The rate of short Gamma Ray Bursts and NS^2 mergers

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The Hebrew University

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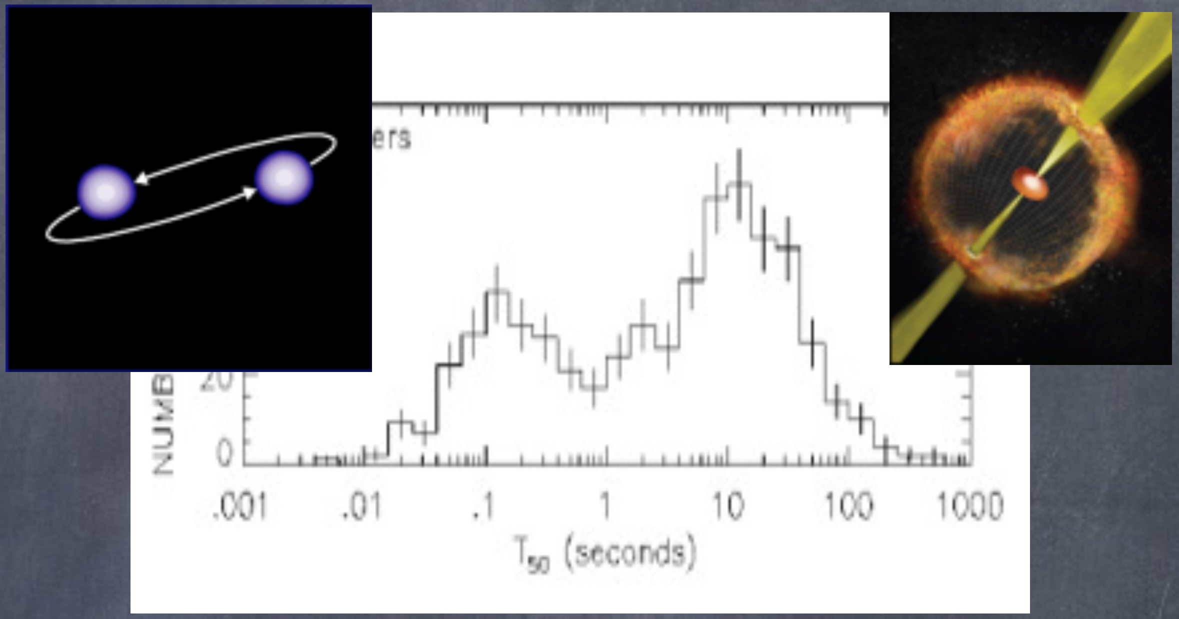
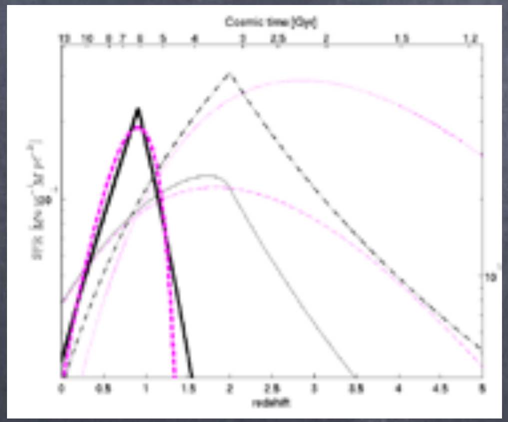
Origins: From the Big Bang to Planets
I-CORE

Outline

- Long and short GRBs vs Collapsars and non-Collapsars
- The rate of non-Collapsar short GRBs
- Implications

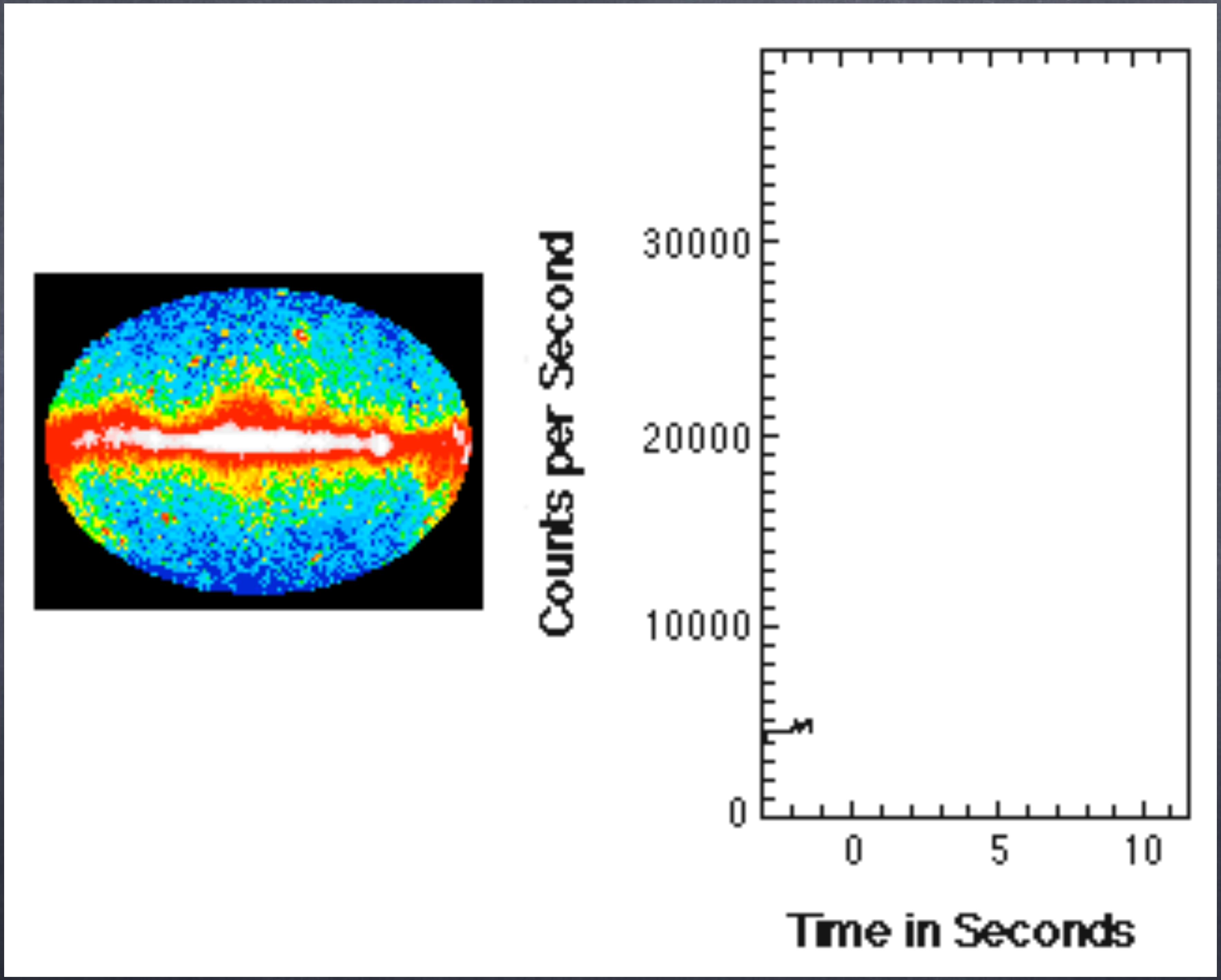




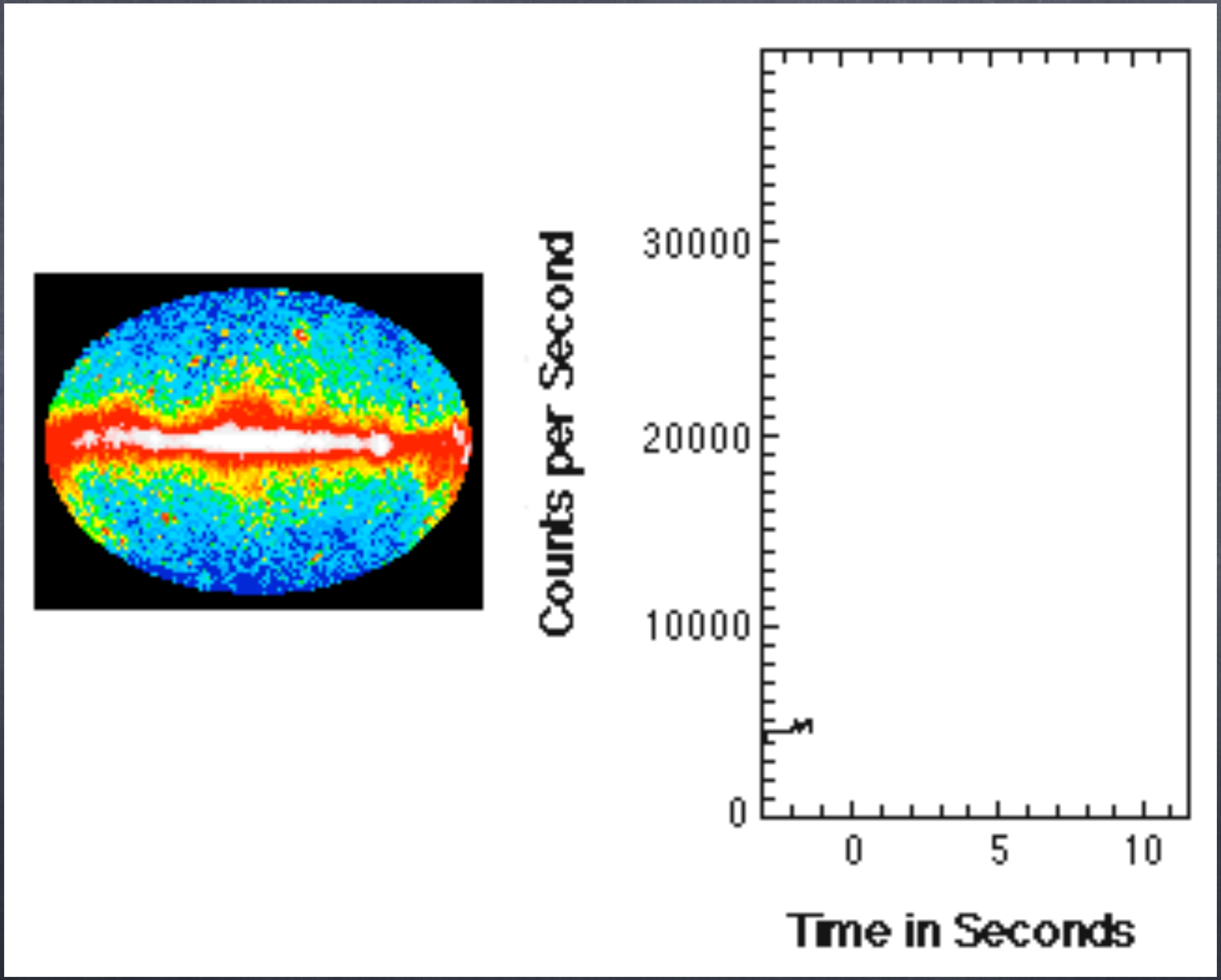
A Quick Summary

- About 1/3 of <u>Swift</u> short (<2sec) GRBs are Collapsars
- The rate of non-Collapsar short GRBs (sGRbs) is $4.1^{+2.3}_{-1.9}$ $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ (depending on the assumed minimal luminosity).
- A LIGO detection rate of 3-100 per year (0.1-3 coinciding with a sGRB)*
- A typical time delay of ~3 Gyr after SFR
- An initial separation of $\sim 2 \times 10^{11}$ cm
- With beaming of ~30 and mass ejection of 0.02 M_{sun} - compatible with R-process nucleosynthesis for A>110 elements.

Gamma-Ray Bursts



Gamma-Ray Bursts

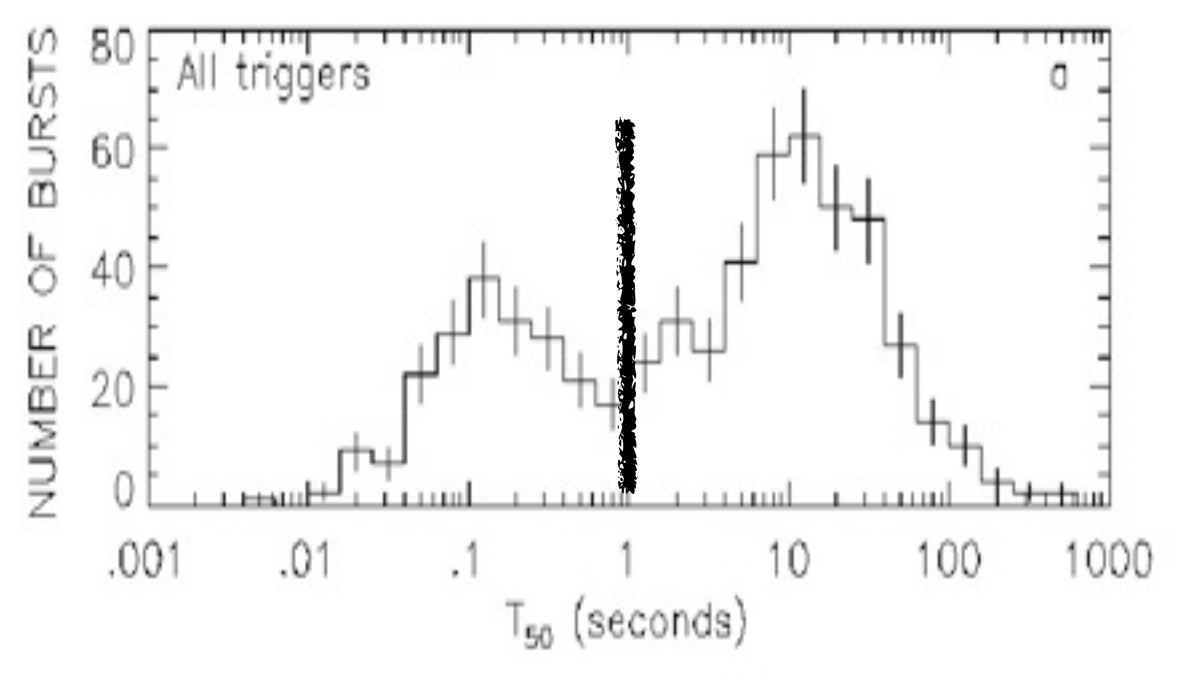


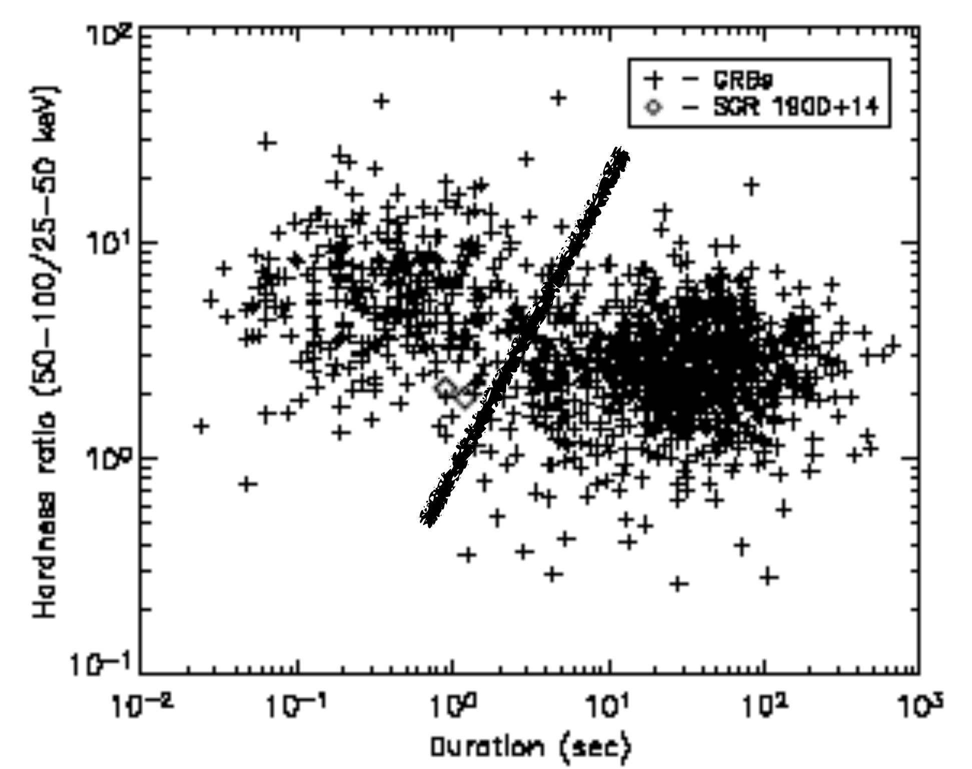
Long and Short GRBs

- Duration 0.01-1000s

Two populations: long (>2 sec) and short (<2 sec)

