle[7], G. Tagliaferri[1], L. A. Antonelli[8], S. Covino[1], G. Ghirlanda[1], G. Ghisellini[1], A. Melandri[1], E. Pian[9,10], R. Salvaterra[11], G. Cusumano[12], V. D'Elia[13,8], D. Fugazza[1], E. Palazzi[14], B. Sbarufatti[1] & S. D.Vergani[1]



Campana et al. 2006, Soderberg et al. 2008, Mazzali et al. 2008, Piran et al. 2013; Tsutsui & Shigeyama 2013; Campana et al. 2011

Summary

1. Supernova Taxonomy
2. GRB-SN properties
3. Progenitors Mass
4. GRB and SN rates
5. GRB populations
6. Conclusions
7. Open Issues

Conclusions

All long duration GRBs are connected with HNe, but "viceversa" is not true. HL-GRBs / HNe $<20\%$, LL-GRBs/HNe $< 40\%$.

Progenitors of GRB-SNe are W-R stars

GRBs are very rare phenomena

GRB/SNe-Ibc $< 1.5\%$

Conclusions cont'd

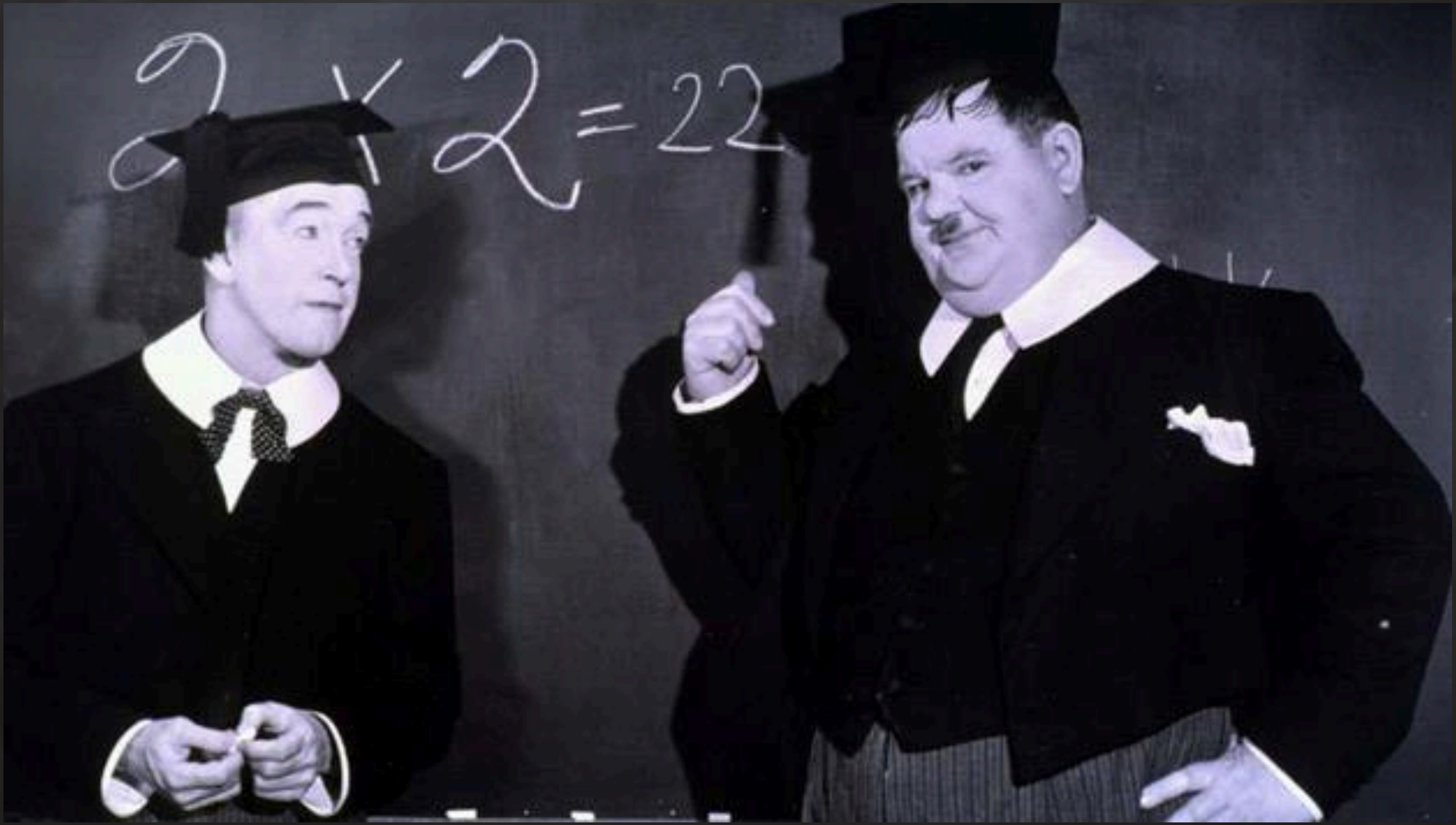
The energetic budget of most GRBs (LL-GRBs 10x) is a fraction (of a tiny fraction) of Ek of HNe.

They might well be related to relatively low energy phenomena ($E_\theta < \sim 10^{50}$ erg) such as SN *shock break-out* (2006aj/060218) or *jet failed* (2008D/XRF 080109) events or *gravitational capture* (GRB 101225A) of minor bodies onto compact stellar remnants.

Conclusions cont'd

The so called "cosmological GRBs" $E_{iso} \sim 10^{52-54}$ erg ($E_{\theta} < \sim 10^{52}$ erg, after correction for beaming) are more energetic events (SN 2013/GRB 130427A) that have been explained with different models. They can be powered by the rotational energy of new-born NSs or by even more extreme scenarios.

