The Origin of Cosmic Fireworks

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Julian Krolik, Eli Livne, Ehud Nakar,
Martin Obergaulinger, Re'em Sari

A Tale of Three Explosions

- Gamma Ray Bursts of all sorts
- Radio Flares from Neutron star mergers
- Tidal Disruption Events

I. The origin of GRBs?

- Bromberg, Nakar & TP, ApJL 2011

  Bromberg, Nakar, TP & Sari, ApJ 2011
- Bromberg, Nakar, TP & Sari, arXiv 1111.0969
- Bromberg, Nakar & TP to be submitted 2011
- Genet, Livne, Obergaulinger & TP to be submittd 2011

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- Duration 0.01-1000s

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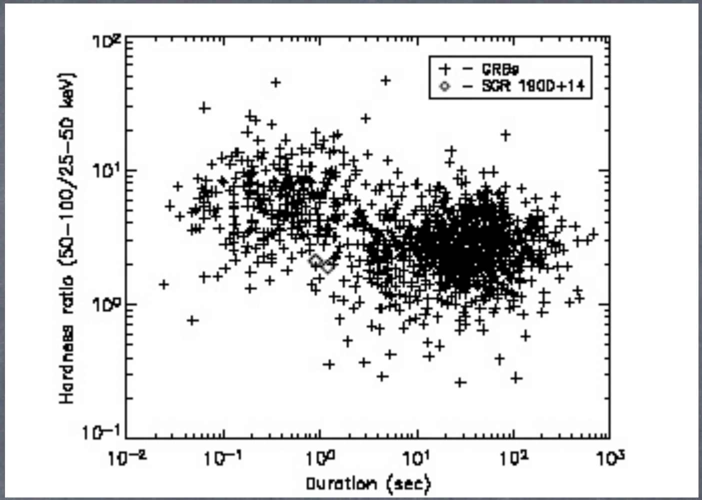

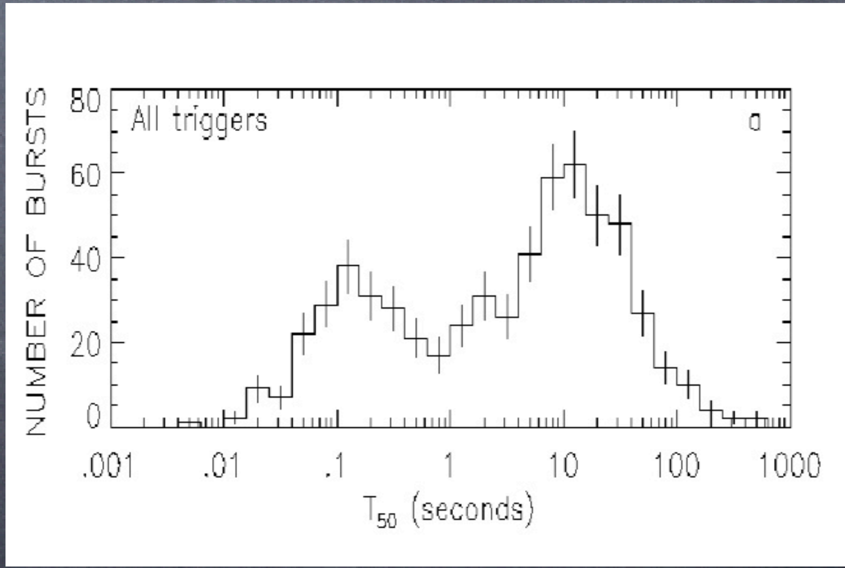

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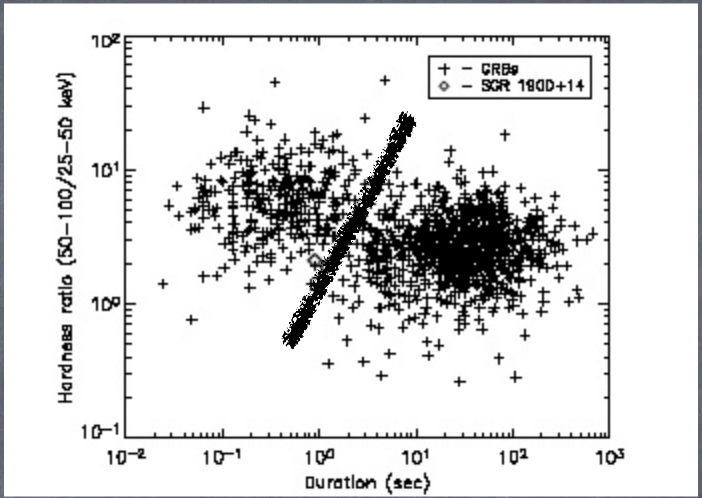

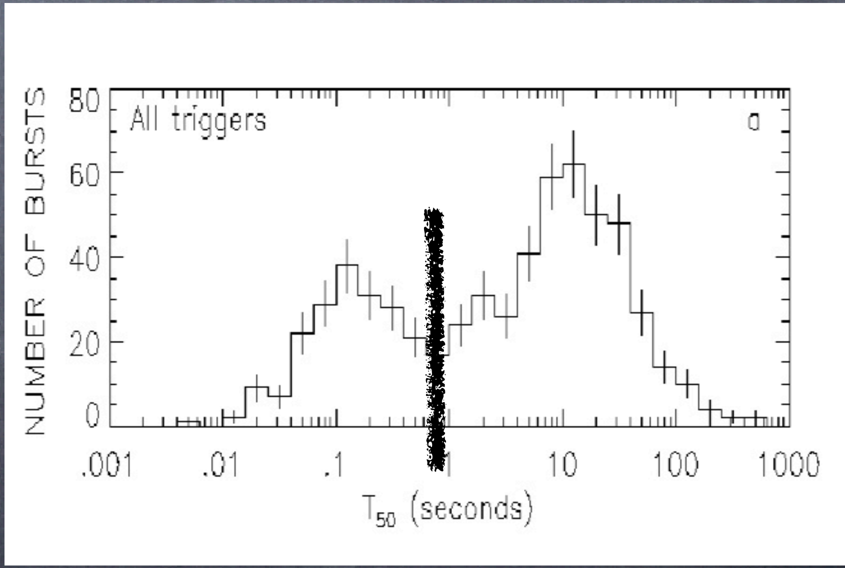

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  (very high energy tail,

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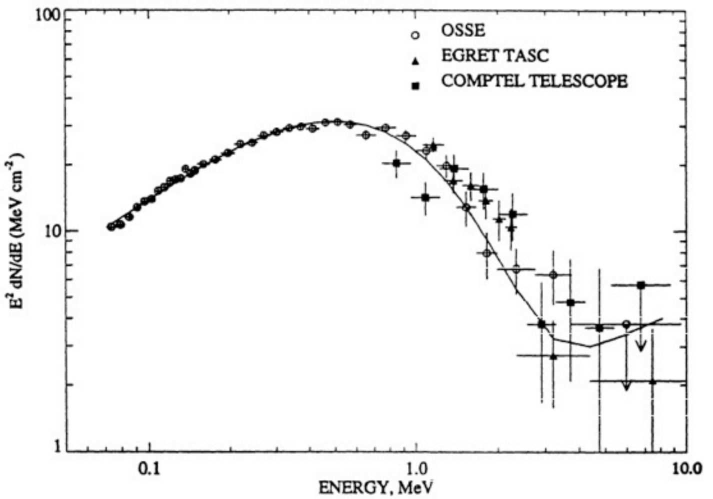

Figure 9 The spectrum of GB 910601 observed over a wide energy range, as measured by three experiments on *CGRO* (Share et al 1994). A typical broad spectrum with a peak power at about 600 keV is seen. (The fitted spectral up-turn above 4 MeV is not significant.)

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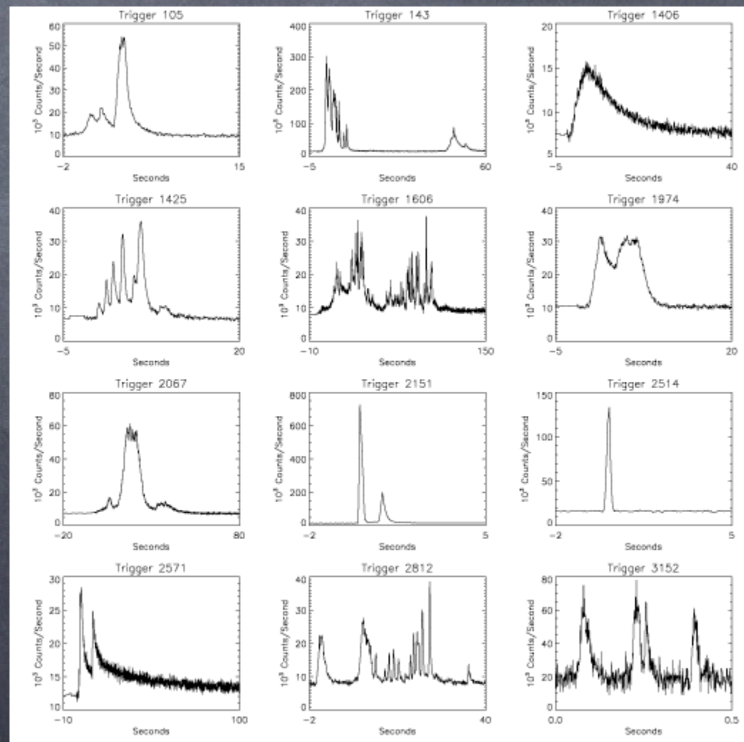

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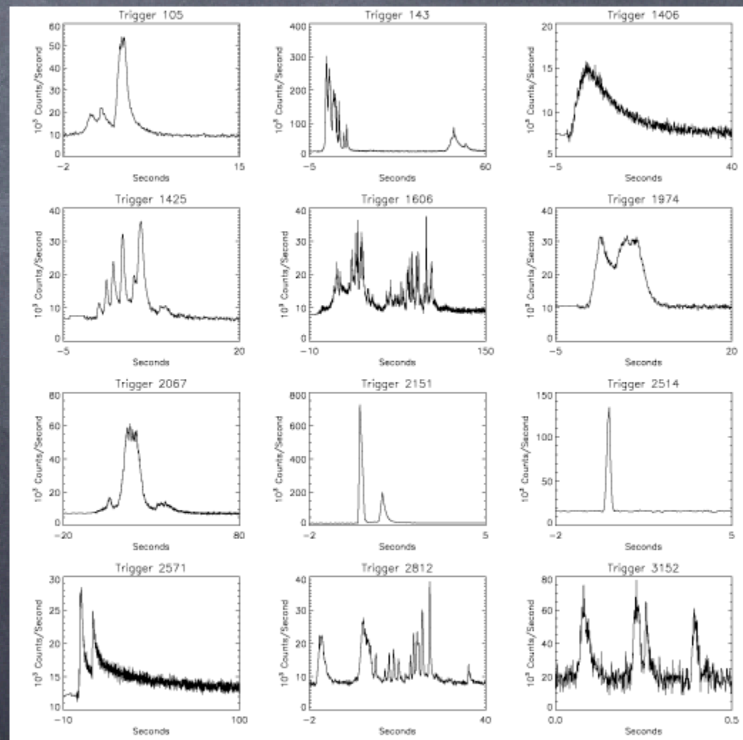

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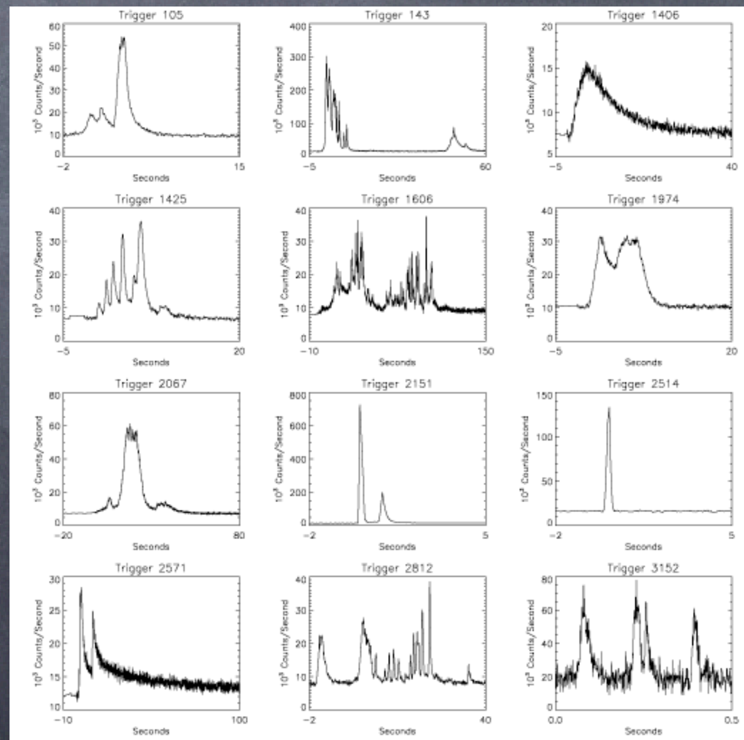

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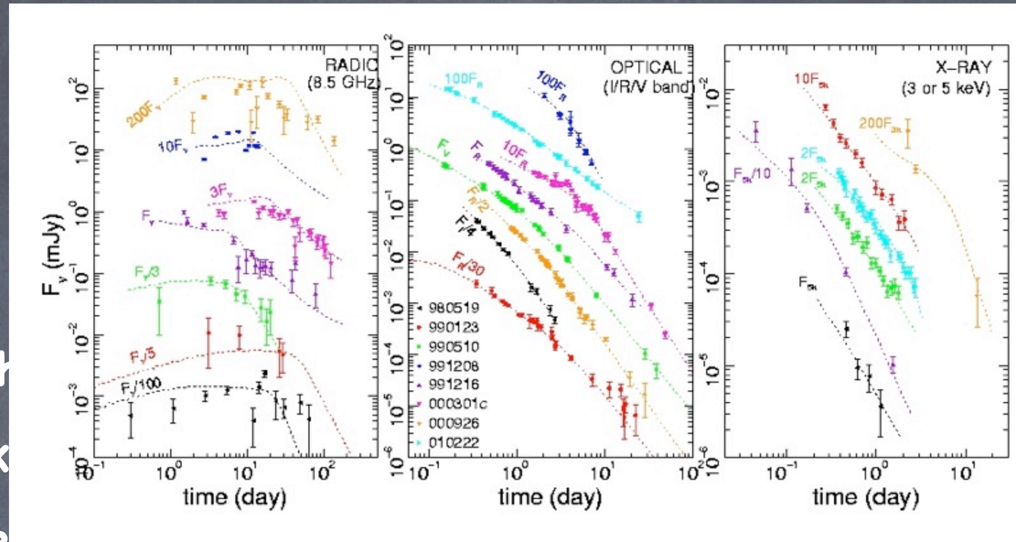
- Followed by multiwavelength

  Afteglow



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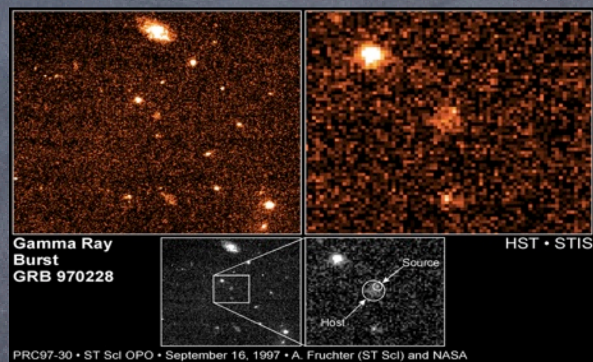
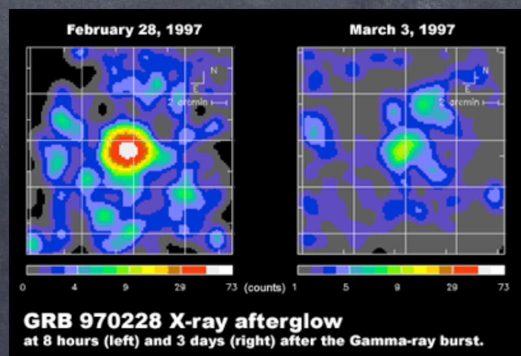
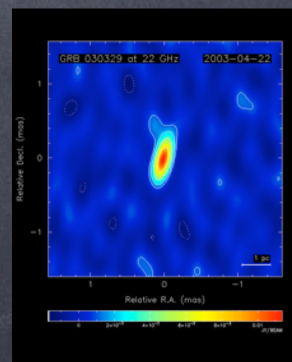


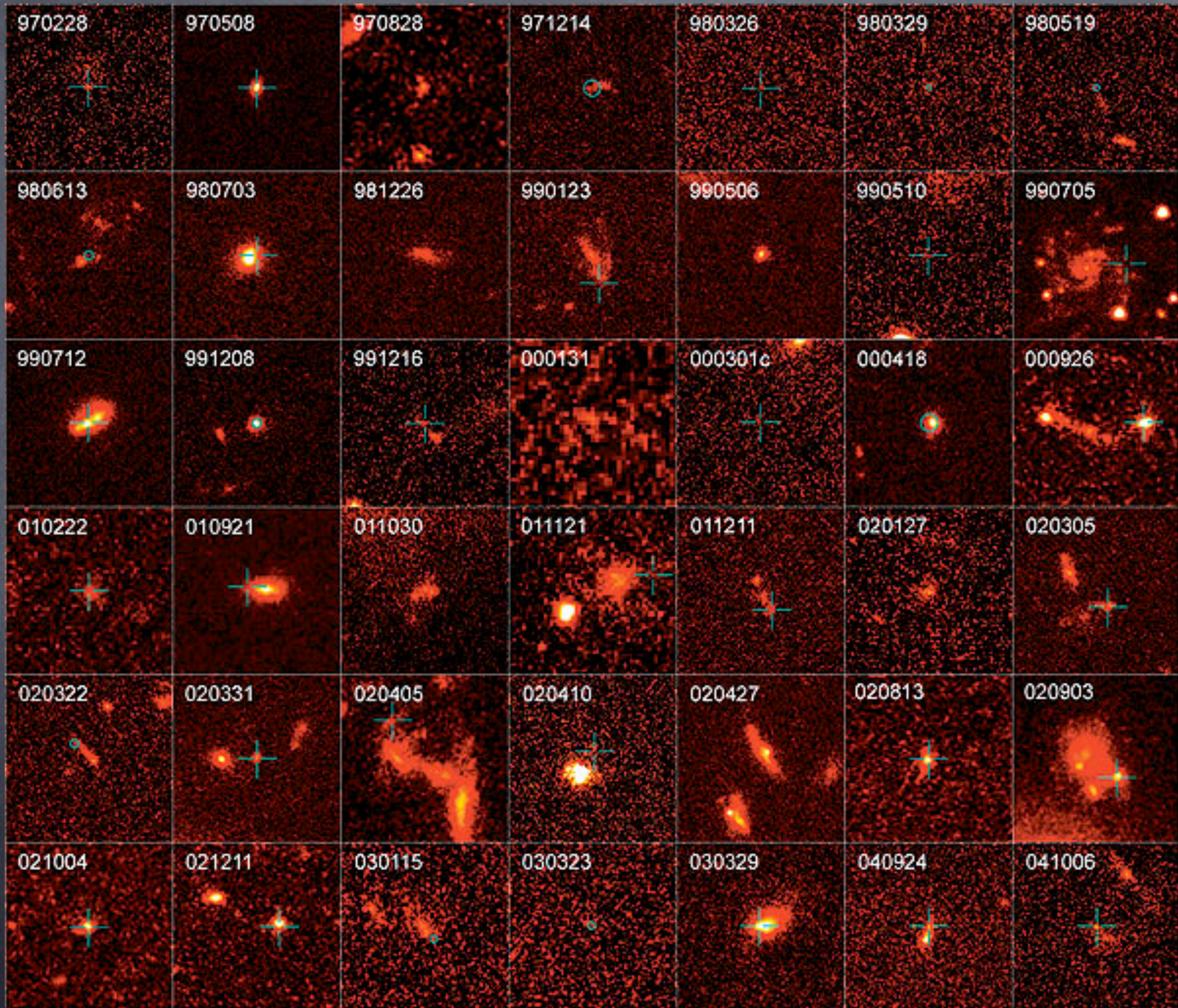




Energy, Energy, Energy + Time

- $E \approx 10^{51}$-10^{52} ergs ≈ the binding energy of a compact stellar mass object.
- 0.01-100 sec + $E \approx 10^{51}$-10^{52} ergs
  ⇒ a newborn stellar mass compact object.
- ⇒ Collapsing stars or mergers.

The (long) GRB-Supernova connection



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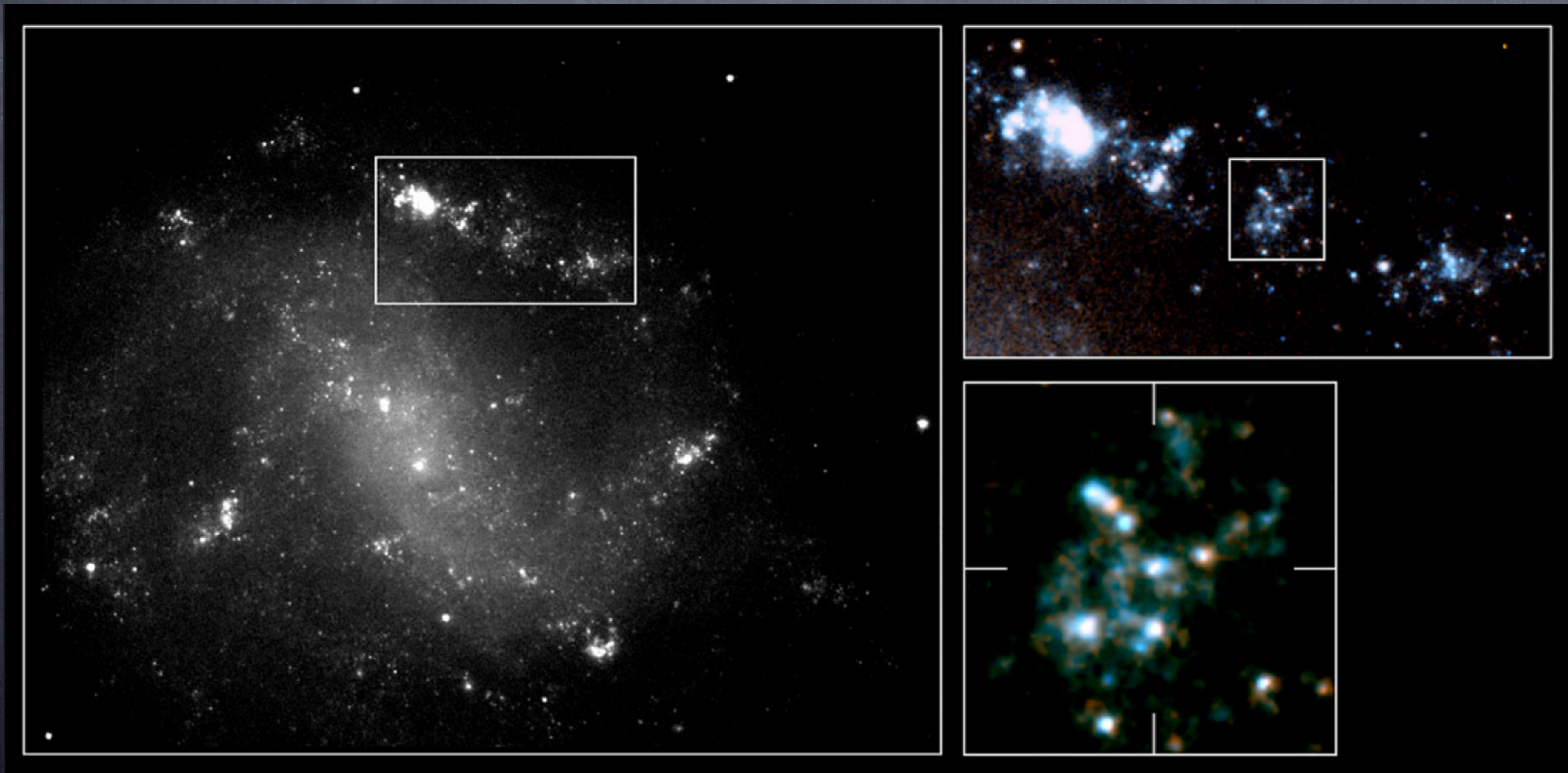
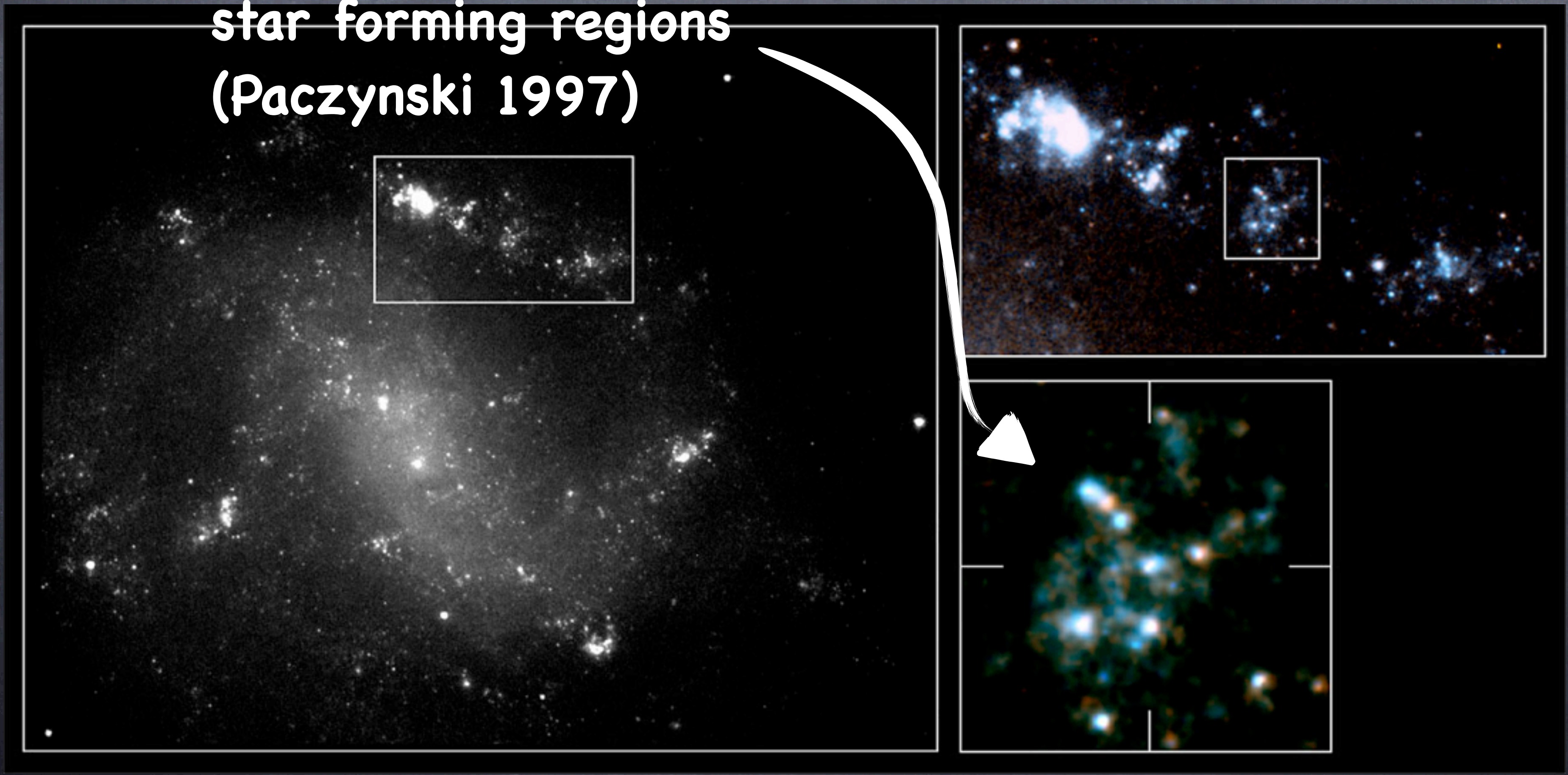