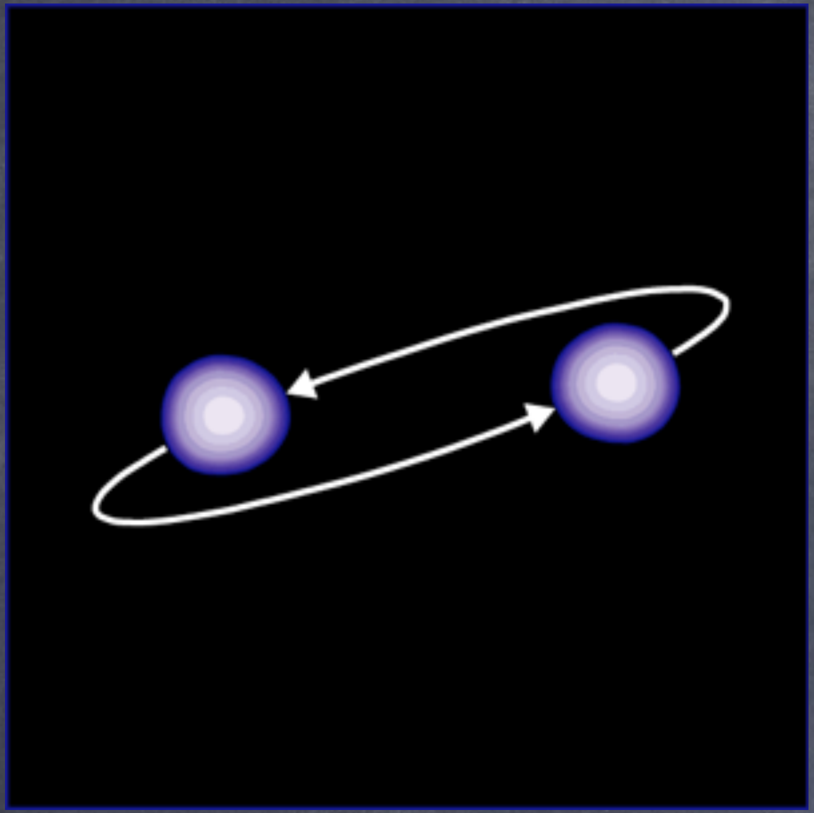
The short GRBs are typically harder

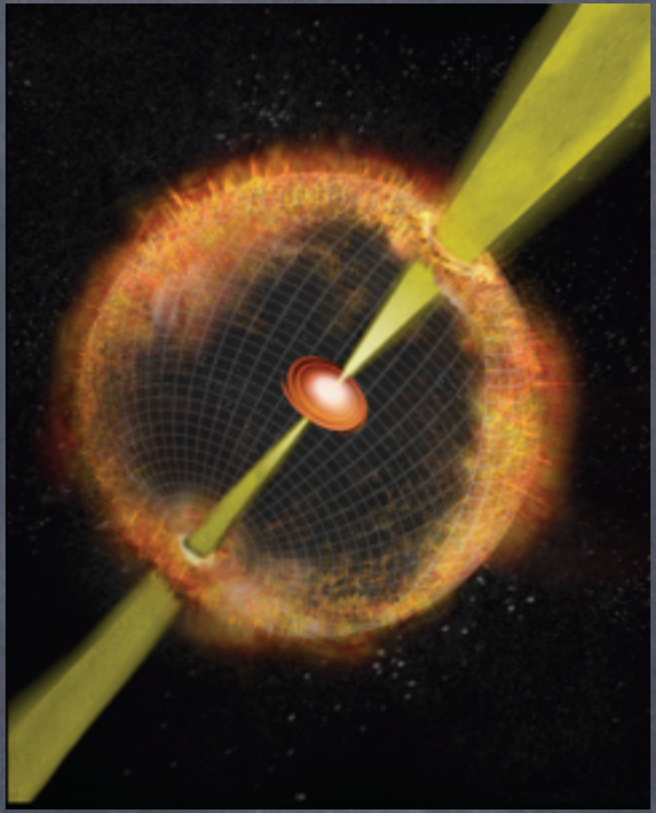


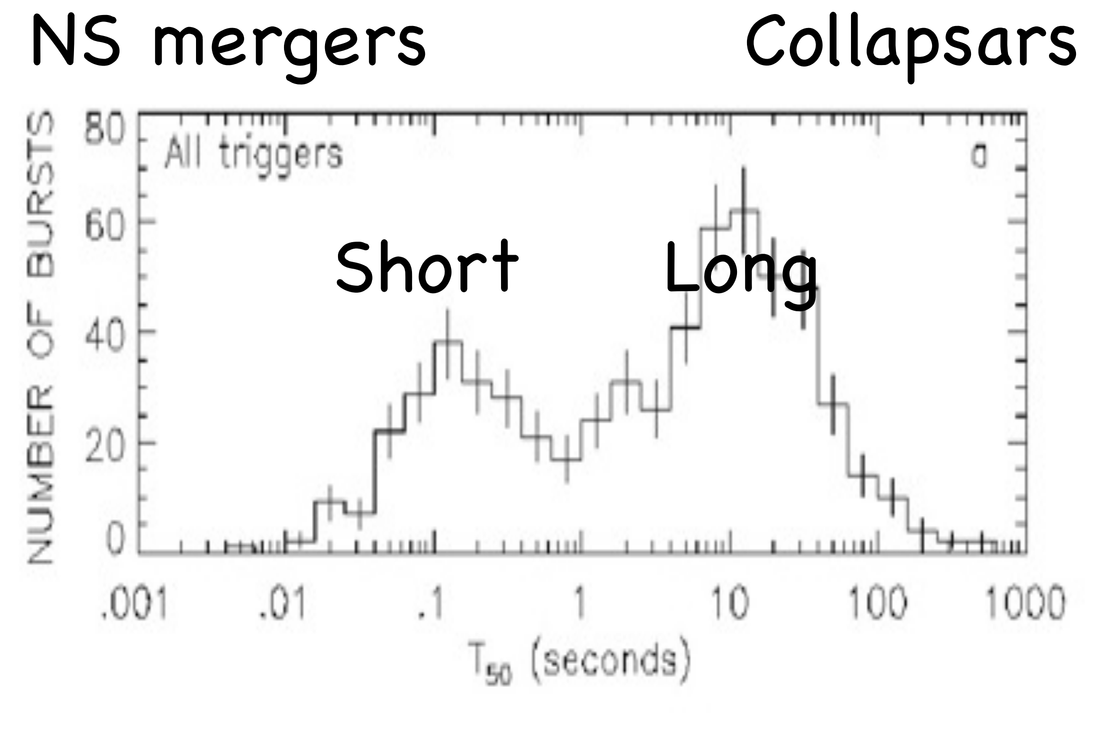


Eichler, Livio, TP,
Schramm, 89

MacFadyen & Woosley,
98







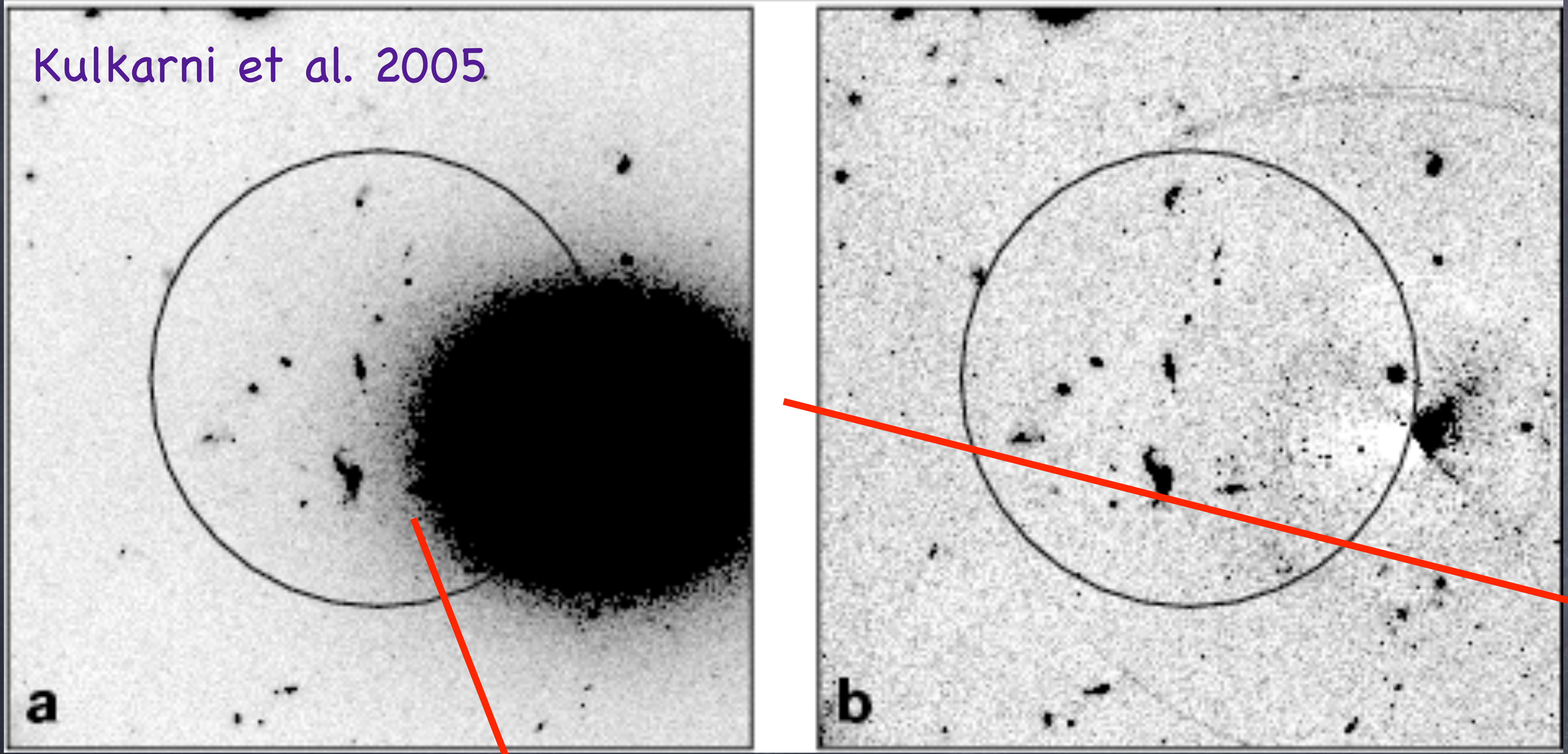
Indirect
Evidence

Direct
Evidence

GRB 050509b

Swift/XRT position intersects a bright elliptical at z = 0.226

No optical/radio afterglow



Kulkarni et al. 2005

Elliptical host

⇓

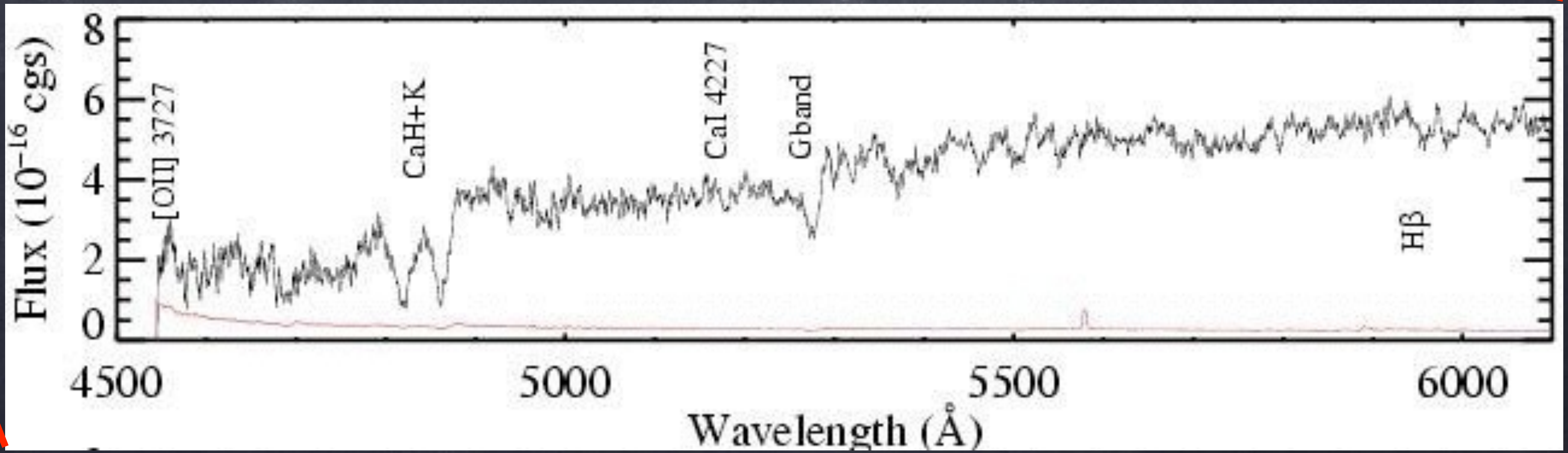
Old stellar population

Bloom et al. 2005

Castro-Tirado et al. 2005

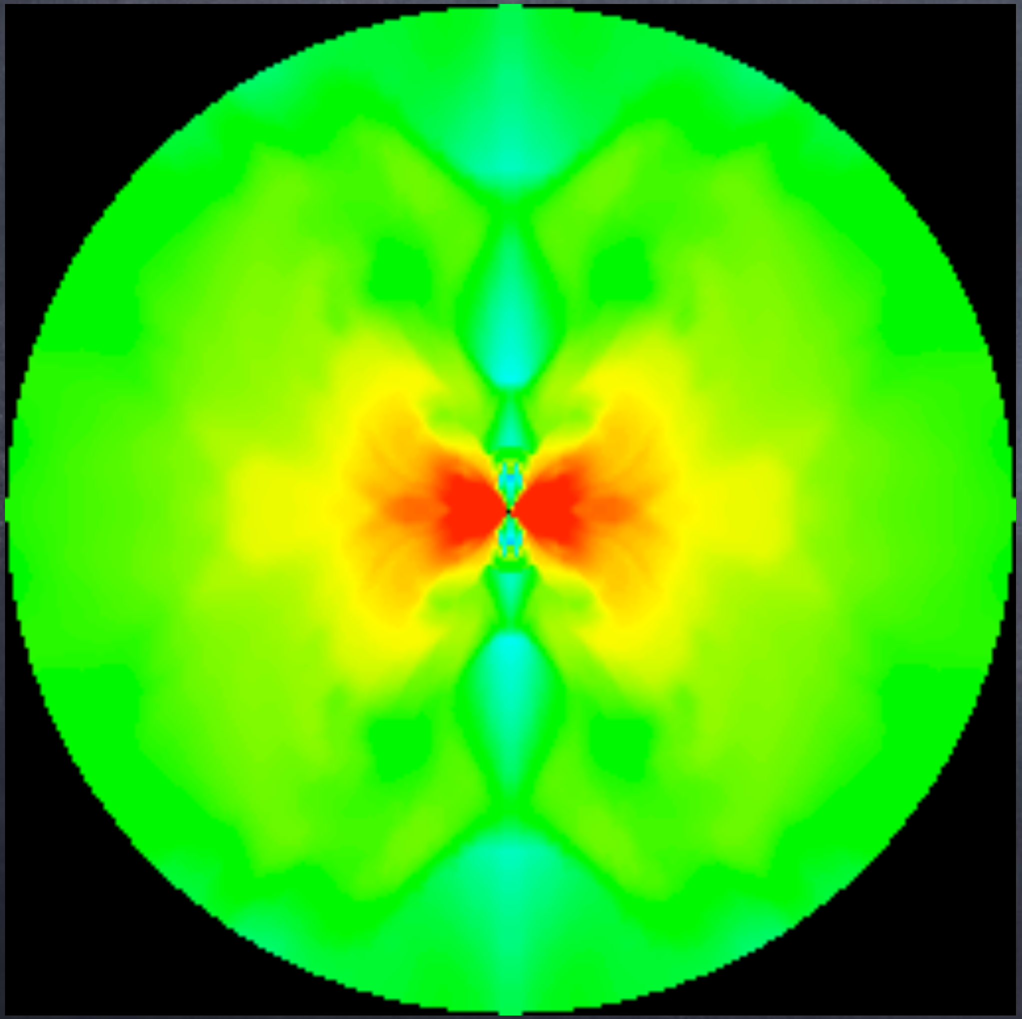
Gehrels et al. 2005

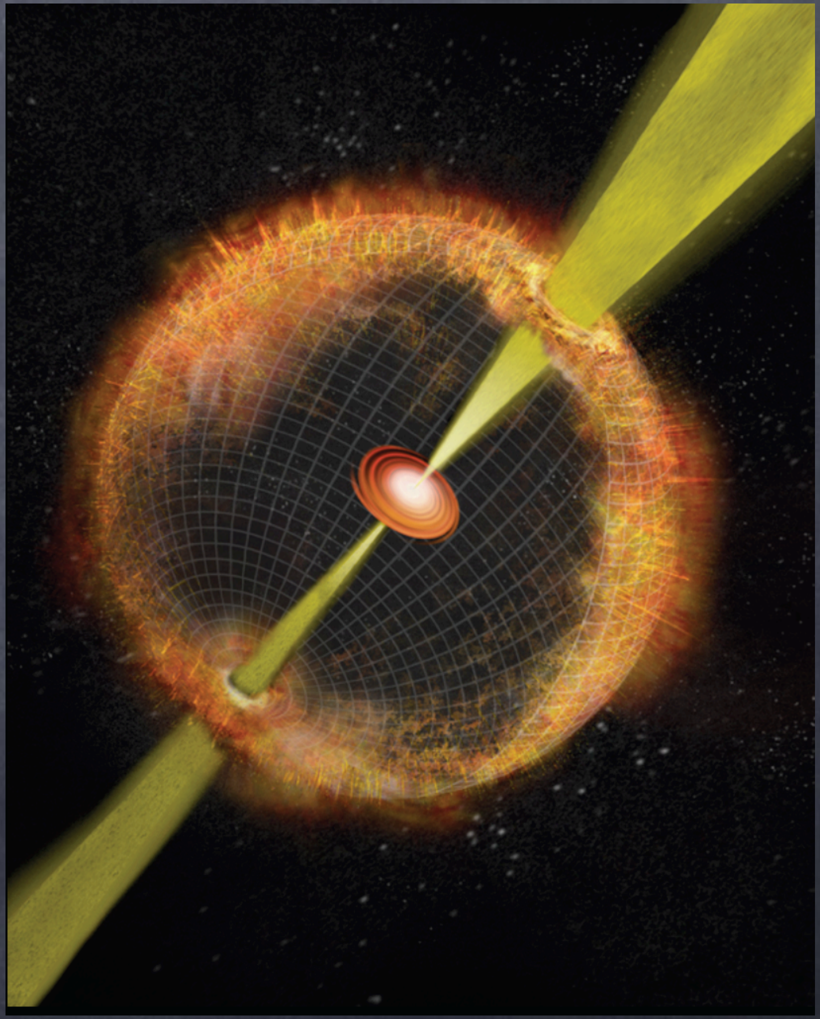
Hjorth et al. 2005



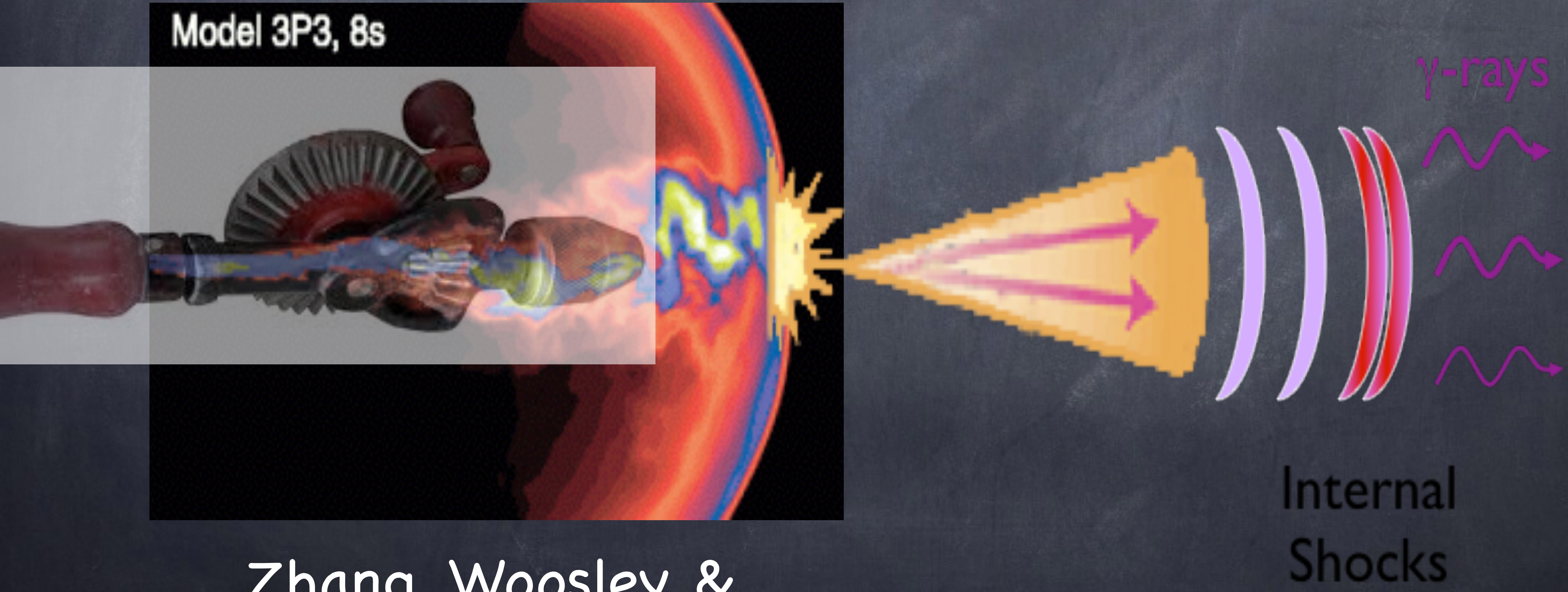
The Collapsar Model

(MacFadyen & Woosley 1998)



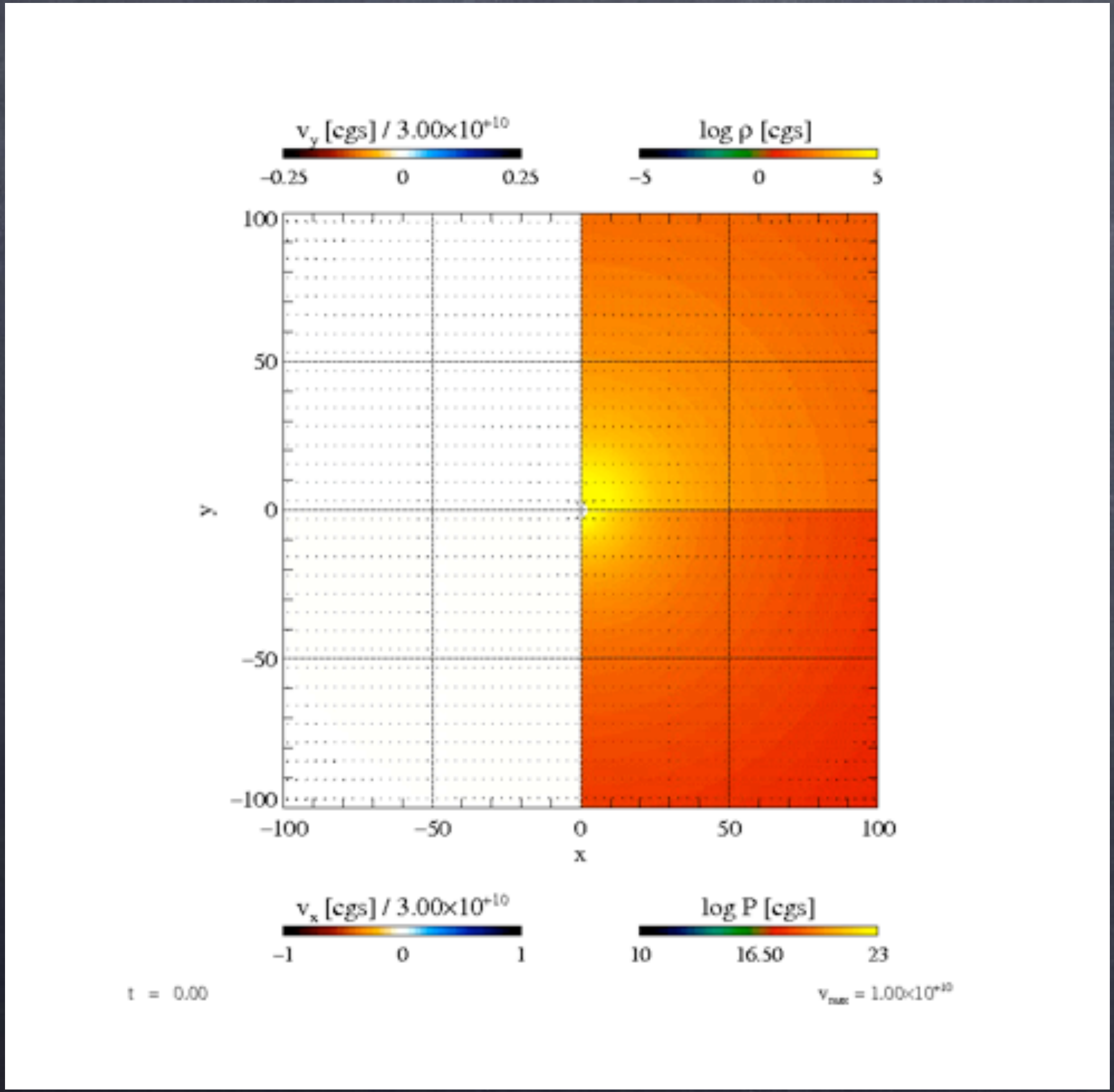


The Jet drills a hole in the star Model



Zhang, Woosley &
MacFadyen 2004

Jet Simulations (Obergaulinger, TP 11)



Opening angle of 15° degrees at 2000 km into a star of 15 solar masses and solar metallicity. Constant energy injection rate, 5 * 10^{50}erg /s, through the entire run of the model. Lorentz factor at injection 7

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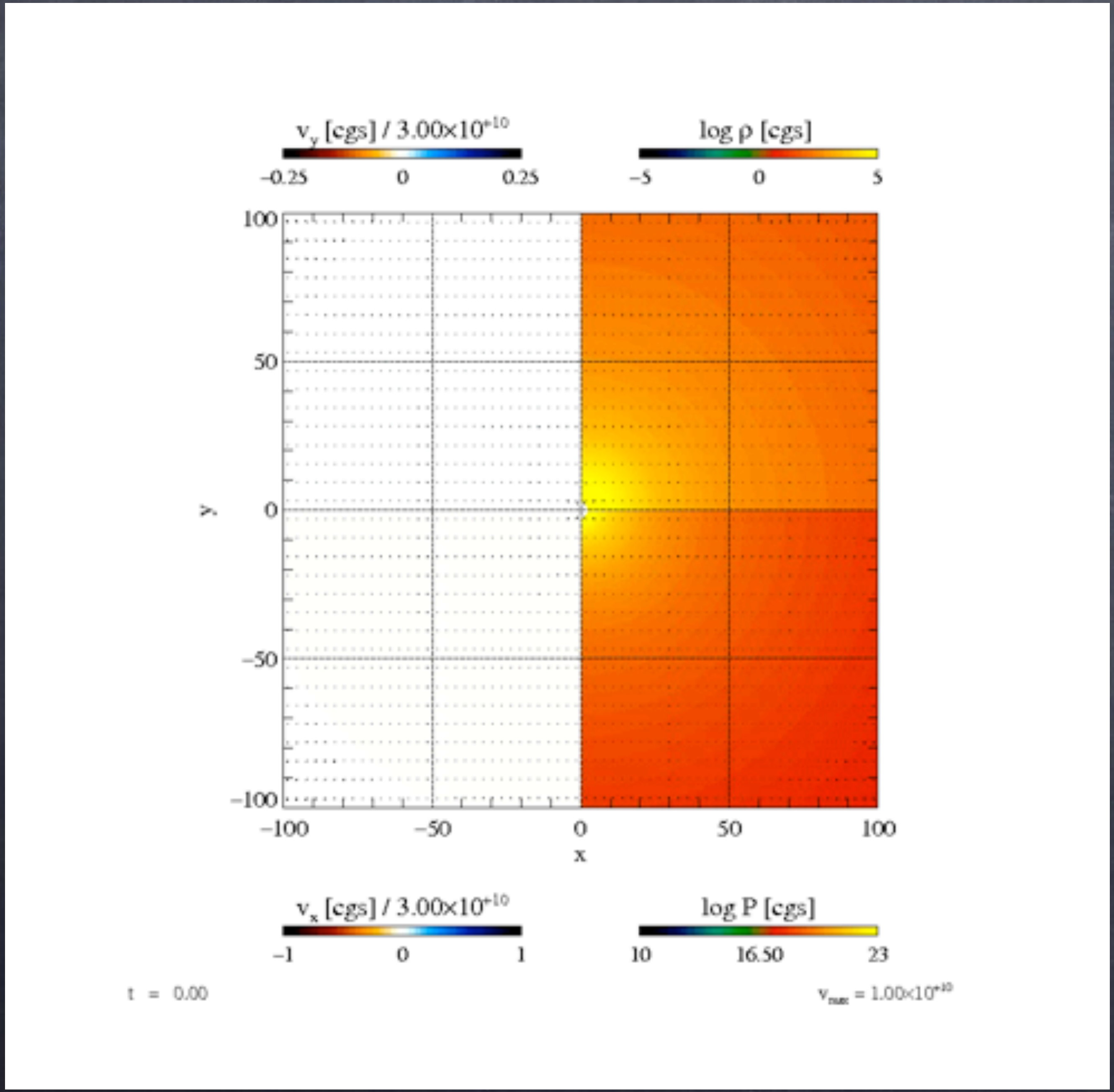
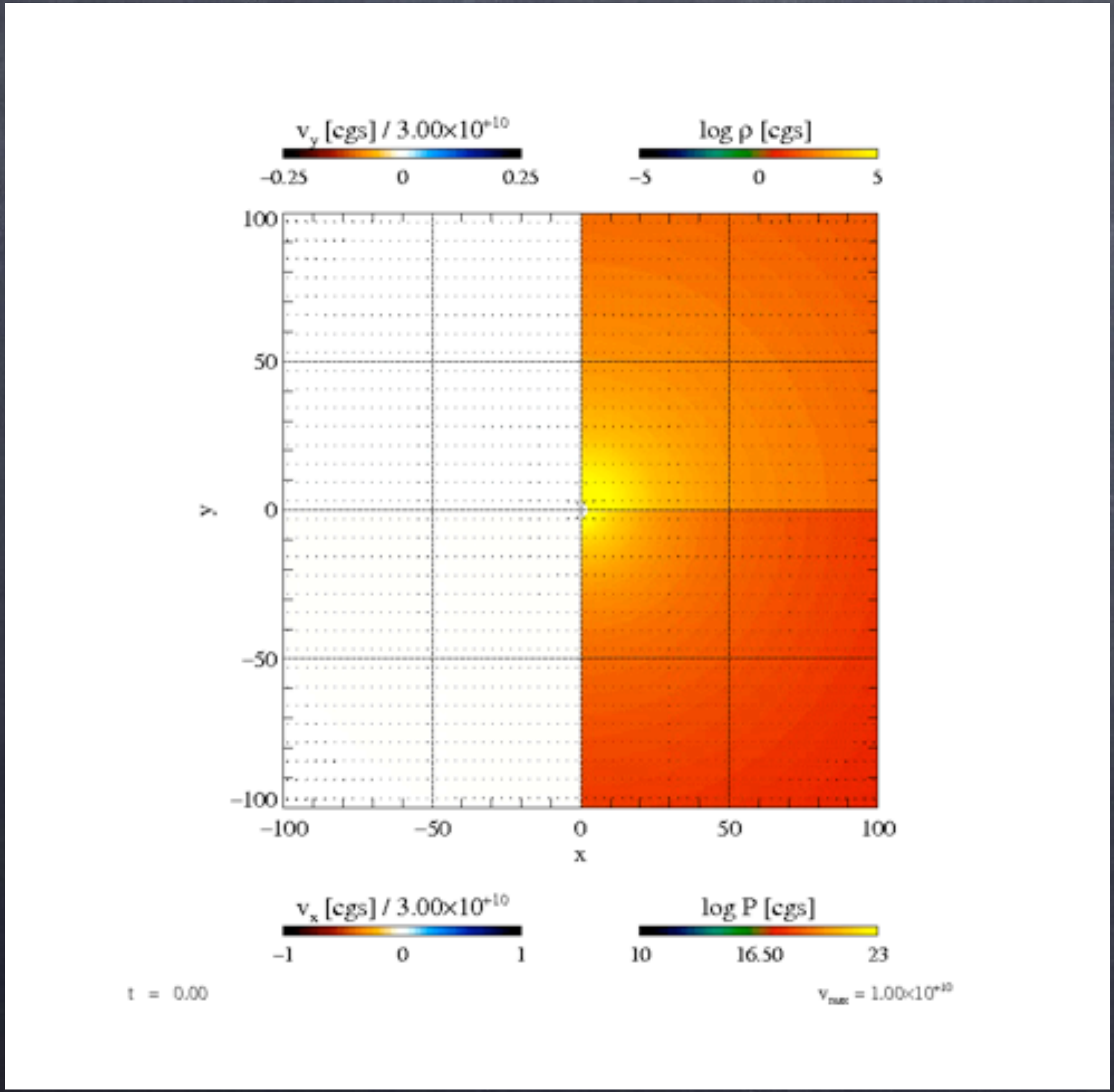
(Obergaulinger, TP 11)



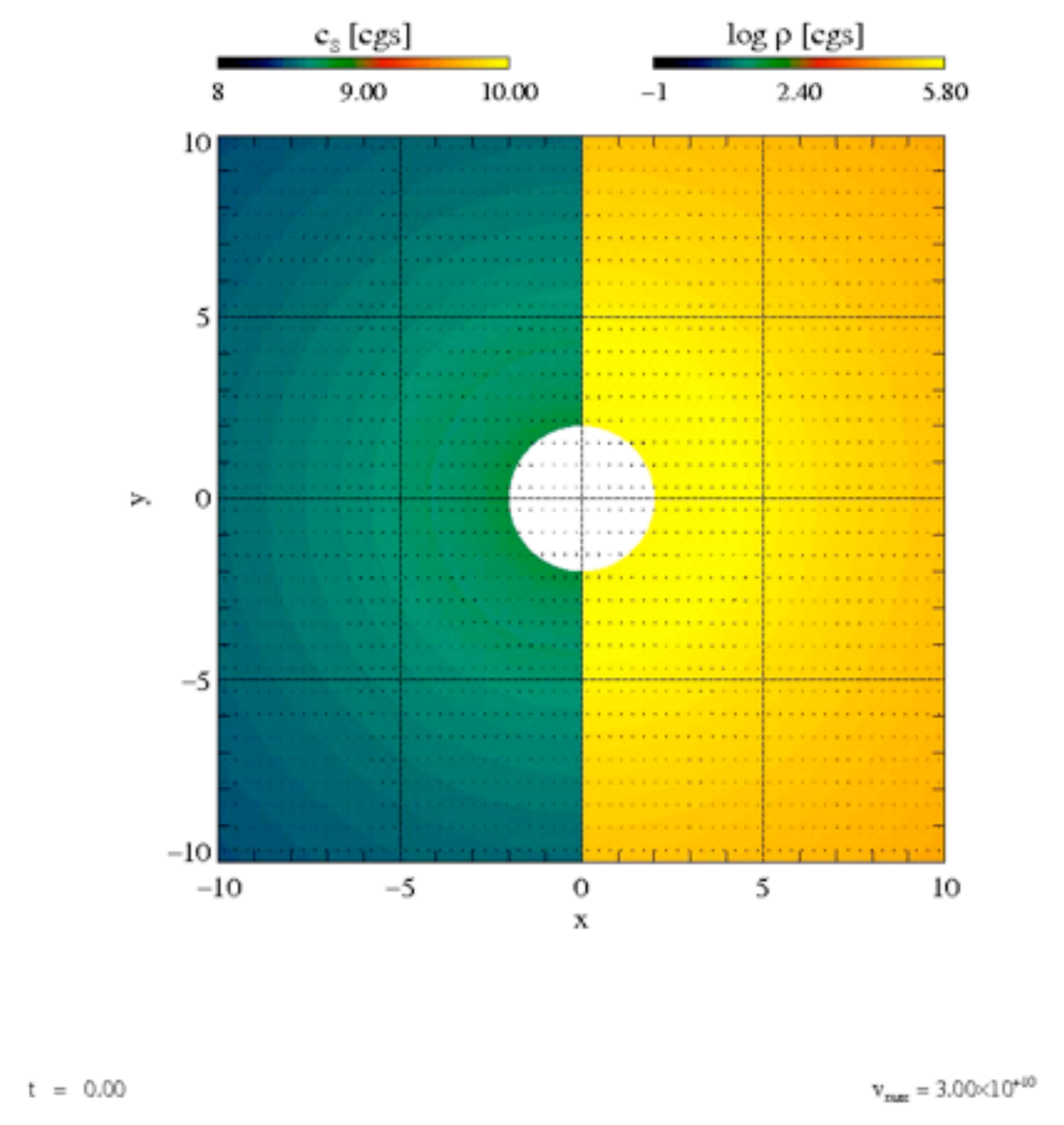
Opening angle of 15° degrees at 2000 km into a star of 15 solar masses and solar metallicity. Constant energy injection rate, 5 * 10^{50}erg /s, through the entire run of the model. Lorentz factor at injection 7

Jet Simulations
(Obergaulinger, TP 11)



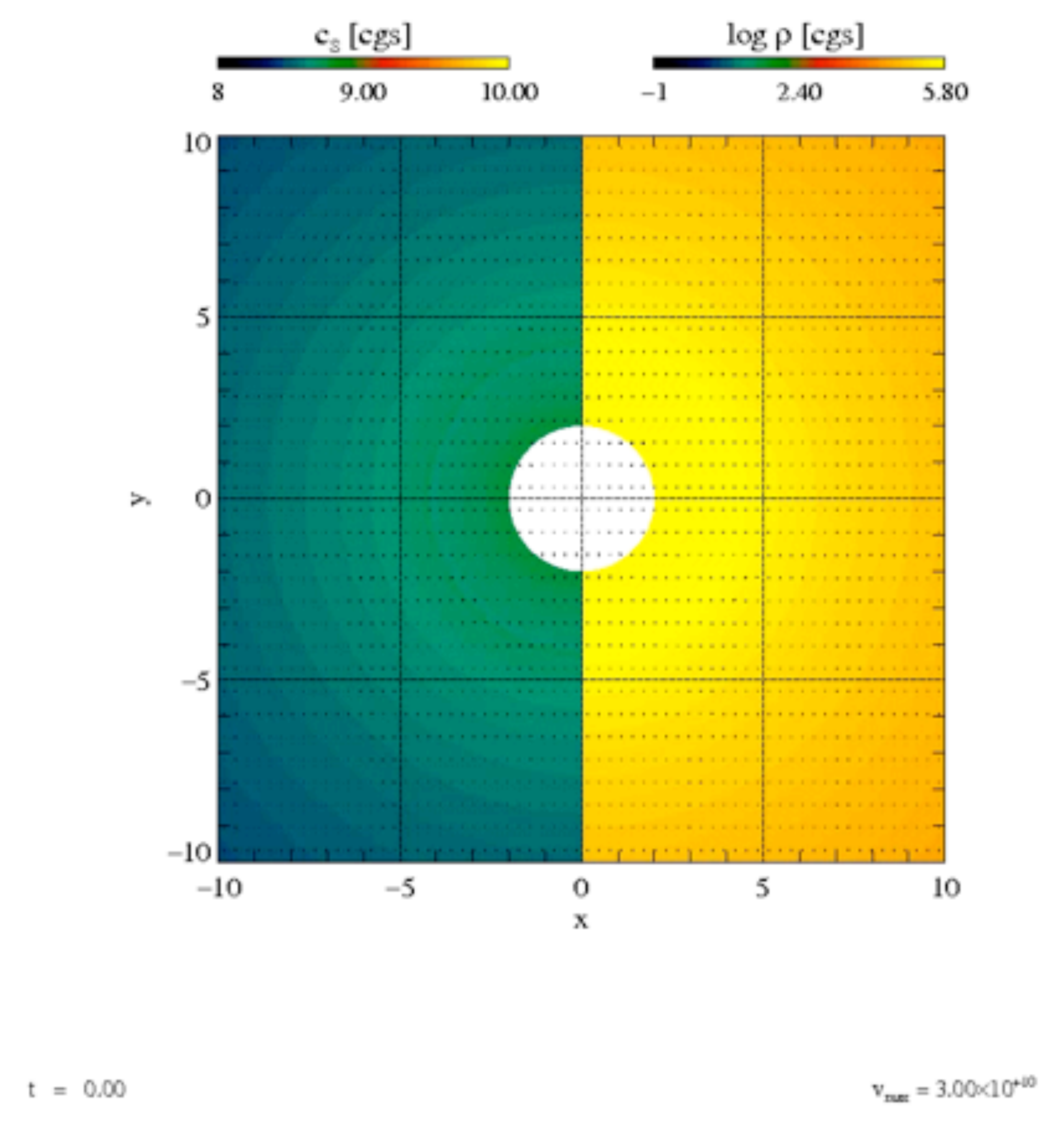
Opening angle of 15^{o} degrees at 2000 km into a star of 15 solar masses and solar metallicity. Constant energy injection rate, 5 * 10^{50}erg /s, through the entire run of the model. Lorentz factor at injection 7

Jet Simulations - A Failed Jet (Obergaulinger, Piran + 11)



Opening angle of 15° degrees at 2000 km into a star of 15 solar masses and solar metallicity. Constant energy injection rate, 5 * 10^{50}erg/s, for 2 seconds.