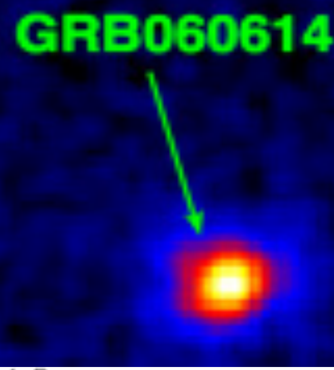
Open Issues



“Much ado about nothing": GRB 060614

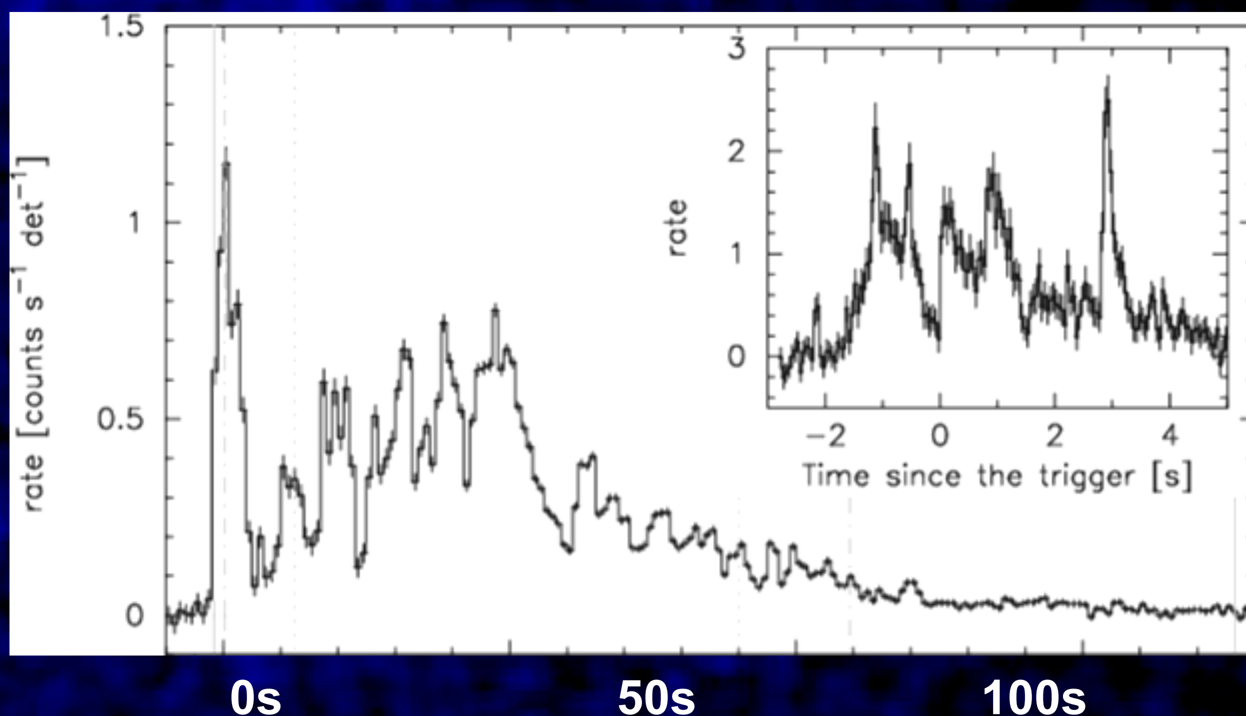
Low redshift:
z = 0.125

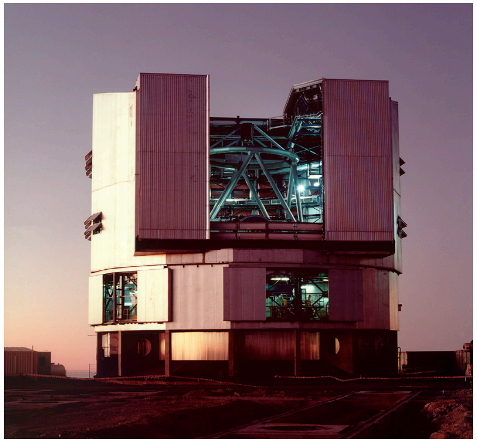
SN search?