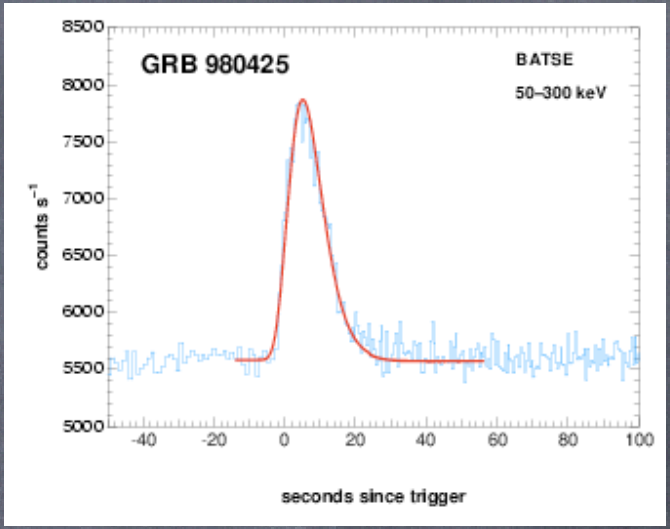
The (long) GRB-Supernova connection

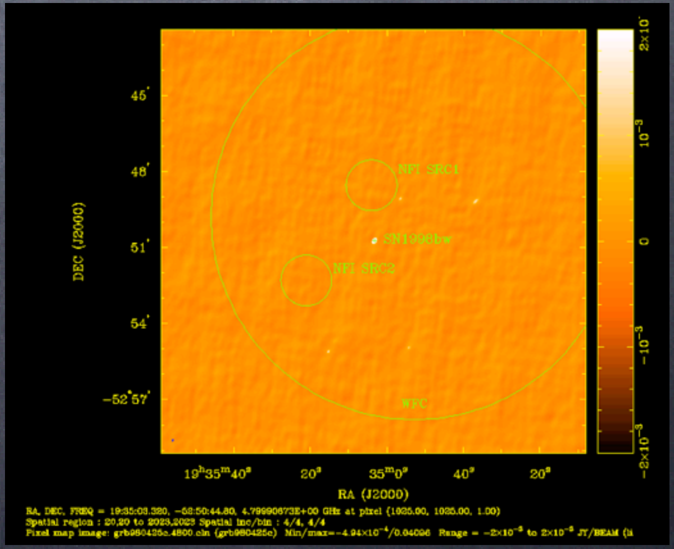
- **Observational indications**
  - **Long GRBs arise in star forming regions (Paczynski 1997)**



Supernova 1998bw-GRB980425

$E_p \approx 67 \pm 40$ keV
$E_\gamma \approx 7\ 10^{47}$ erg
z=0.085





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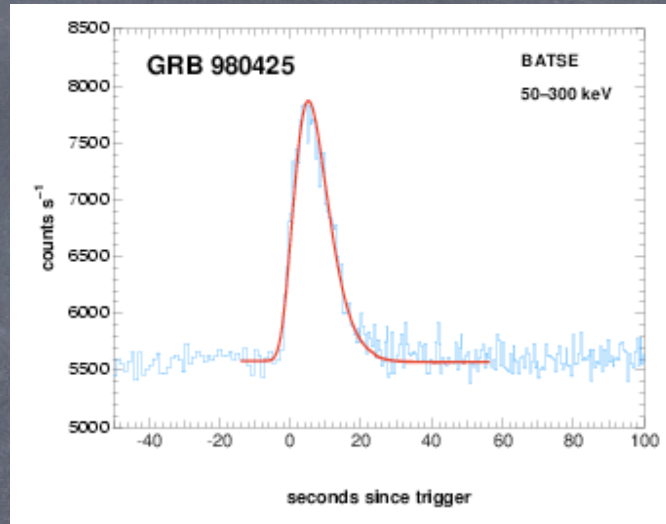

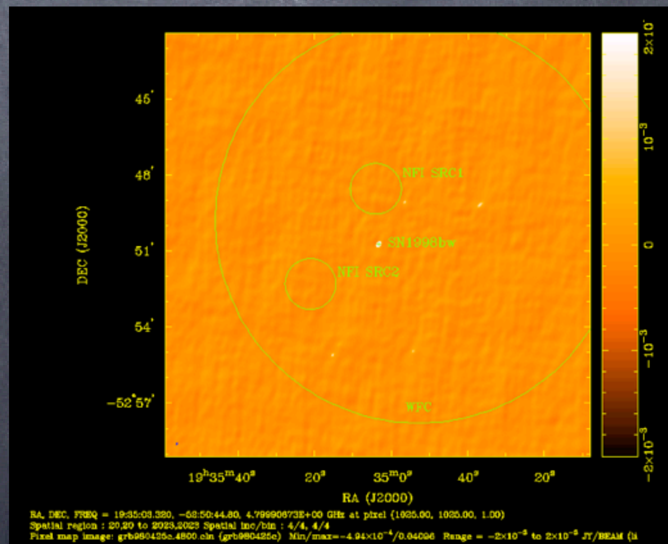

The Smoking Gun

GRB030329-SN 2003dh - a regular GRB with a 98bw like supernova.

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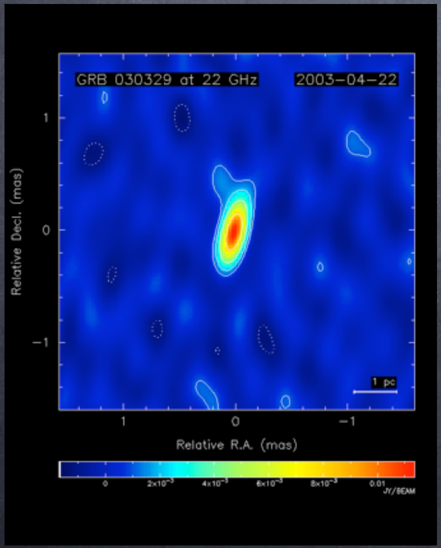

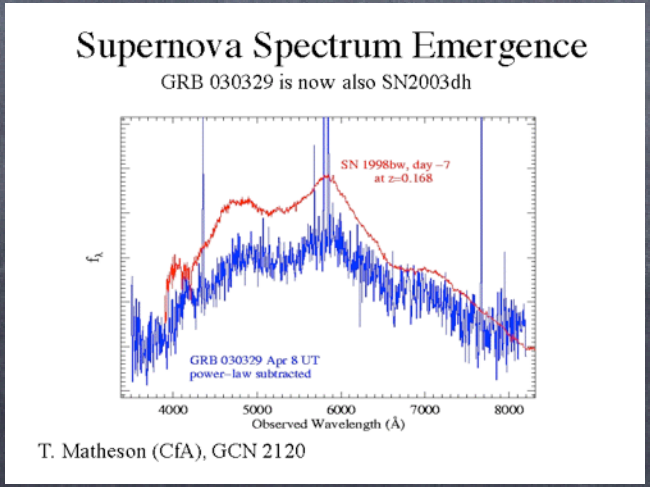

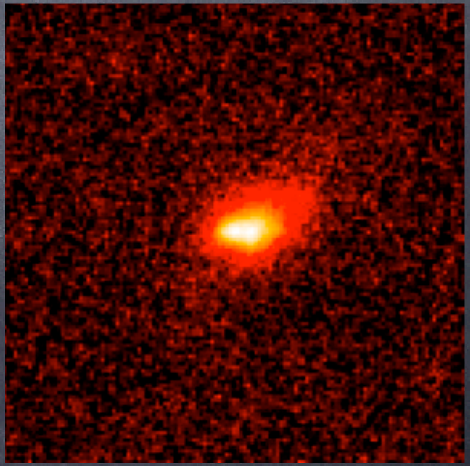

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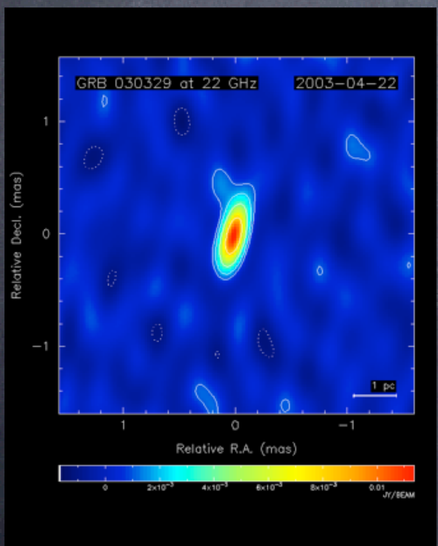
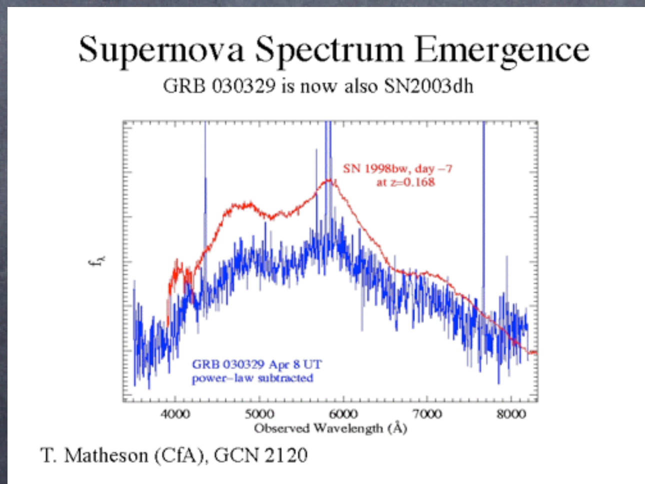
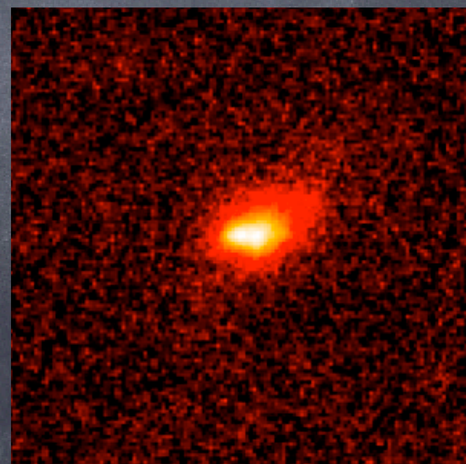
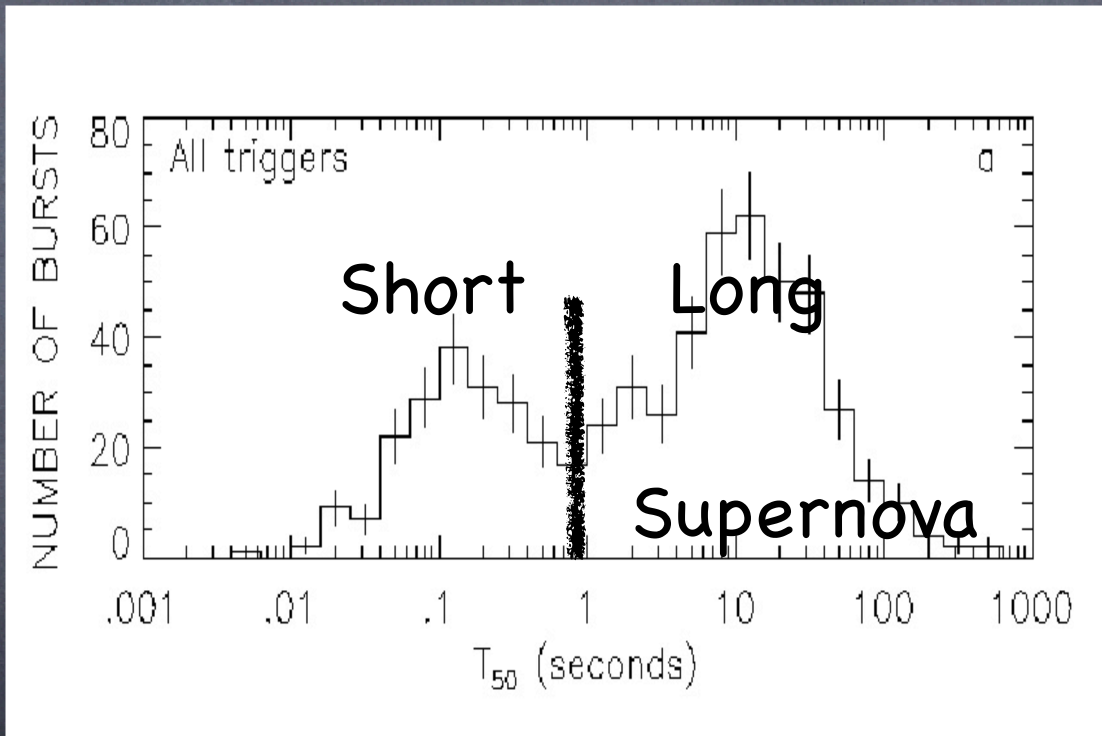






- Recently we have also GRB101219B - SN 2010ma


NUMBER OF BURSTS
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All triggers
a
Short
Long
Supernova
.001
.01
.1
1
10
100
1000
T50 (seconds)

Prologue

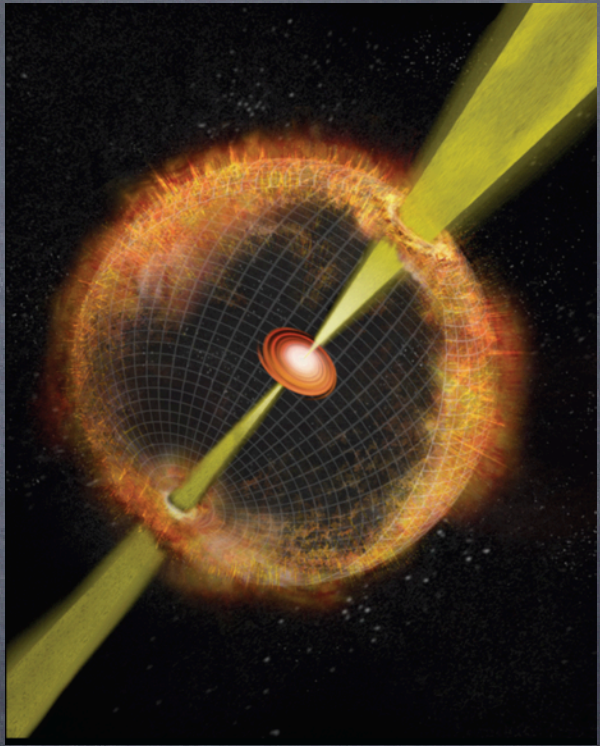
Several times during the short history of GRBs just when we thought we understood something Nature showed us to be wrong.

This may be one of these cases...

Or maybe not?

The Collapsar Model

(MacFadyen & Woosley 1998)



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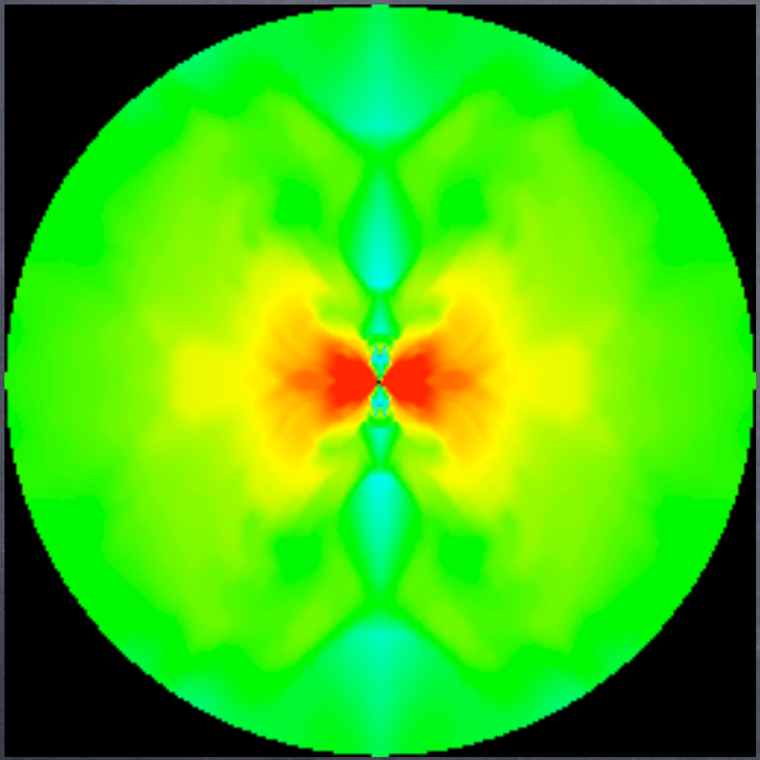
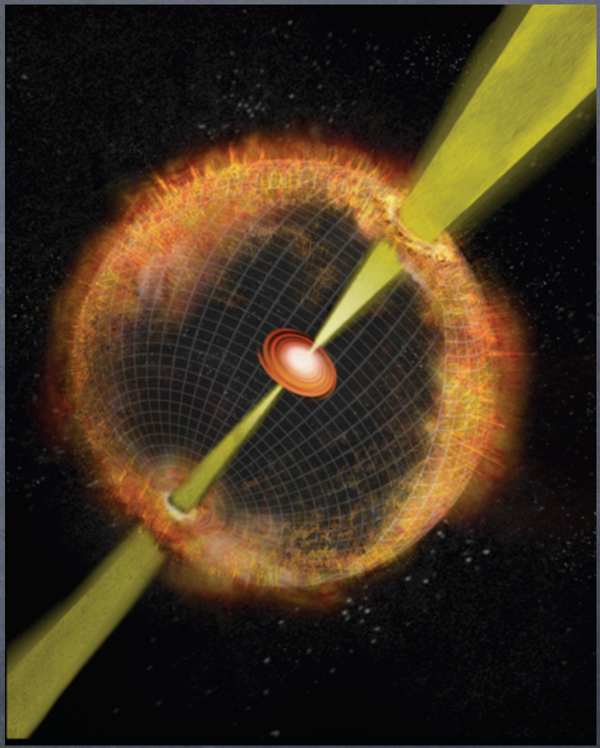
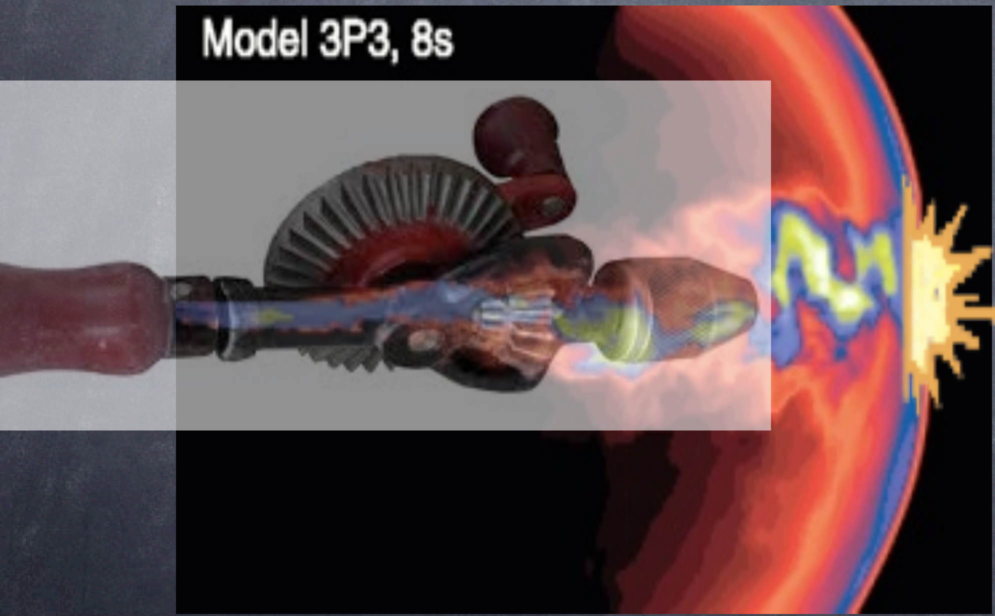
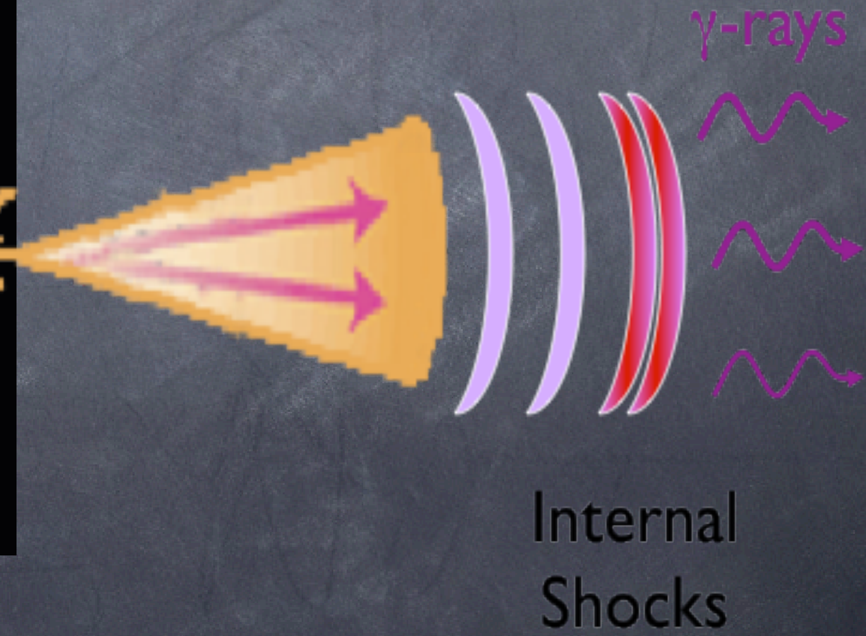