Jet Simulations - A Failed Jet (Obergaulinger, Piran + 11)



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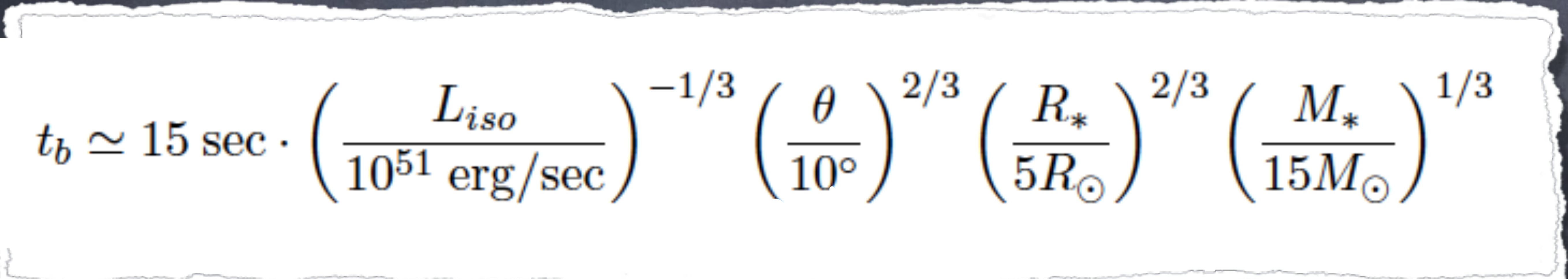
Jet breakout time

(Bromberg Nakar, TP, Sari 11)



$$t_b \simeq 15\,\mathrm{sec} \cdot \left(\frac{L_{iso}}{10^{51}\ \mathrm{erg/sec}}\right)^{-1/3} \left(\frac{\theta}{10^\circ}\right)^{2/3} \left(\frac{R_*}{5R_\odot}\right)^{2/3} \left(\frac{M_*}{15M_\odot}\right)^{1/3}$$

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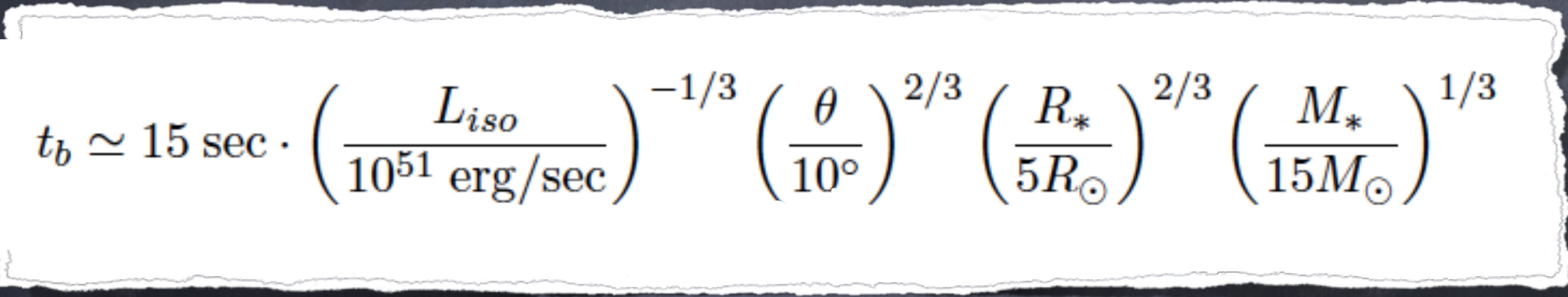

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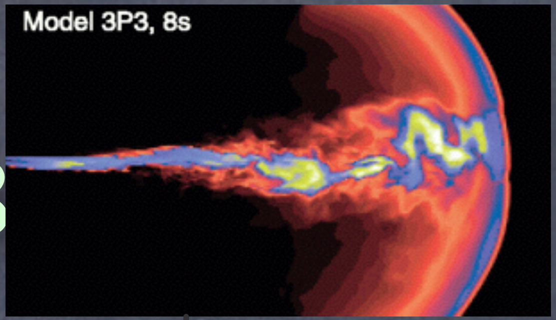
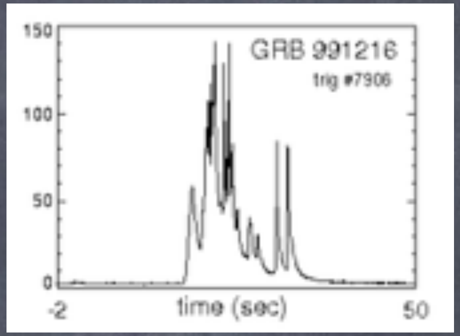
The engine must be active until the jet's head breaks out!*

$$T_e = T_B + T_{90}$$

T_B



T_{90}



T_e

A prediction of the Collapsar model

$$\overset{\text{Observed duration}}{T_{90}} = \underset{\text{Engine time}}{T_e} - \underset{\text{Break out time}}{T_B}$$

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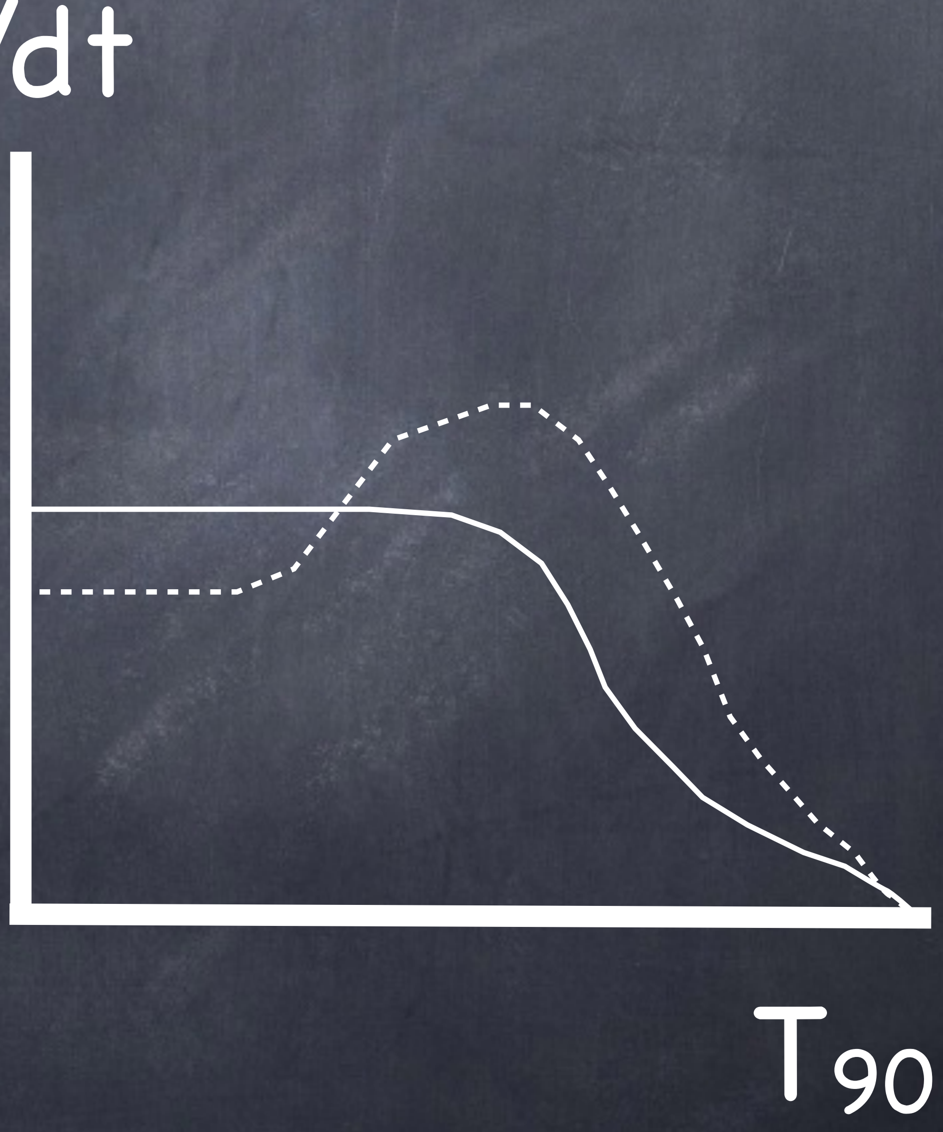


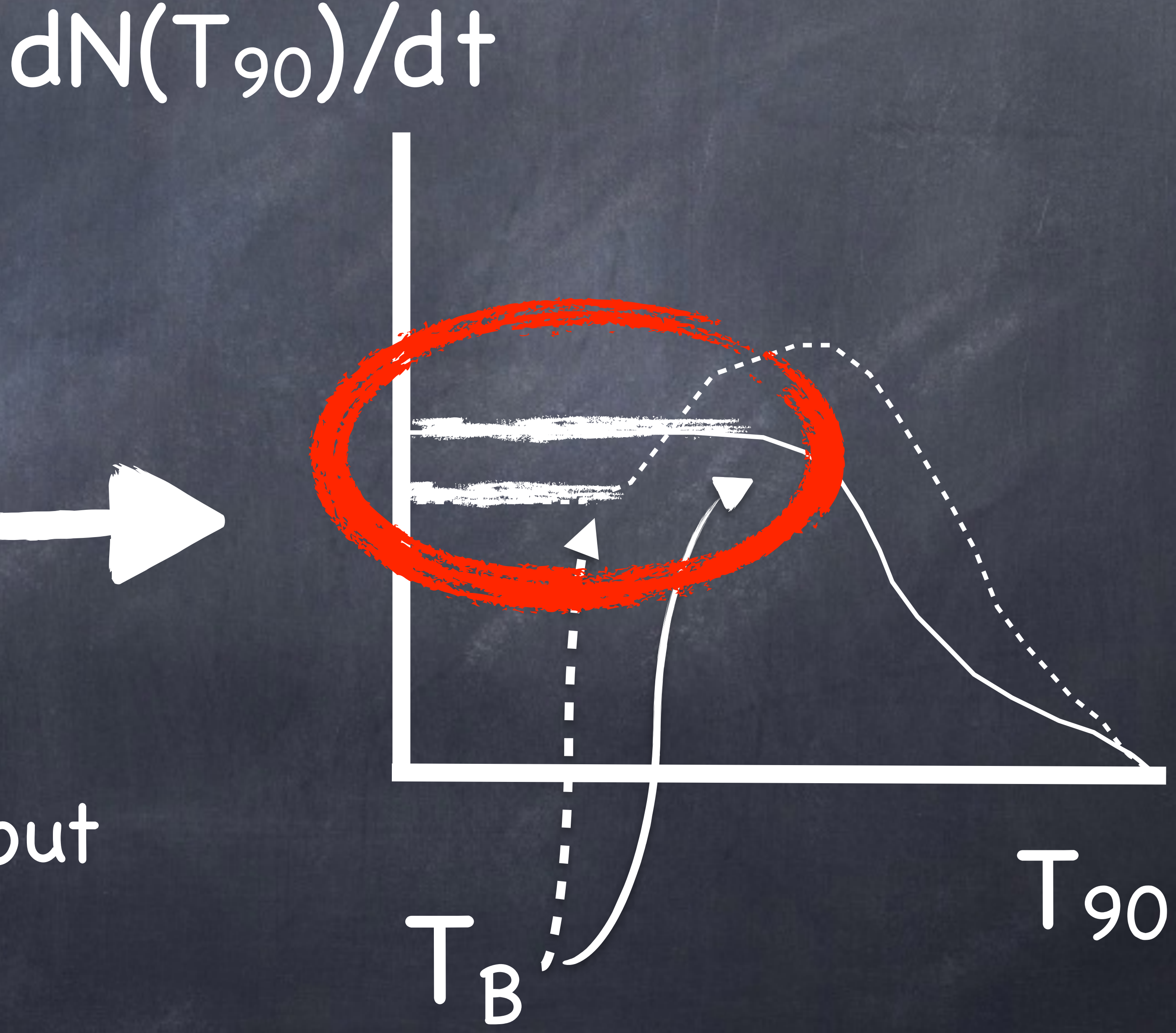
A prediction of the Collapsar model

Observed duration

$$T_{90} = T_e - T_B$$

Engine time

Break out time



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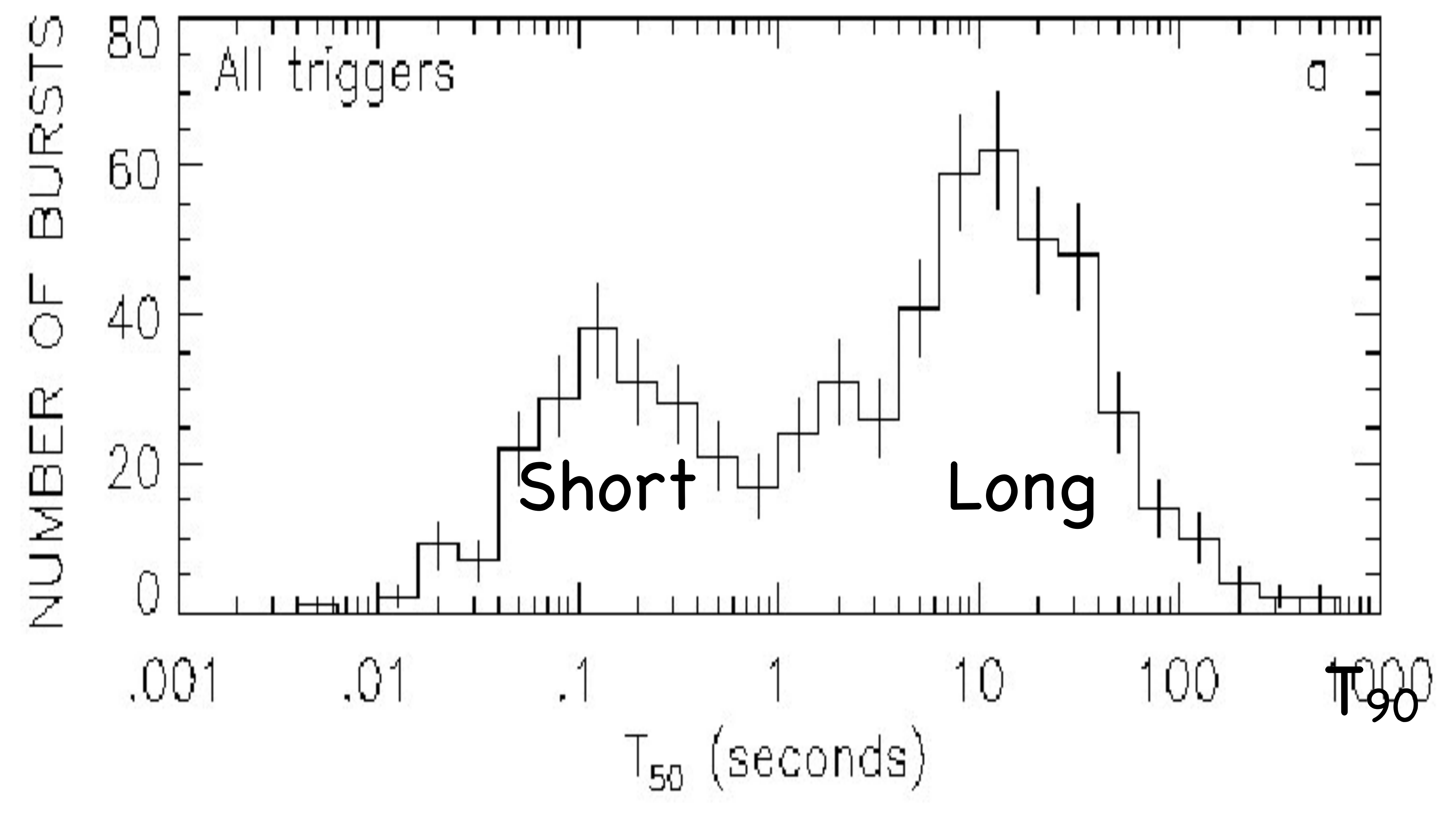
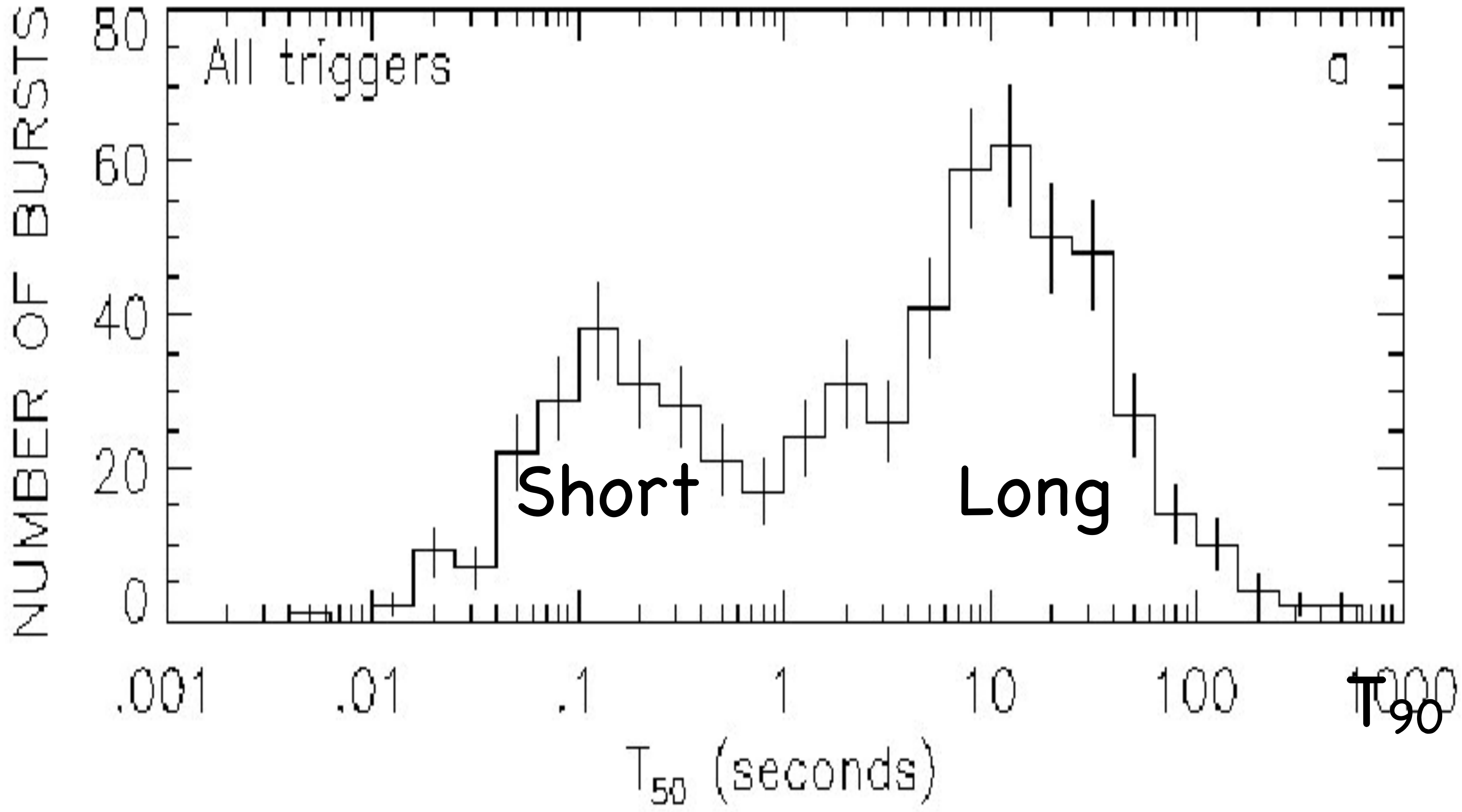

All triggers
a
NUMBER OF BURSTS
0
20
40
60
80
.001
.01
.1
1
10
100
1000
T_{50} (seconds)
Short
Long
T_{90}

?

$d\log(N)/dT_{90}$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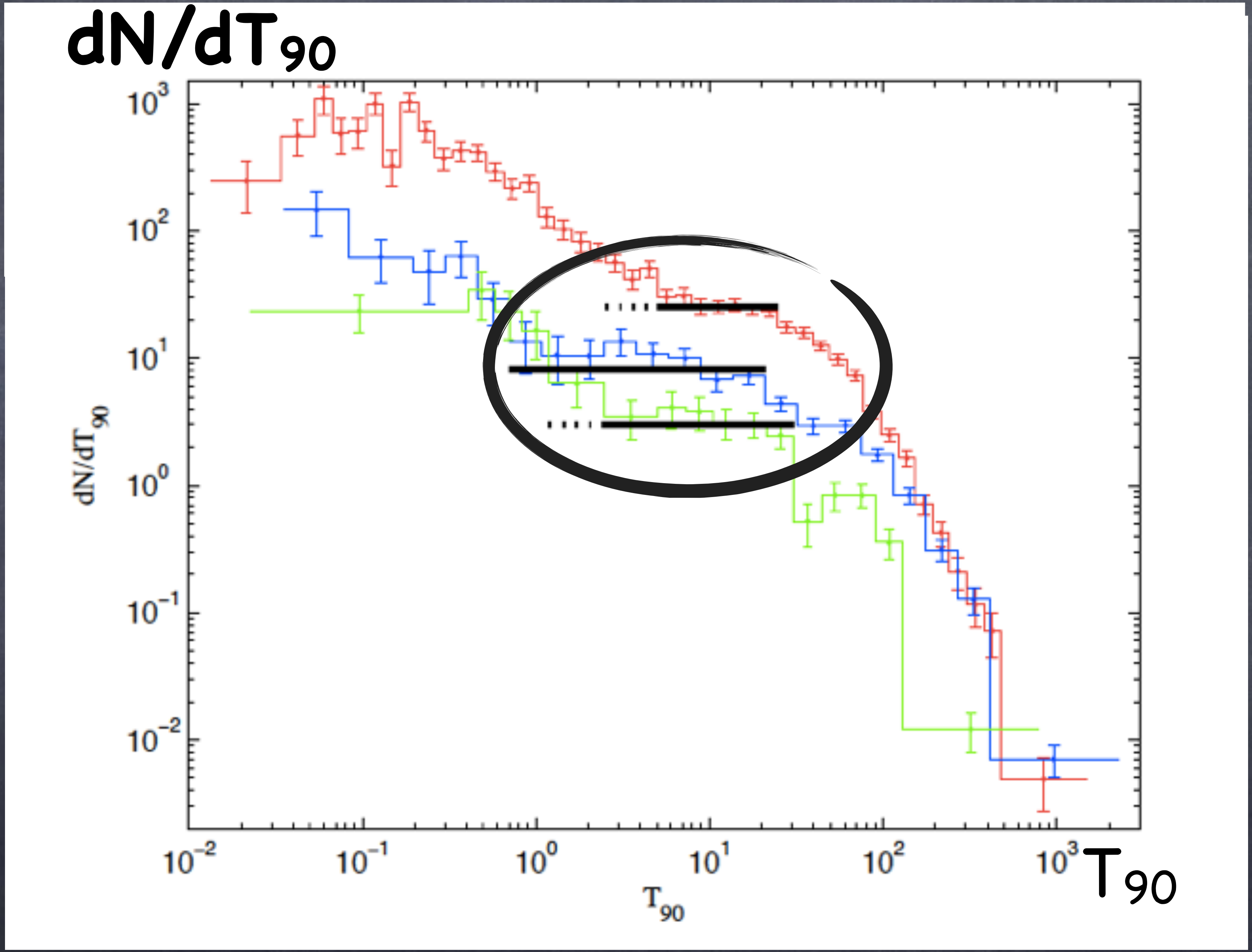
T_{50} (seconds)

A second look

(Bromberg Nakar, TP & Sari, 2011)



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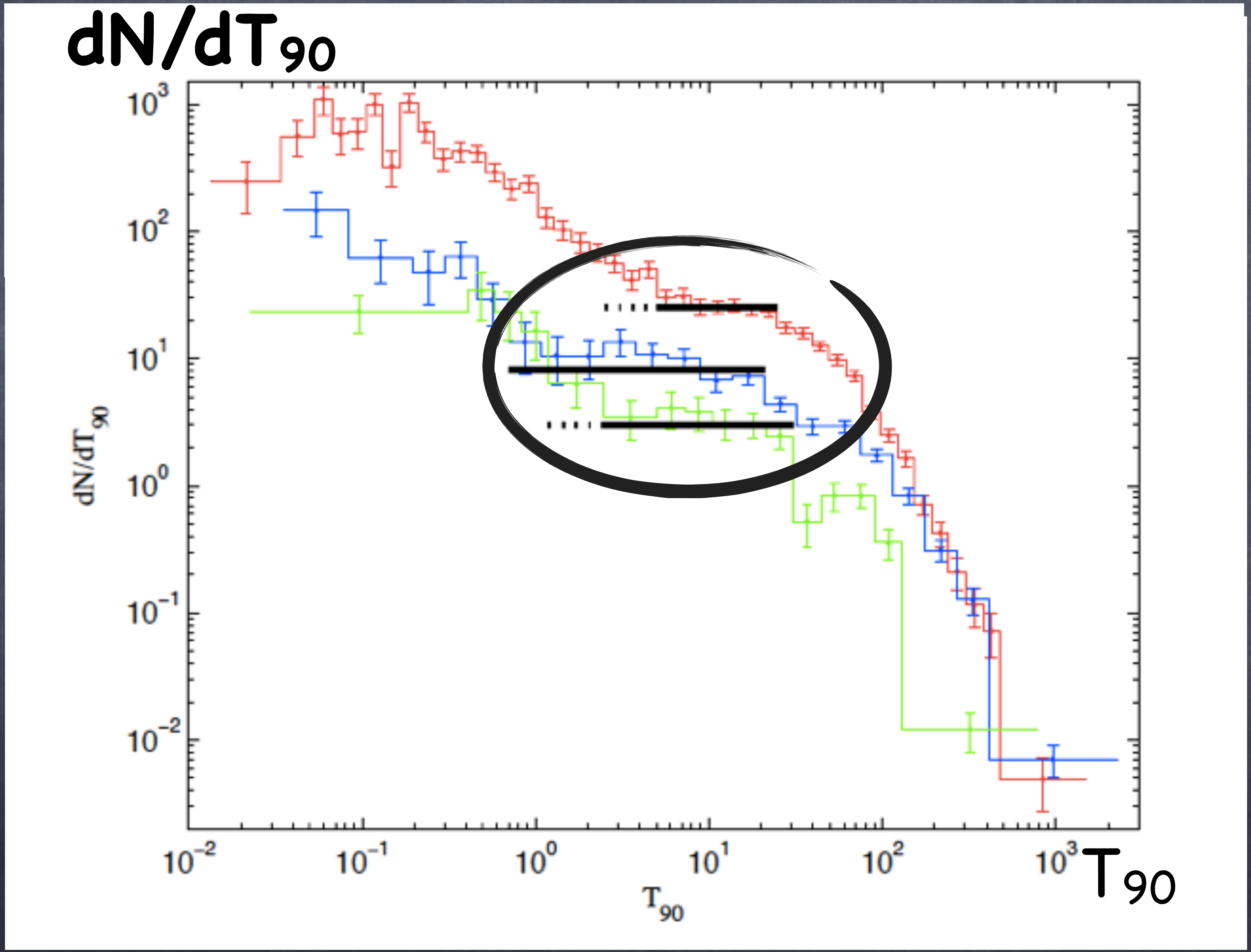
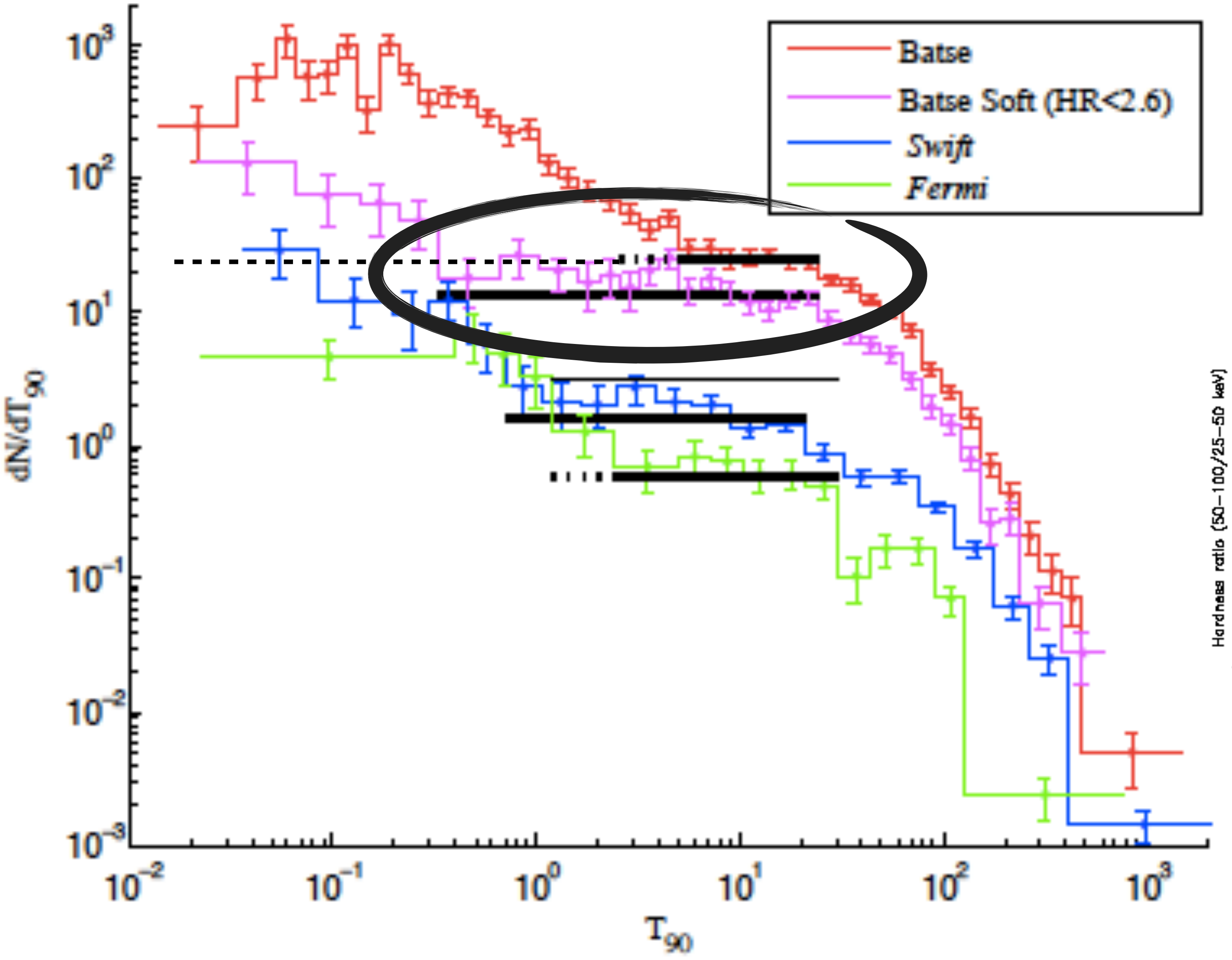


A direct observational proof of the Collapsar model.