Gehrels et al. 2006

Mangano et al. 2007



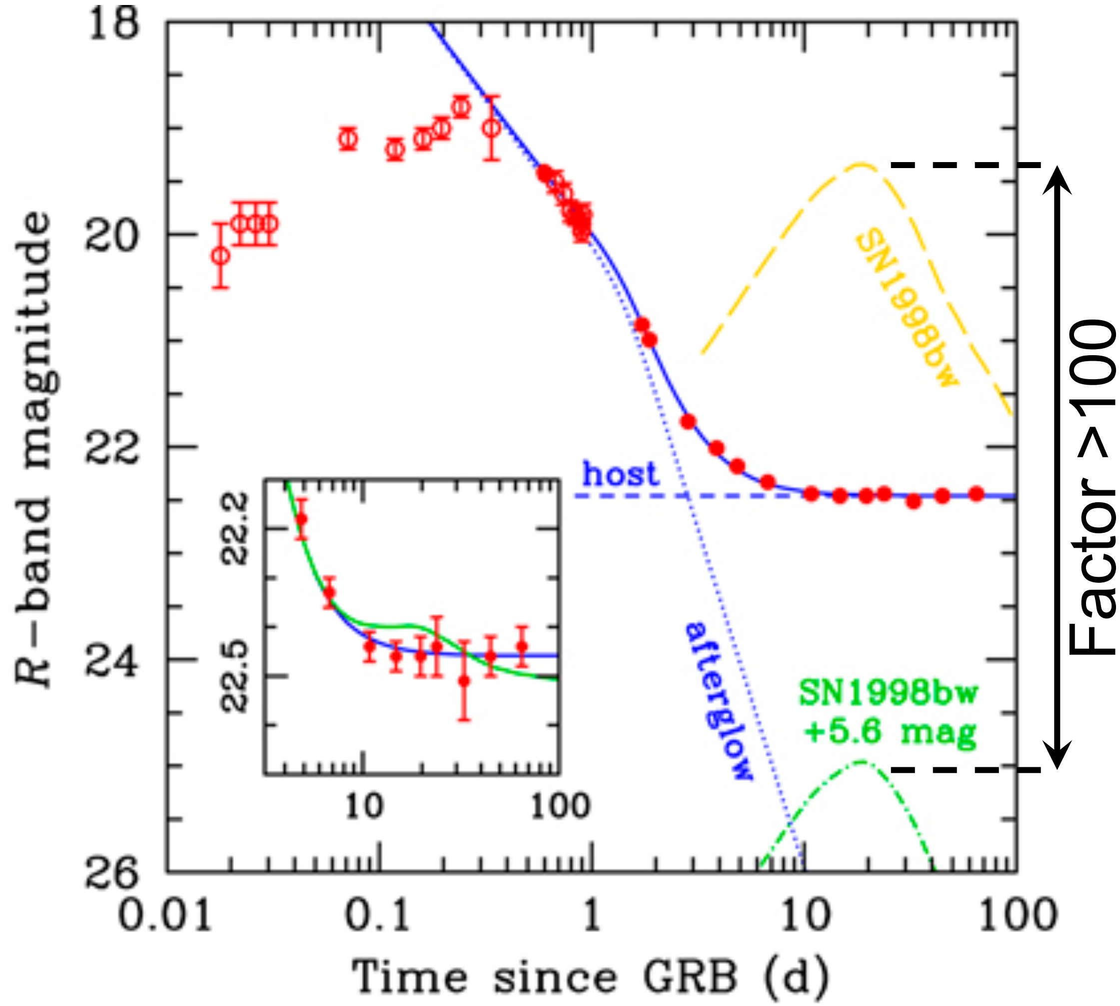


Late time:

host galaxy contribution (no variation)

Upper limit:

M_V > -13.5 (3σ)



Della Valle et al. 2006 (see also **Gal-Yam et al. 2006 – Fynbo et al. 2006**)