The Jet drills a hole in the star Model

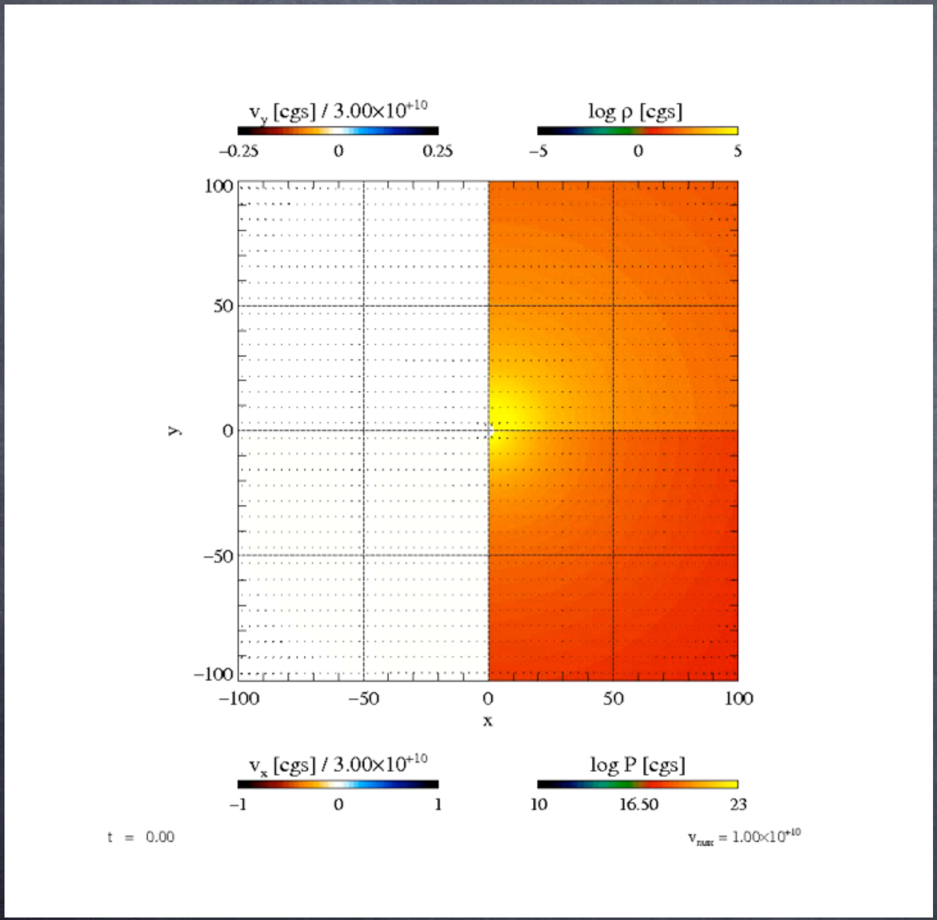


Zhang, Woosley & MacFadyen 2004



Jet Simulations

(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, through the entire run of the model. Lorentz factor at injection 7

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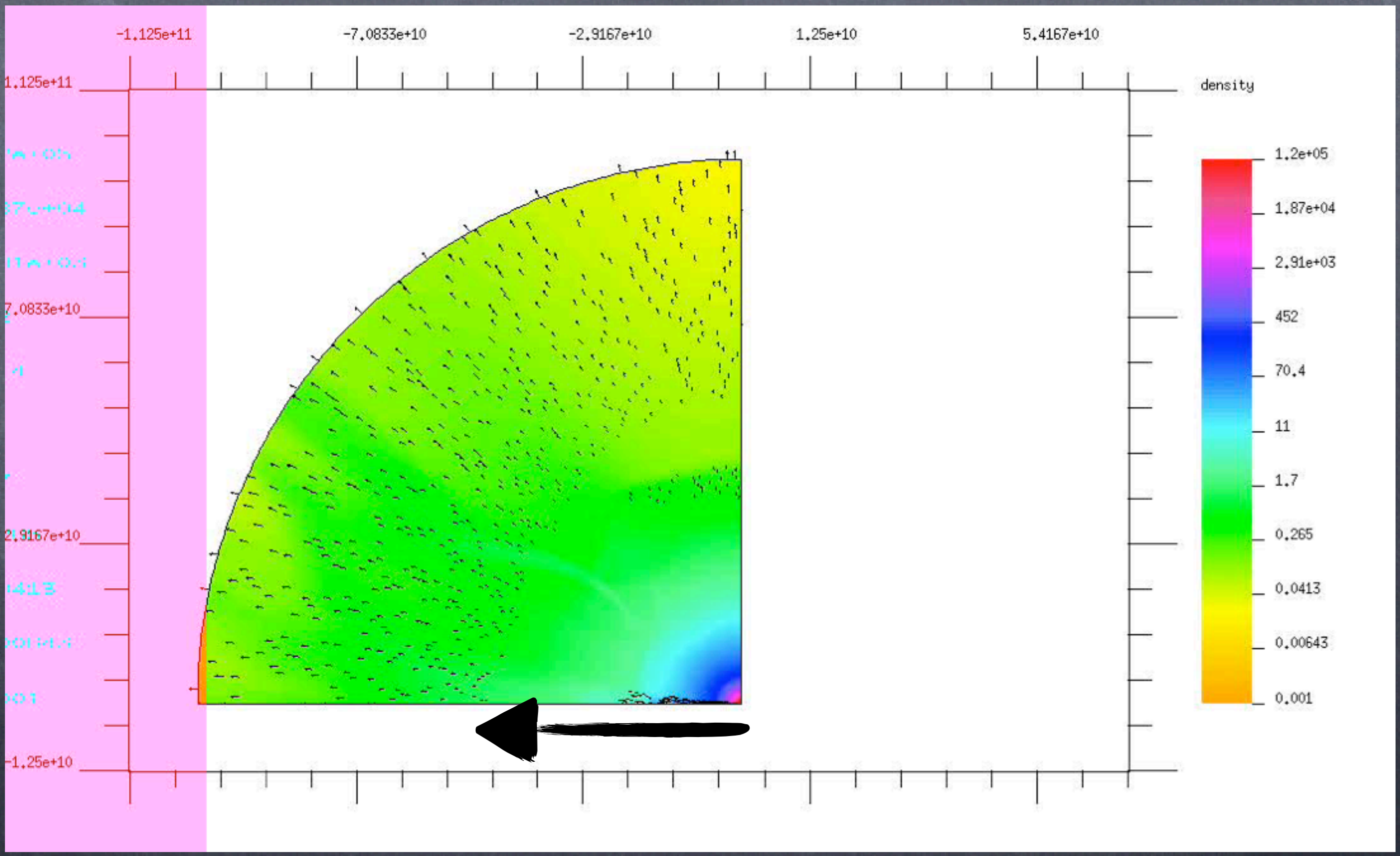
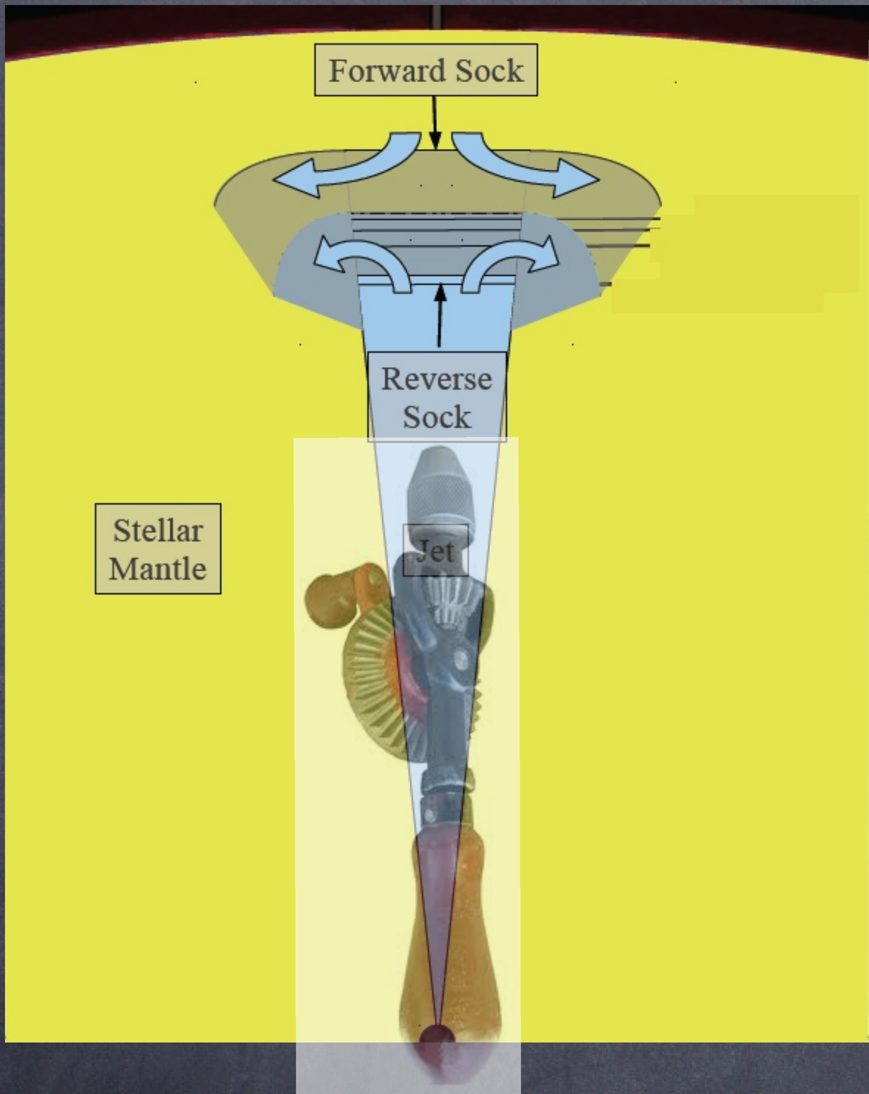
Another explosion - Disruption of the Stellar envelope by the jet -

Genet, Livne, Obergaulinger & TP 2011

About one solar mass is ejected non spherically





Bromberg Nakar, TP, Sari 11 ApJ 2011

- The jet dissipates its energy while propagating.
- The jet is slowed down to about 0.1c

Jet breakout time

(Bromberg Nakar, TP, Sari 11 ApJ 2011)

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

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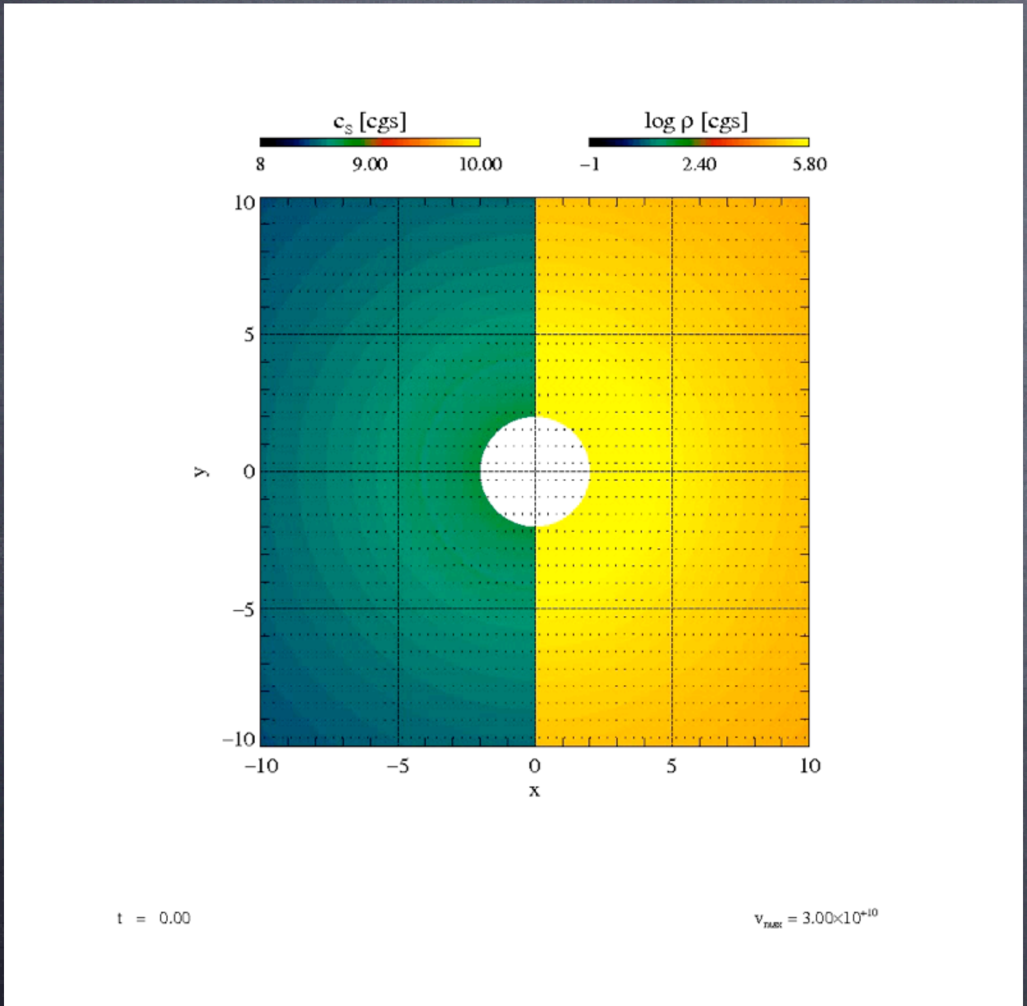
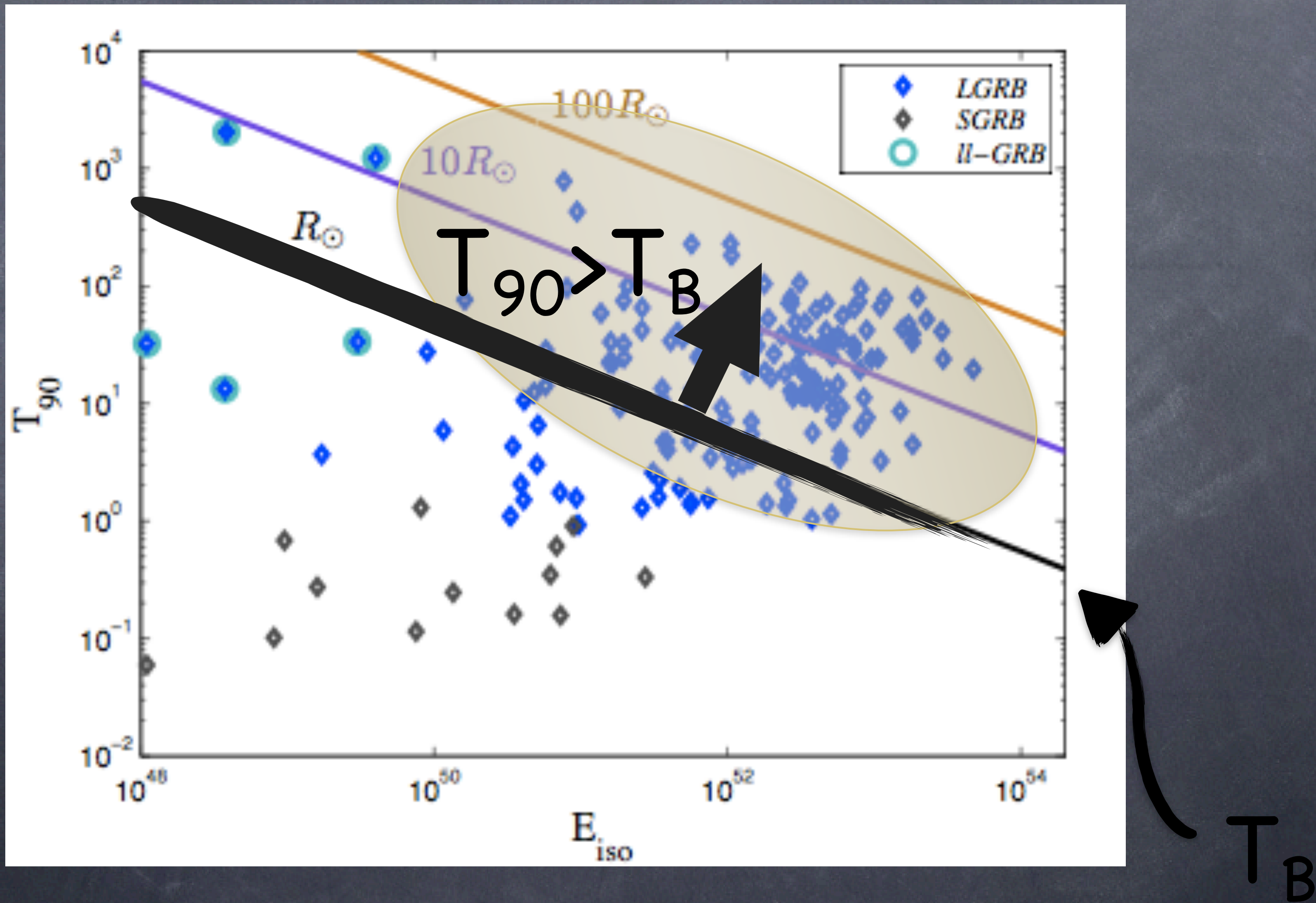
The engine must be active until the jet's head breaks out!*

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.

Duration (T_{90}) vs Energy



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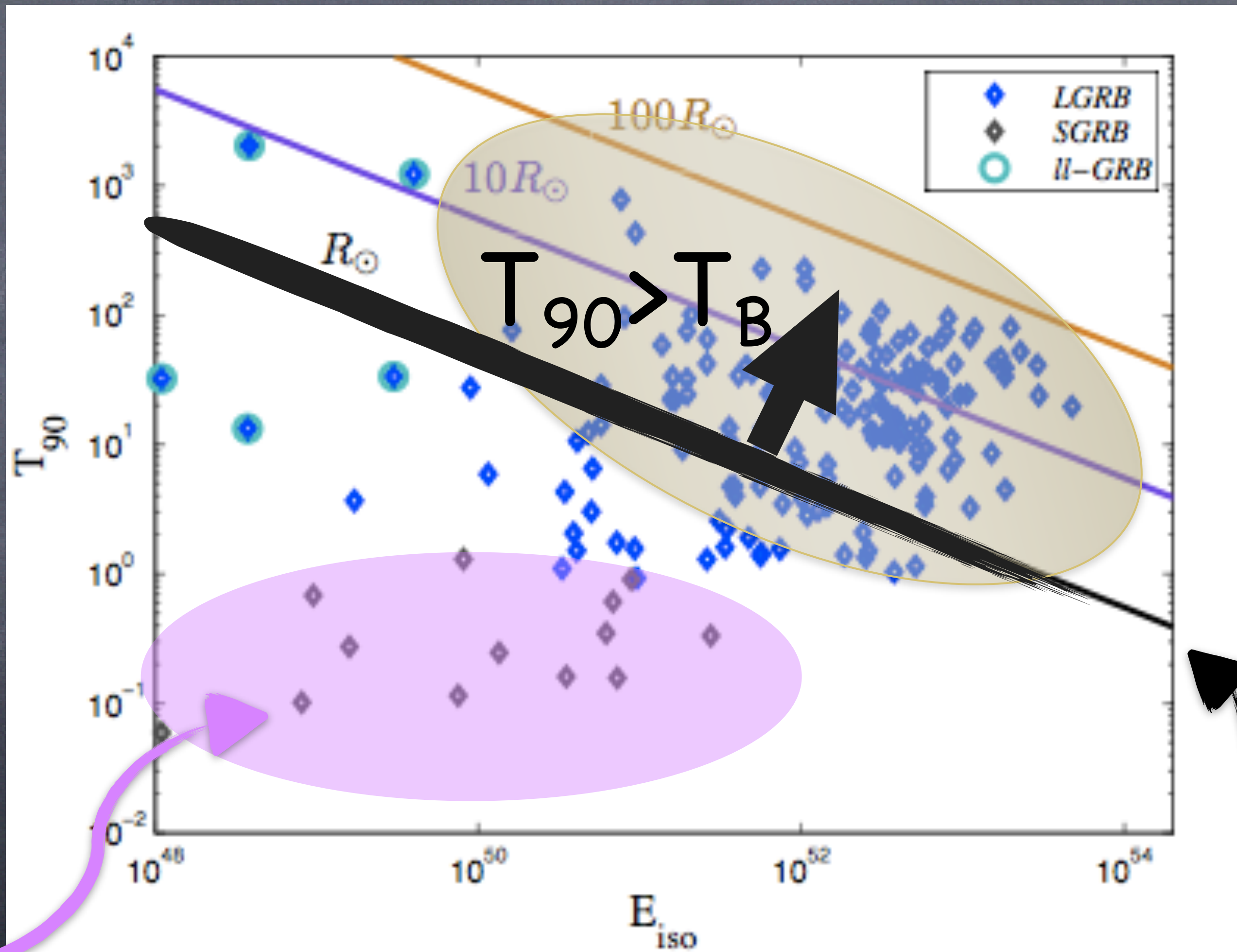

Short GRBs

T_B

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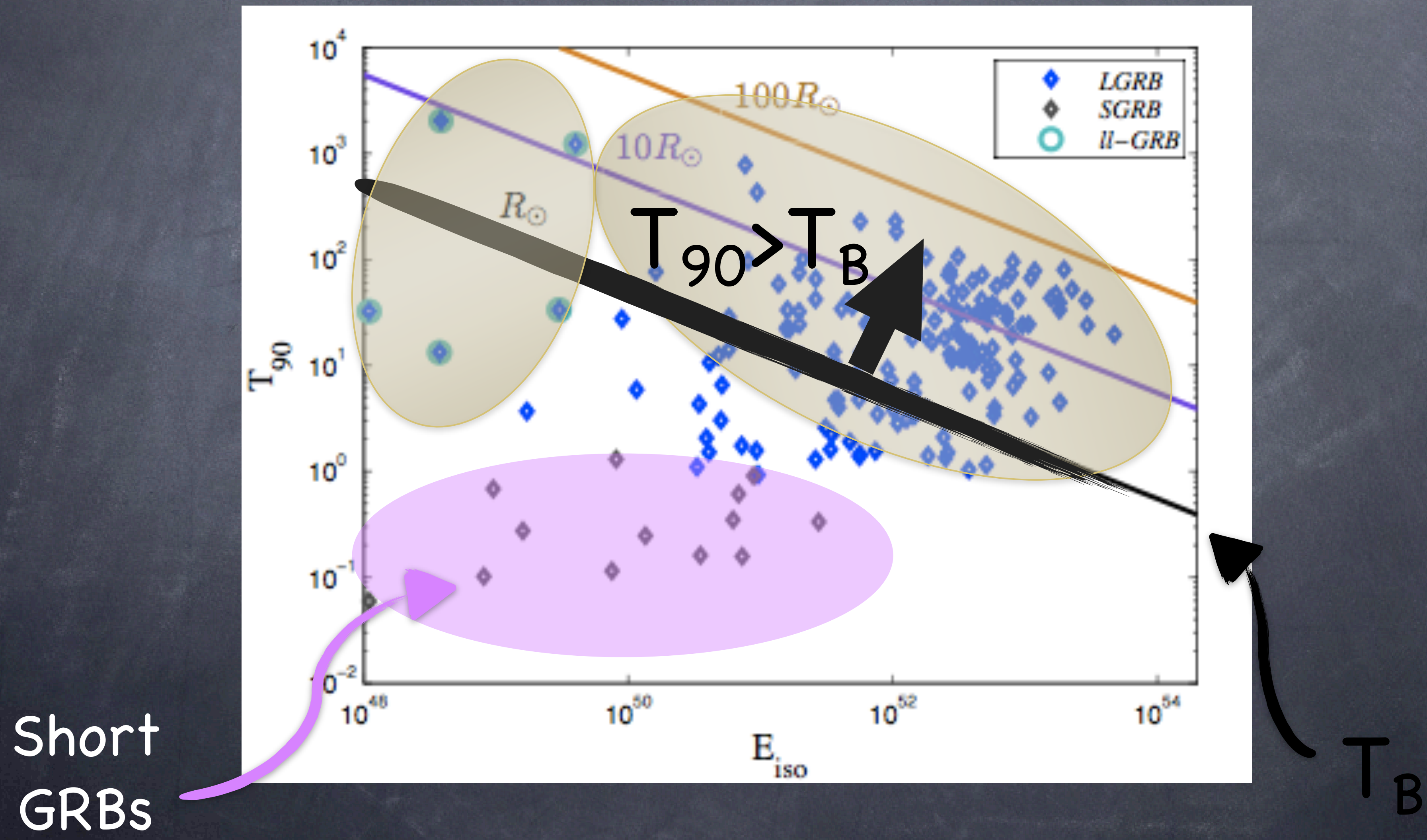
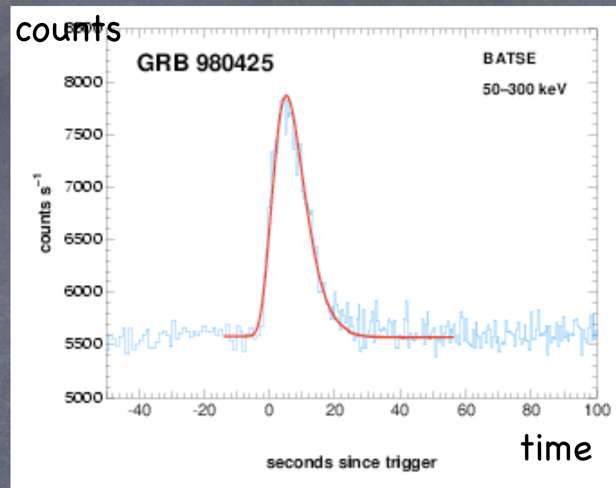
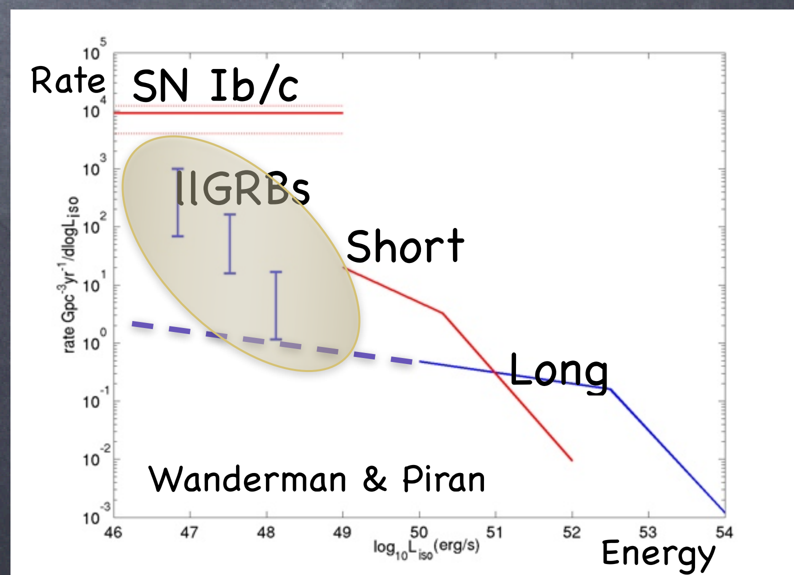