Short (Non-Collapsars) GRBs are harder



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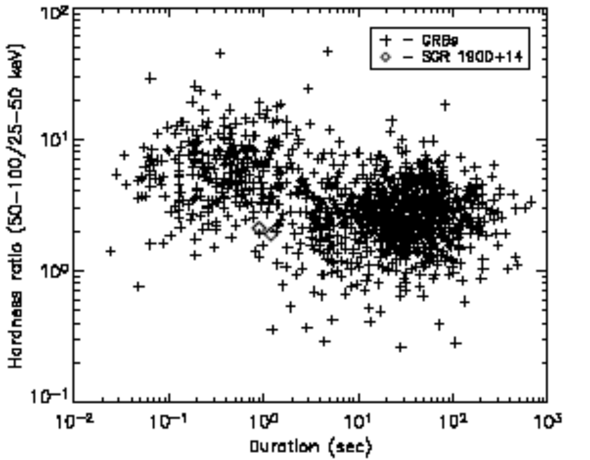

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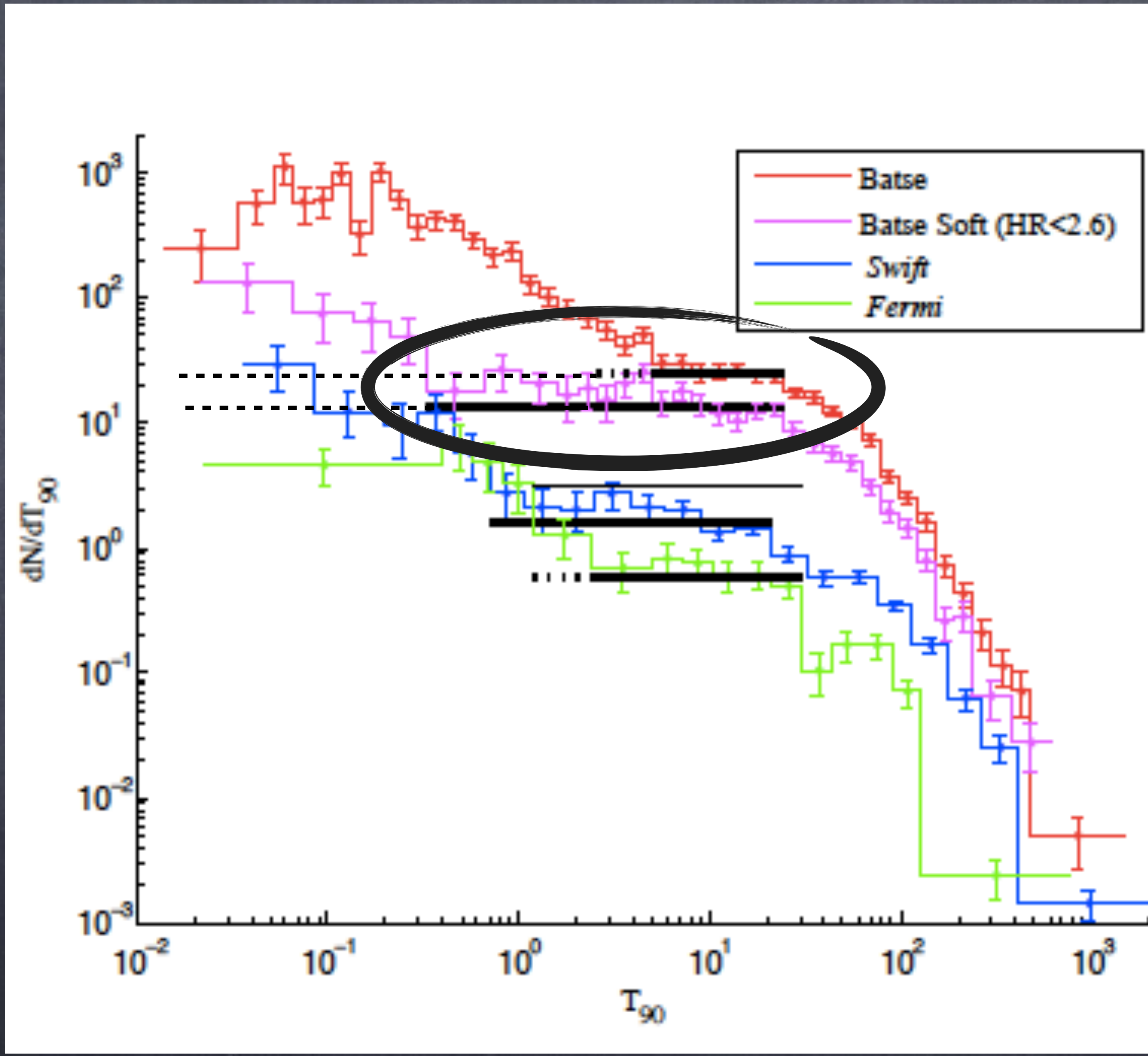

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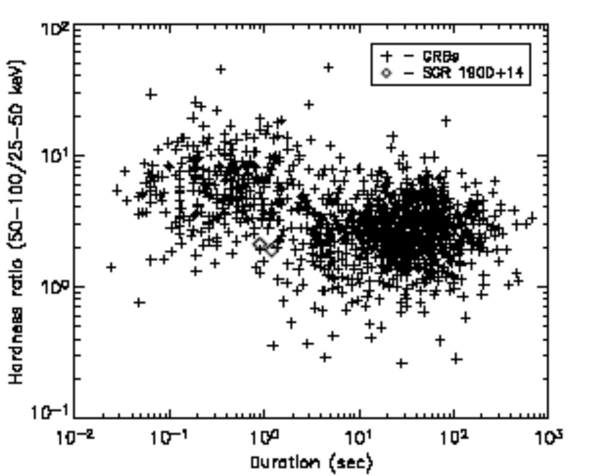

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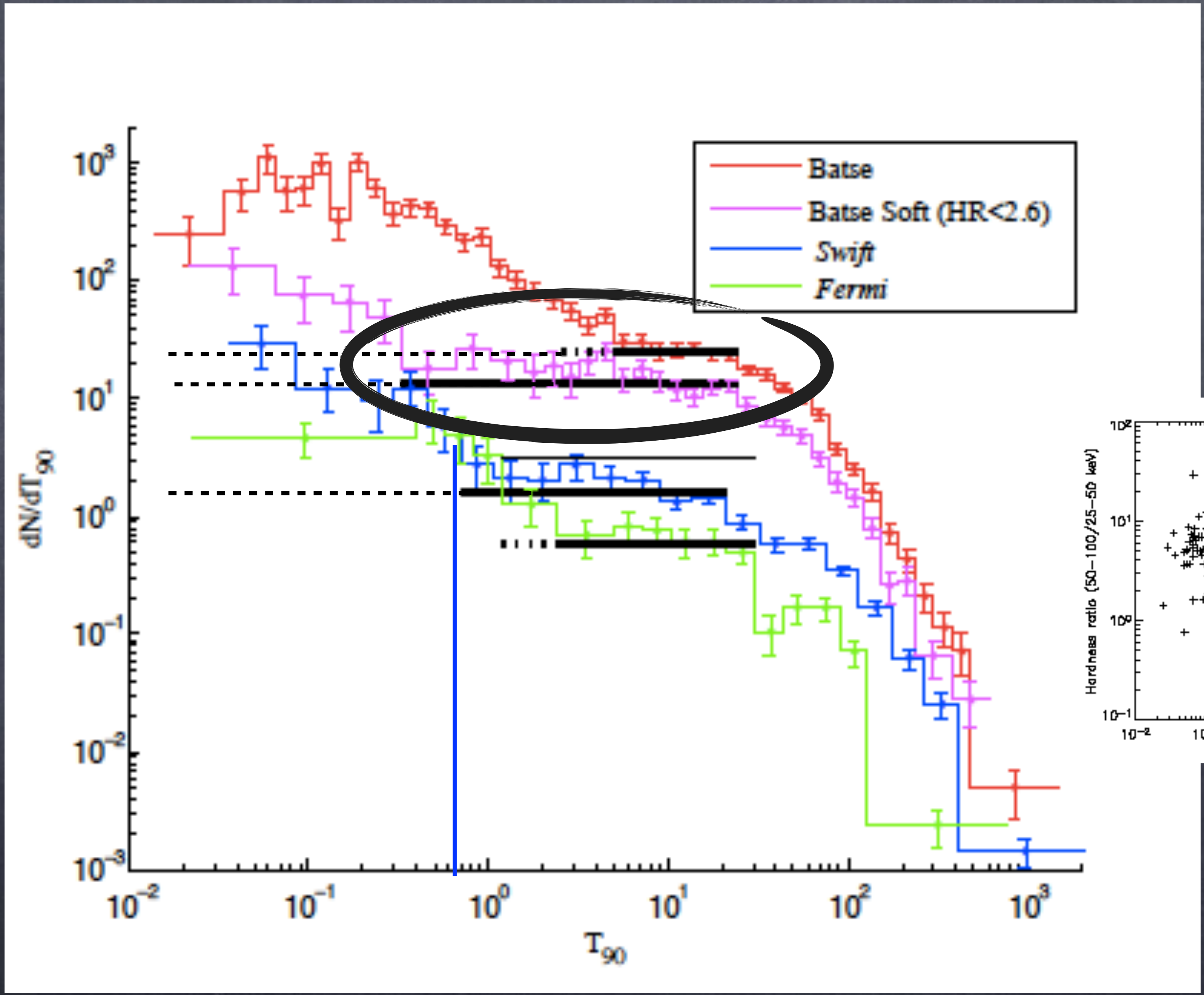

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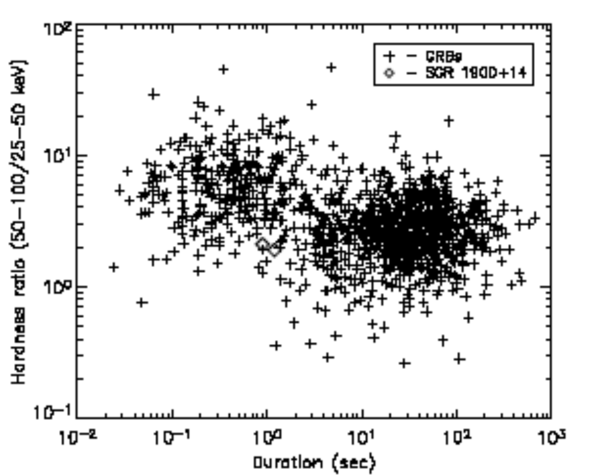

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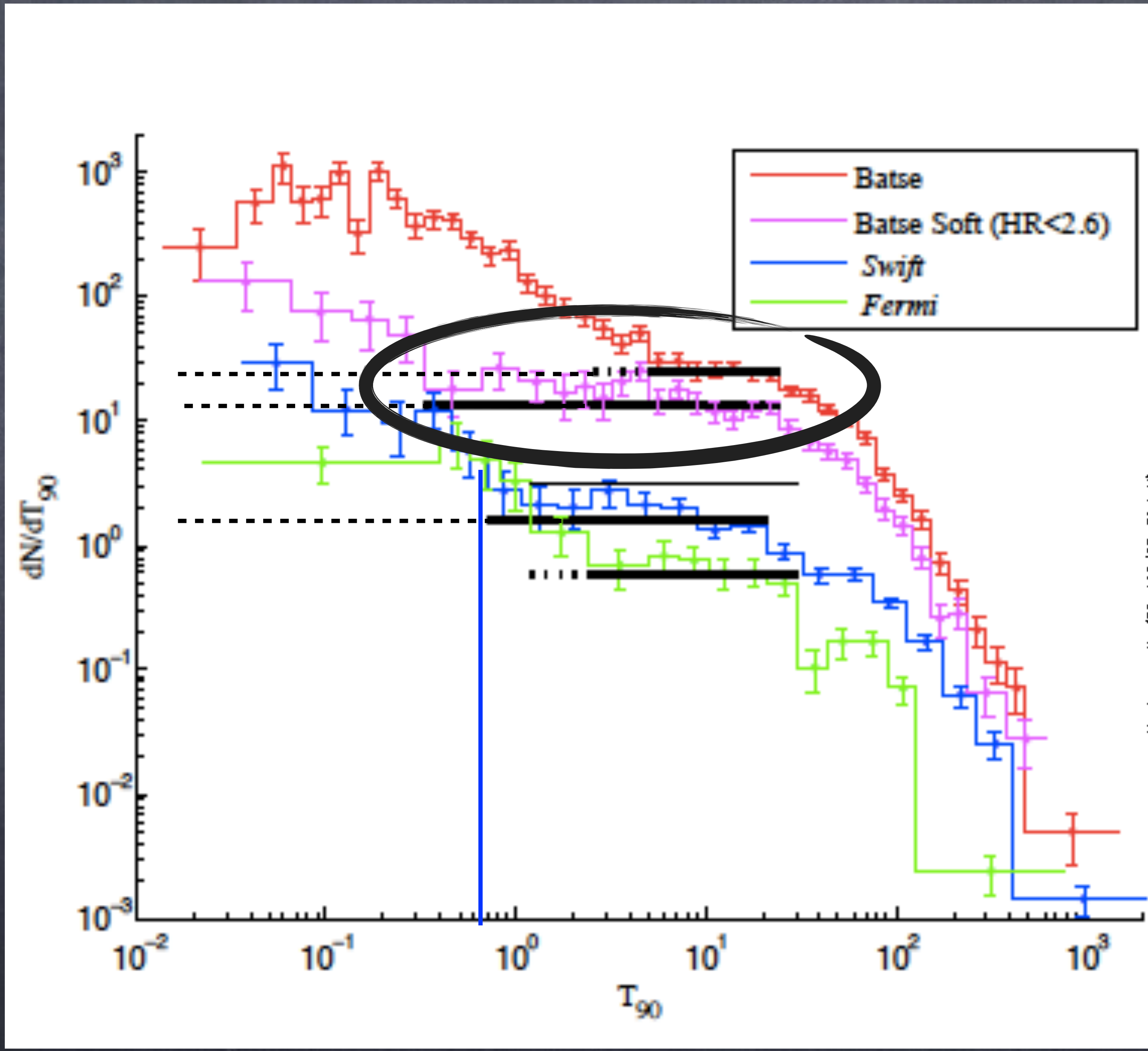
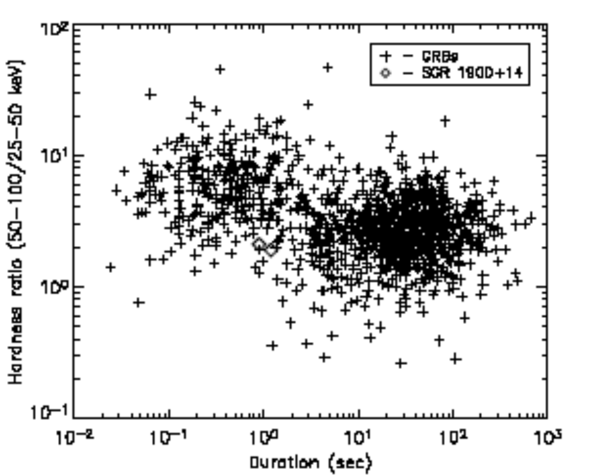
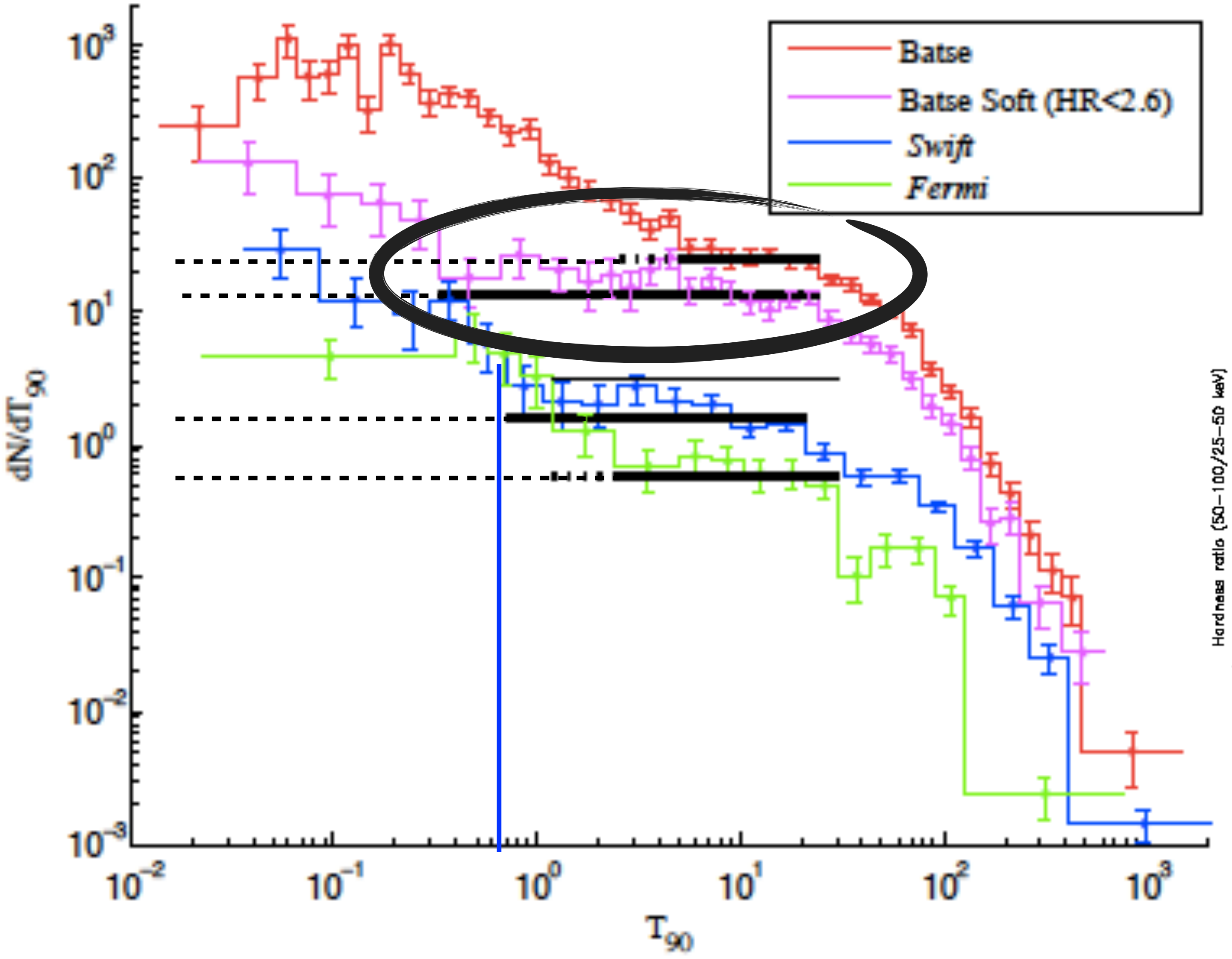




Short GRBs
are harder

BASTE shows a longer plateau for soft Bursts

Short (Non-Collapsars) GRBs are harder



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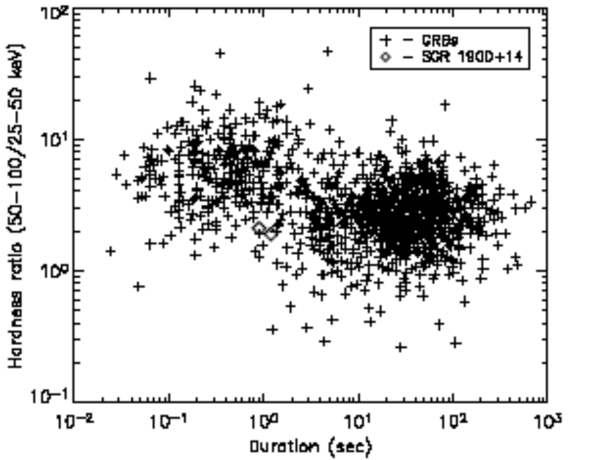

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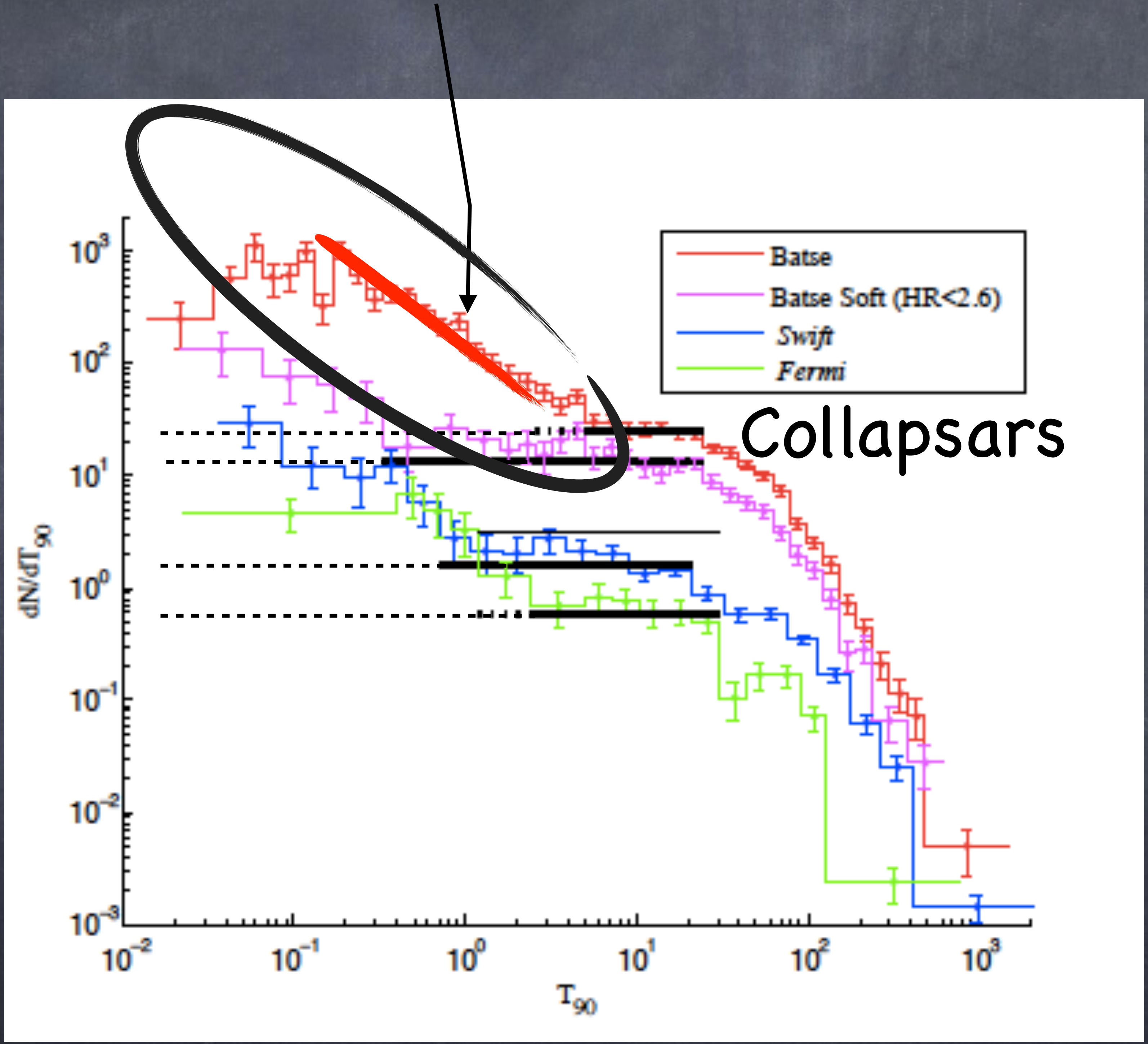
Short (Non-Collapsars)



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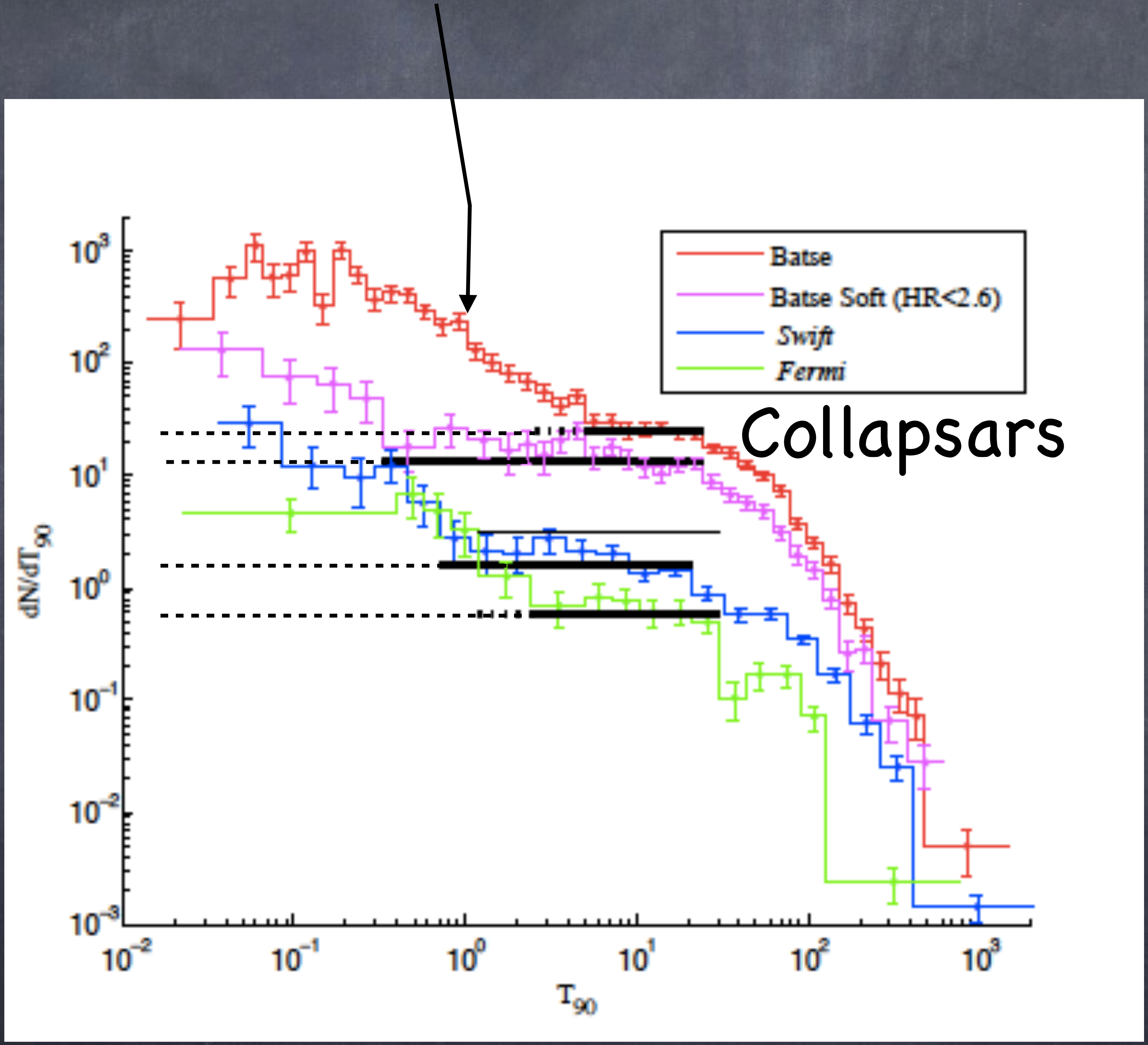