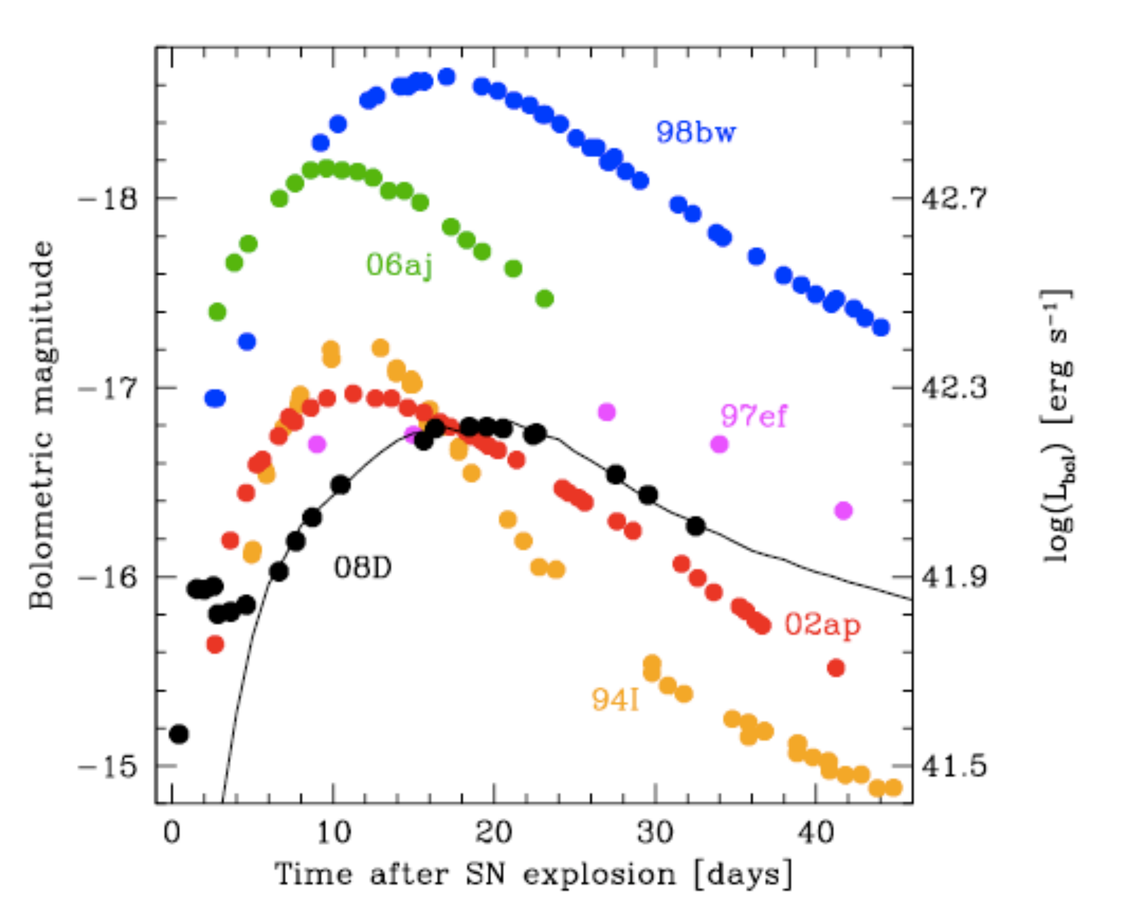
Scenarios without Supernova

1. Supranova → SN occurs (months, years) before the GRB (Vietri & Stella 1998)

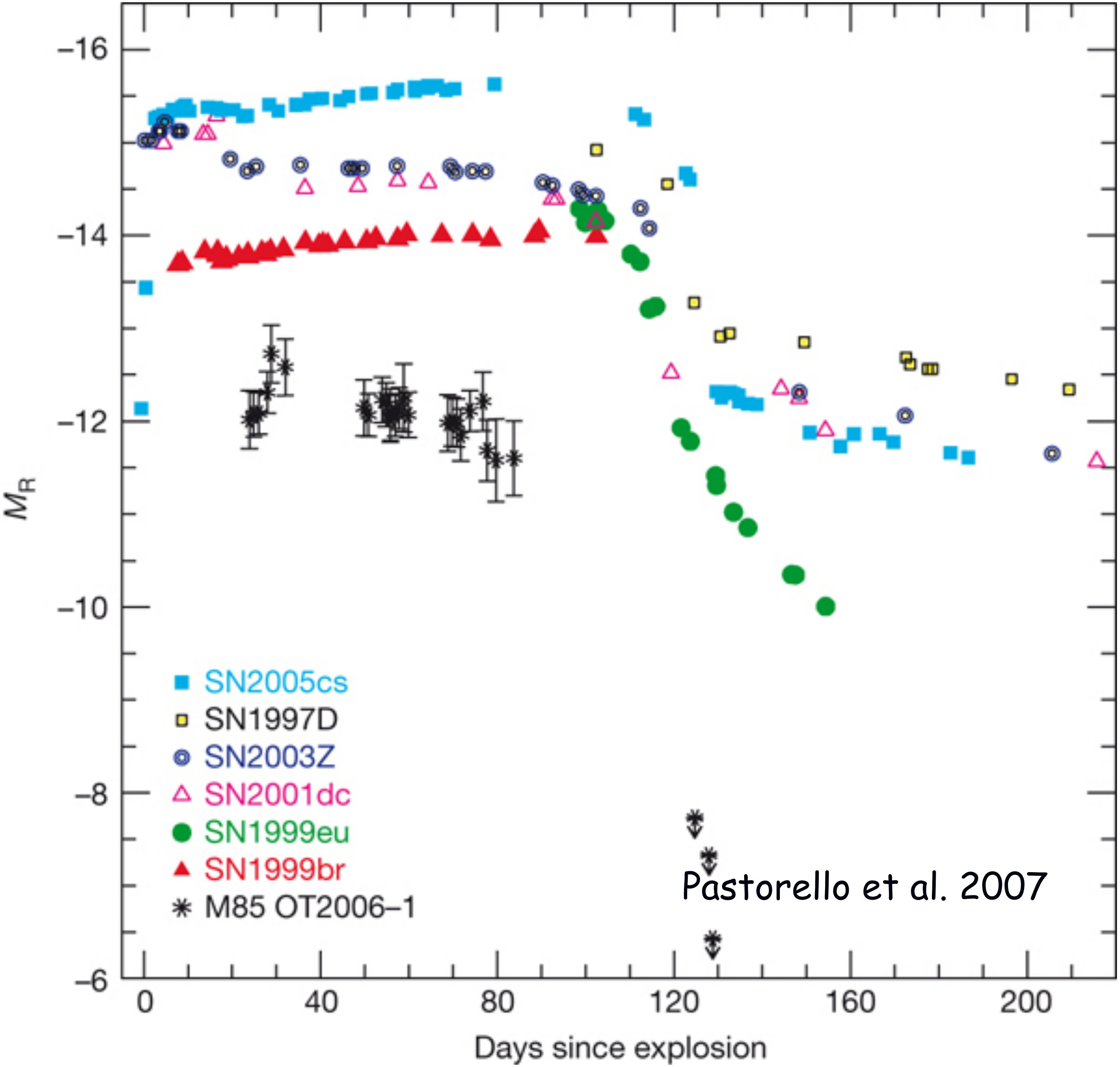
2. NS→ QS (Berezhiani et al. 2003; Drago et al. 2008)

3. Binary merging mechanisms similar to those proposed to power short GRBs (Gehrels et al. 2006, Caito et al. 2008; van Putten et al. 2014)