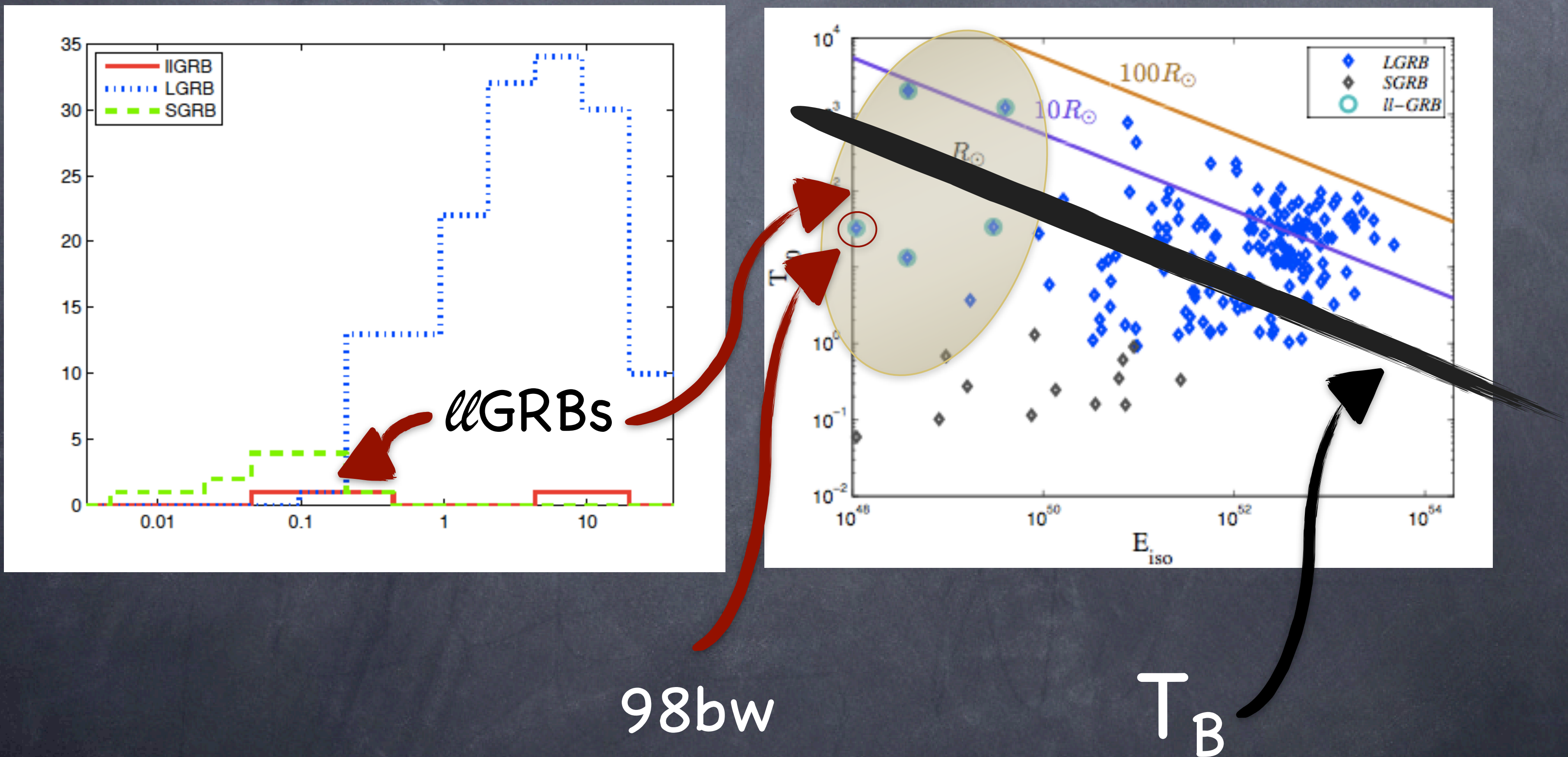
Low Luminosity GRBs - ℓℓGRBs

Bromberg Nakar, TP, 11 ApJL 2011

- Low luminosity GRBs:
  - E_{iso}~10^{48}-10^{49} ergs
  - **Smooth** single peaked light curve.
  - **Soft** Emission (E_{peak} <150 keV)
  - Much more numerous than regular long GRBs!
  - ℓℓGRBs dont have enoug power to penetrate the star

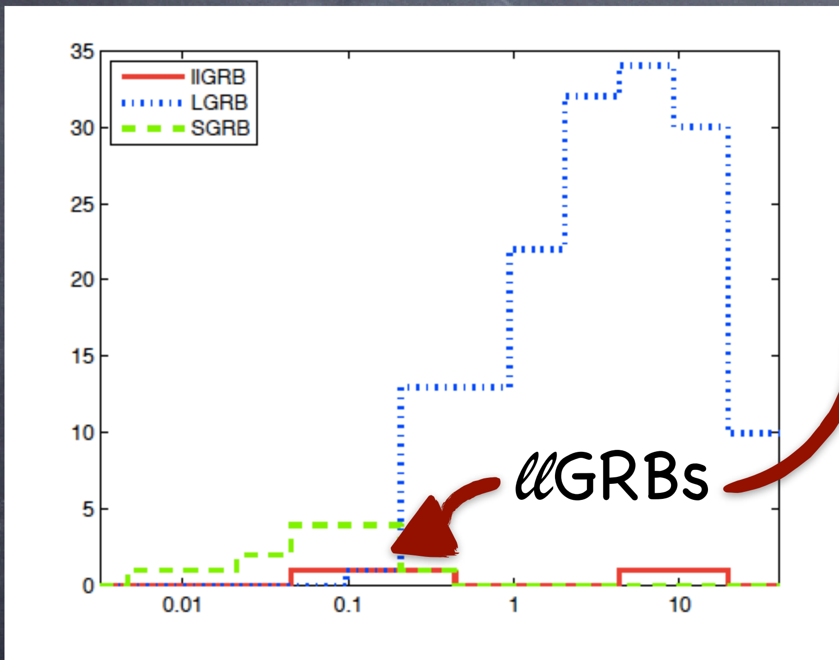


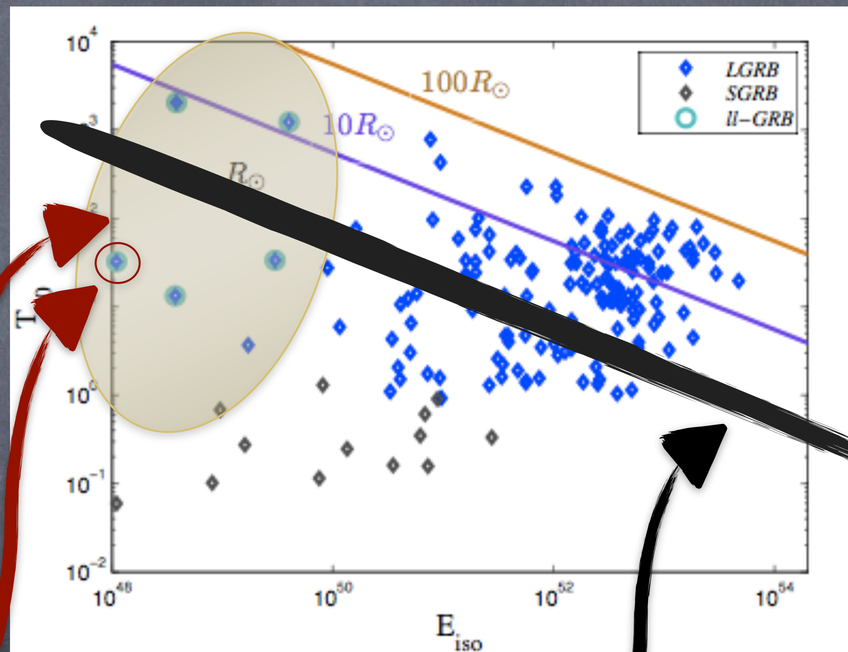




llGRB
LGRB
SGRB
35
30
25
20
15
10
5
0
0.01
0.1
1
10
$100R_\odot$
$10R_\odot$
$R_\odot$
LGRB
SGRB
ll−GRB
10^4
10^0
10^{-1}
10^{-2}
10^{48}
10^{50}
10^{52}
10^{54}
E_{iso}
llGRBs
98bw
T_B

Low luminosity GRBs - $\ell\ell$GRBs cannot arise from Collapsars



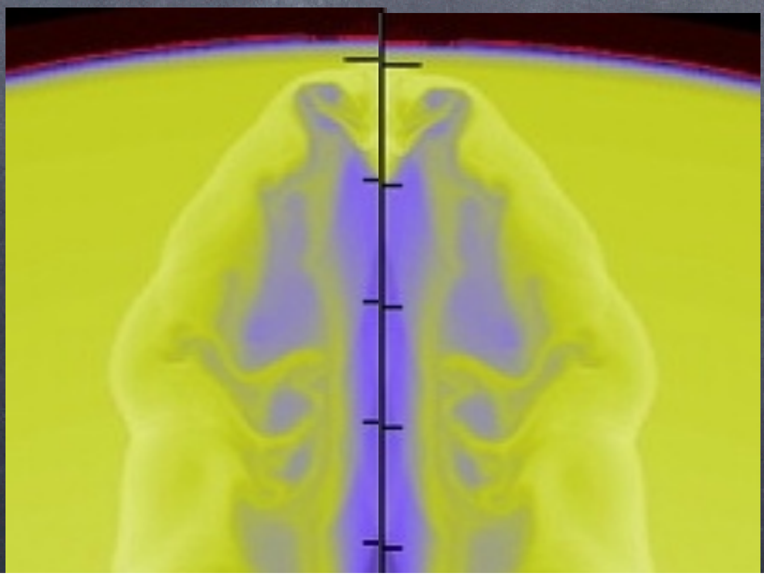


$\ell\ell$GRBs

98bw

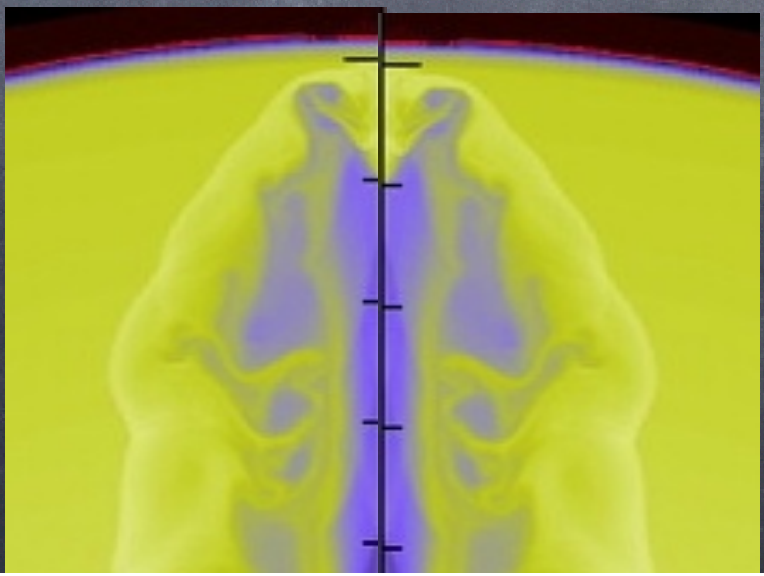
T_B

What makes a ℓℓGRBs?



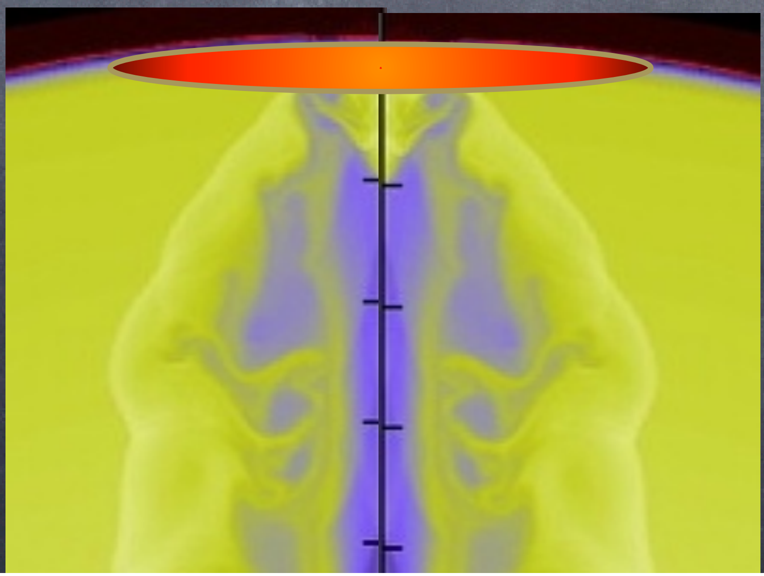
What makes a ℓℓGRBs?

- A weak jet that fails to break out ("**a failed GRB**").



What makes a *ll*GRBs?

- A weak jet that fails to break out ("**a failed GRB**").
- We observe the shock breakout form the stellar envelope (Colgate, 1967; Katz, Budnik, Waxman, 2010; Nakar & Sari, 2011)



Almost ALL GRBS accompanied by SNe

are

*ll*GRBs

?

A prediction of the Collapsar model

Observed duration

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

Engine time

Break out time

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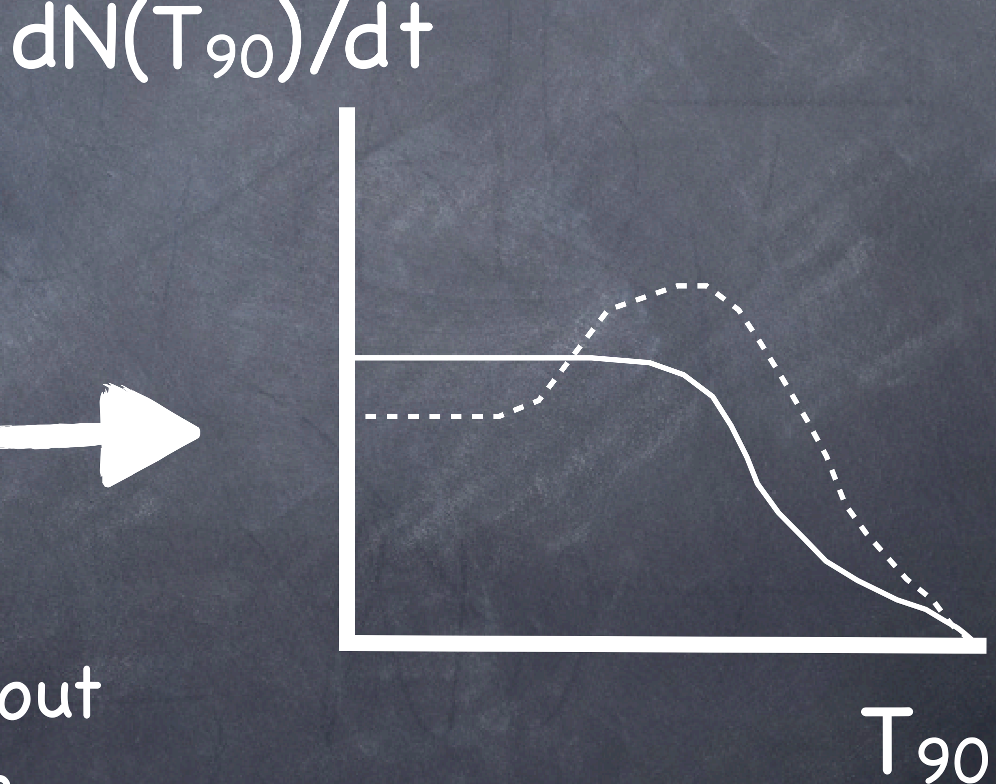

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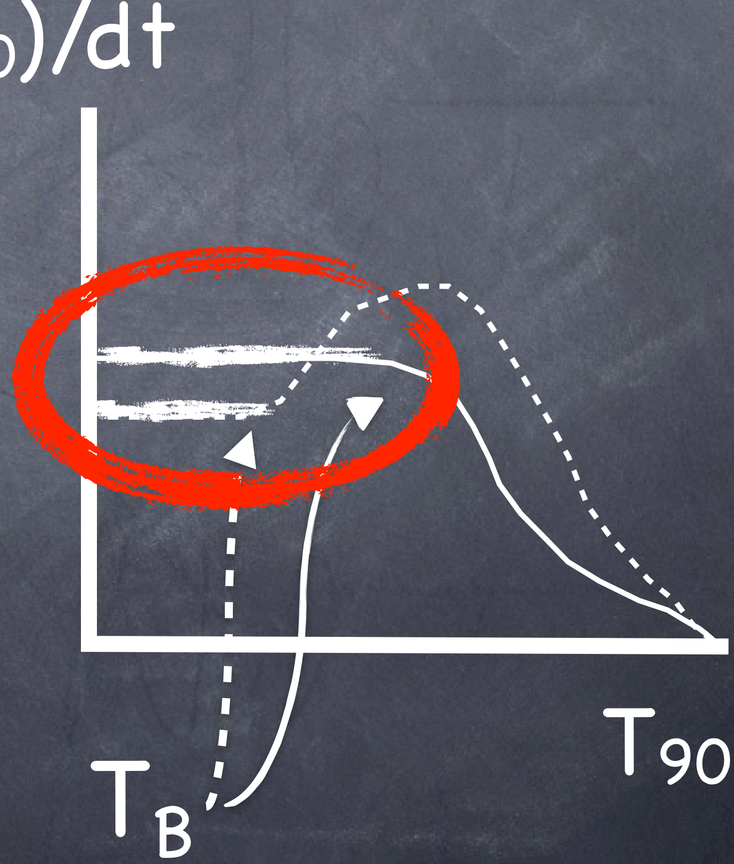

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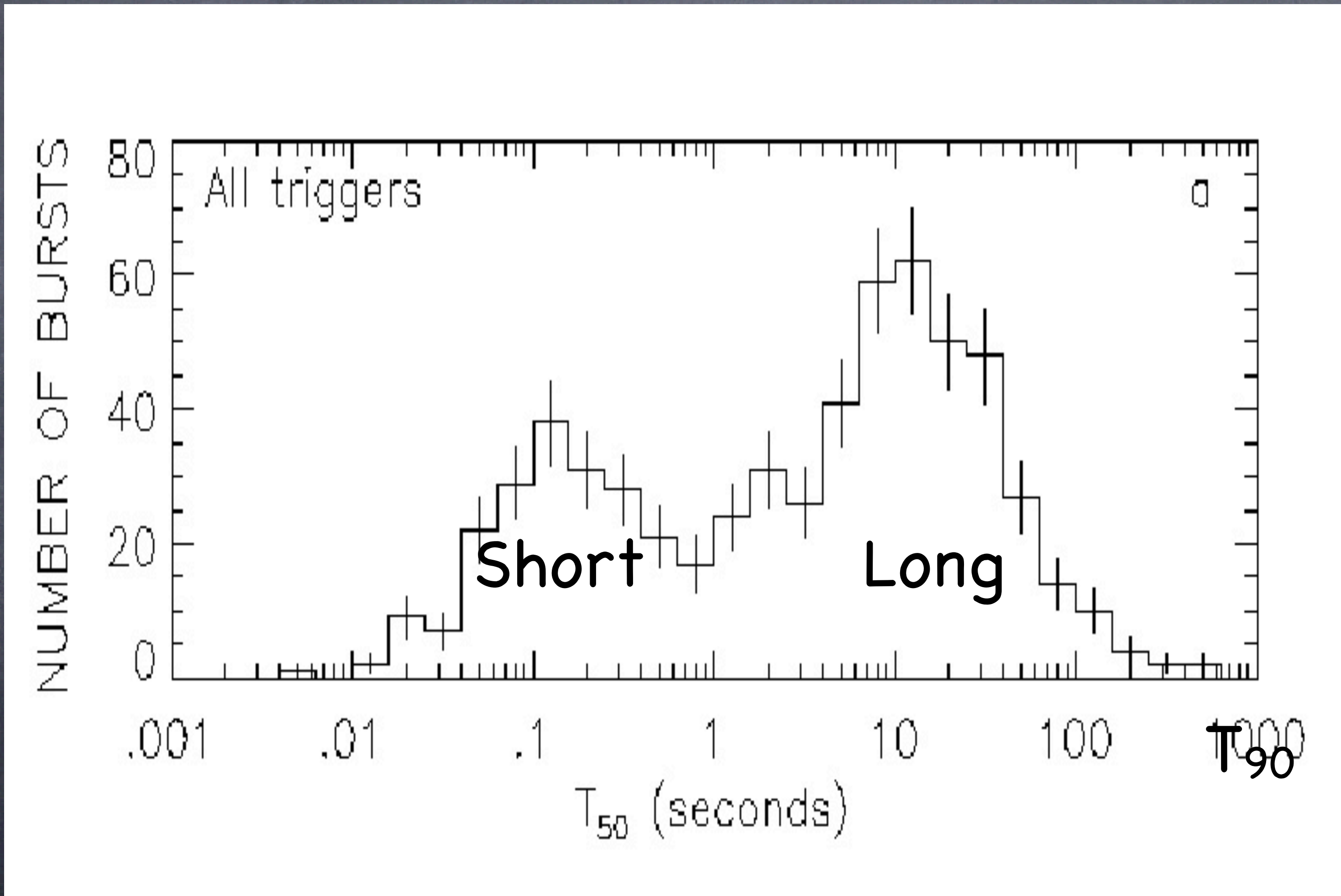