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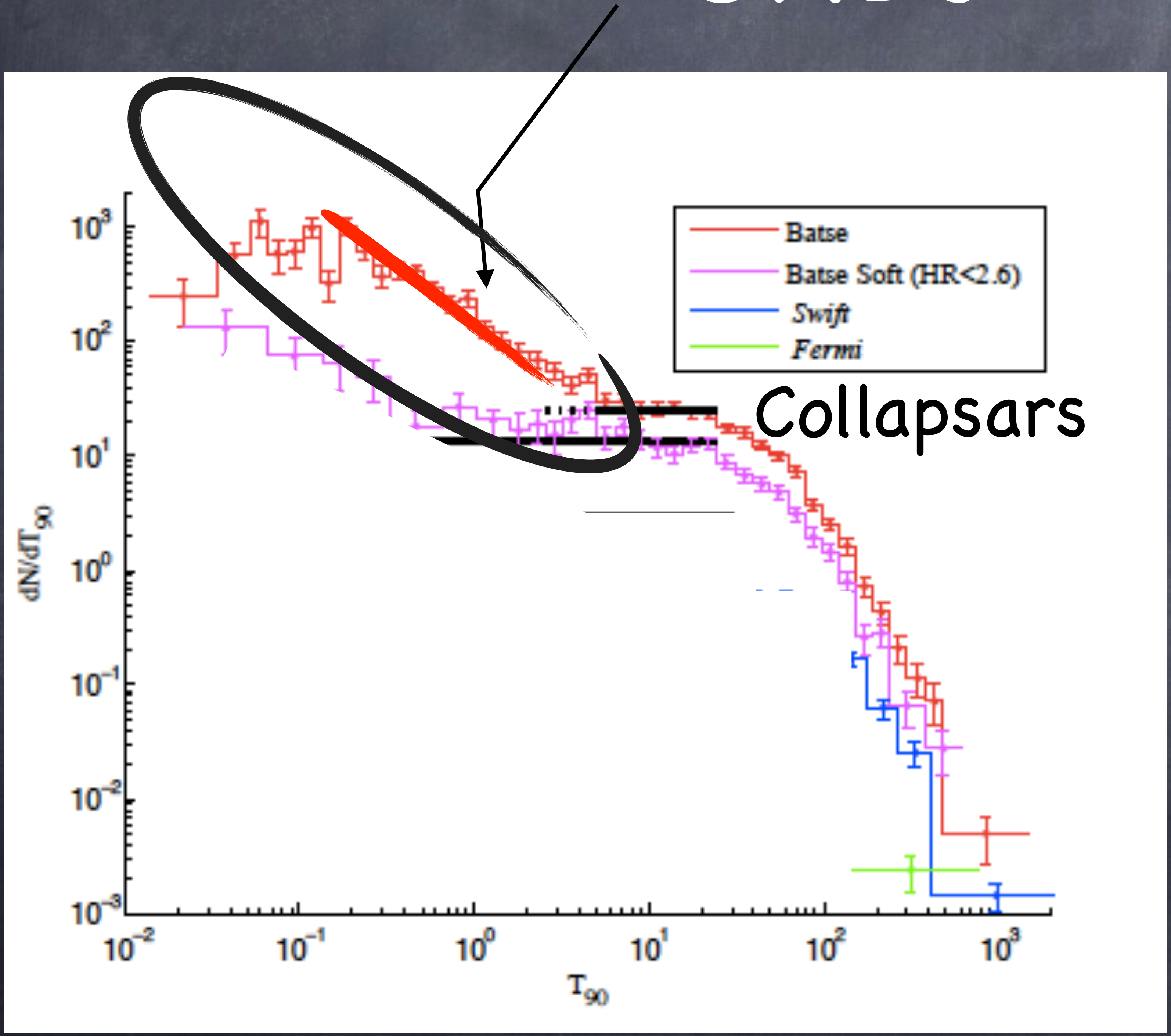
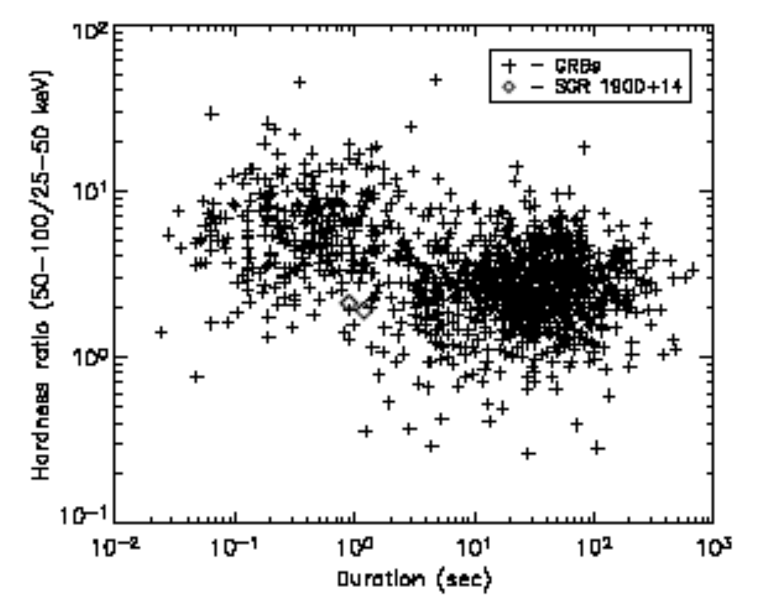


Collapsars



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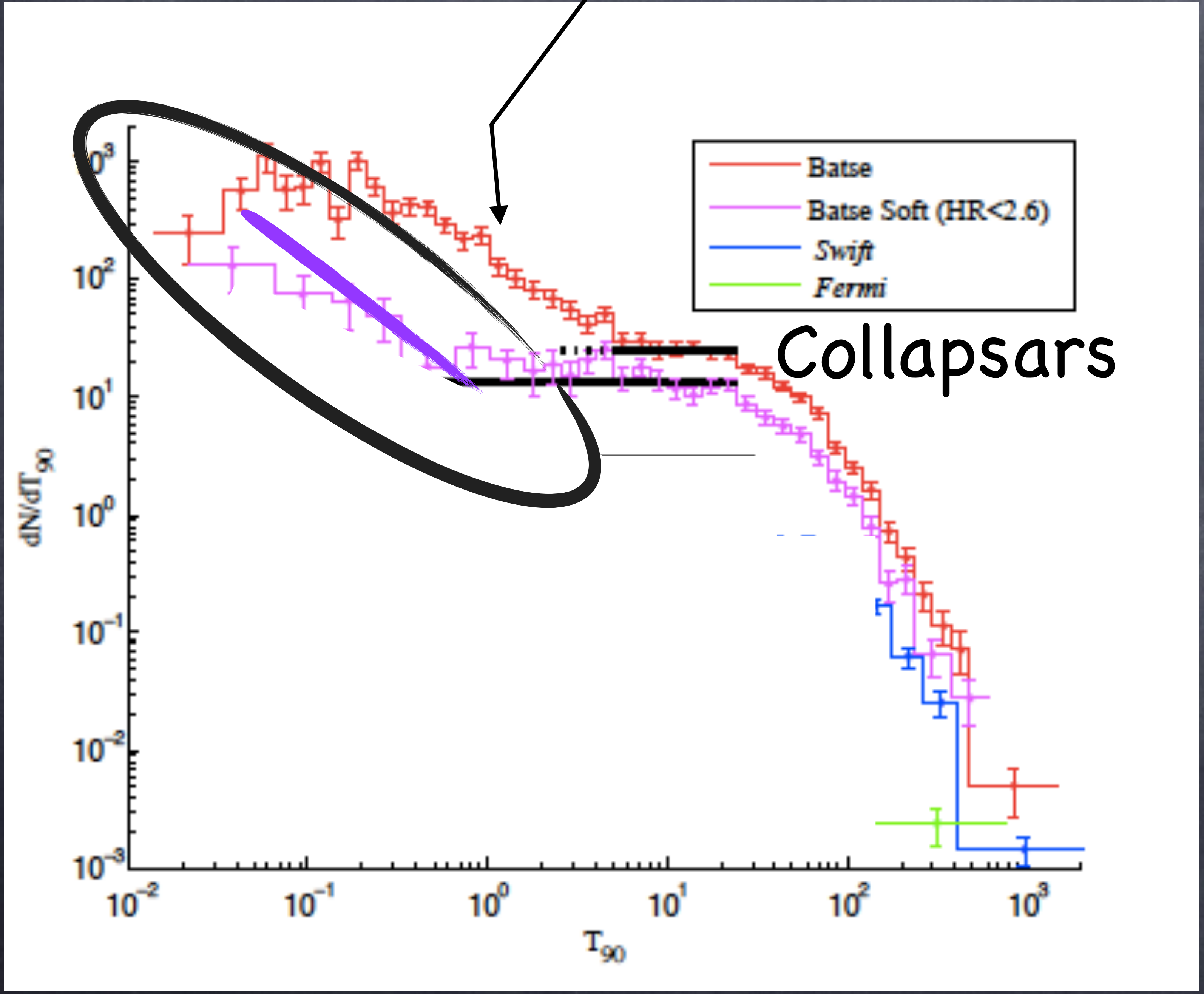
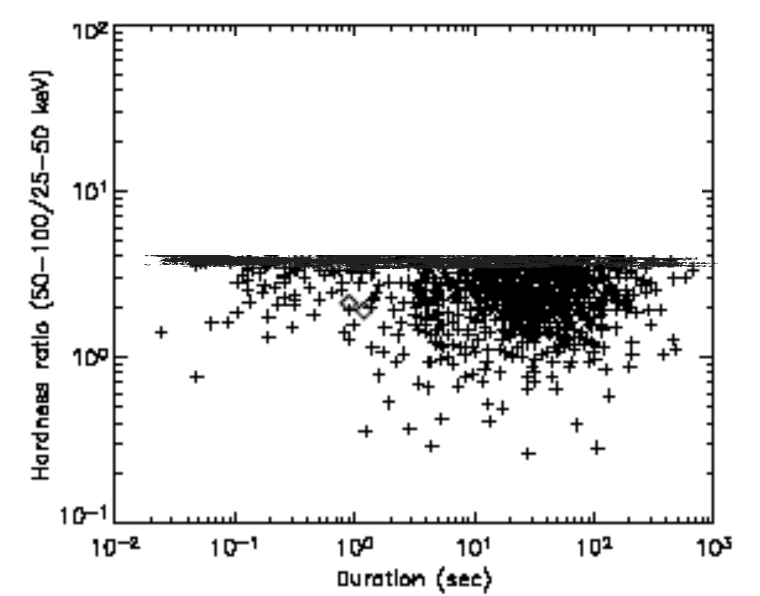
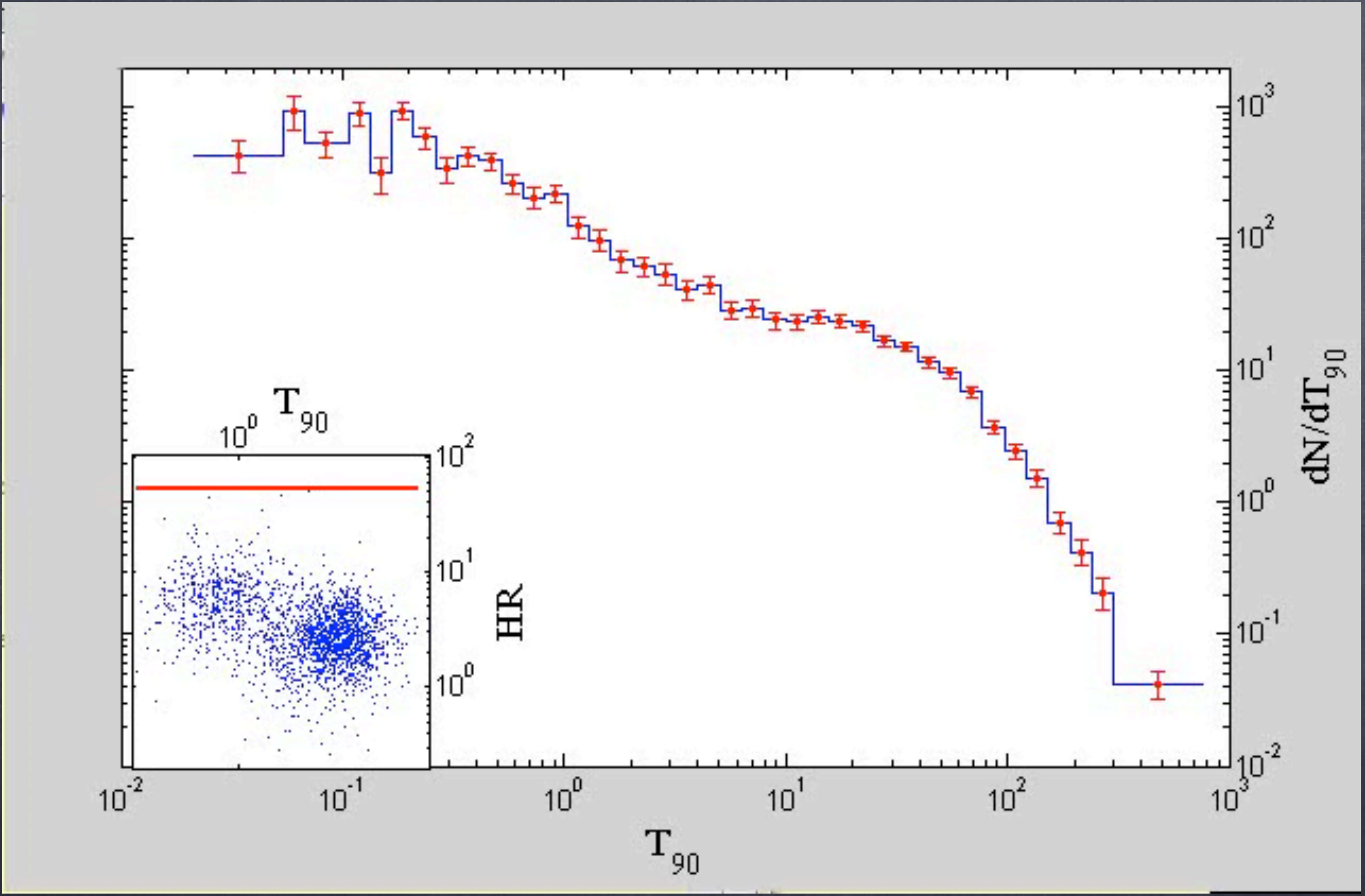
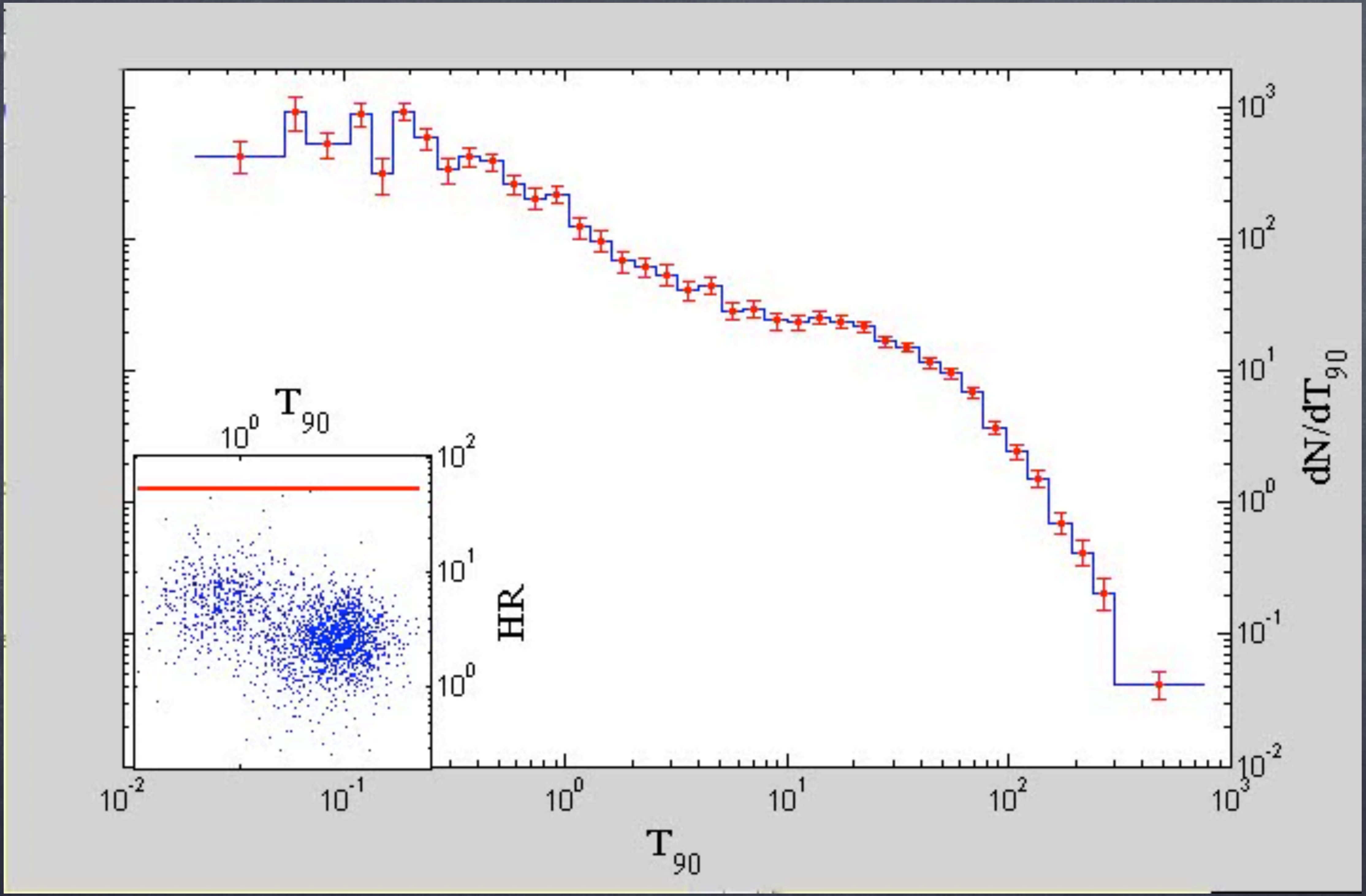


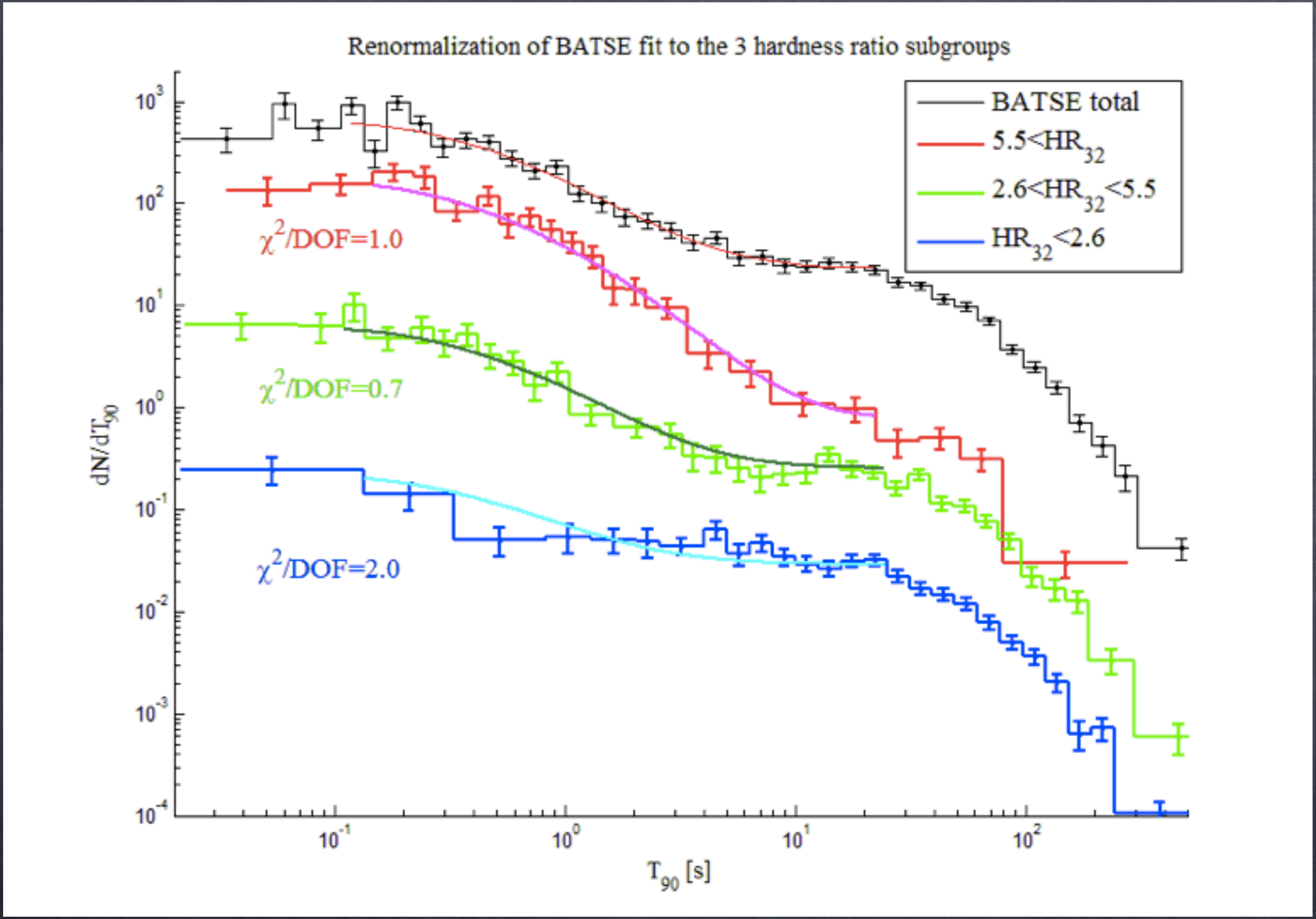
Collapsars





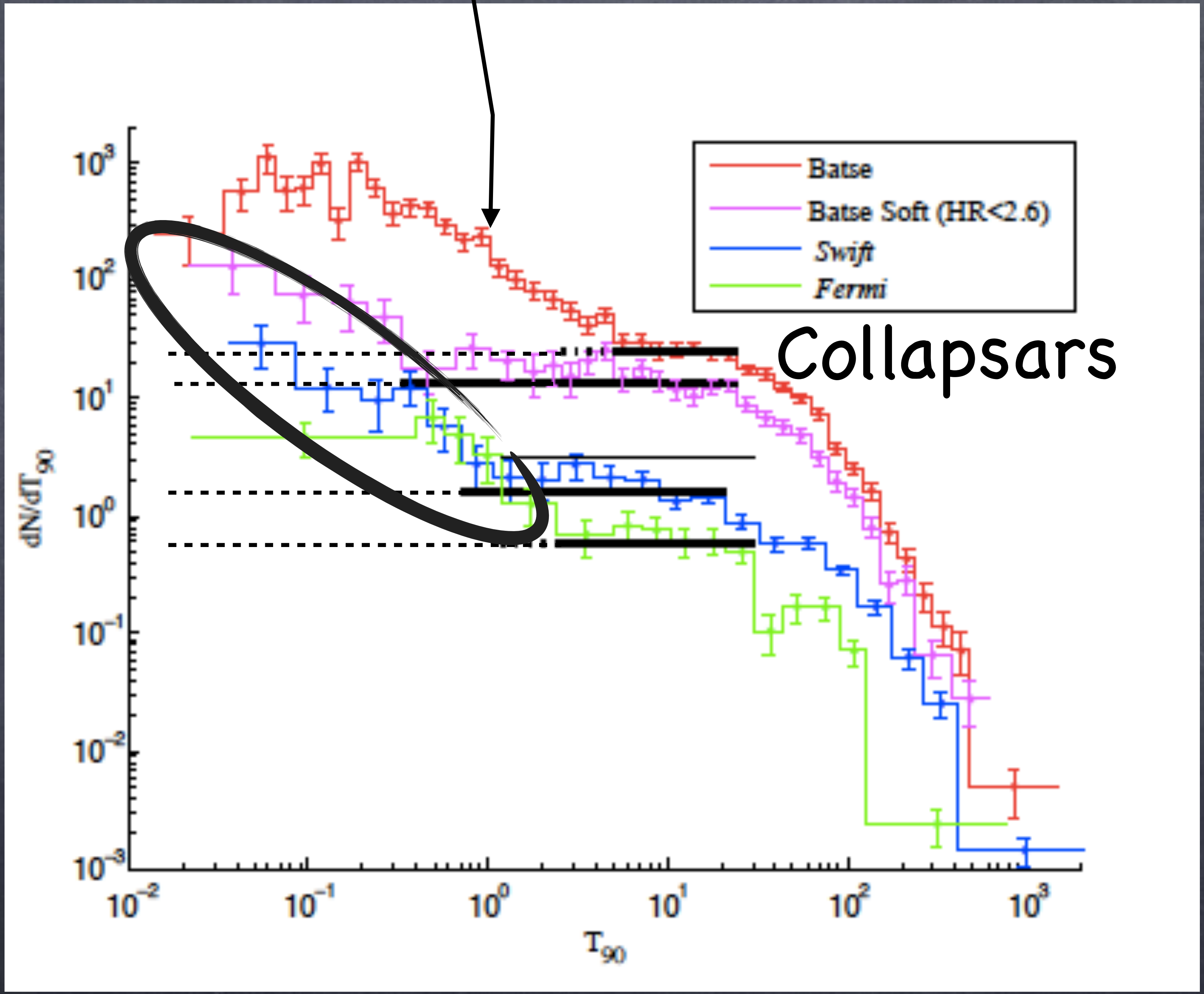
T$_{90}$
10^{0}
10^{2}
10^{1}
10^{0}
HR
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
dN/dT$_{90}$
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
T$_{90}$


10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
T_{90}
dN/dT_{90}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
T_{90}
10^{0}
HR
10^{0}
10^{1}
10^{2}