Scenarios with Supernova



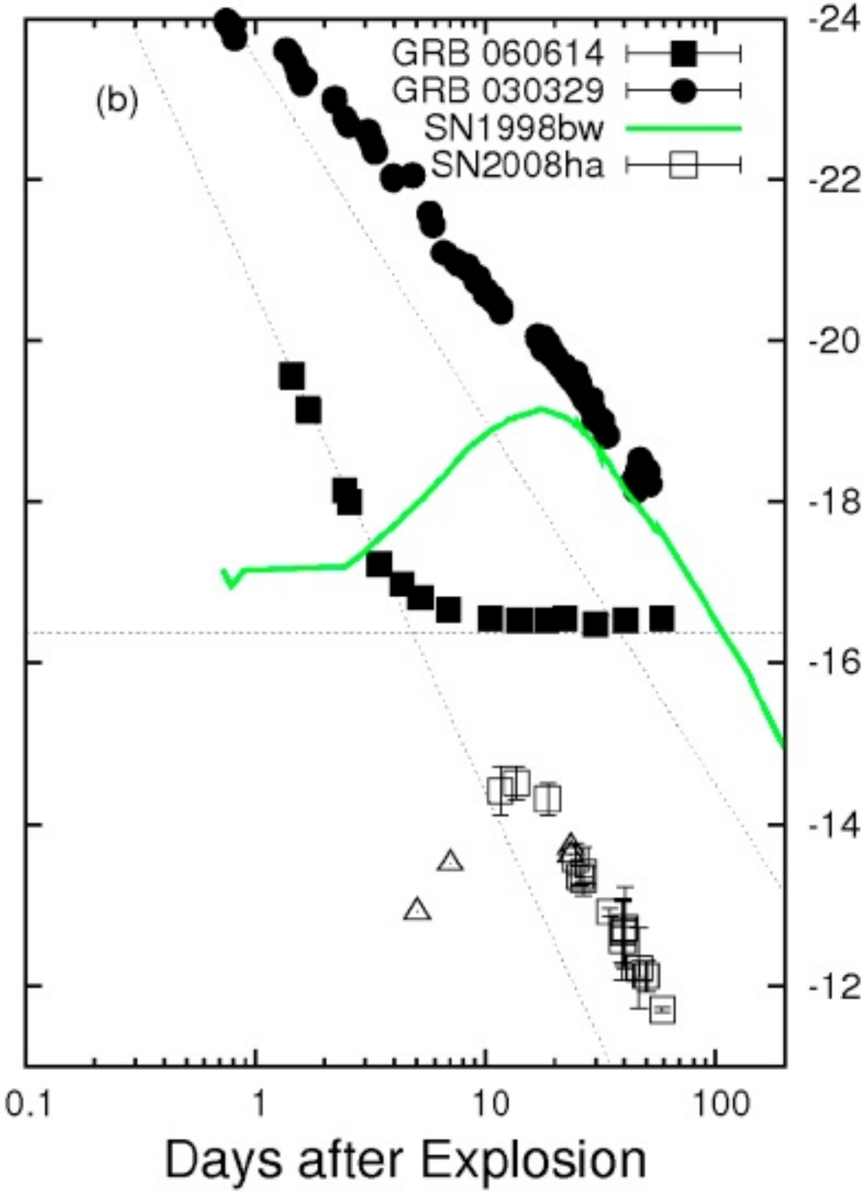
-13.5



Pastorello et al. 2007

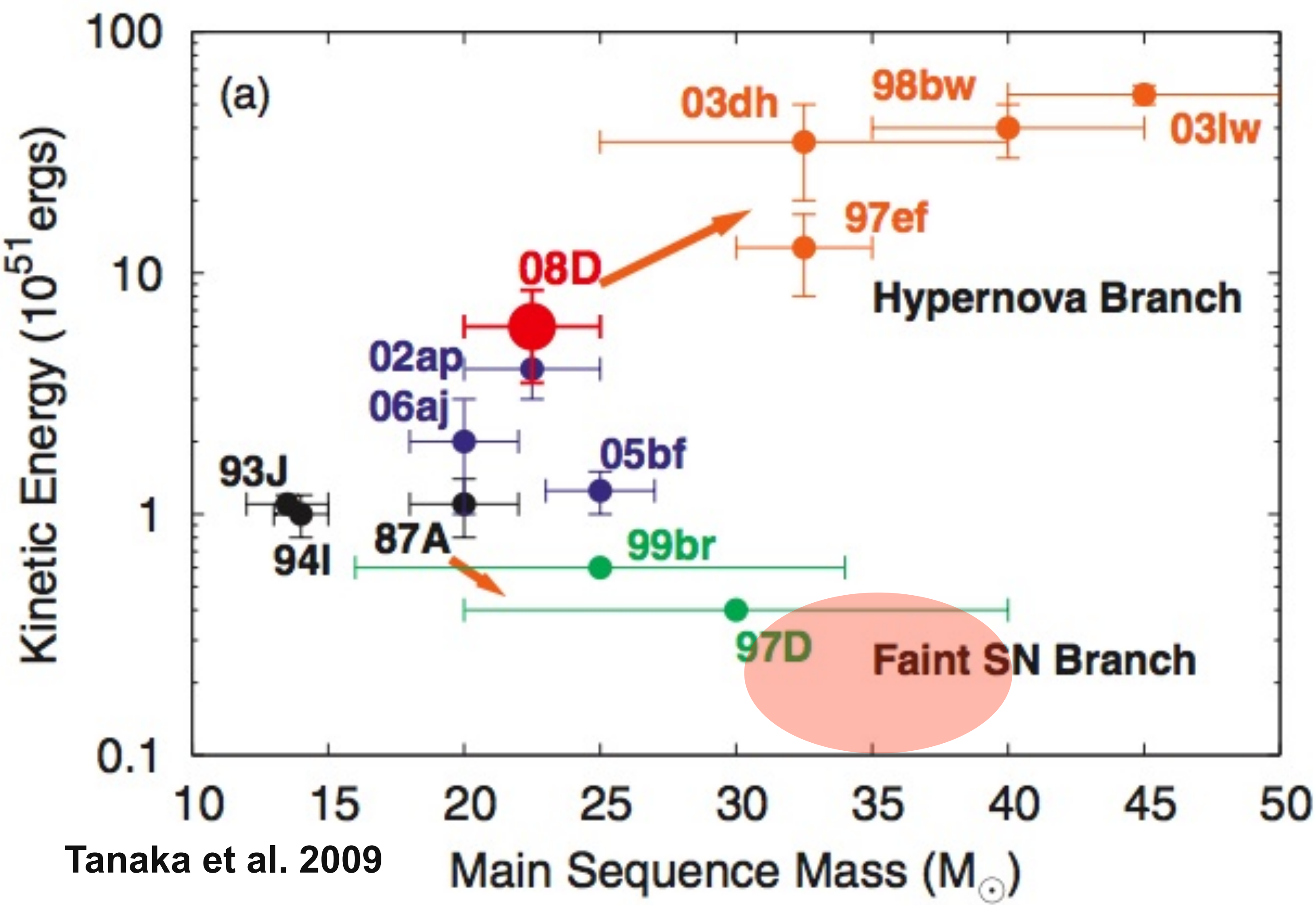
A low energy core-collapse supernova without a

, P.A. Mazzali[2,3], J. Manteca[4], S.
tyunyan[2,7], V. P. Hentunen[8,9], M.
Smartt[1]



SN 2008ha is the first faint, hydrogen deficient, low-energy core-collapse supernovae ever detected.