All triggers
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NUMBER OF BURSTS
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0
Short
Long
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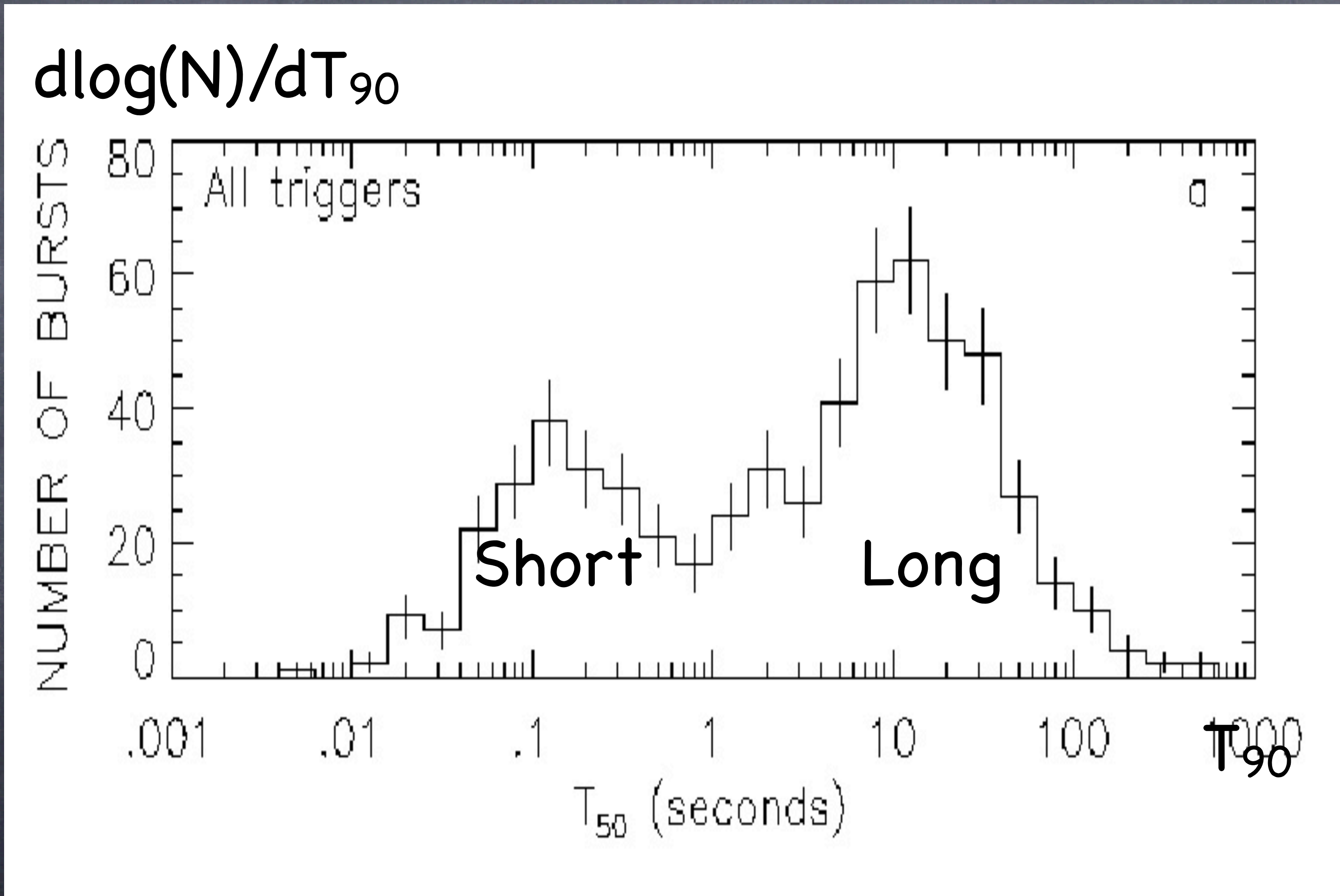
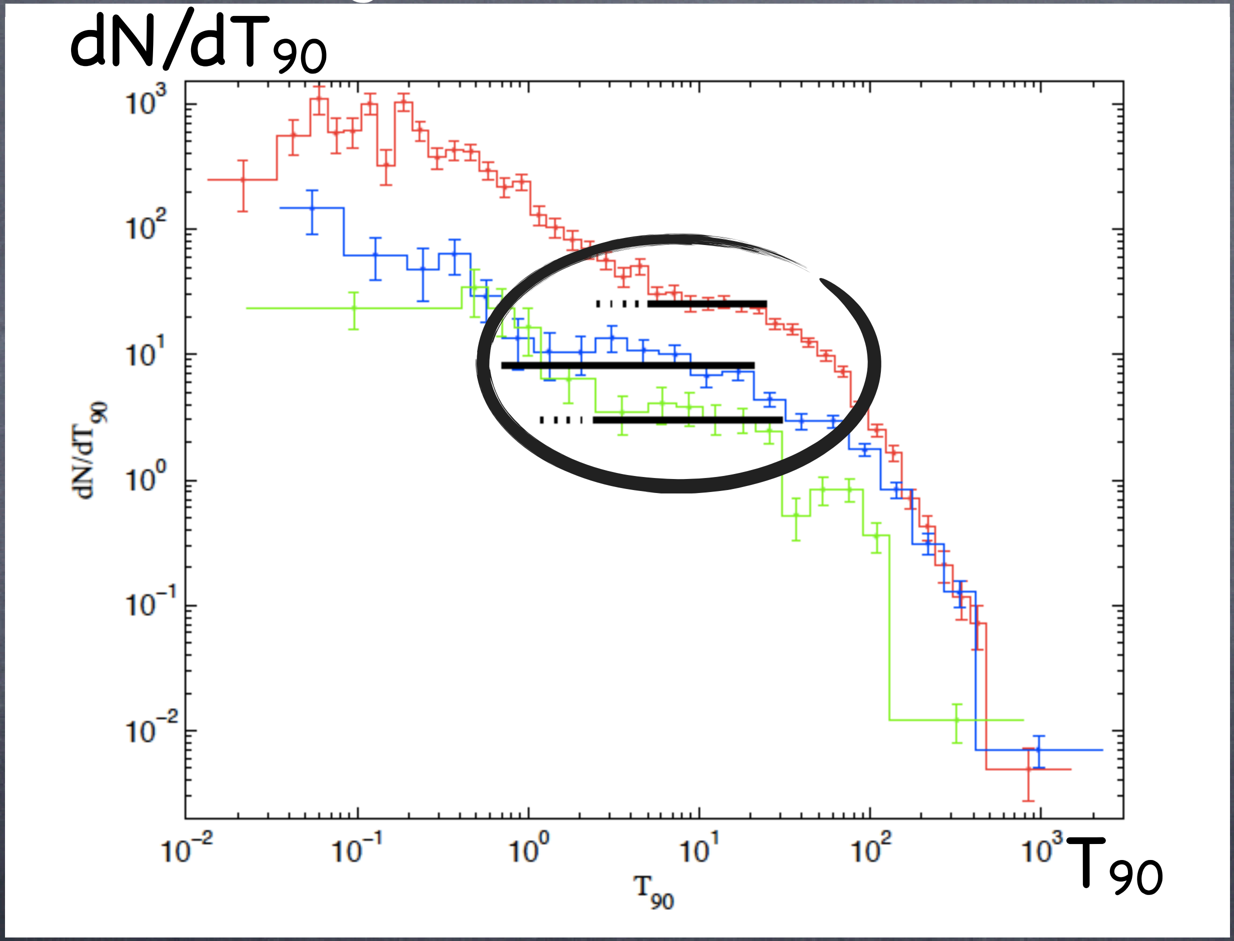
.01
.1
1
10
100
1000
T90
T50 (seconds)

?


dlog(N)/dT90
NUMBER OF BURSTS
80
60
40
20
0
All triggers
a
Short
Long
.001
.01
.1
1
10
100
1000
T90
T50 (seconds)

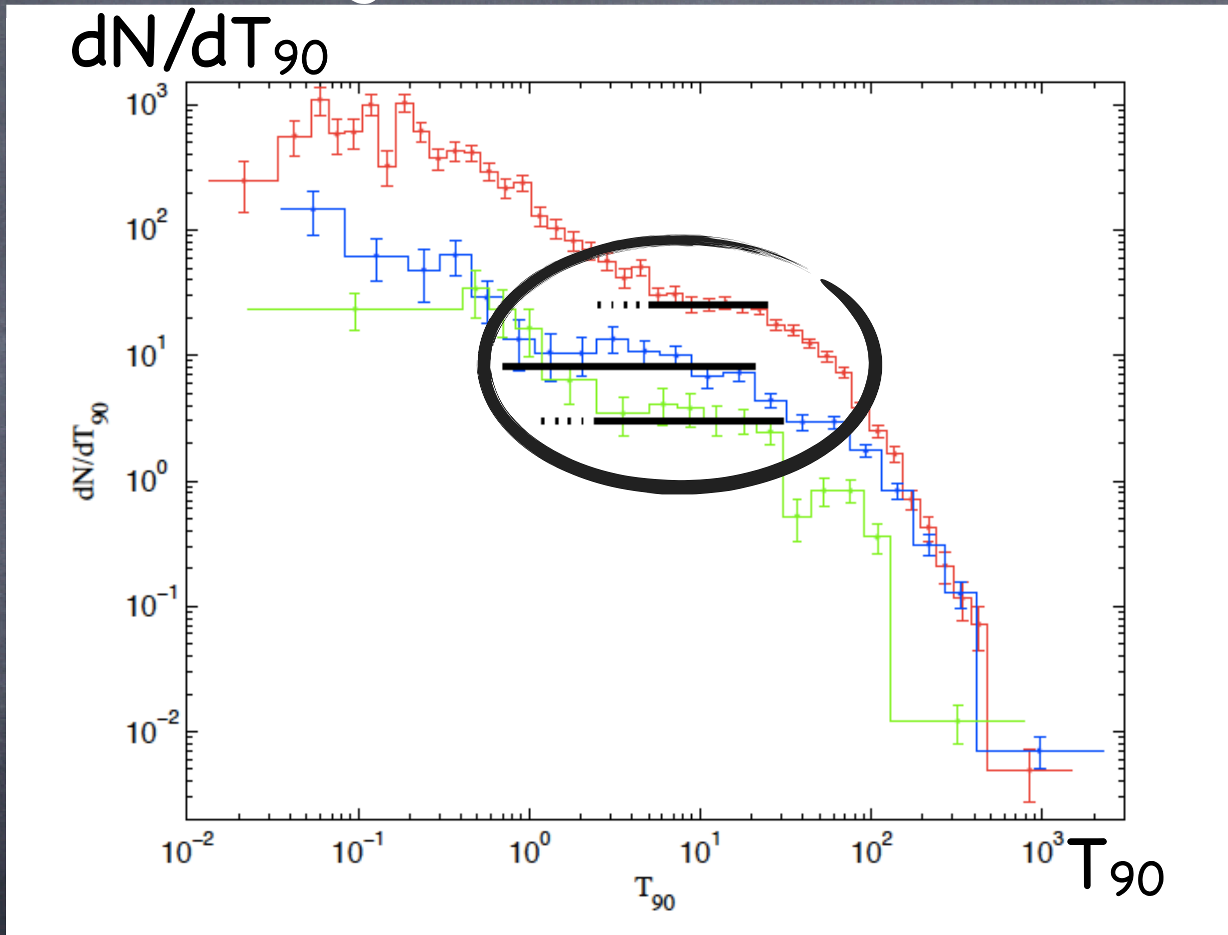
A second look

(Bromberg Nakar, TP & Sari, 2011)



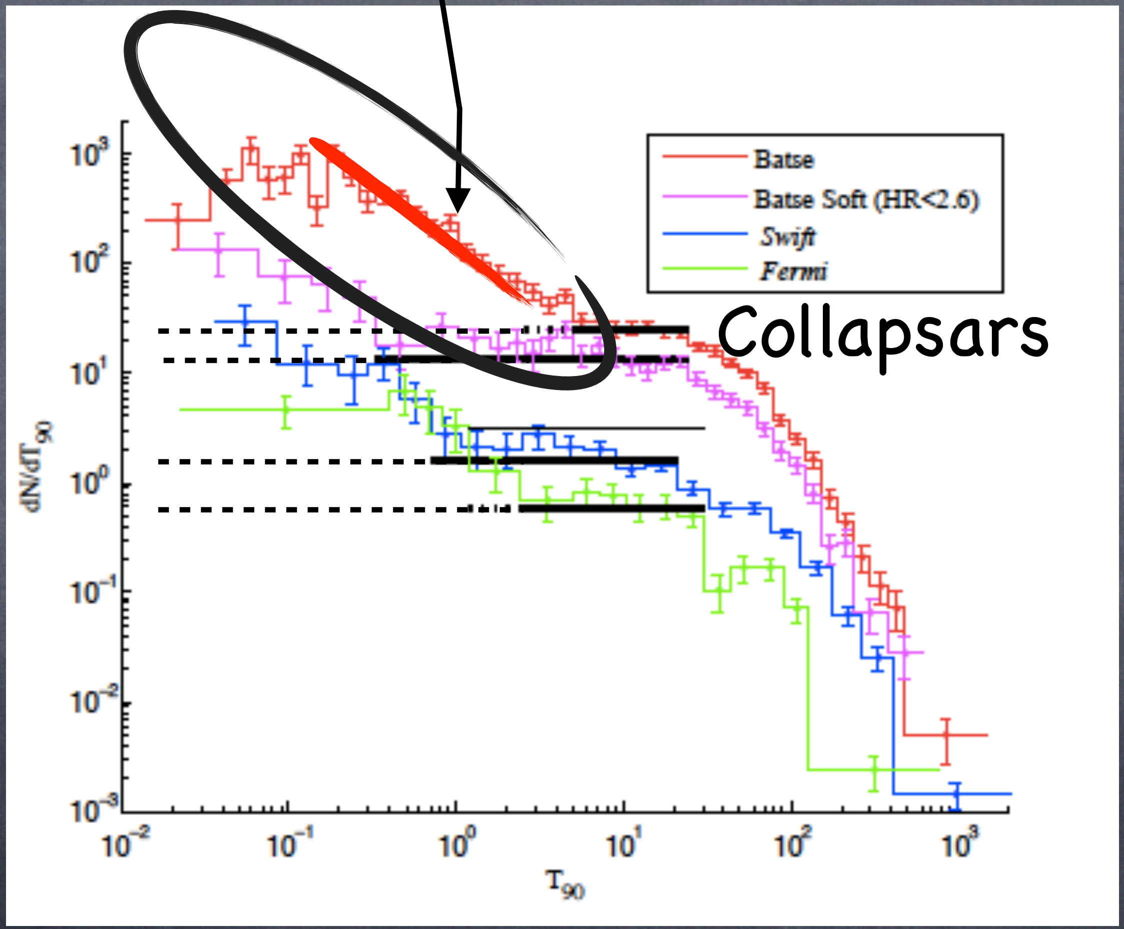
A second look

(Bromberg Nakar, TP & Sari, 2011)

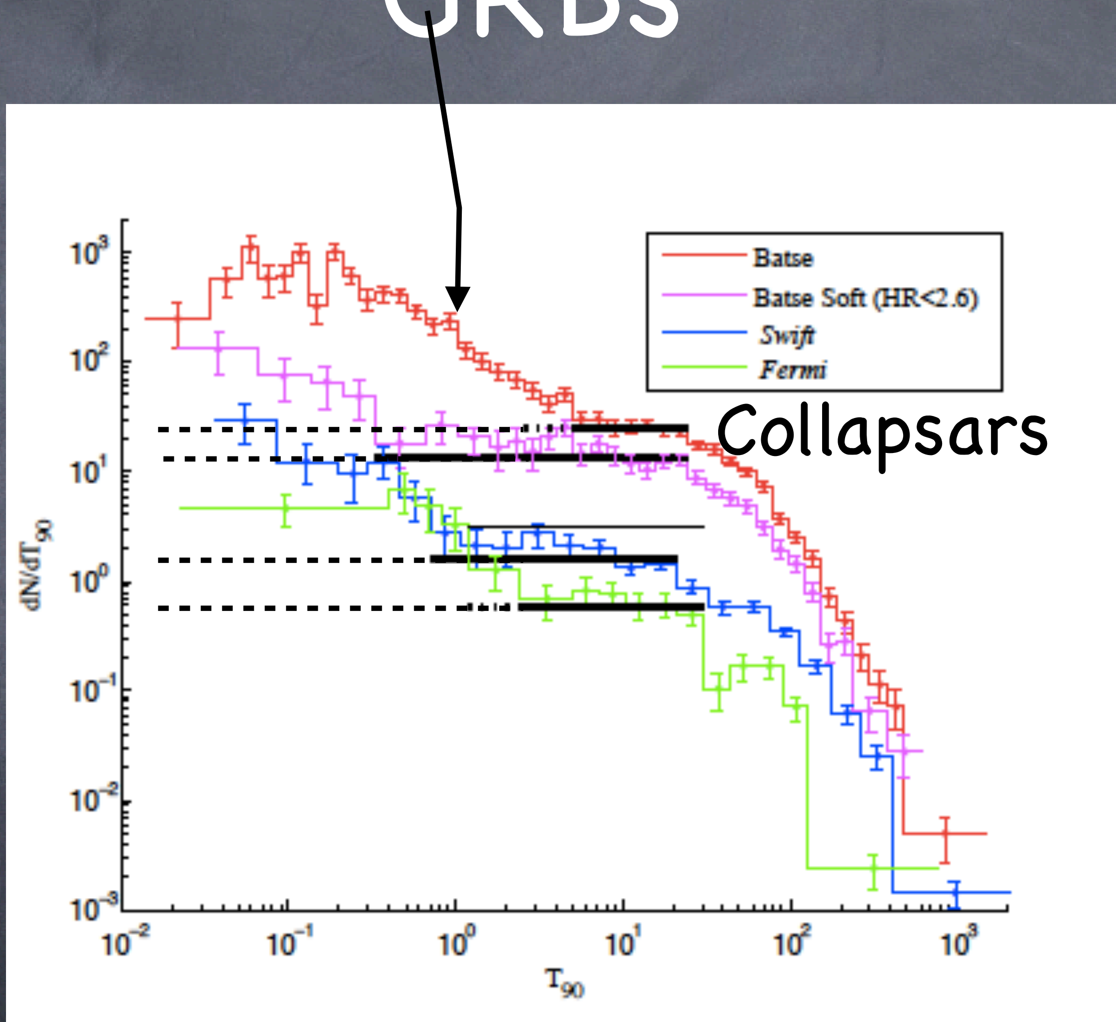


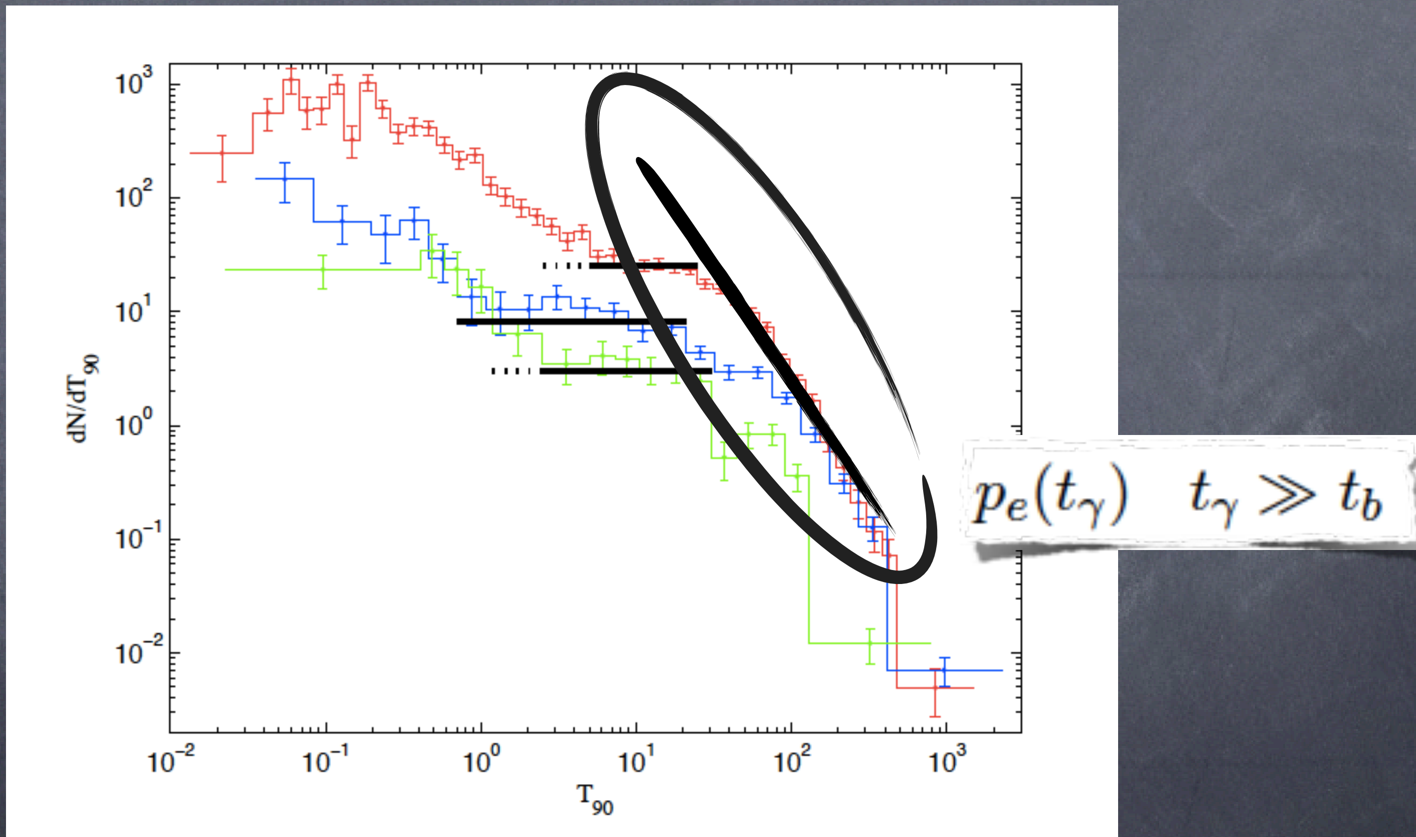
This provides a direct observational proof of the Collapsar model.

Short (Non-Collapsars) GRBs



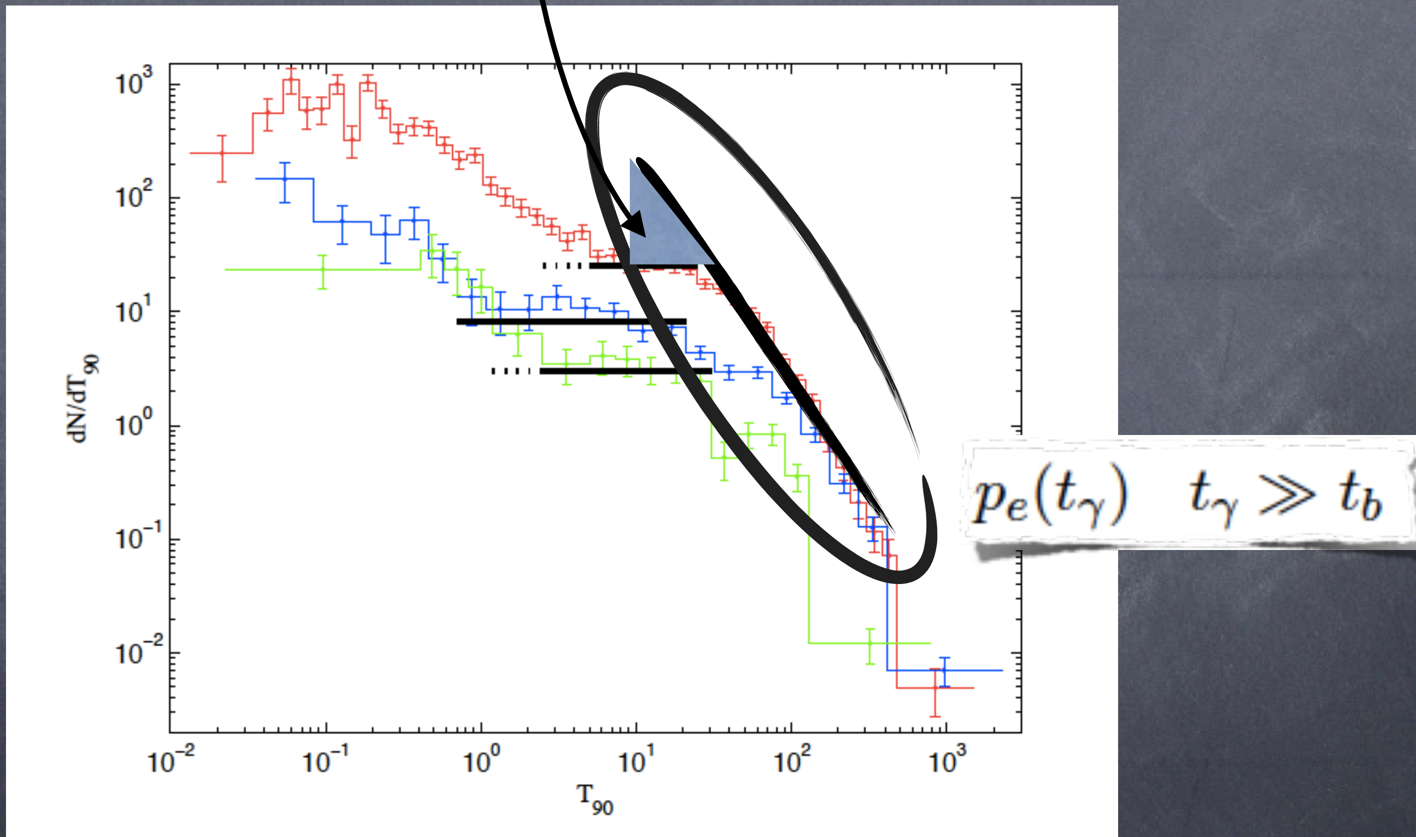
Short (Non-Collapsars) GRBs





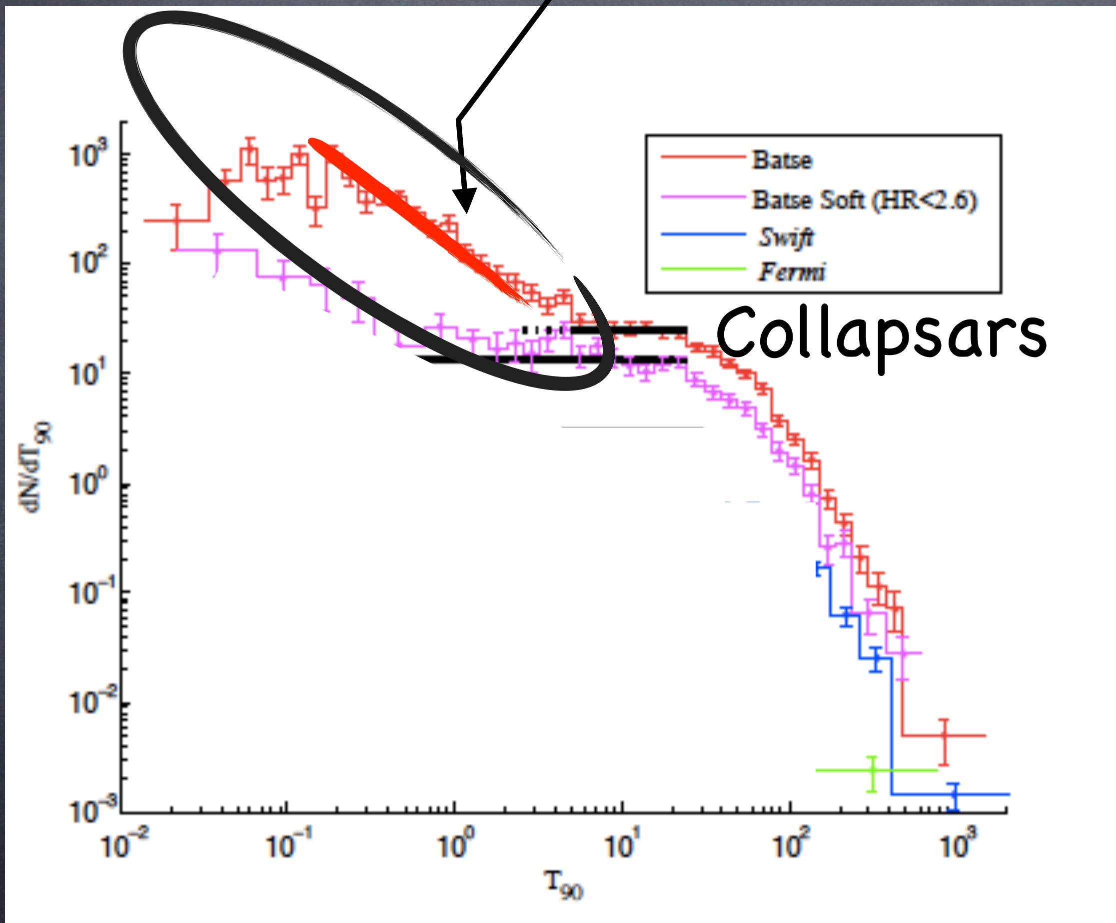
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
dN/dT$_{90}$
10^{-2} 10^{-1} 10^0 10^1 10^2 10^3
T$_{90}$
$p_e(t_\gamma) \quad t_\gamma \gg t_b$