Renormalization of BATSE fit to the 3 hardness ratio subgroups

Swift Short (Non-Collapsars) GRBs



Collapsars

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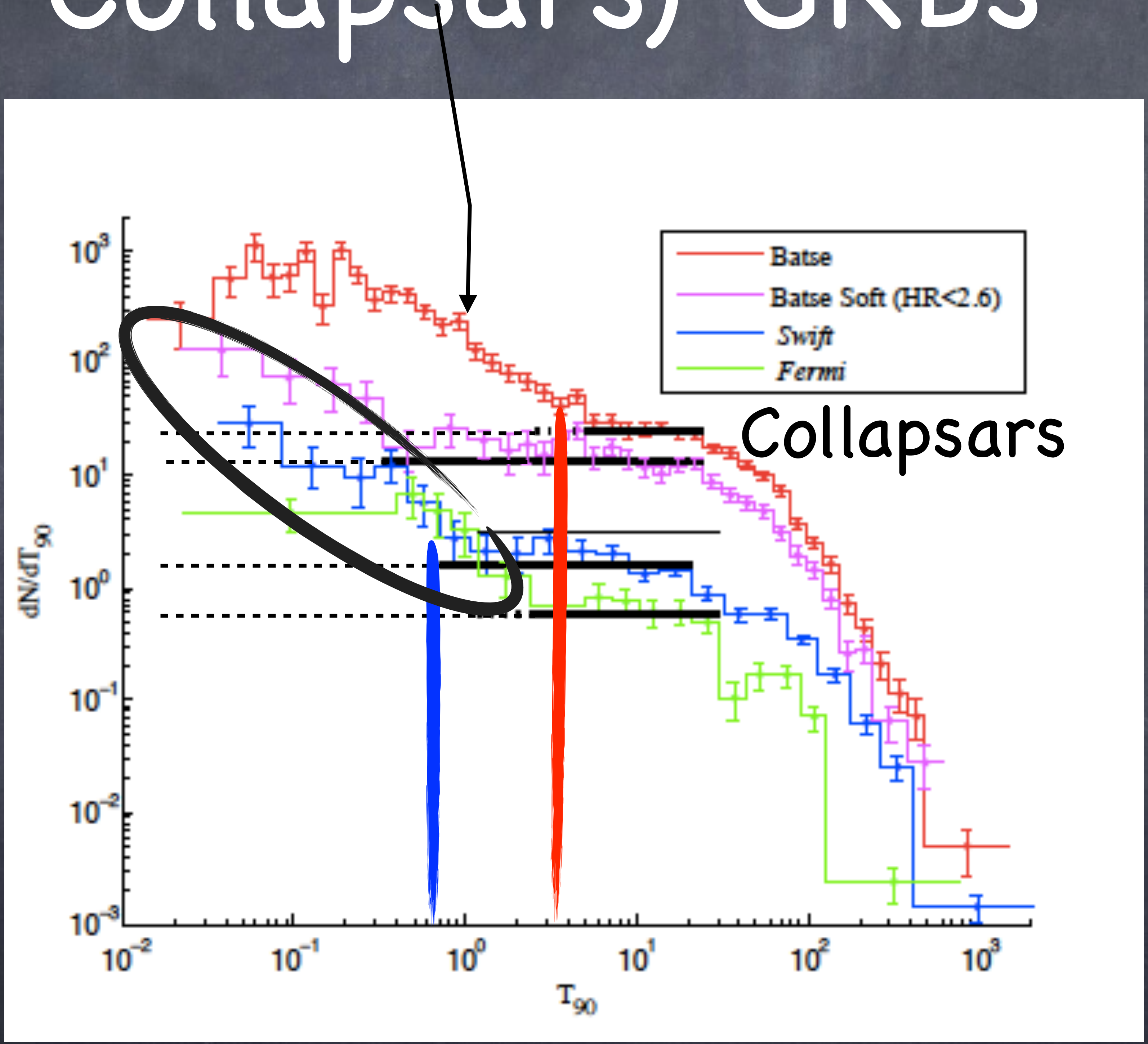

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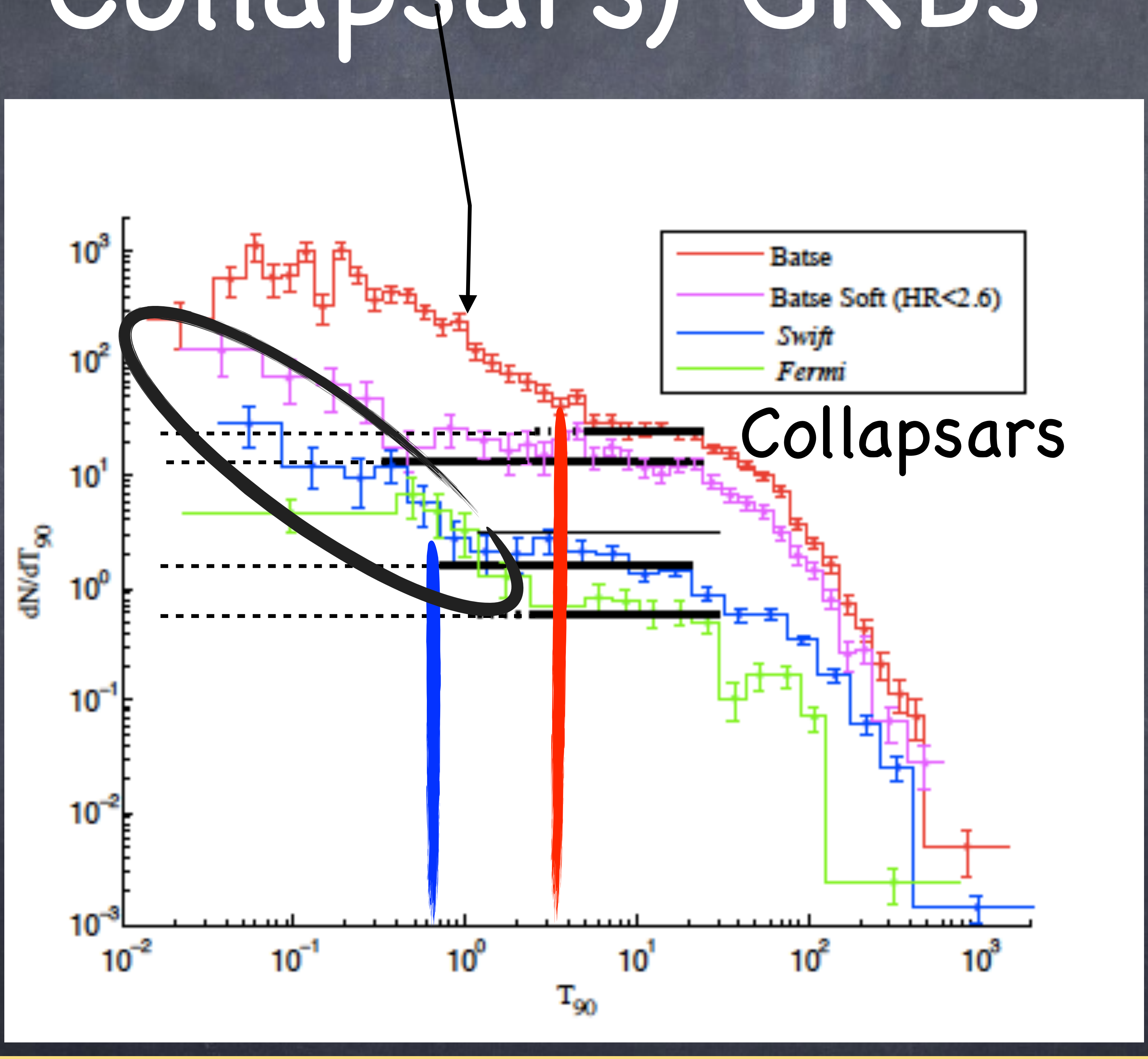
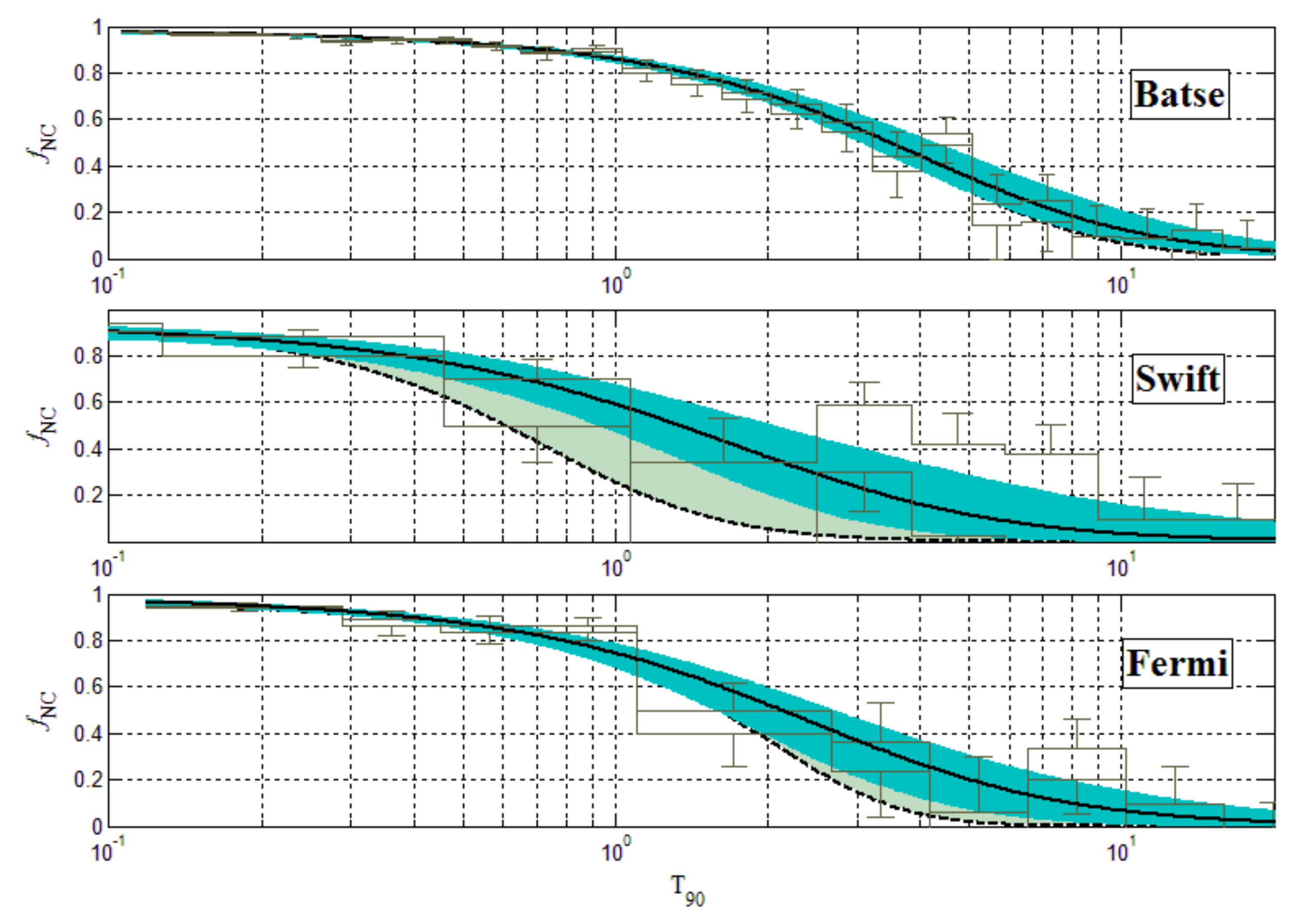


Short Swift GRBs with T_{90}>0.7sec are not "short"!

SGRB Fraction



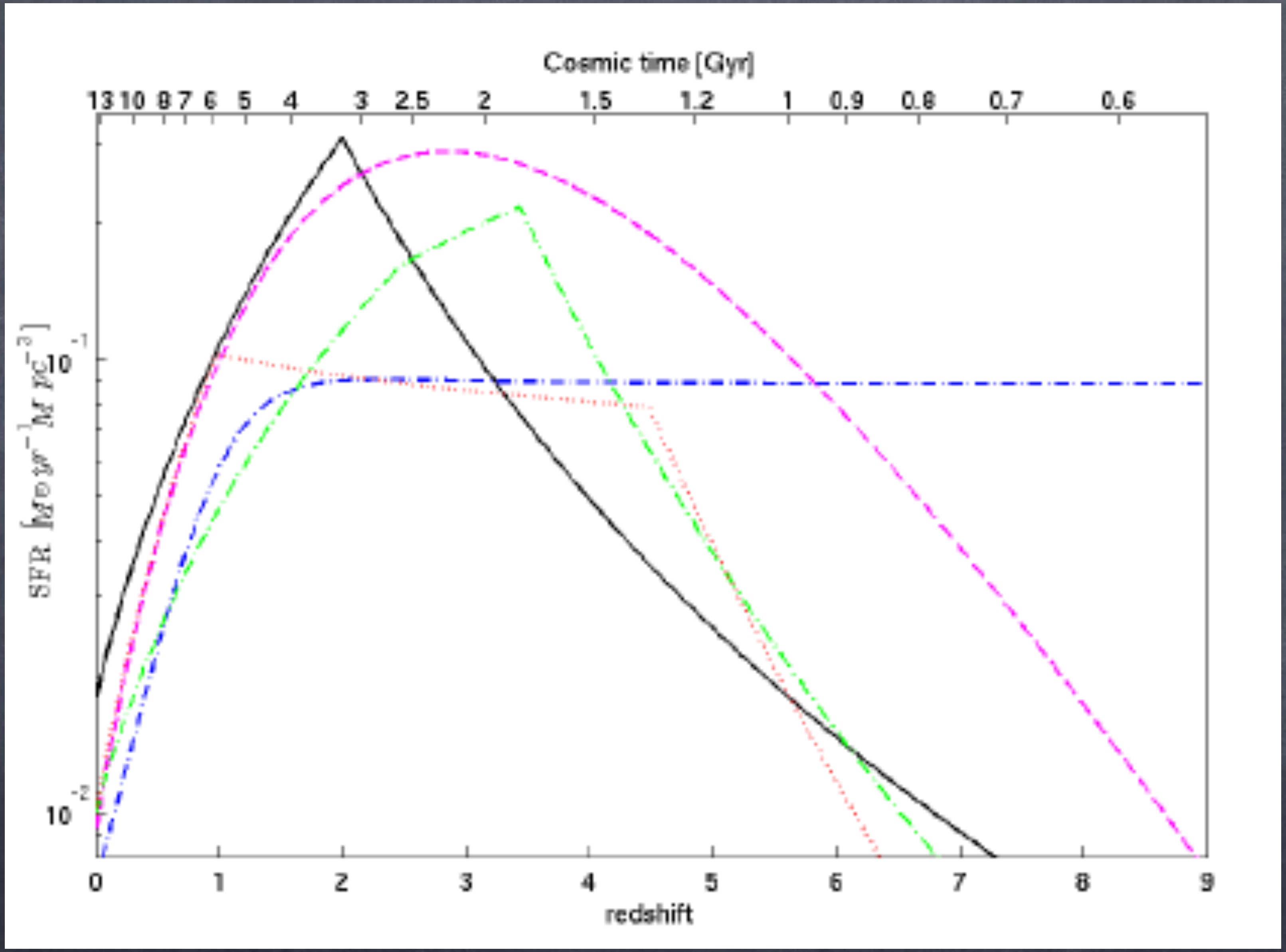
Bromberg et al , 2012 in perparation

The Rate of “non-Collapsars”

Wanderman & TP, 14

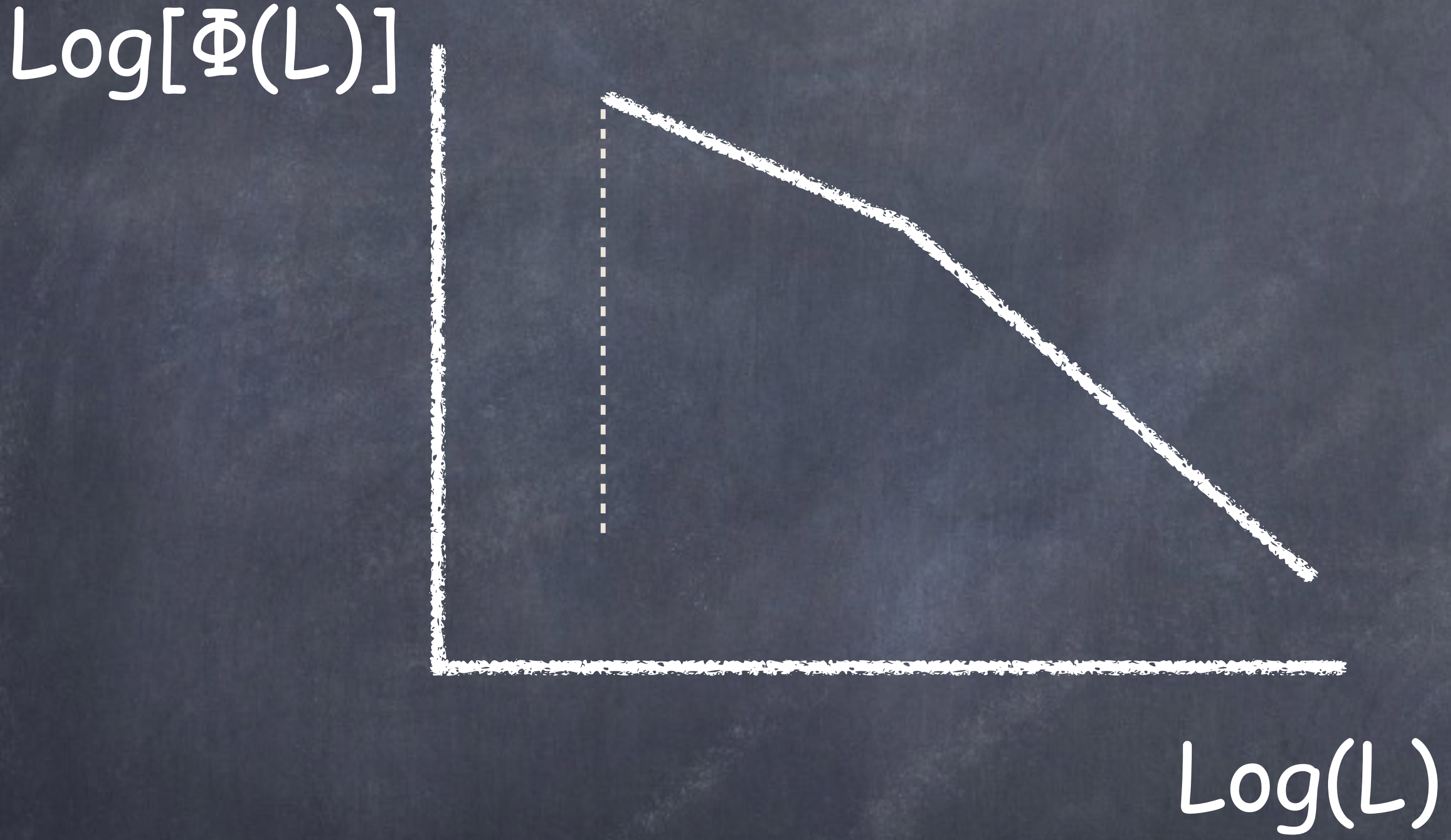
- Our Sample
  - BATSE short (<2 sec bursts) [peak flux]
  - Fermi short (<2 sec bursts) [peak flux]
  - Swift short with redshift and high probability of being non-Collapsars

The Rate



$$R_{sGRB}(z) \propto \int_z^{\infty} SFR(z')(f(t(z) - t(z'))\frac{dt}{dz'}dz' \, .$$

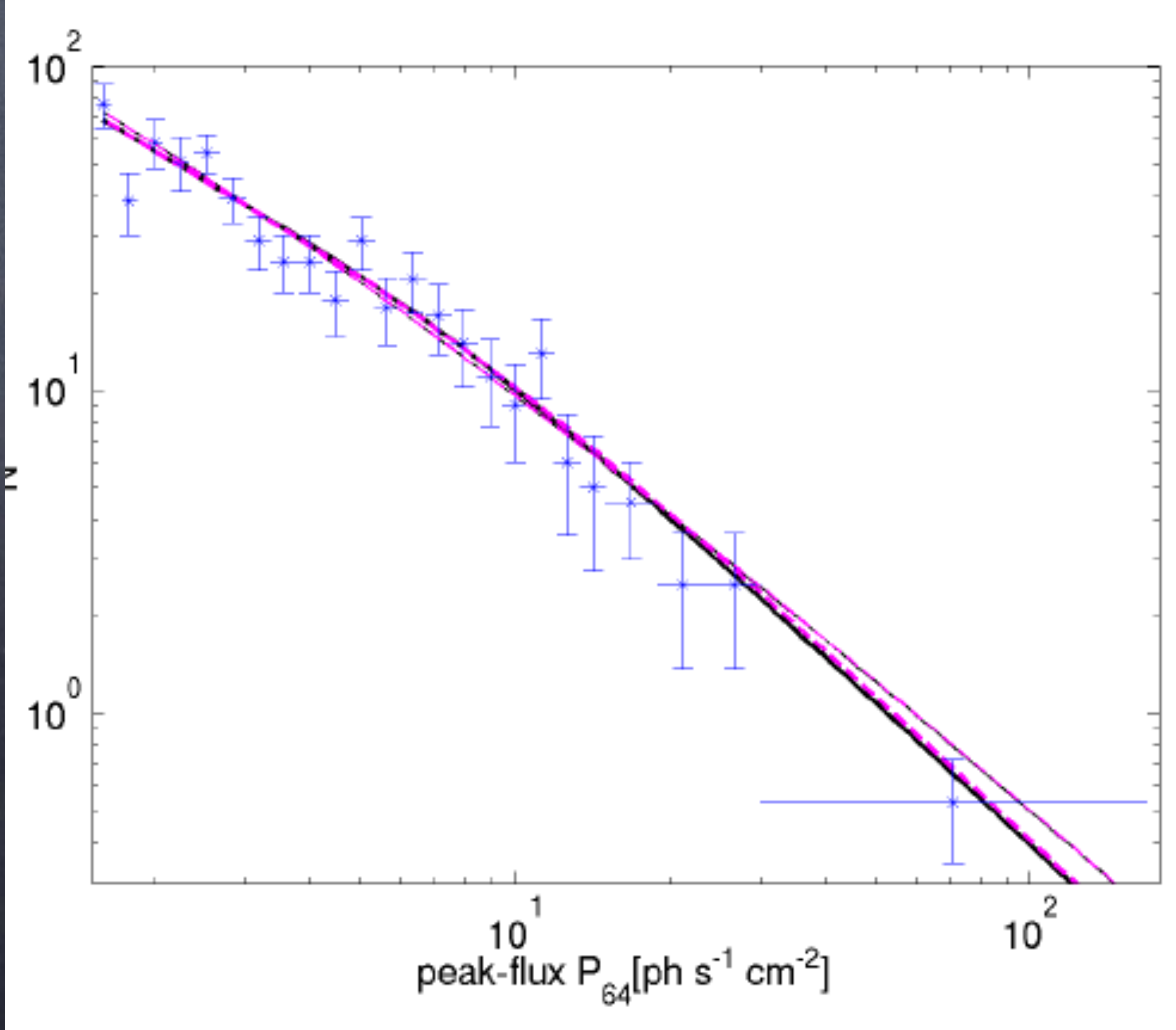
The Luminosity Function



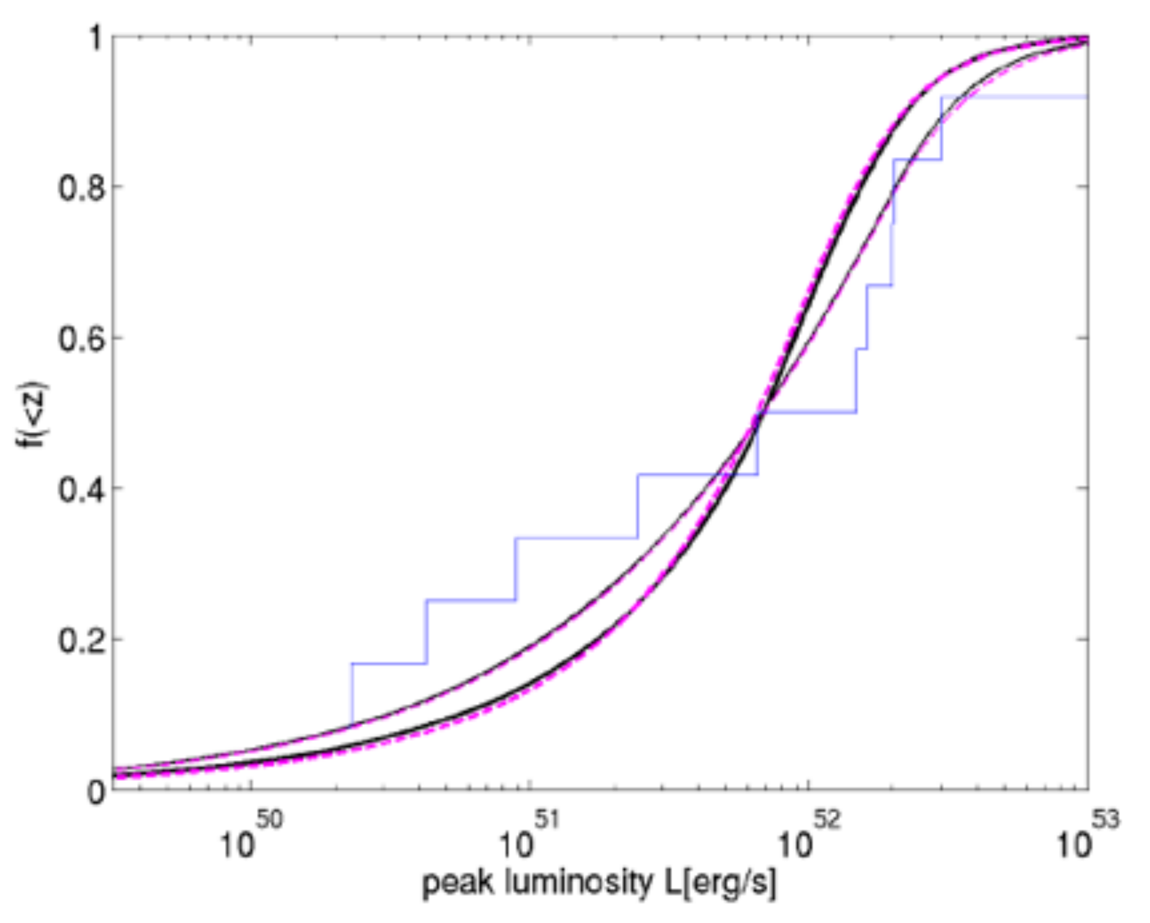
$$\phi_0(L) = \begin{cases} \left(\frac{L}{L^*}\right)^{-\alpha_L} & L < L^*\,; \\ \left(\frac{L}{L^*}\right)^{-\beta_L} & L > L^*\,. \end{cases}$$

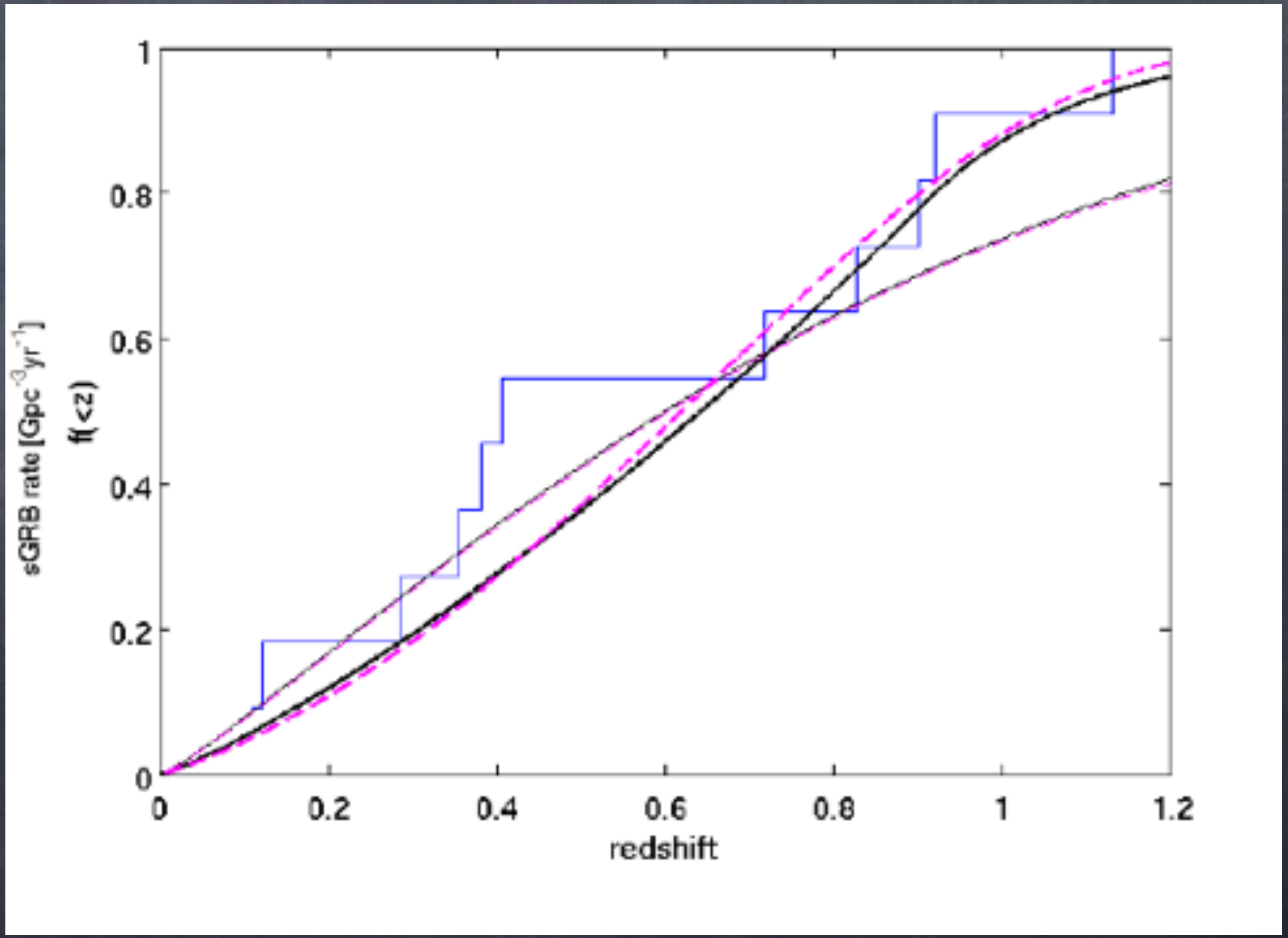
MAXIMUM LIKELIHOOD

$$\mathcal{L} = \prod_{i}^{BATSE} \left(\frac{N'(P_i)}{\int_{P_{min}^{BATSE}}^{P_{max}^{BATSE}} N'(P)dP} \right) \prod_{j}^{Fermi} \left(\frac{N'(P_j)}{\int_{P_{min}^{Fermi}}^{P_{max}^{Fermi}} N'(P)dP} \right) \prod_{k}^{Swift} \left(\frac{\phi_0(L_k) R_{sGRBs}(z_k)}{\int_{P_{min}^{Swift}}^{P_{max}^{Swift}} N'(P)dP} \right)$$