Potential “dark SN” (GRB progenitor) ?



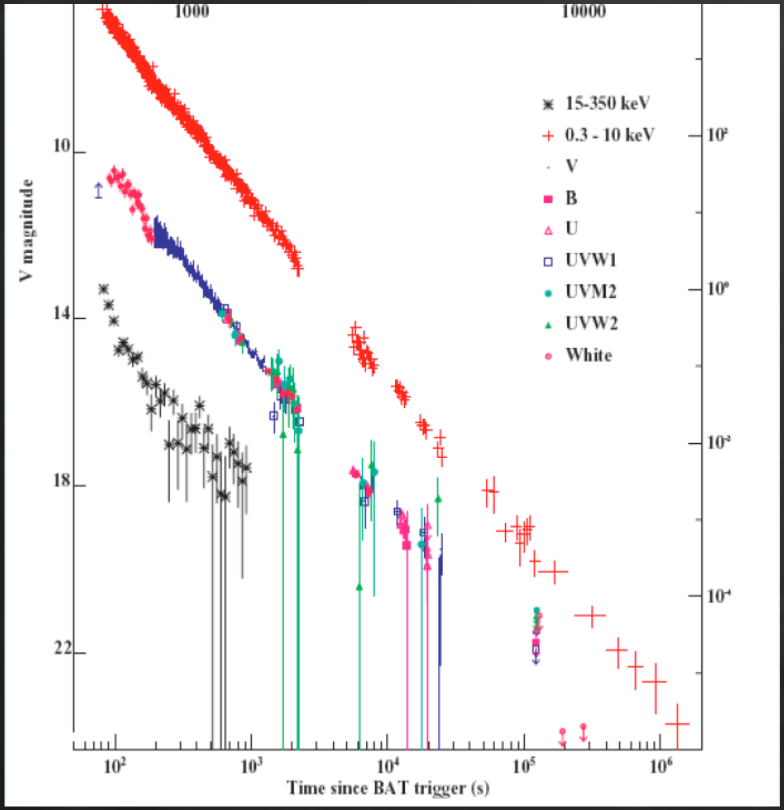
Tanaka et al. 2009

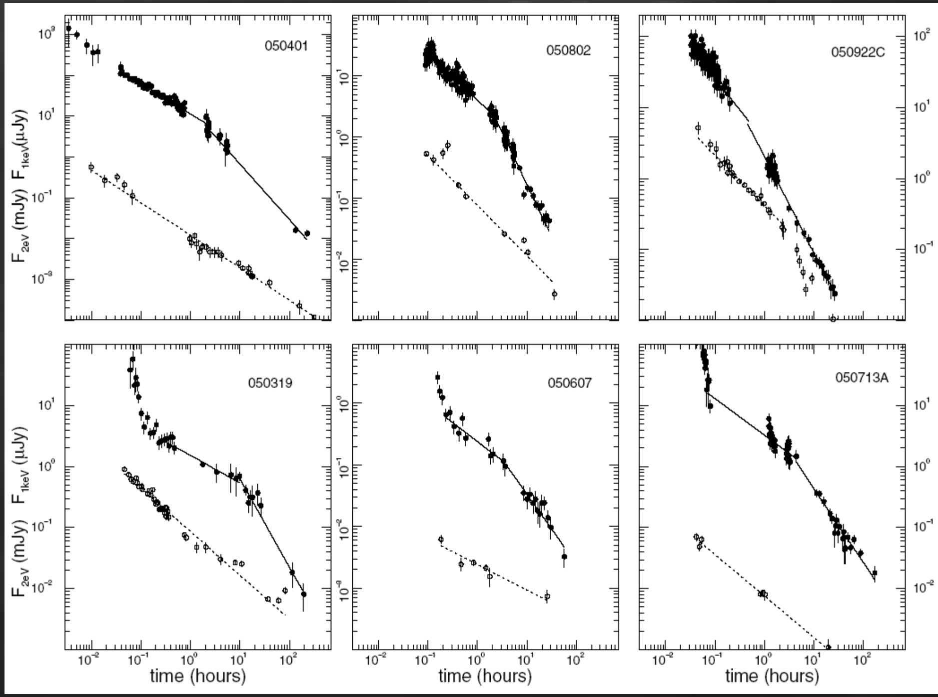
GRB 060614: SN with small explosion energy → low expansion velocity → most ^{56}Ni falls back into the BH → small ^{56}Ni mass in the ejecta → < $10^{-4/-5}$ $M_\odot$ ^{56}Ni → "Dark Supernovae" (see also DV et al. 2006, Nomoto et al. 2007 and Tominaga et al. 2007)