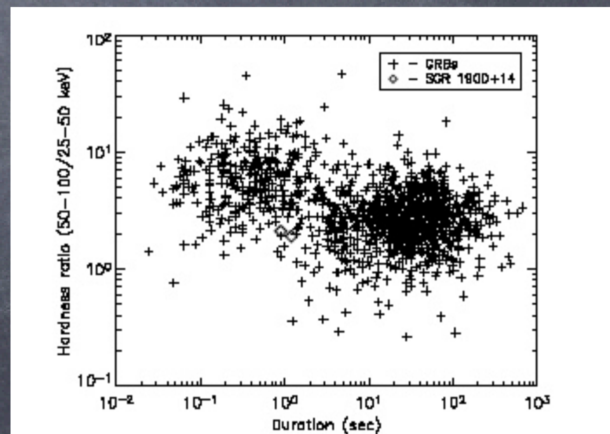
A large number of “failed or Choked” jets - a “failed GRB” ✓



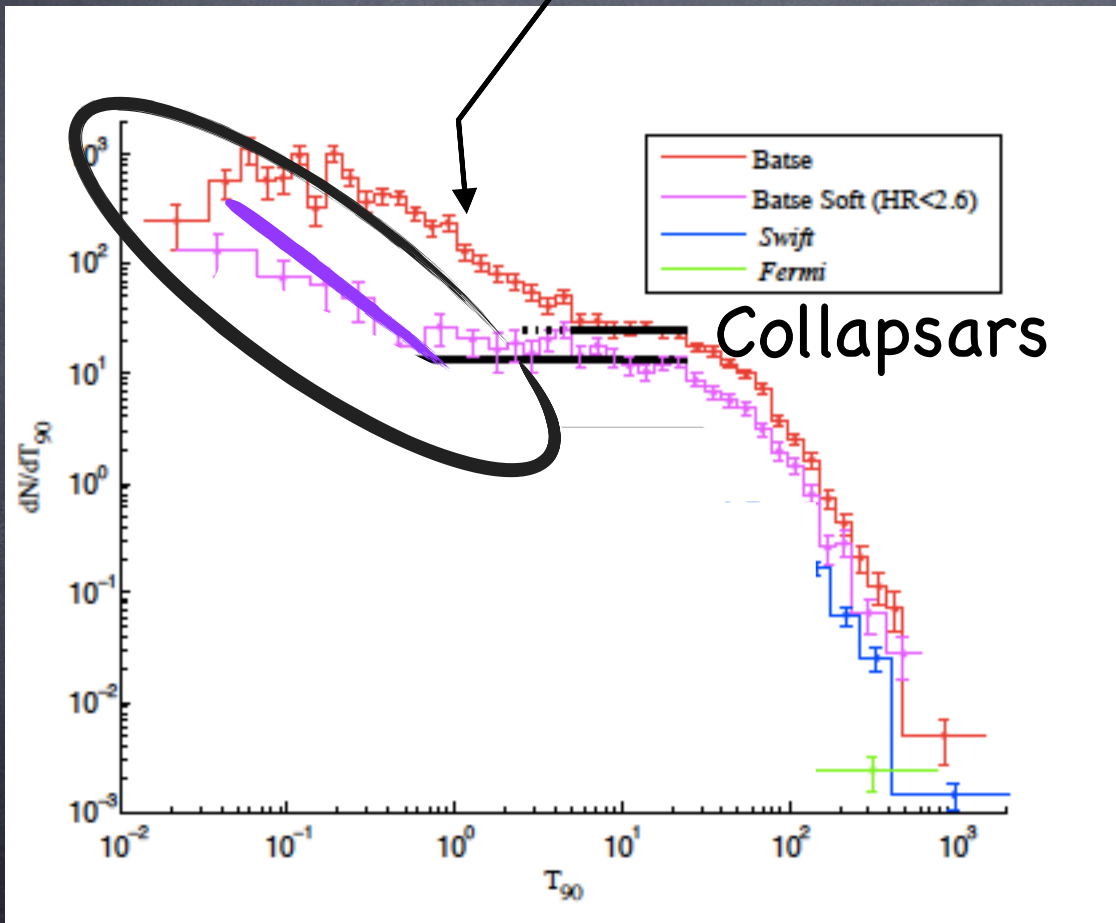
The rate of $\ell\ell$GRBs is very large

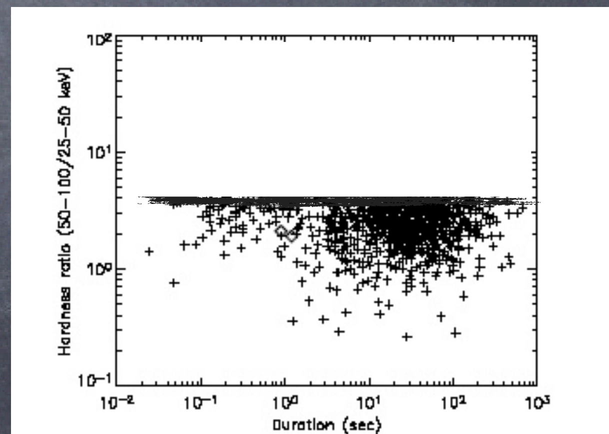
Short (Non-Collapsars) GRBs



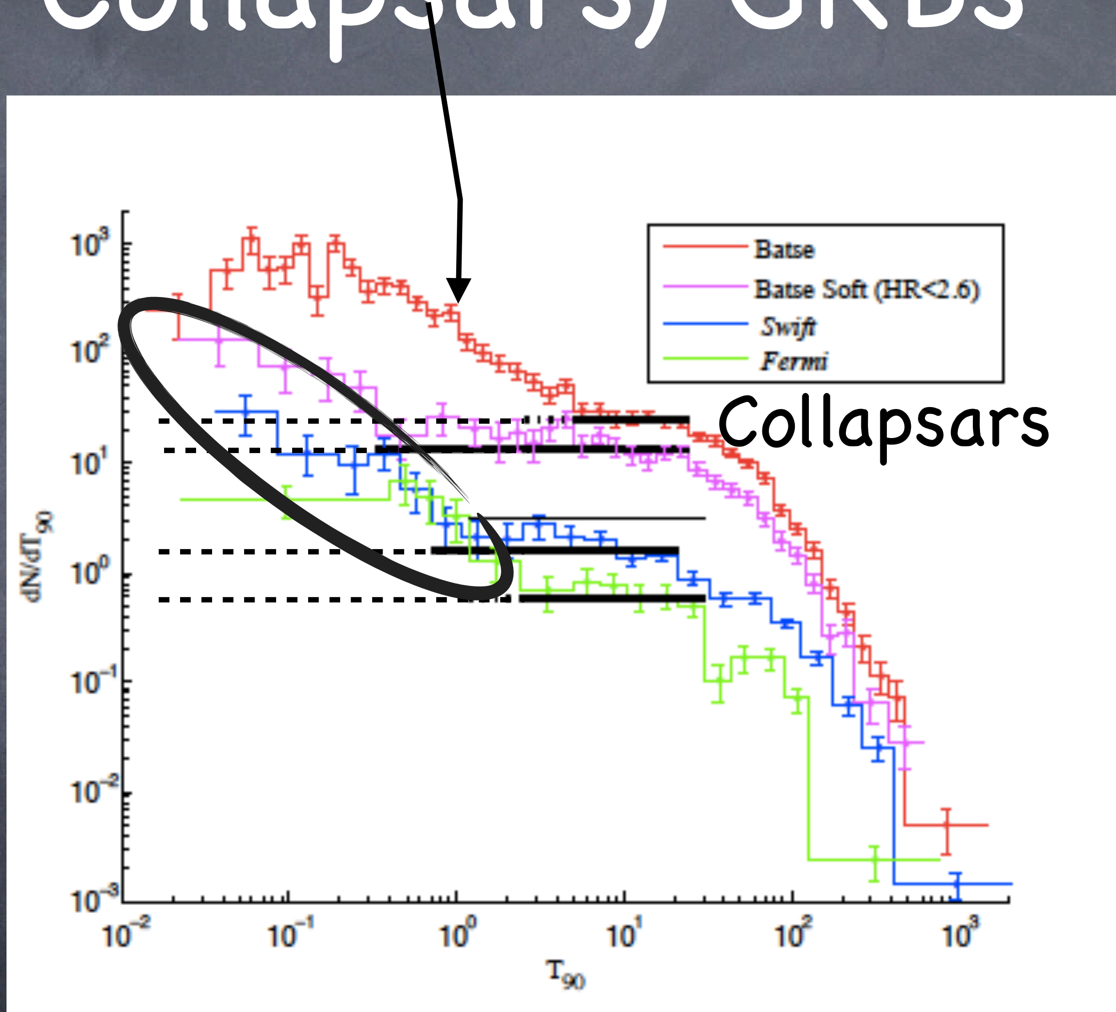


Short (Non-Collapsars) GRBs

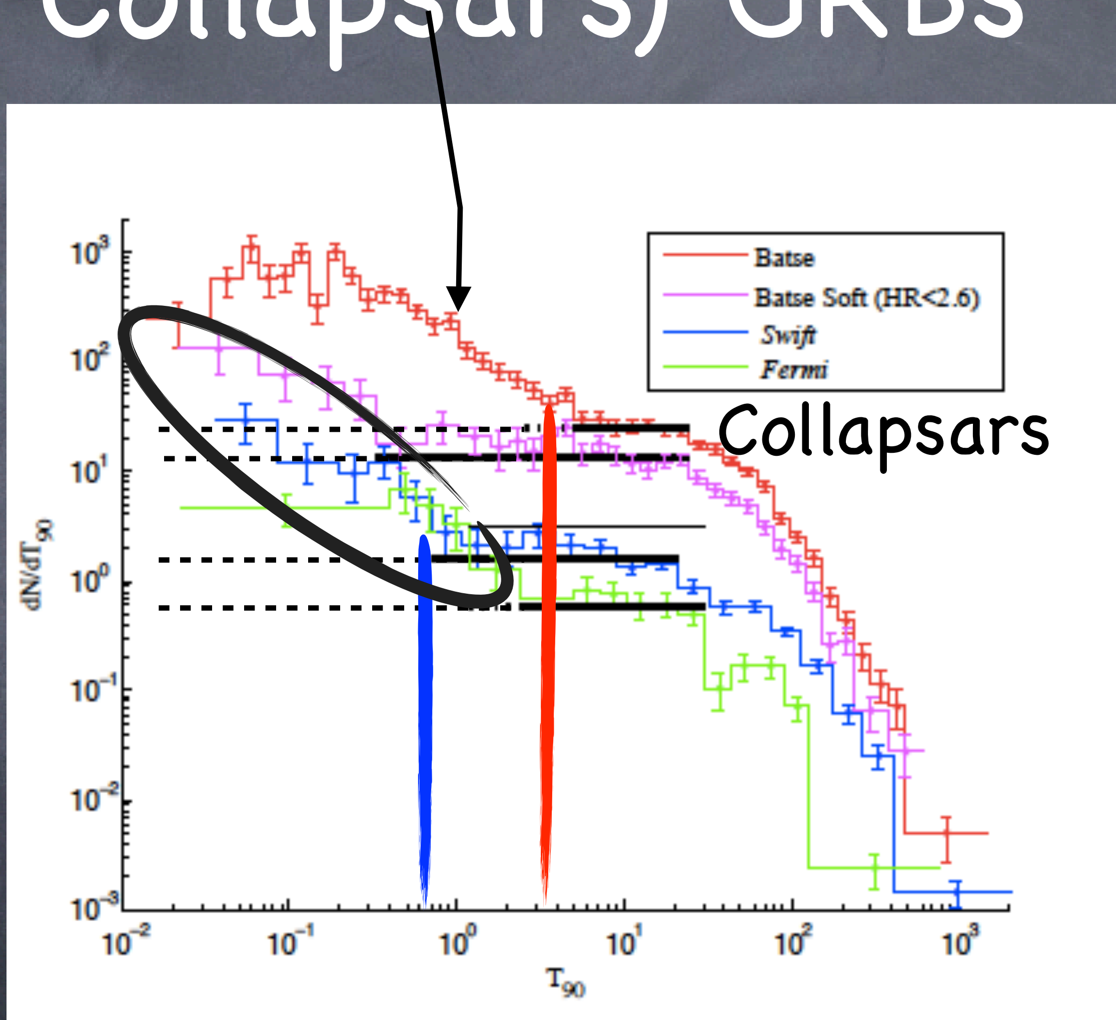




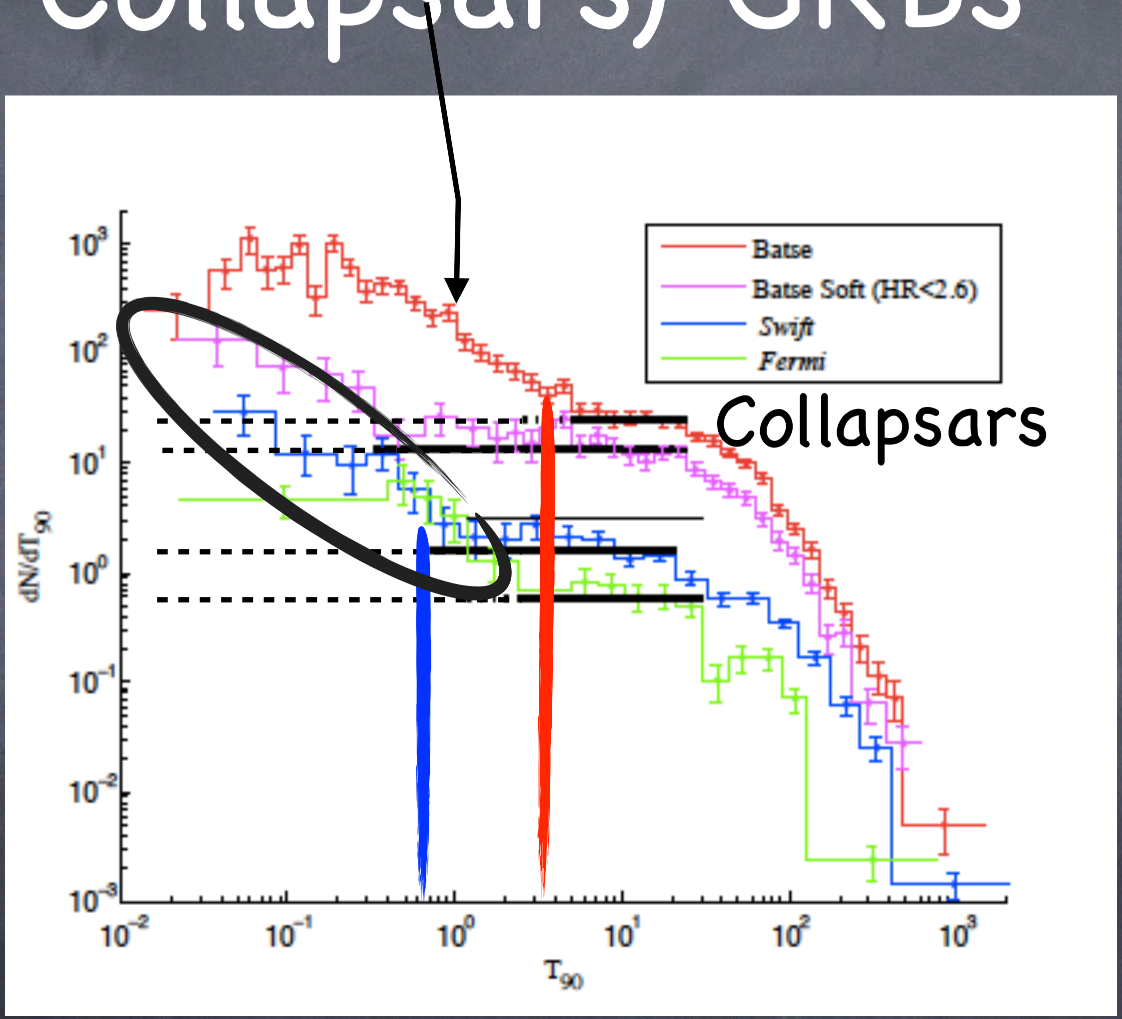
Swift Short (Non-Collapsars) GRBs



Swift Short (Non-Collapsars) GRBs



Swift Short (Non-Collapsars) GRBs

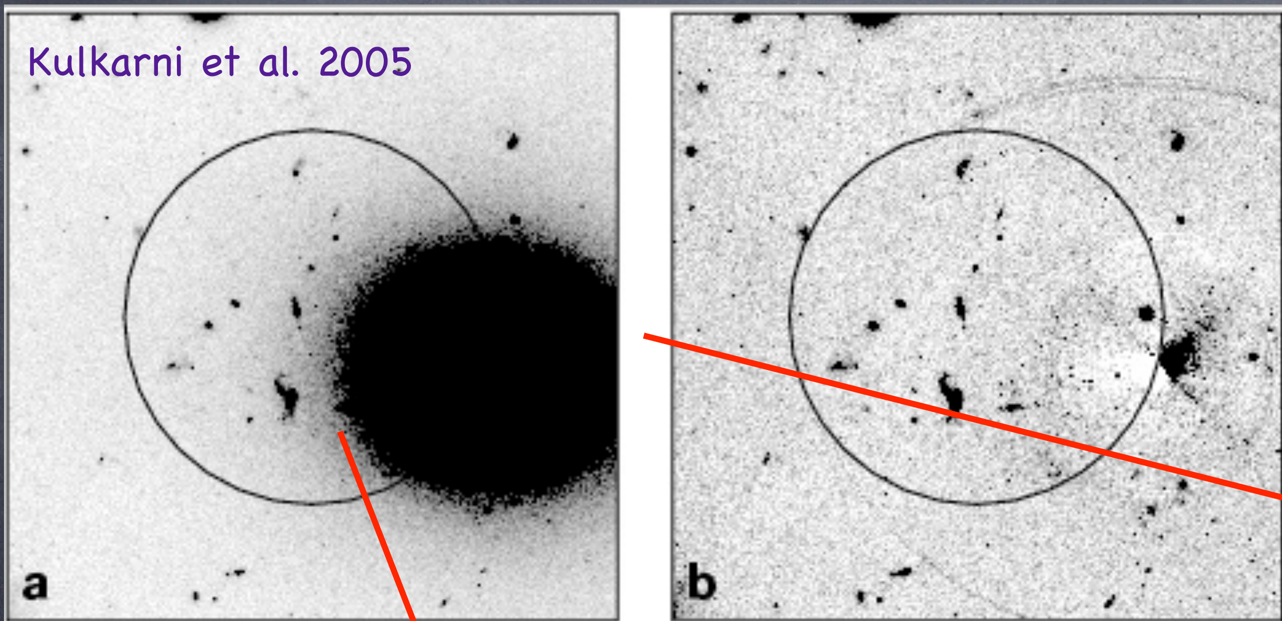


Short Swift GRBs with T_{90}>0.7sec are not "short"!