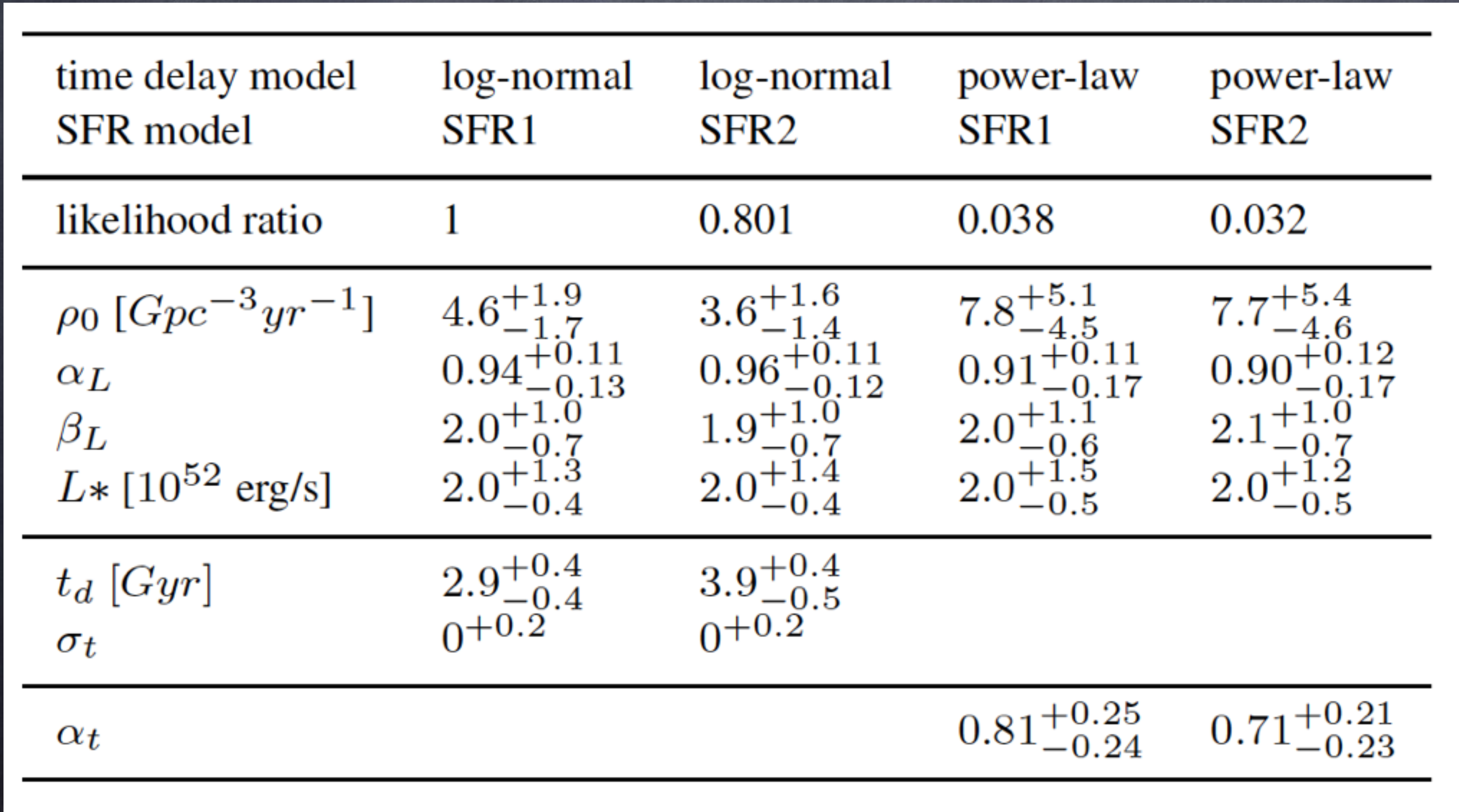


FITTING THE DATA



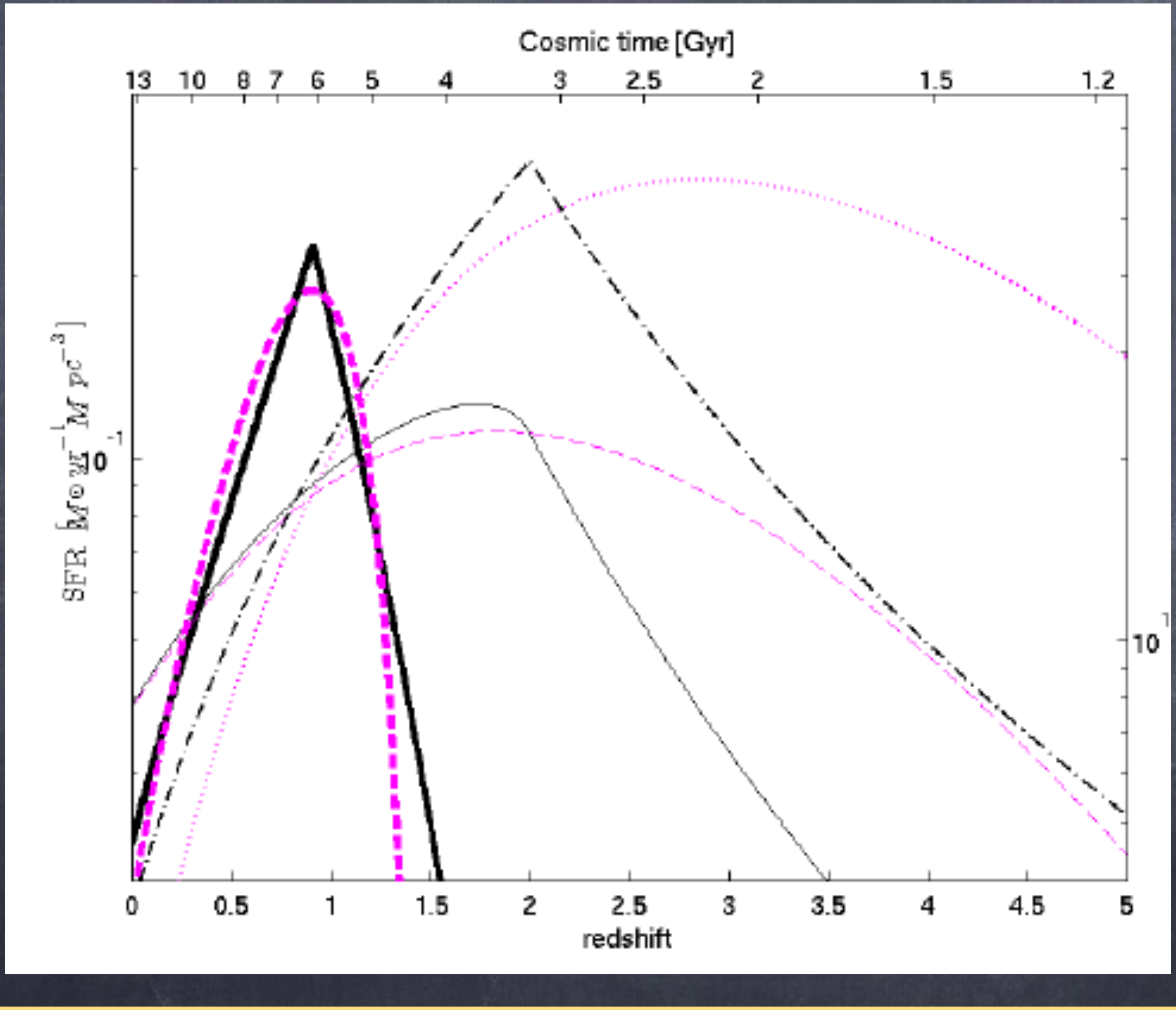


Best Fit Parameters



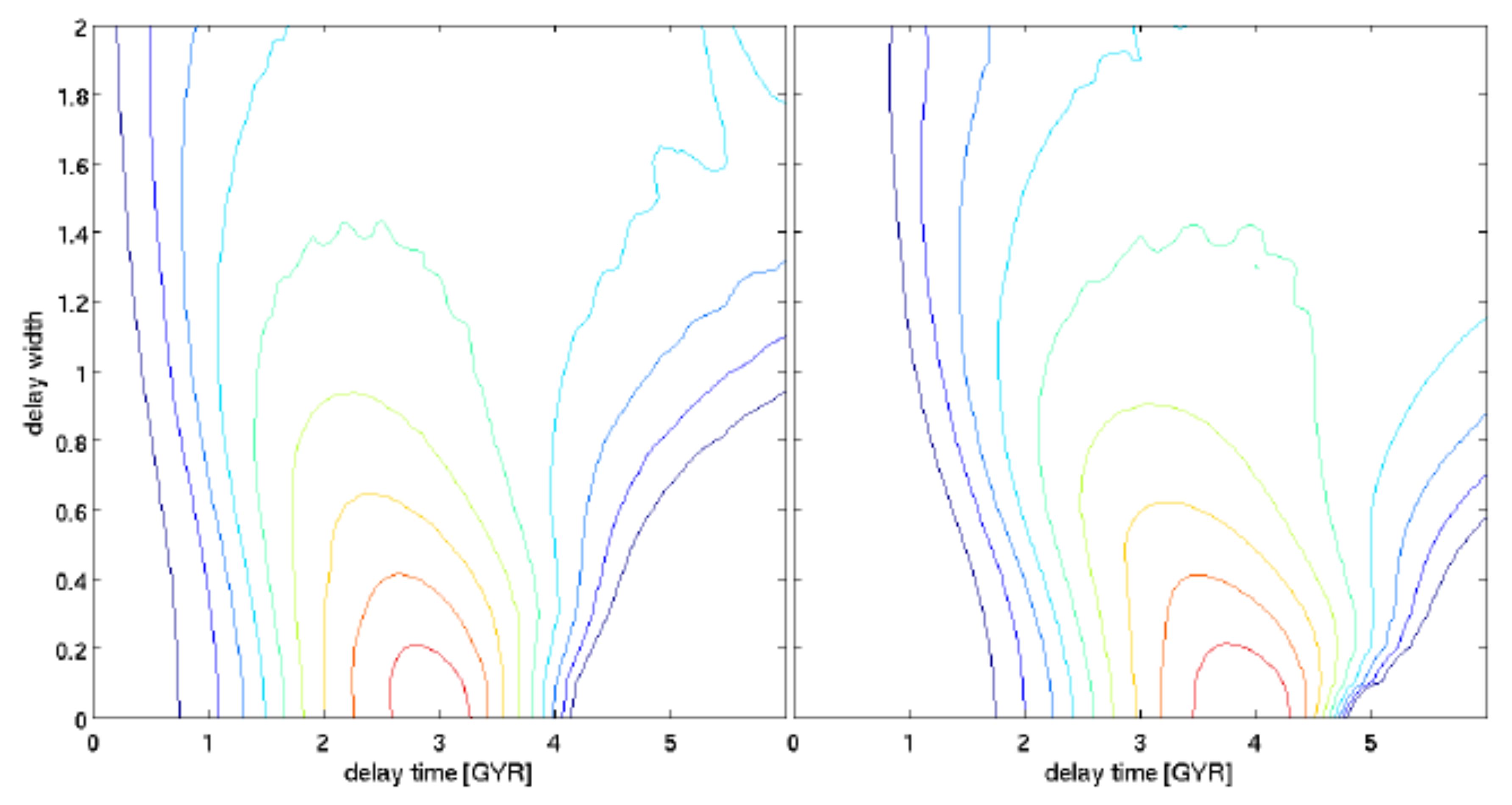
time delay model SFR model	log-normal SFR1	log-normal SFR2	power-law SFR1	power-law SFR2
likelihood ratio	1	0.801	0.038	0.032
ρ_0 $[Gpc^{-3} yr^{-1}]$	$4.6^{+1.9}_{-1.7}$	$3.6^{+1.6}_{-1.4}$	$7.8^{+5.1}_{-4.5}$	$7.7^{+5.4}_{-4.6}$
α_L	$0.94^{+0.11}_{-0.13}$	$0.96^{+0.11}_{-0.12}$	$0.91^{+0.11}_{-0.17}$	$0.90^{+0.12}_{-0.17}$
β_L	$2.0^{+1.0}_{-0.7}$	$1.9^{+1.0}_{-0.7}$	$2.0^{+1.1}_{-0.6}$	$2.1^{+1.0}_{-0.7}$
$L*$ $[10^{52}$ erg/s$]$	$2.0^{+1.3}_{-0.4}$	$2.0^{+1.4}_{-0.4}$	$2.0^{+1.5}_{-0.5}$	$2.0^{+1.2}_{-0.5}$
t_d $[Gyr]$	$2.9^{+0.4}_{-0.4}$	$3.9^{+0.4}_{-0.5}$		
σ_t	$0^{+0.2}$	$0^{+0.2}$		
α_t			$0.81^{+0.25}_{-0.24}$	$0.71^{+0.21}_{-0.23}$

The intrinsic redshift distribution



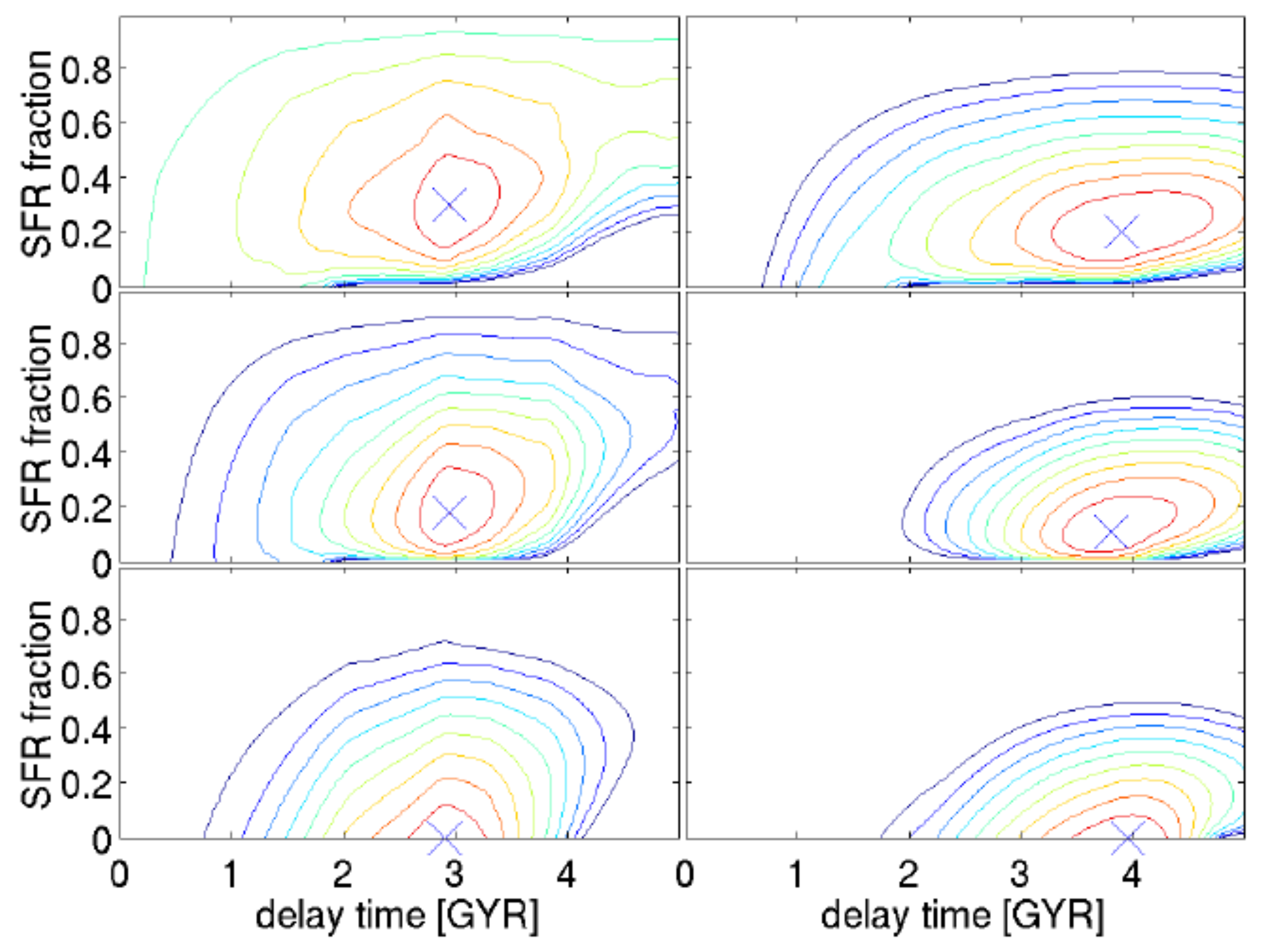
The rate was higher in the past

The time delay

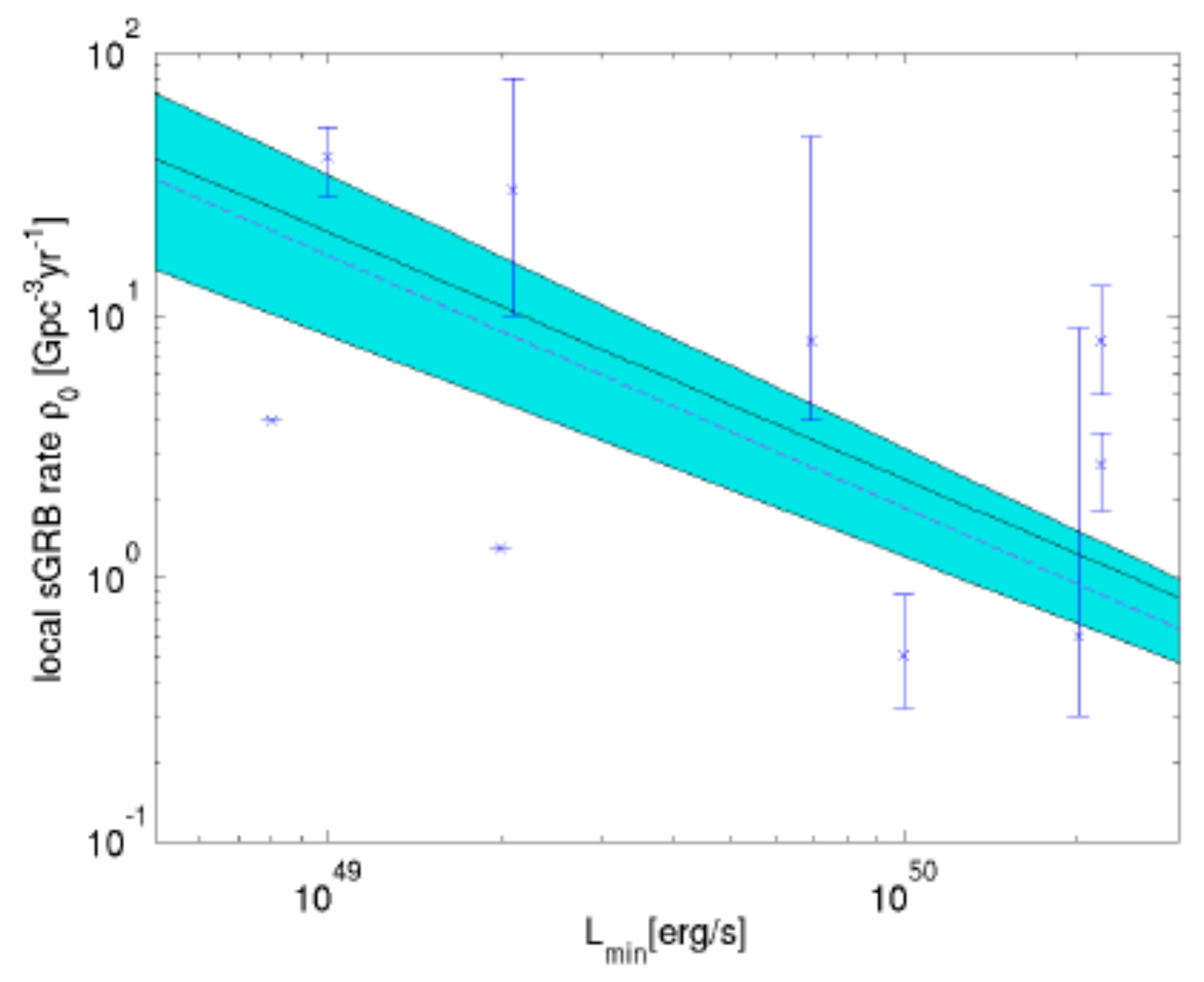


Collapsars and non-Collapsars

$$R(z) = (1 - f_{SFR}) \cdot R_{sGRB}(z) + f_{SFR} \cdot SFR(z),$$



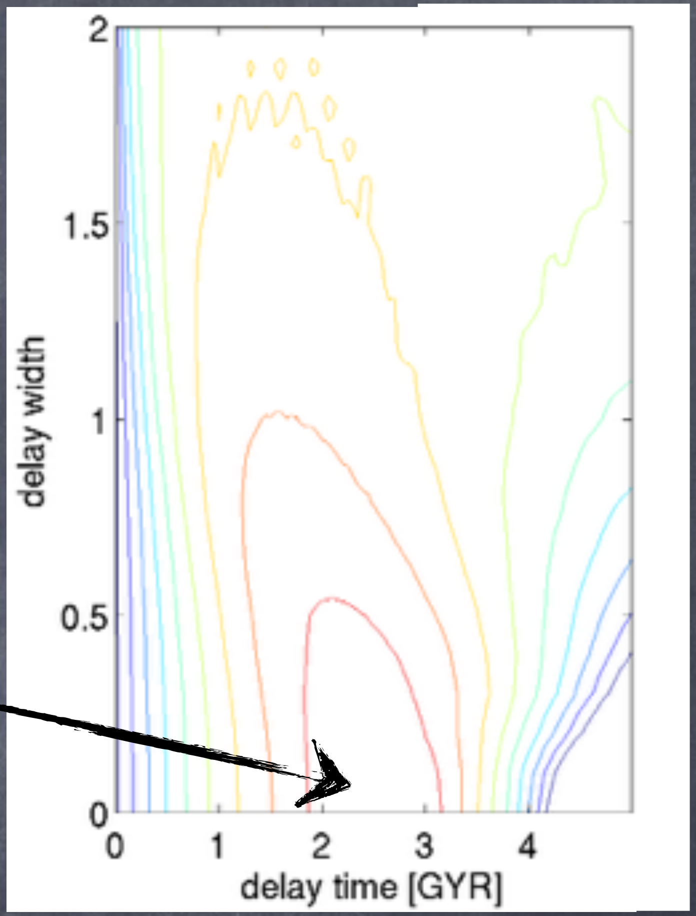
The local sGRB rate



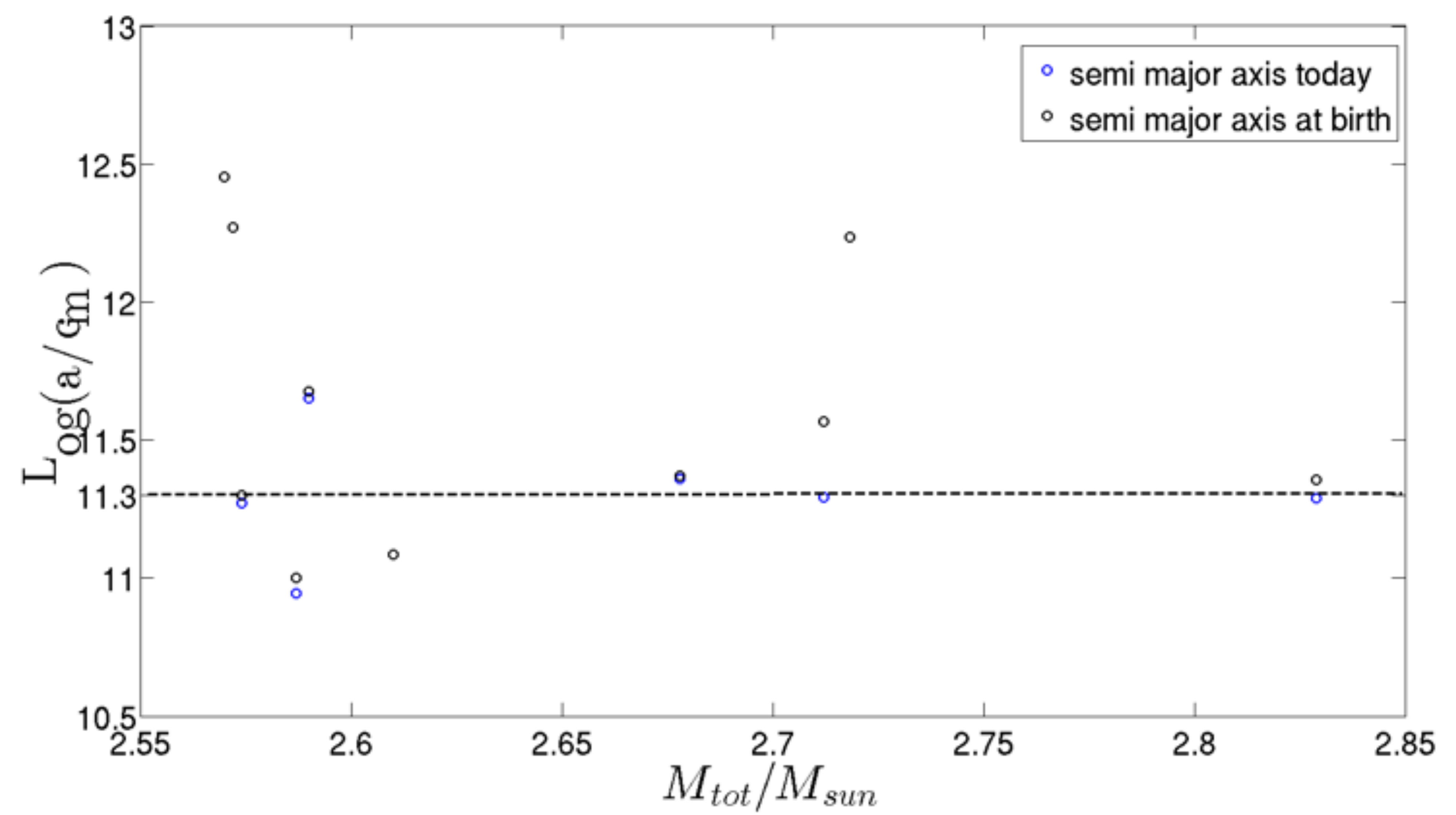
The rate of sGRBs

Guetta & TP 2006; Wanderman & TP 2014

- $R_{sgrb}=4\pm2\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
- Typical spiral-in phase of 2.5 Gyr.
- Consistent with $R_{merger} = 200\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ for a reasonable beaming factor of 30.
- Consistent with rate estimaes based on galactic neutron star binaries.