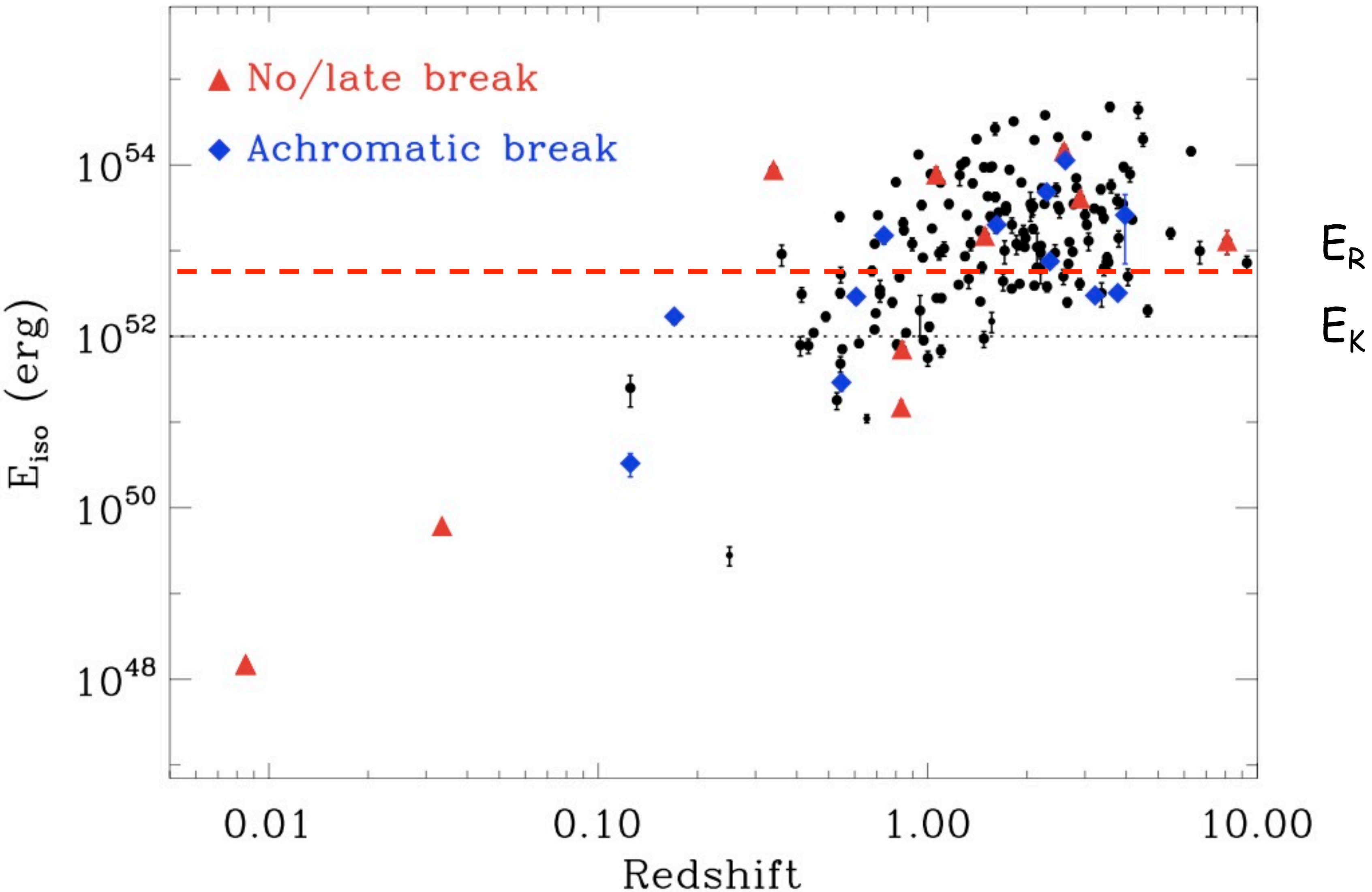
Open Issues

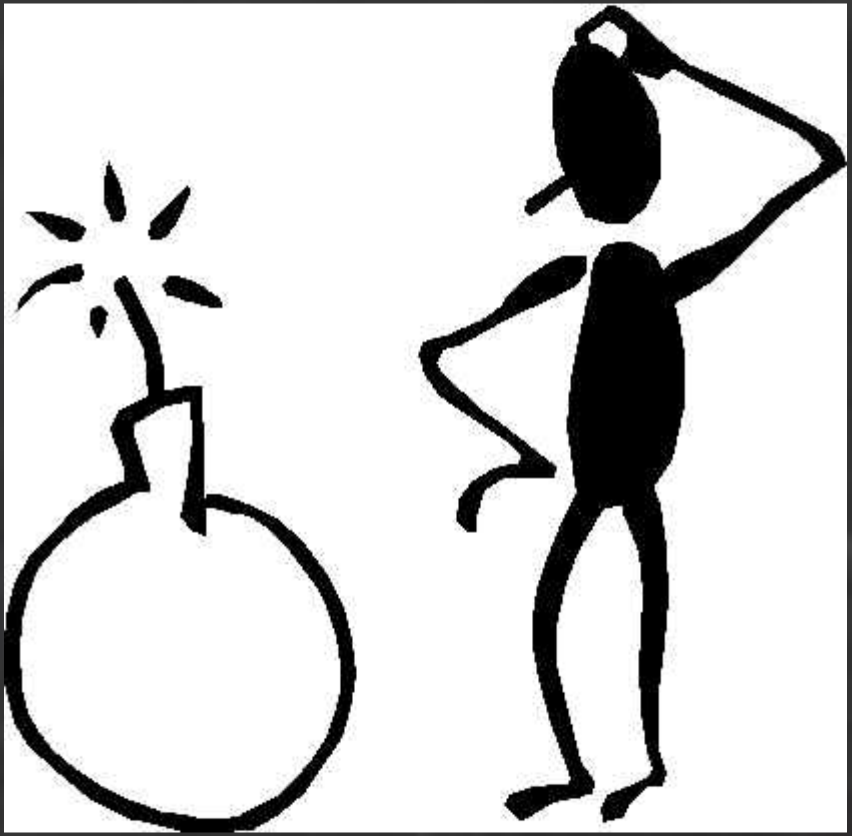
To BE*am* or not to BE*am*

In some cases there is not evidence for beaming, i.e. an achromatic break was not detected (Covino et al. 2006; Panaitescu et al. 2006) .