Short GRBs - GRB 050509b

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

No optical/radio afterglow



Elliptical host

⇓

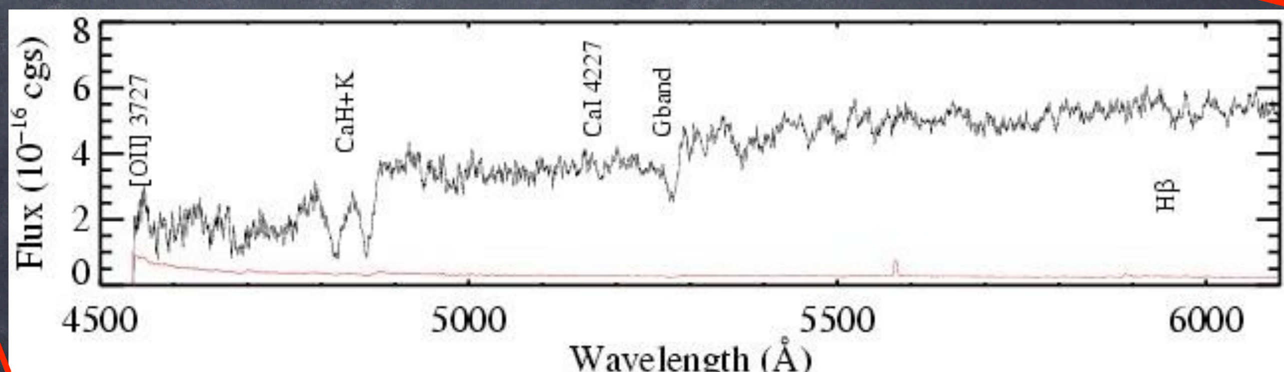
Old stellar population

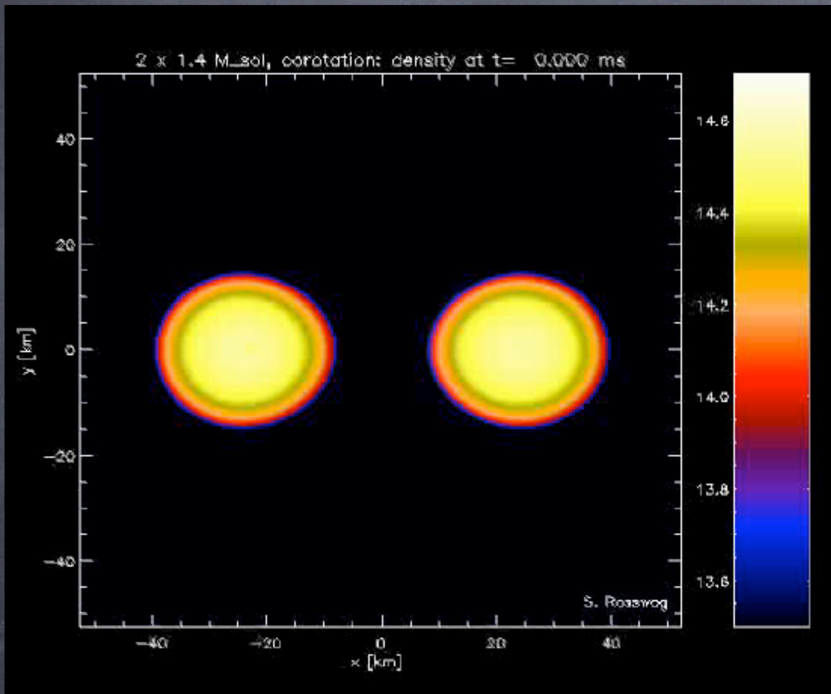
Bloom et al. 2005

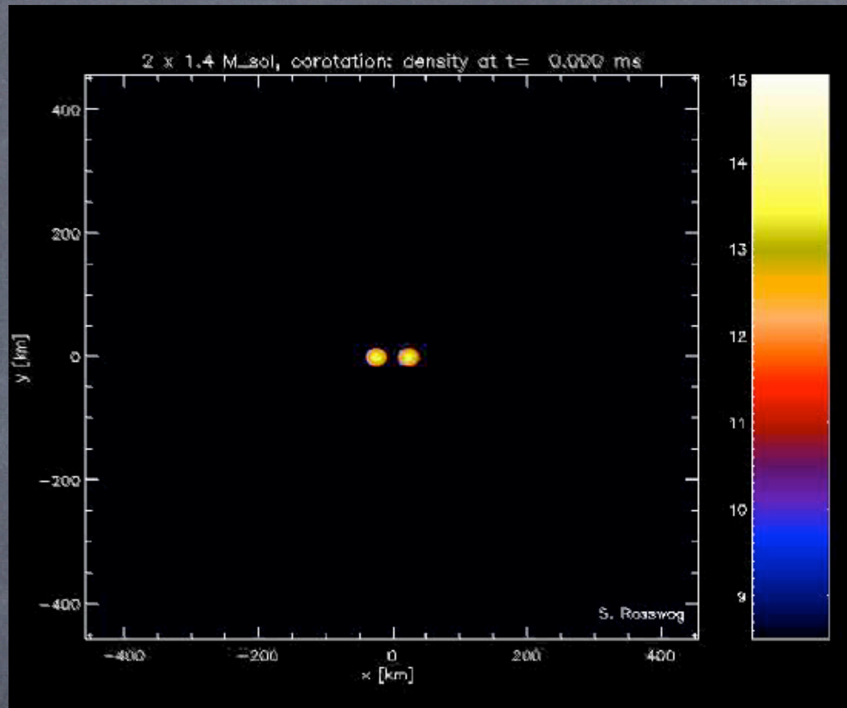
Castro-Tirado et al. 2005

Gehrels et al. 2005

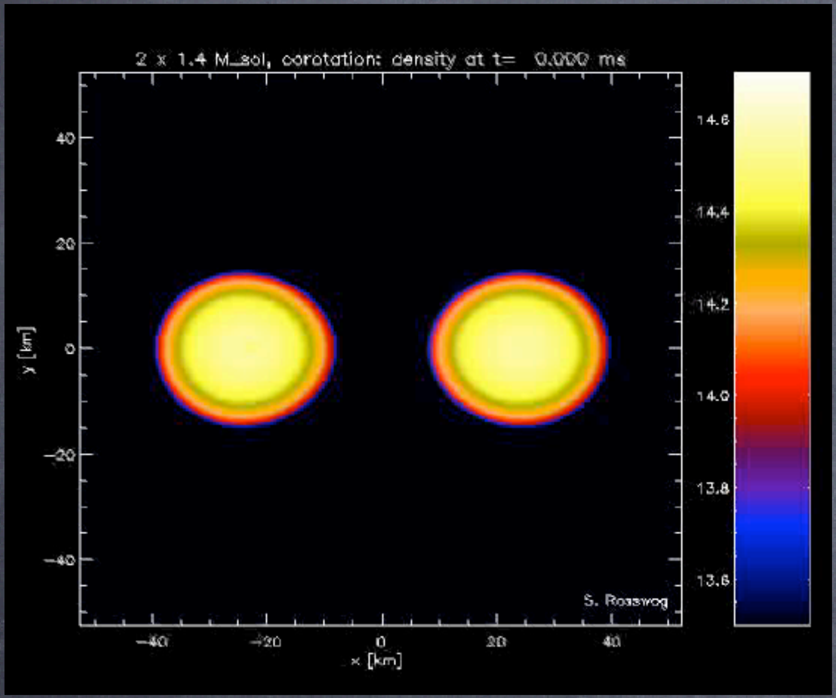
Hjorth et al. 2005



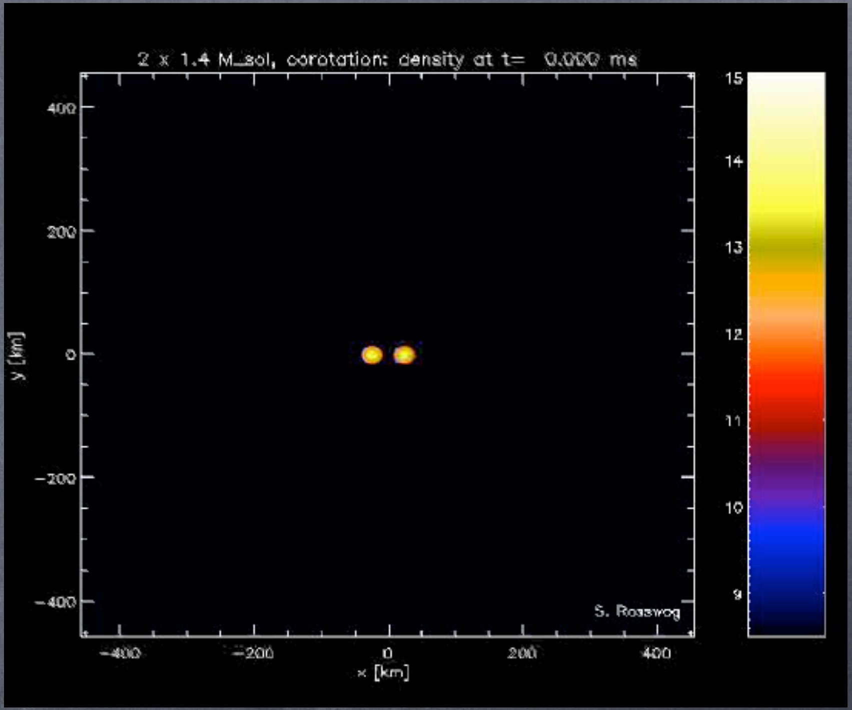




Price & Rosswog

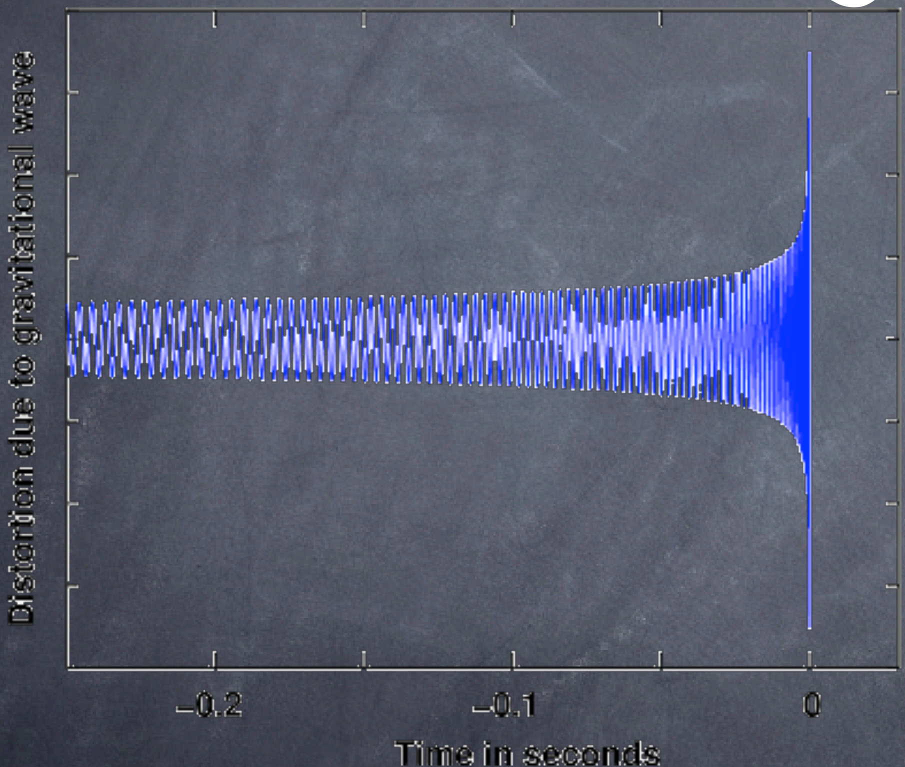


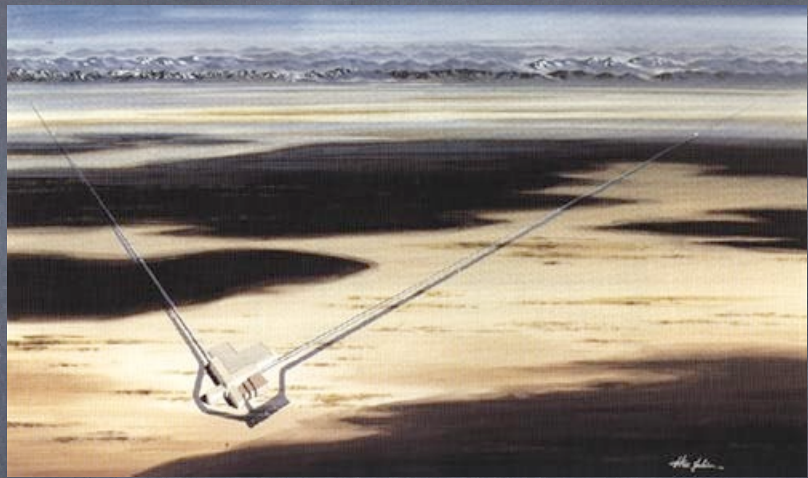
Price & Rosswog



Price & Rosswog

Short GRBs-NS Mergers ?

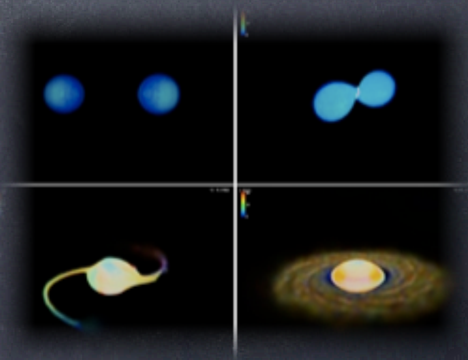




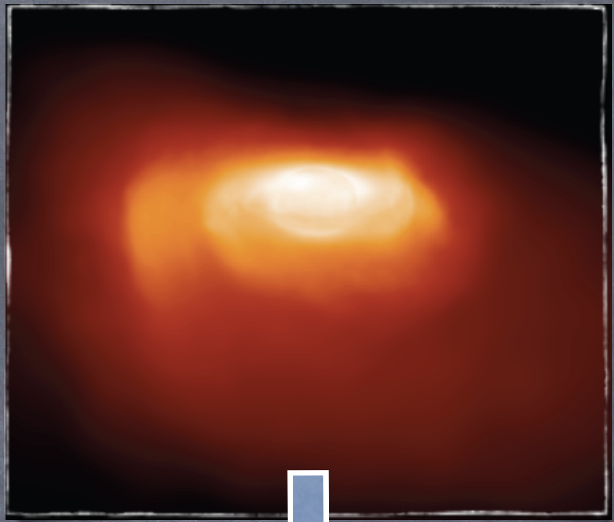
To be confirmation with detection of Gravitational radiation

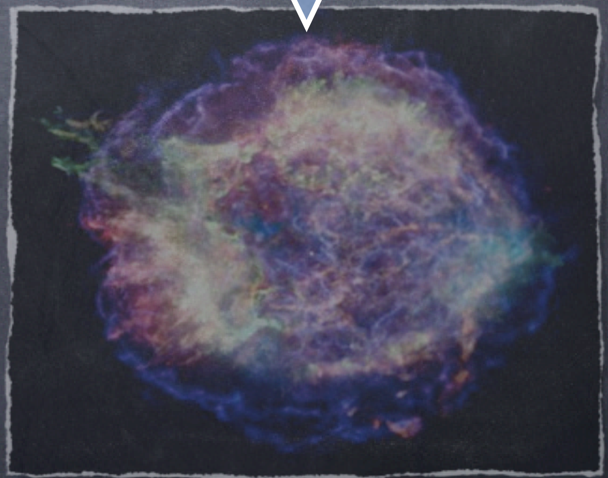
II. Radio Flares from Neutron Star merges - The Electromagnetic signals that follow the Gravitational Waves

Nakar + TP, Nature 2011, Nakar, TP & Rosswog in preparation



The Model

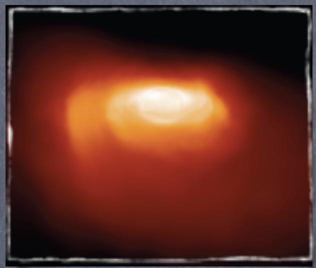


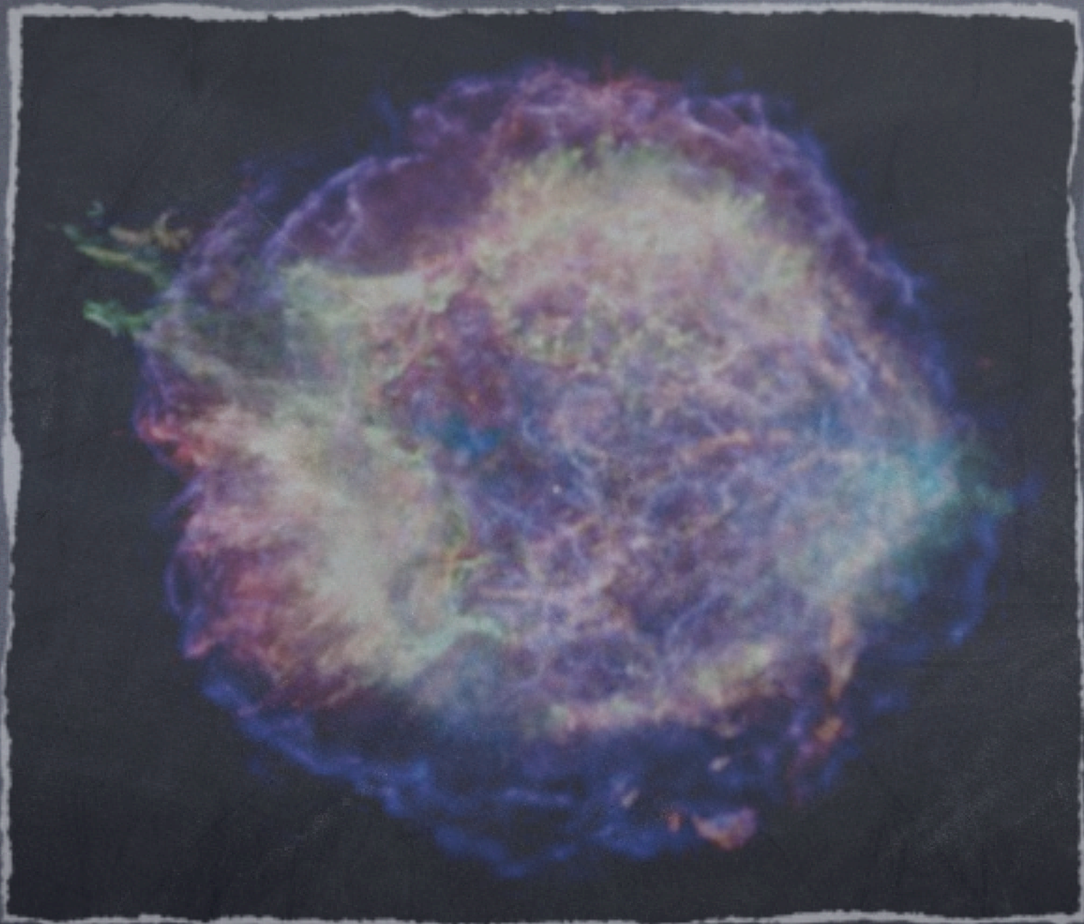


Numerous numerical simulations show that NS merger eject Sub - or Mildly relativistic outflow with E~10^{49} erg

Lorentz factor $(\Gamma-1)\approx 1$

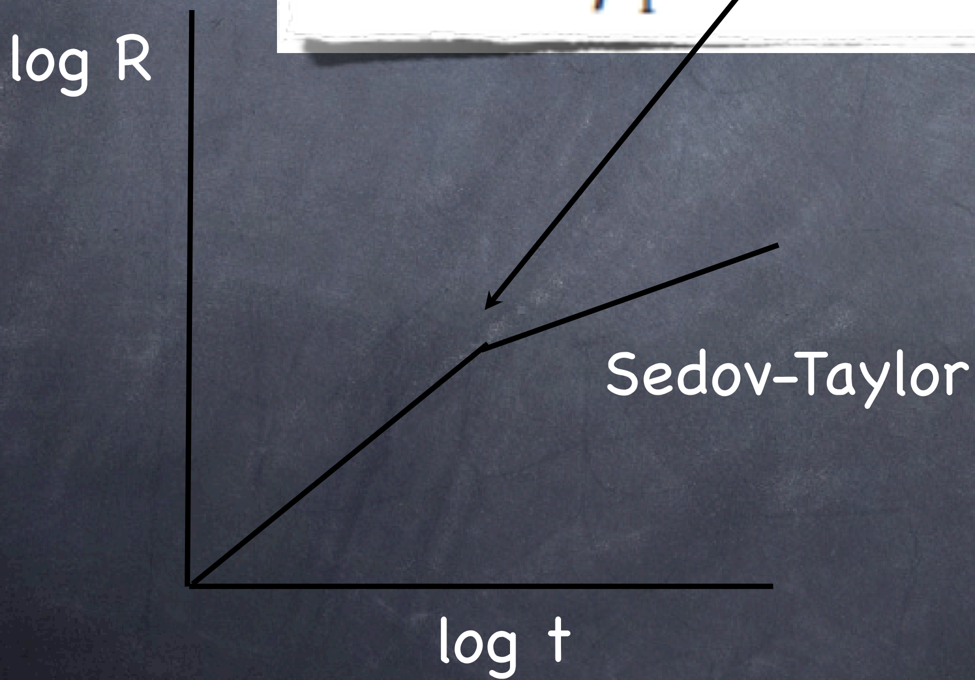
Interaction of the outflow with the ISM



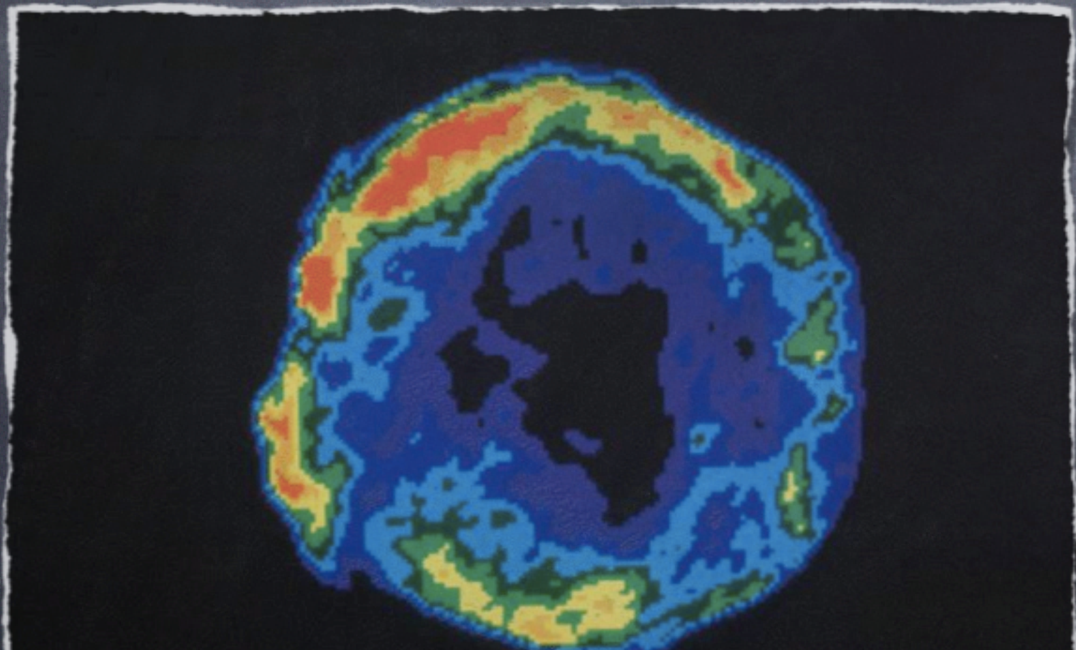


Dynamics

$$t_{\rm dec} = \frac{R_{\rm dec}}{c\beta_{\rm i}} \approx 30\ E_{49}^{1/3}\, n_0^{-1/3}\, \beta_{\rm i}^{-5/3}\ \text{days}$$



Radio Supernova
e.g. 1998bw (Chevalier 98)



Tycho's **supernova** remnant seen at **radio** wavelengths

$e_e = \varepsilon_e e$

$e_B = B^2/8\pi = \varepsilon_B e$

$N(\gamma) \propto \gamma^{-p}$ for $\gamma > \gamma_m$

$p = 2.5 - 3$

$\gamma_m = (m_p/m_e) e_e (\Gamma - 1)$

$\nu = (3/4\pi) eB \gamma^2$

$F_\nu = (\sigma_T c/e) N_e B$

Frequency and Intensity

(Nakar & TP Nature, 2011)

$$\nu_{m,dec} \equiv \nu_m(t_{dec}) \approx 1\ \mathrm{GHz}\ n^{1/2}\epsilon_{B,-1}^{1/2}\epsilon_{e,-1}^{2}(\Gamma_0 - 1)^{5/2},$$

$$F_{\nu_{obs},peak}[\nu_{obs} > \nu_{m,dec},\ \nu_{a,dec}] \approx$$

$$0.3 E_{49} n_0^{\frac{p+1}{4}} \varepsilon_{B,-1}^{\frac{p+1}{4}} \varepsilon_{e,-1}^{p-1} \beta_i^{\frac{5p-7}{2}} d_{27}^{-2} \left(\frac{\nu_{obs}}{1.4}\right)^{-\frac{p-1}{2}}$$

$$N_{all-sky}(1.4\mathrm{GHz}) \approx 20 E_{49}^{11/6} n^{\frac{9p-1}{24}} \epsilon_{B,-1}^{\frac{3(p+1)}{8}} \epsilon_{e,-1}^{\frac{3(p-1)}{2}} (\Gamma_0 - 1)^{\frac{45p-83}{24}} \mathcal{R}_{300} F_{lim,-1}^{-3/2} \ .$$

$$N_{all-sky}(1.4\mathrm{GHz}) \approx 20 E_{49}^{11/6} n^{\frac{9p-1}{24}} \epsilon_{B,-1}^{\frac{3(p+1)}{8}} \epsilon_{e,-1}^{\frac{3(p-1)}{2}} (\Gamma_0 - 1)^{\frac{45p-83}{24}} \mathcal{R}_{300} F_{ltm,-1}^{-3/2} \,.$$

$$N_{all-sky}(1.4\mathrm{GHz}) \approx 20 E_{49}^{11/6} n^{\frac{9p-1}{24}} \epsilon_{B,-1}^{\frac{3(p+1)}{8}} \epsilon_{e,-1}^{\frac{3(p-1)}{2}} (\Gamma_0 - 1)^{\frac{45p-83}{24}} \mathcal{R}_{300} F_{lim,-1}^{-3/2} .$$

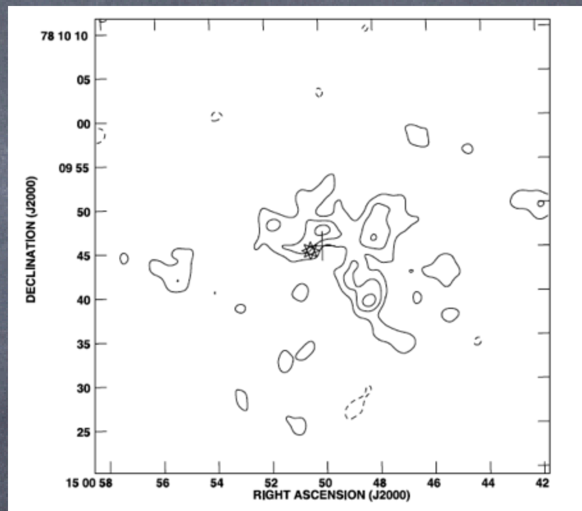
Detectability

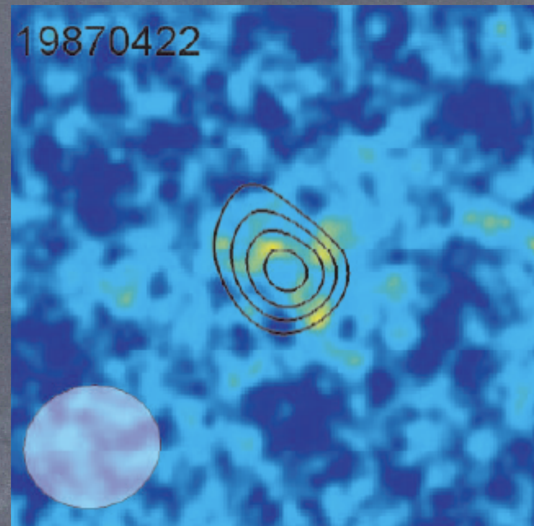
Table 1 | Observing radio flares

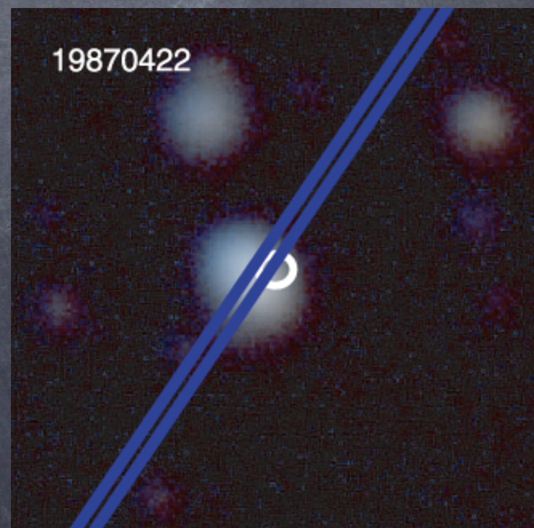
Radio facility	Observing frequency (GHz)	Field of view (deg^2)	One-hour r.m.s.* (μJy)	One-hour detection horizon†			Ten-hour detection horiz
				$\beta_i \approx 1$, $E_{49} = 1$, $n_0 = 1$	$\beta_i \approx 1$, $E_{49} = 10$, $n_0 = 1$	$\beta_i = 0.2$, $E_{49} = 10$, $n_0 = 1$, $p = 2.5$	$\beta_i \approx 1$, $E_{49} = 1$, $n_0 = 10^{-3}$, $p = 2$
EVLA	1.4	0.25	7	1 Gpc	3.3 Gpc	370 Mpc	140 Mpc
ASKAP	1.4	30	30	500 Mpc	1.6 Gpc	180 Mpc	70 Mpc
MeerKAT	1.4	1.5	35	500 Mpc	1.6 Gpc	165 Mpc	65 Mpc
Apertif	1.4	8	50	400 Mpc	1.25 Gpc	140 Mpc	50 Mpc
LOFAR	0.15	20	1,000	35 Mpc	90 Mpc	70 Mpc	20 Mpc