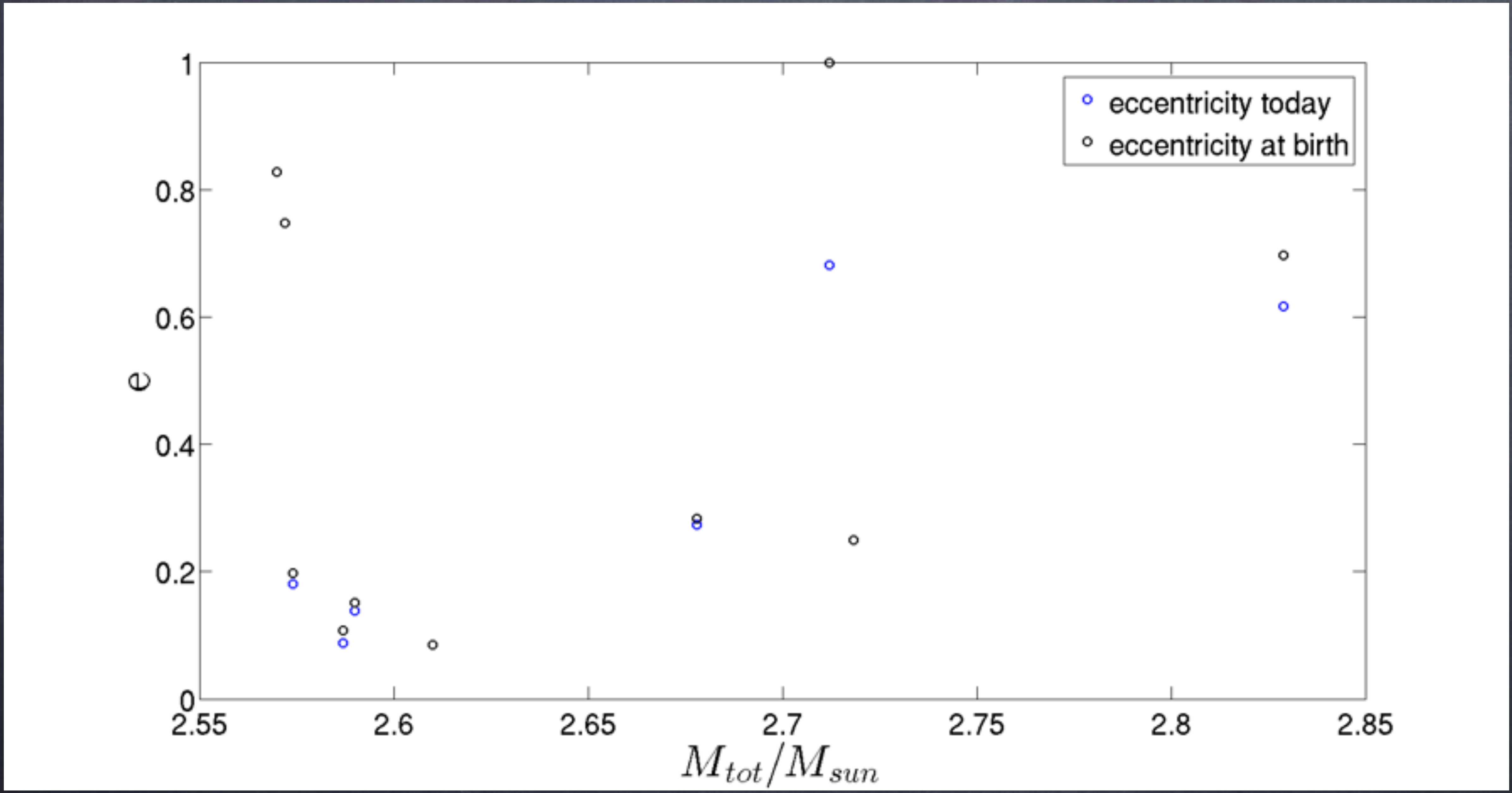
The NS^2 Sample



2.9 Gyr <-> $2\text{x}10^{11}$ cm

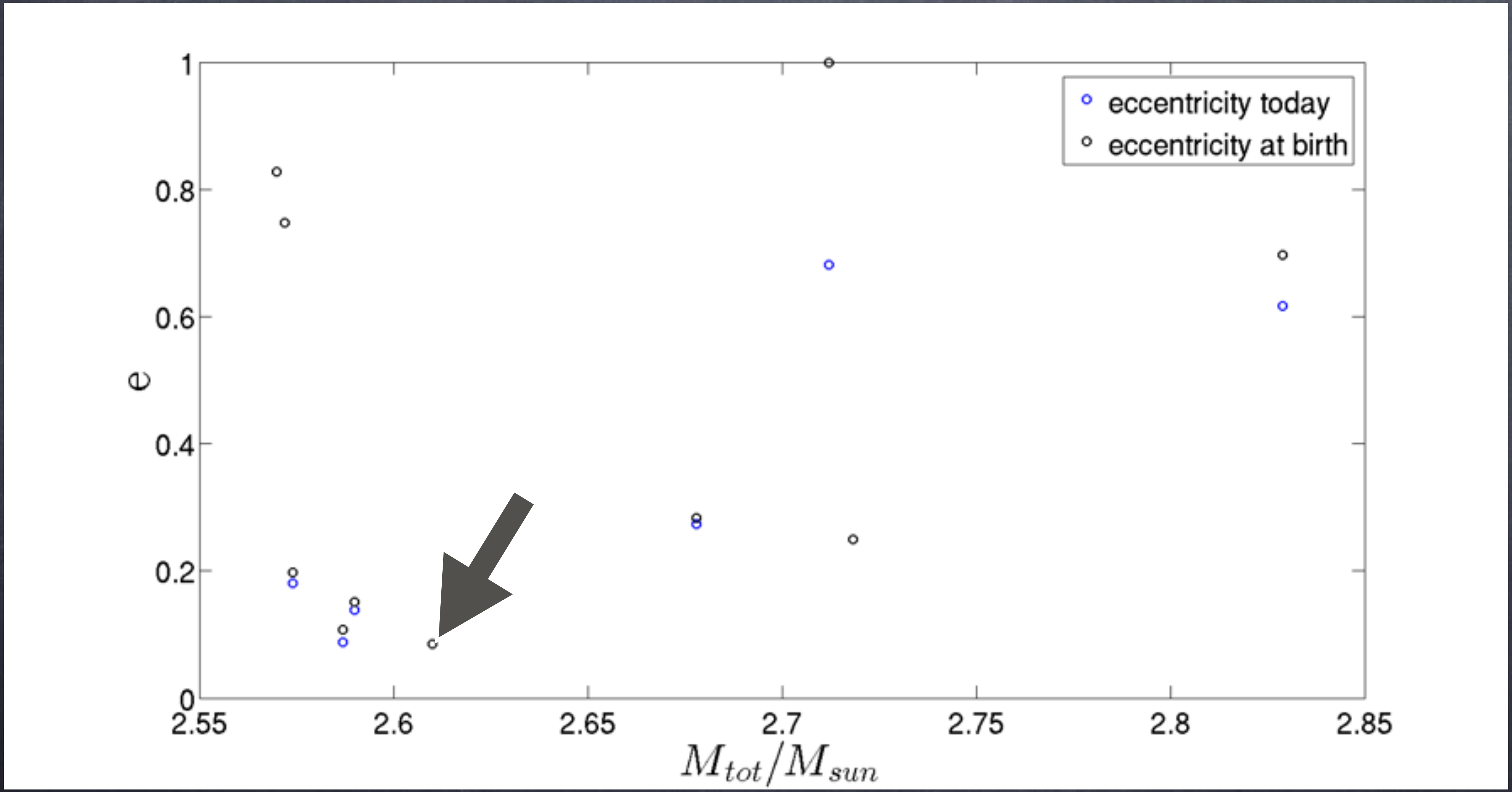
Eccentricity

Biniamini, Korobkin & TP, 14



Eccentricity

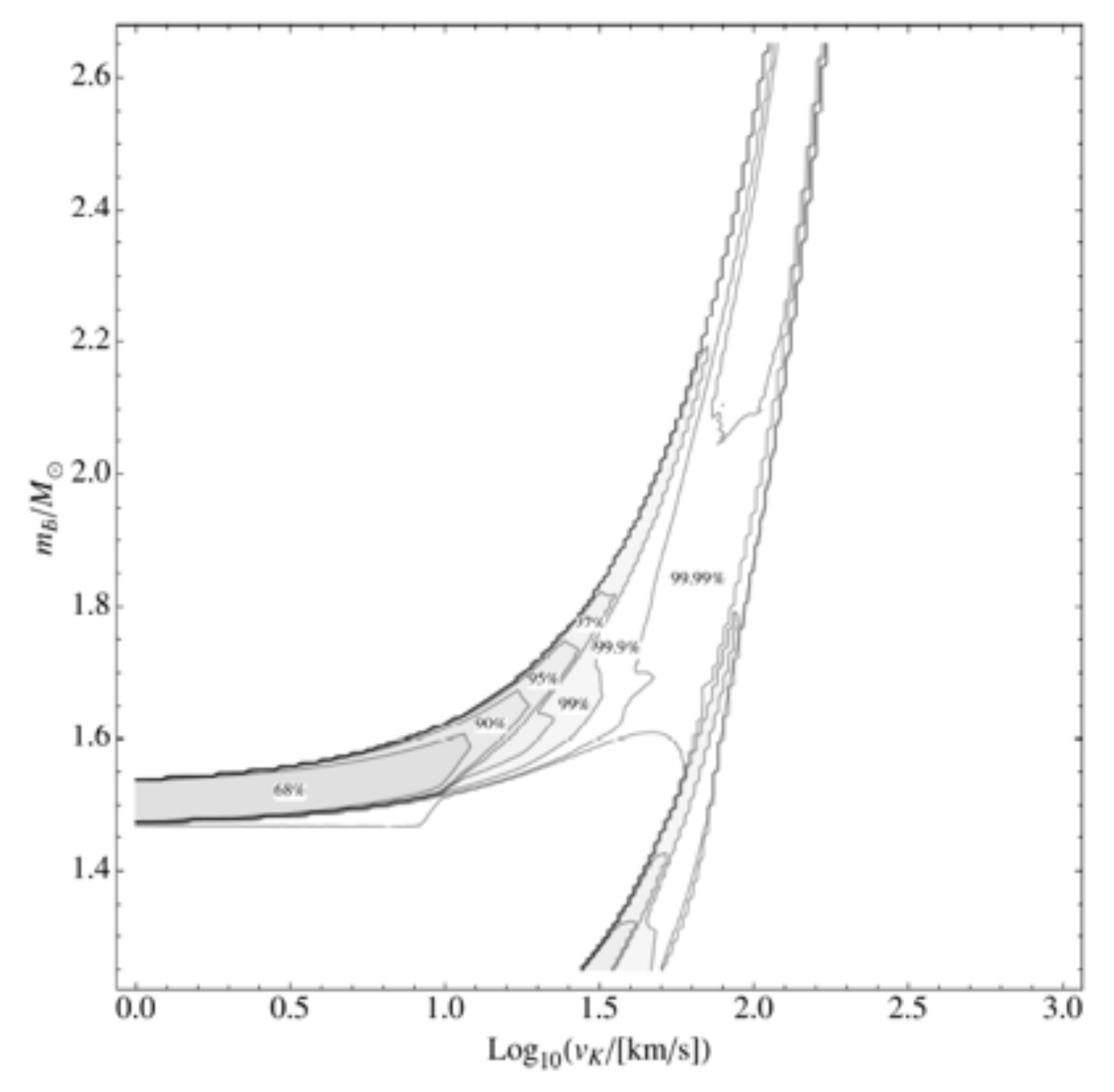
Biniamini, Korobkin & TP, 14



J0737-3039 (the double pulsar)

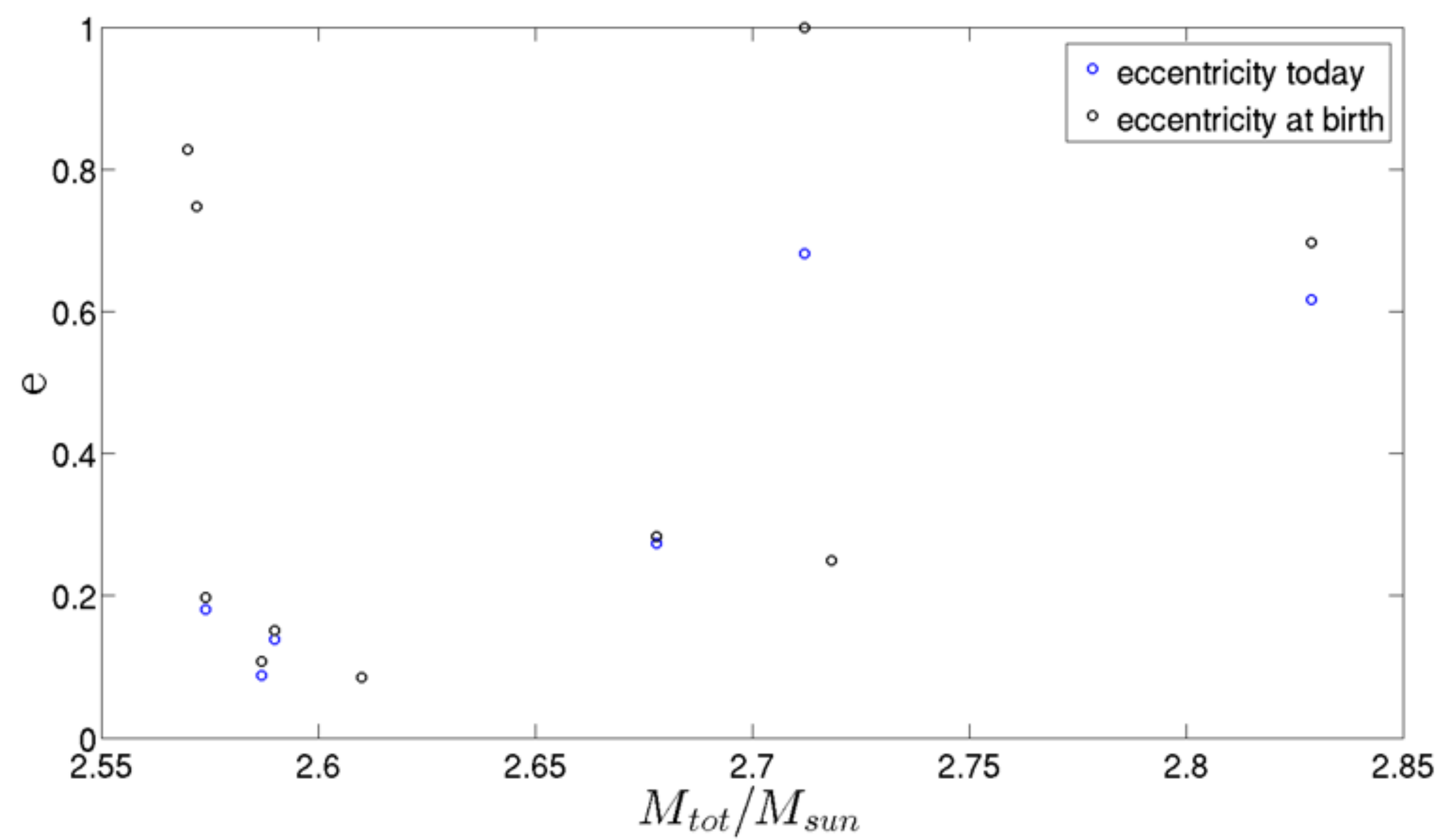
TP & Shaviv 05, Dall'Osso, TP Shaviv 14

- J0737 was not born in a regular SN
- Progenitors mass ~1.5 M_{sun}
- Ejected mass ~0.1-0.15 M_{sun}



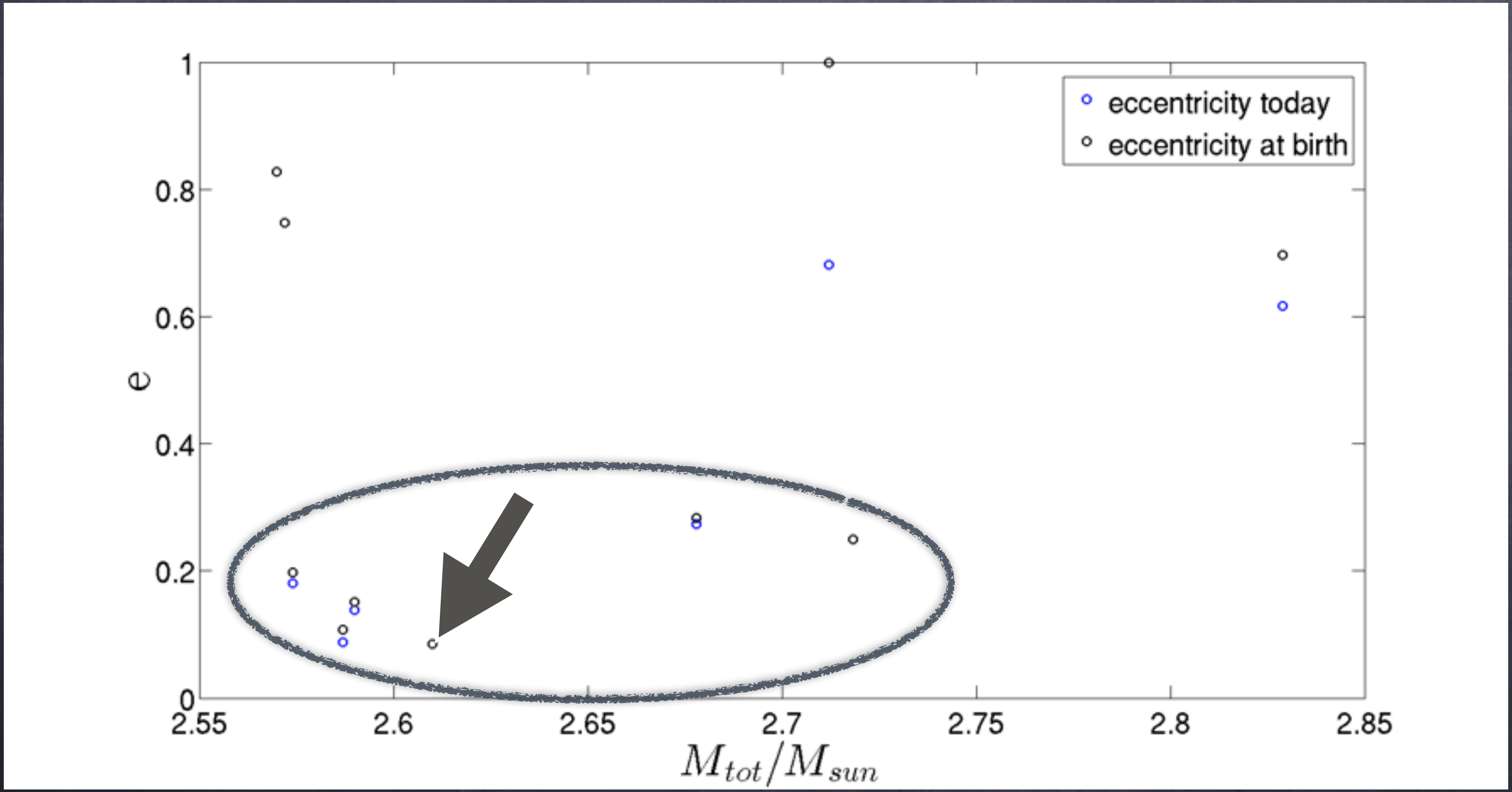
Eccentricity

Biniamini, Korobkin & TP, 14



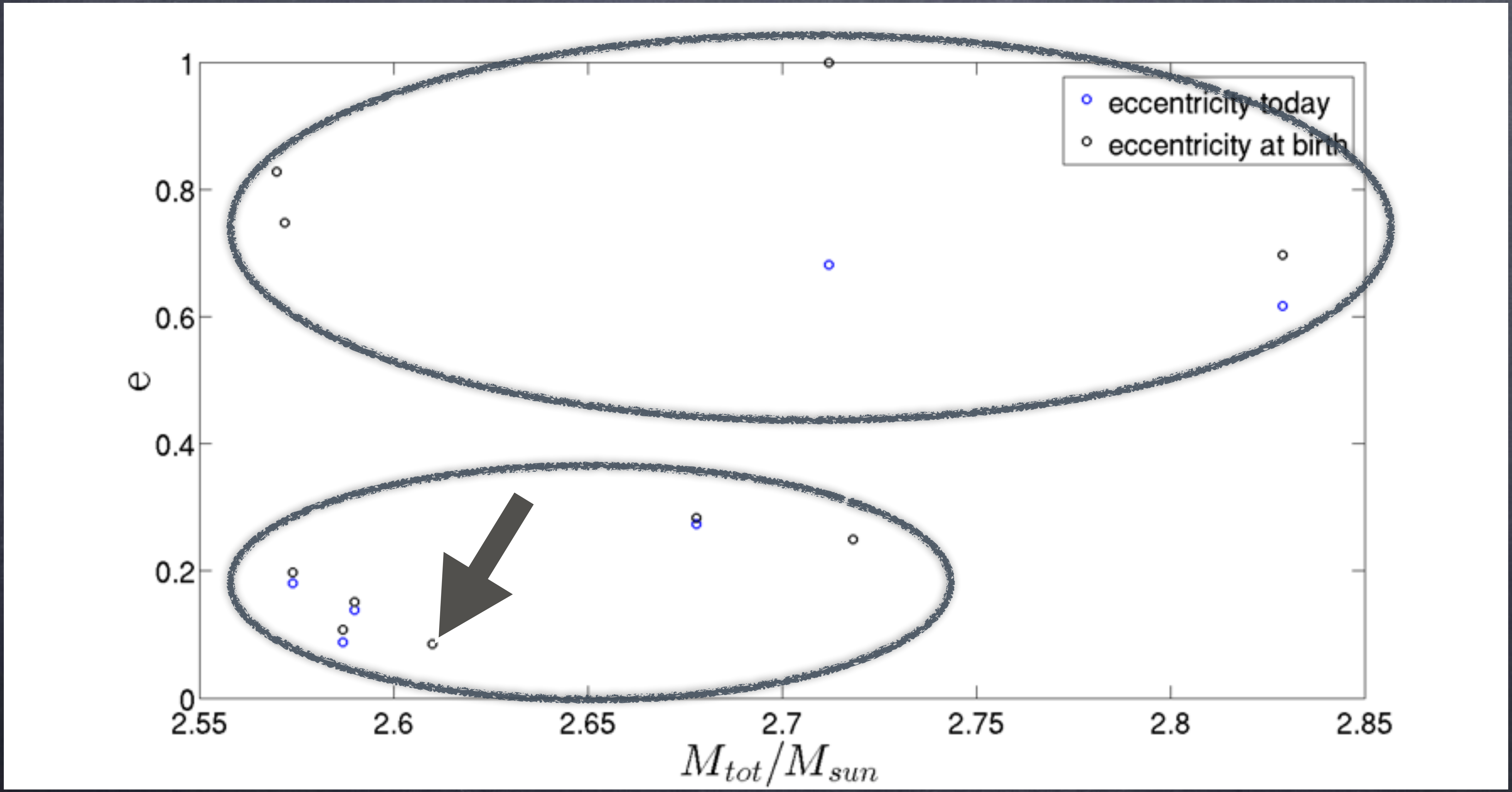
Eccentricity

Biniamini, Korobkin & TP, 14



Eccentricity

Biniamini, Korobkin & TP, 14



ALIGO Detection Rate

- With this rate we expect 0.1-3* joint ALIGO/(300 Mpc) sGRB per year (provided that there is a GRB satellite at the time).
- With a beaming factor of ~30 -> 3-100 ALIGO events per year.

* x covering factor of the GRB detector.

r-process nucleosynthesis

Eichler, Livio, TP & Schtamm, 89;
TP, Korobkin & Rossowg, 14

- 1.4 x 10^4 sGRBs pointing towards us within the Milky way.
- With a beaming factor of 30 -> sufficient to produce the observed heavy r-Process

Early nucleosynthesis - a challenge

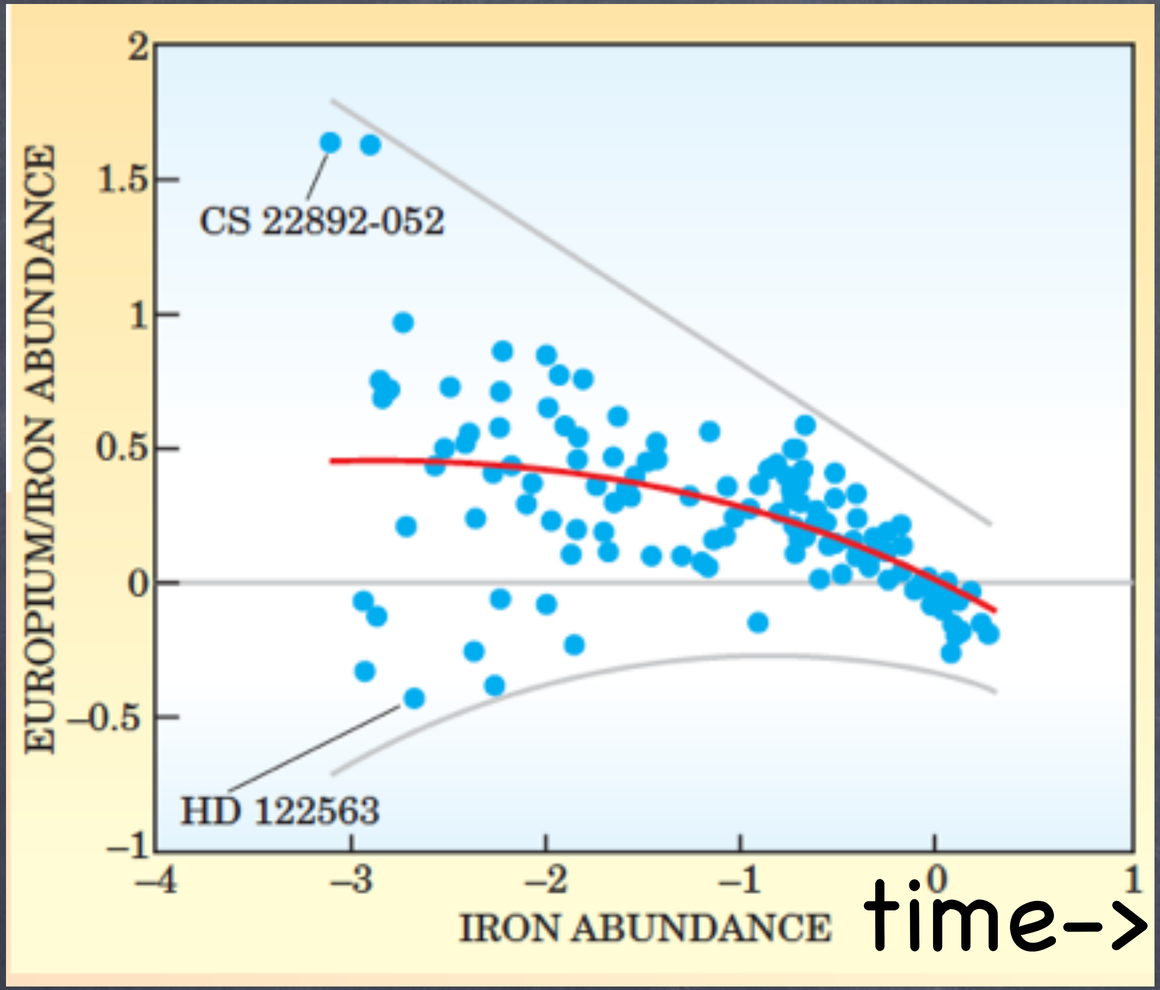


Figure 6. Europium abundance in a large sample of old and young stars, age being inferred from Fe abundance. The halo star HD 122563 is almost as Fe-poor as CS 22892-052, and therefore presumably just about as old, but it has much less Eu, an element made only in the r-process. The red line is a least-square-fit to the data, and the gray flanking curves indicate decreasing scatter in the data with increasing time. Numerical conventions are as in figure 5. Zero on the abscissa means Fe abundance like that of the 4.6-billion-year-old Sun.

A population of fast mergers?

From Cowan and Thielemann

One cannot give a talk in Astronomy these days without a reference to the Solar System and life.

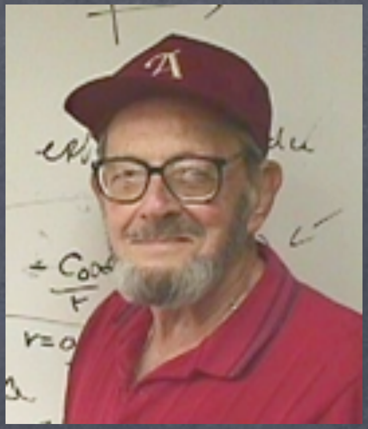
- sGRBs are too weak and too rate to pose danger to life due to events in the Galaxy.

  TP & Jimmenez, 14

Mergers and the early Solar system

Mergers and the early Solar system

- The early Solar System had ^{244}Pu (τ = 117 Myr) Wasserburg et al, (2006).



Gerry Wasserburg

No evidence for ^{244}Pu deposition in deep-sea crust and sediment accumulated over the last ~25 Myr (M. Paul et al., 2001; A. Wallner et al., in preparation).
=> ^{244}Pu is NOT from the Inter Stellar Medium!
=> Actinides production near the early Solar System just prior to formation.

- Irregular production from rare episodes.
  => E.g. a merger within <50 pc=150 lyr from the solar system just prior to its formation?

Summary

- About 1/3 of Swift short (<2sec) GRBs are Collapsars
- The rate of non-Collapsar short GRBs (sGRbs) is $4.1^{+2.3}_{-1.9}$ $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ (depending on the assumed minimal luminosity).
- A LIGO detection rate of 3-100 per year (0.1-3 coinciding with a sGRB*
- A typical time delay of ~3 Gyr after SFR
- Corresponding to an initial separation of $\sim 2 \times 10^{11}$ cm
- With beaming of ~30 and mass ejection of 0.02 M_{sun} - compatible with R-process nucleosynthesis for A>110 elements.

The END