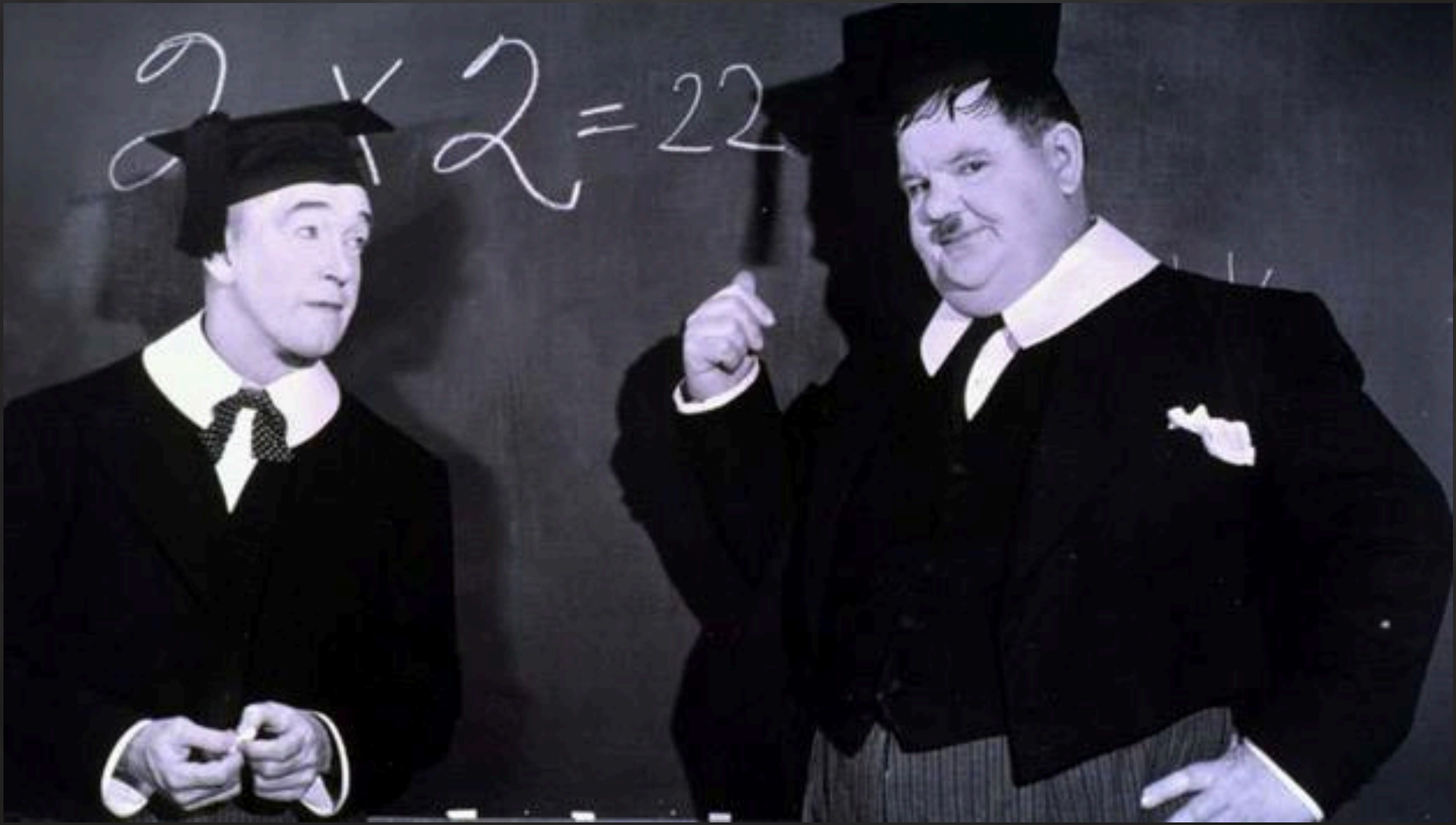



No/late break
Achromatic break
E_{iso} (erg)
10^{54}
10^{52}
10^{50}
10^{48}
0.01
0.10
1.00
10.00
Redshift
E_R
E_K



We have to figure out a mechanism in which a SN event ($E_K < 10^{52}$ erg) can originate a GRB (~$10^{53 \div 54}$ erg) which is energetically dominant →
These GRBs require more energetic scenarios likely based on black hole formation, such as spin-down of Kerr-BH (Bisnovatyi-Kogan 70's; van Putten et al. 2011); or Induce Collapse scenario ? (Ruffini 1998, Fryer, Ruffini & Rueda 2014)

Open Issues



GRBs are very rare phenomena

GRB/SNe-Ibc: 1.5%

Ibc/CC ~ 0.30

GRB/CC-SN ~ 5×10^{-3}

$$\frac{N(30M_\odot - 120M_\odot)}{N(8M_\odot - 30M_\odot)} \sim 0.15 \text{ (Salpeter IMF)}$$

What causes some small fraction of CC-SNe to produce observable GRBs, while the majority do not?

Special conditions are requested to stars to be GRB progenitors:

i) to be massive ~ > 30$M_{\odot}$ (Maeda et al. 2006; Raskin et al. 2008; Tanaka et al. 2008)

ii) H/He envelopes to be lost before the collapse of the core, i.e. the GRB progenitor is a WR star (Campana et al. 2006)

iii) low metallicity and star forming environments (Modjaz et al. 2008, Fruchter et al. 2006, Levesque et al. 2012)

iv) binarity (Panagia 1988 and Smartt et al. 2008 → a significant fraction of SNe-Ibc progenitors are binaries)

v) high rotation (Yoon et Langer 2005; Campana et al. 2008, Yoon et al. 2012)

vi) asimmetryc explosion (Taubenberger et al. 2009; Maeda et al. 2008)


ADESSO BASTA!!!