The Bower Transient 19870422

- 5GHz 0.5mJy (<0.036 mJy) t_{next} =96 days 1.5″ from the centroid of MAPS-P023-0189163 a blue Sc galaxy at z=0.249 (1050Mpc) with current star formation



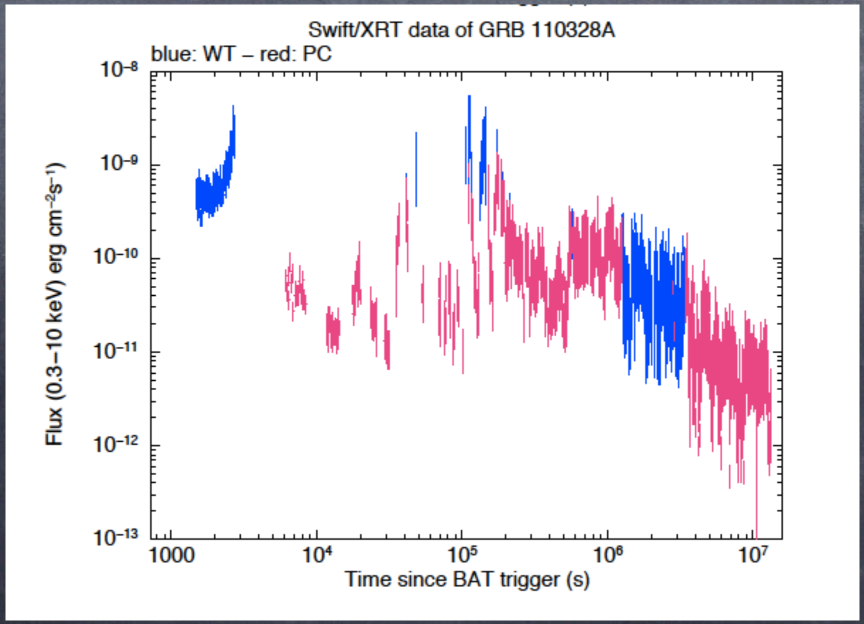




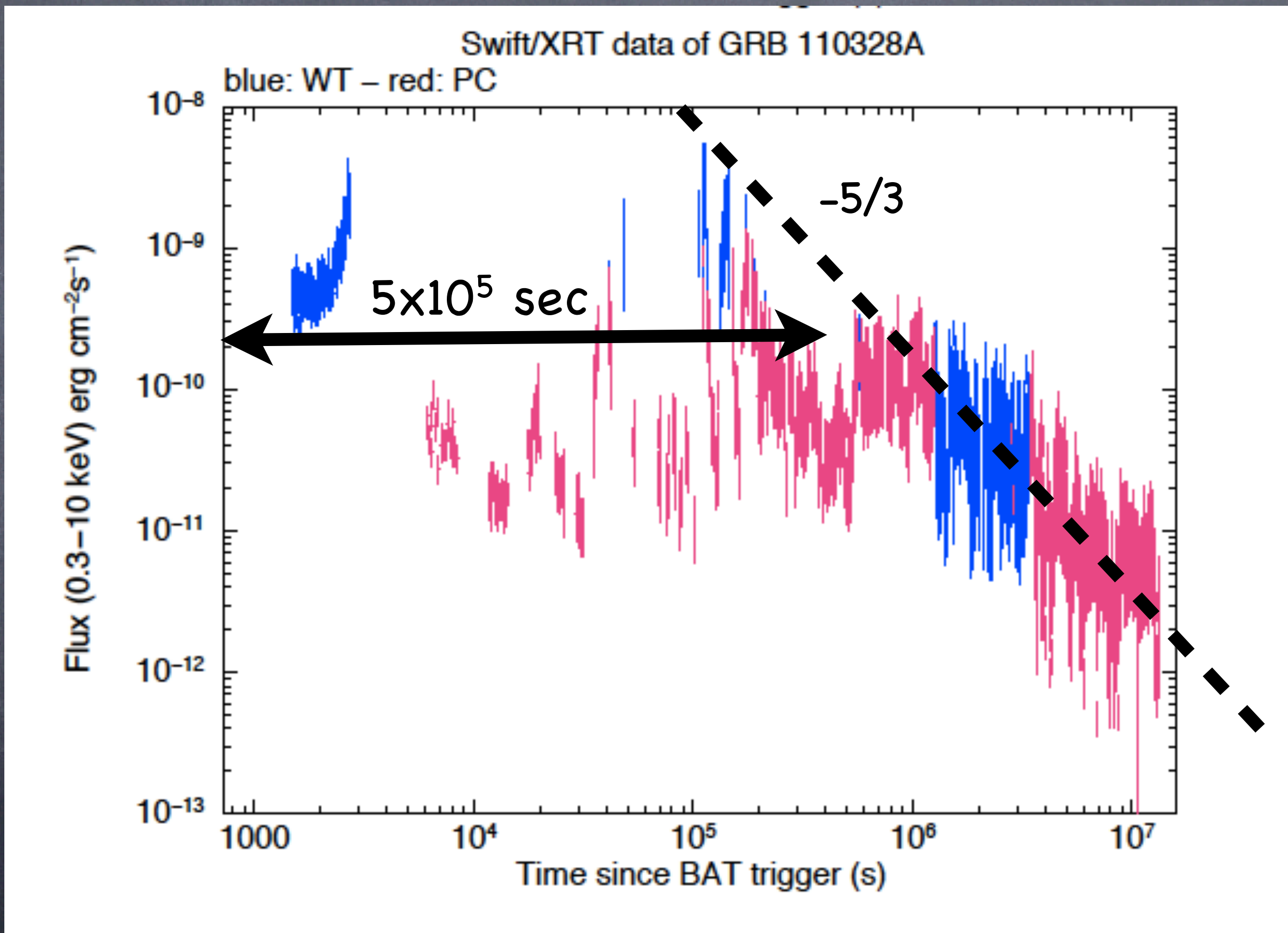
ERROR!

III. TIdal Disruption Events - Swift J1644 (GRB110328) and J2058

TP + Julian Krolik (ApJ. in press + arXiv1111.2802)

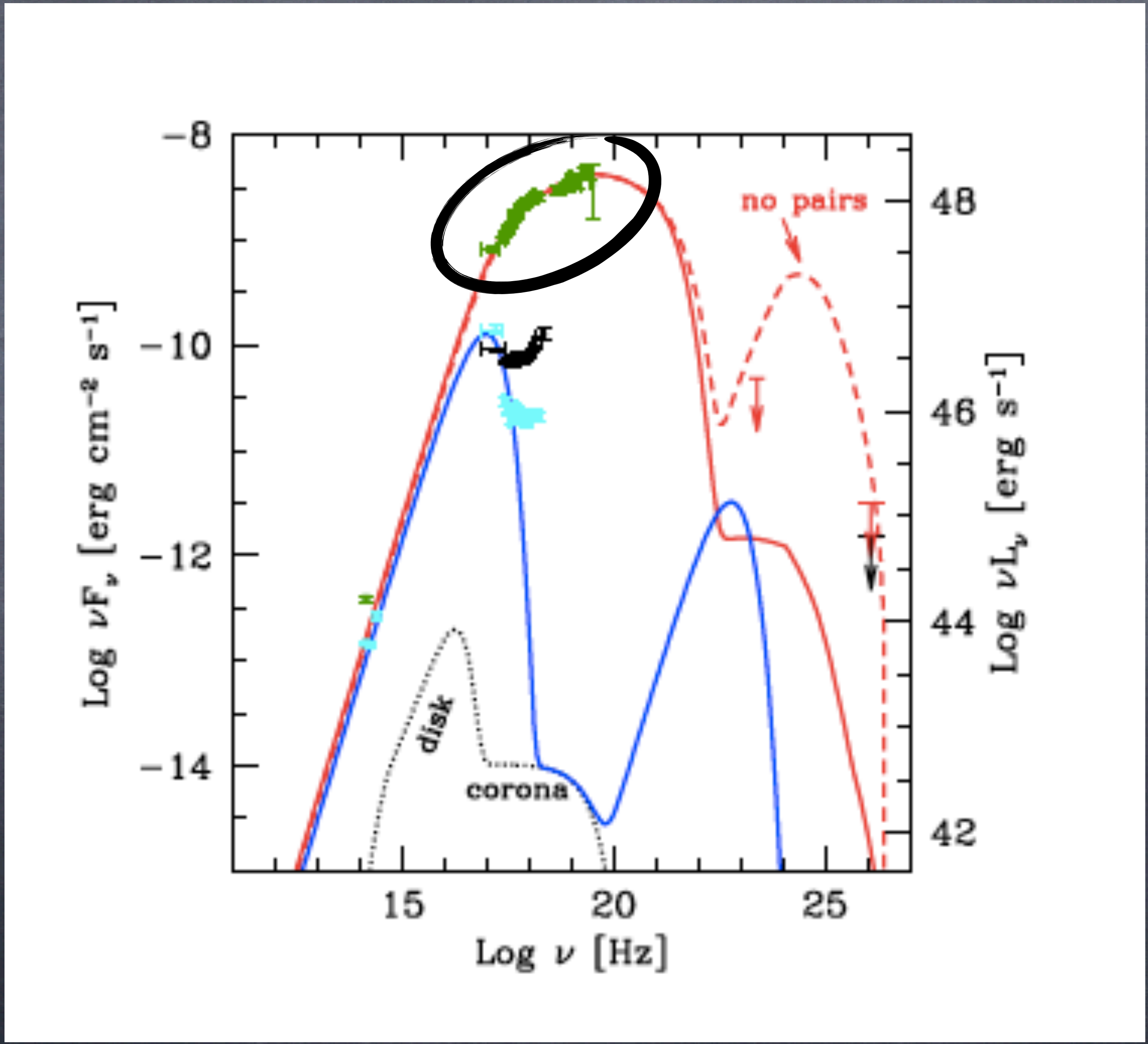


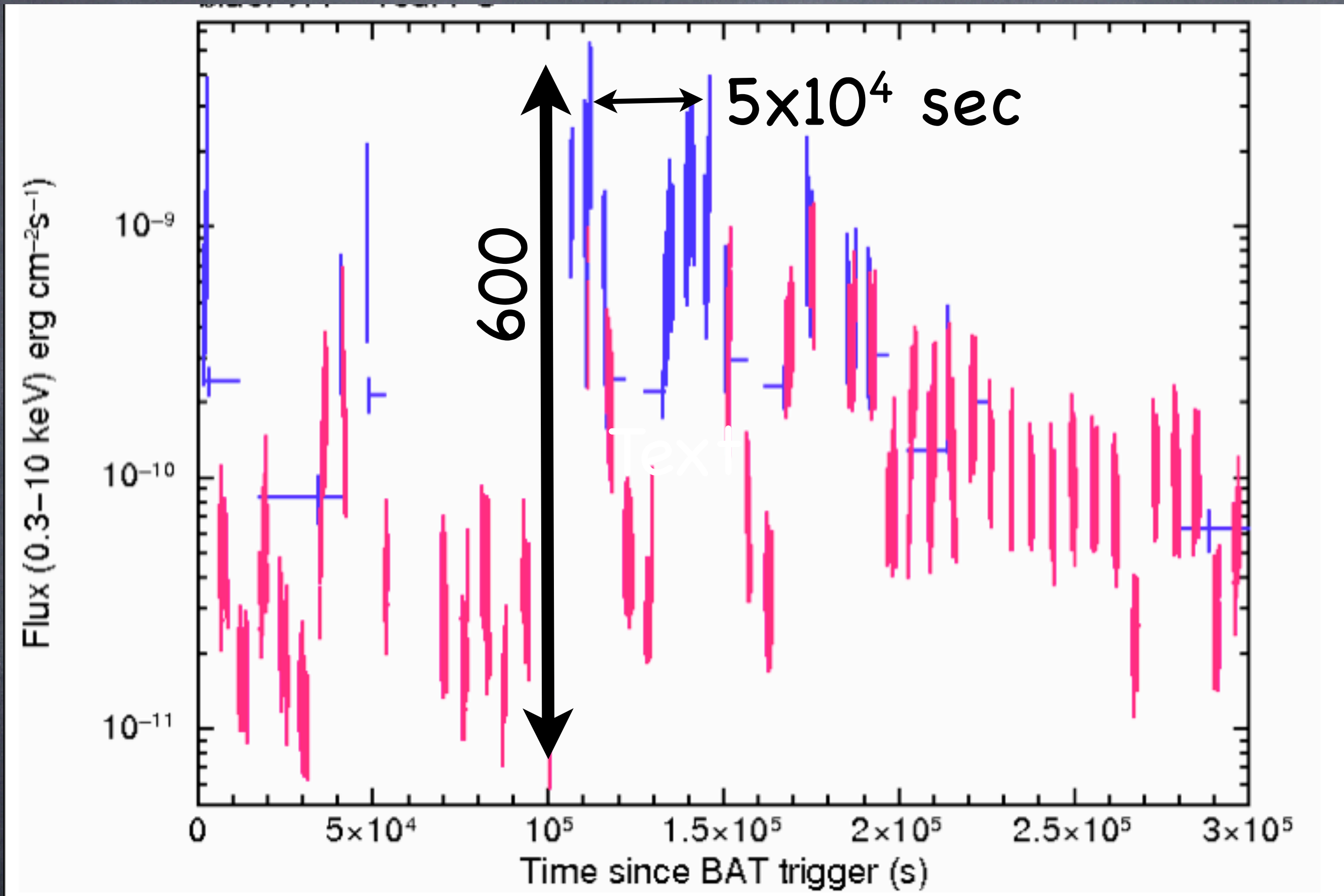
Ligth Curve



Friday, November 18, 2011

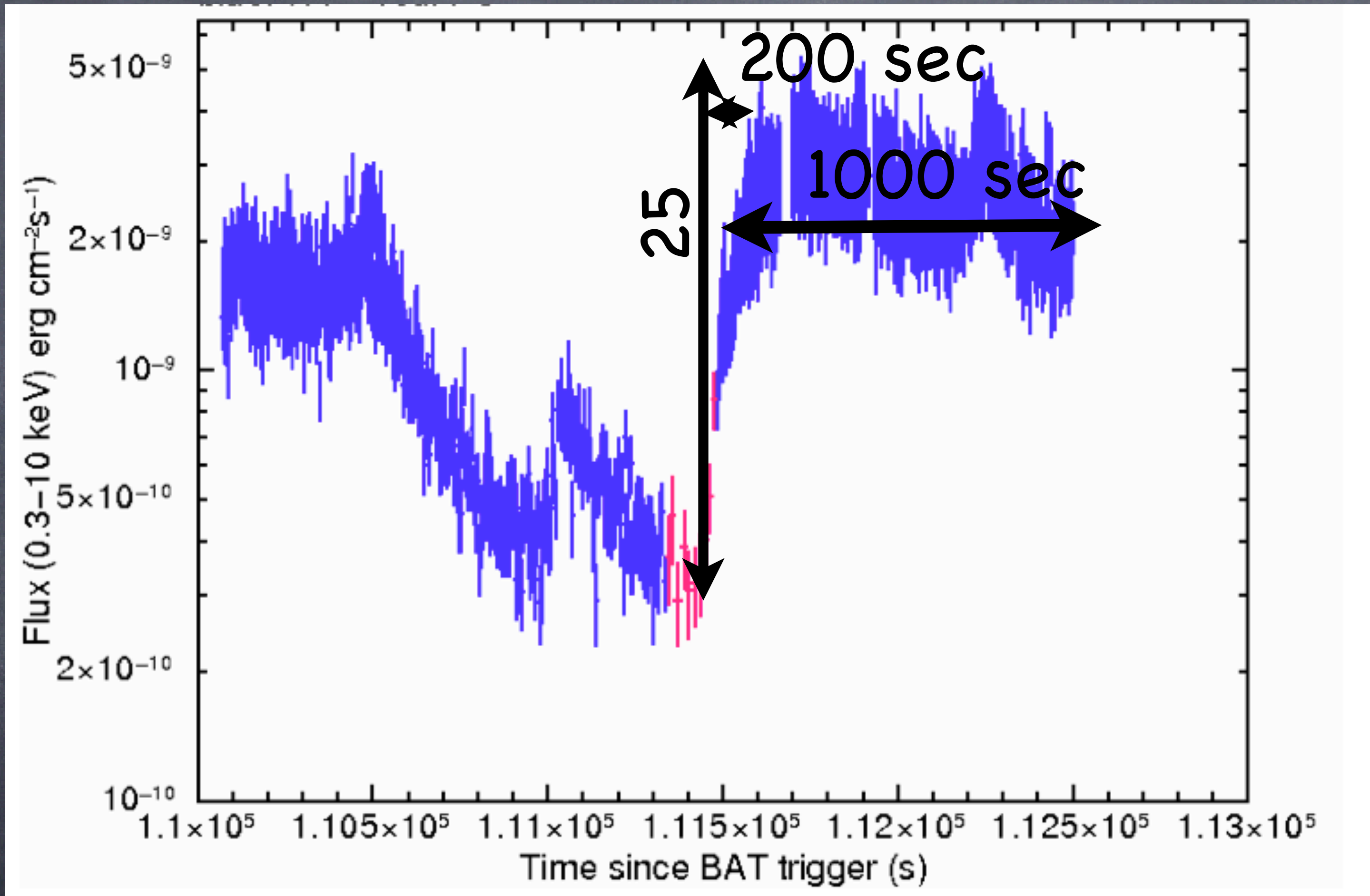
SED (Burrows et al.)





Swift light curve on a linear scale

The Third Flare



Light curve from 1.1×10^5 to 1.13×10^5 sec

Temporal features:

- Strong variability on 100 sec time scale
- Flares last about 1000-2000 sec
- Minima between the flares is a factor of 600 below the maxima
- $3x10^4$ sec between flares
- $2x10^5$ sec - duration before onset of a gradual decay

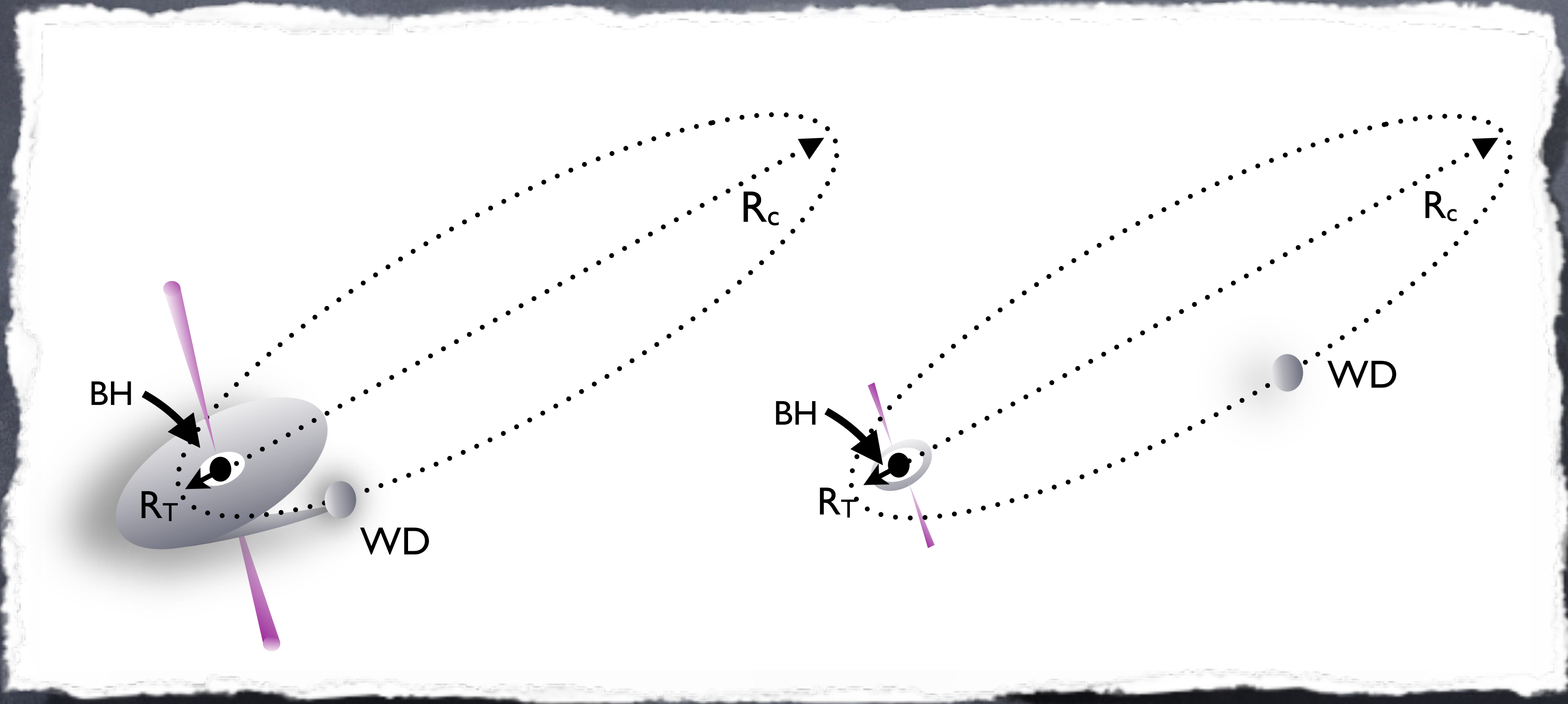
A tidal disruption of a main sequence star

The minimal relevant time scale:

$P_{orb}(R_T) \approx 1/\sqrt{(G \rho)} \approx 10^4$ sec

Impossible to get 200 sec variability

A Disruption of a White Dwarf by a $5 \cdot 10^5\ M_\odot$ black hole



$$P_{orb}(R_T) \approx 1/\sqrt{(G\,\rho)} \approx 6 \text{ sec}$$

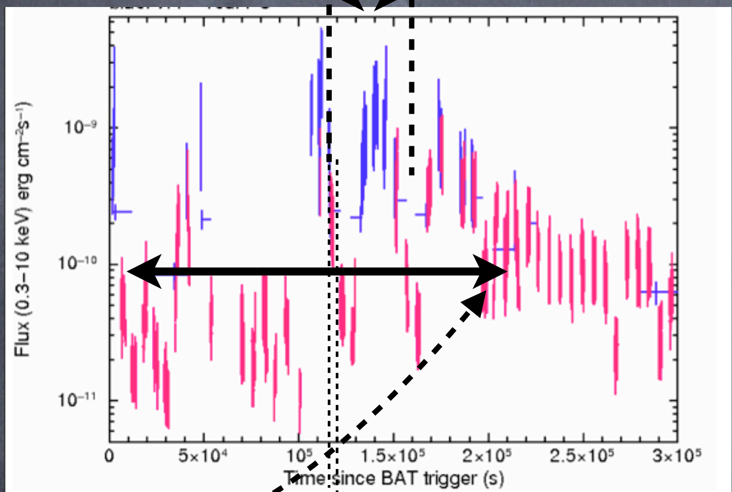
For a White Dwarf

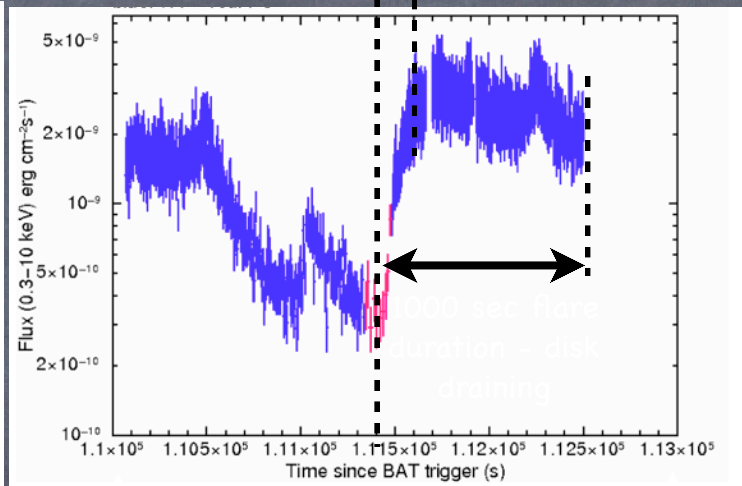
$P_{orb}(R_T) \approx 1/\sqrt{(G\rho)} \approx 6$ sec

- 100 sec rise time - onset of accretion
- 1000 sec flare duration - the "drainage" time of a small accretion disk forms in a partial disruption event.
- 5×10^4 sec between flares - orbital time
- Precurse three days before the event is the "first" tidal passage

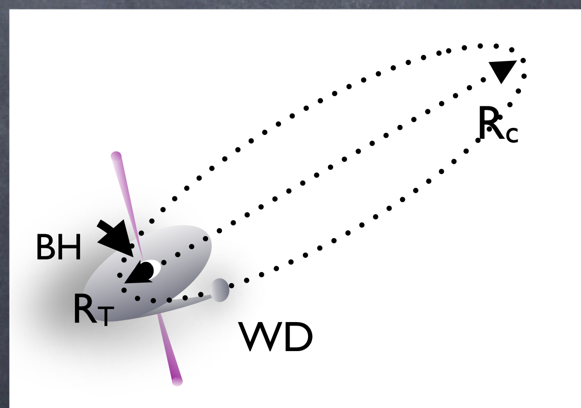
5×10^4 sec- orbital period of WD remnant

200 sec rise time - a few RT orbits



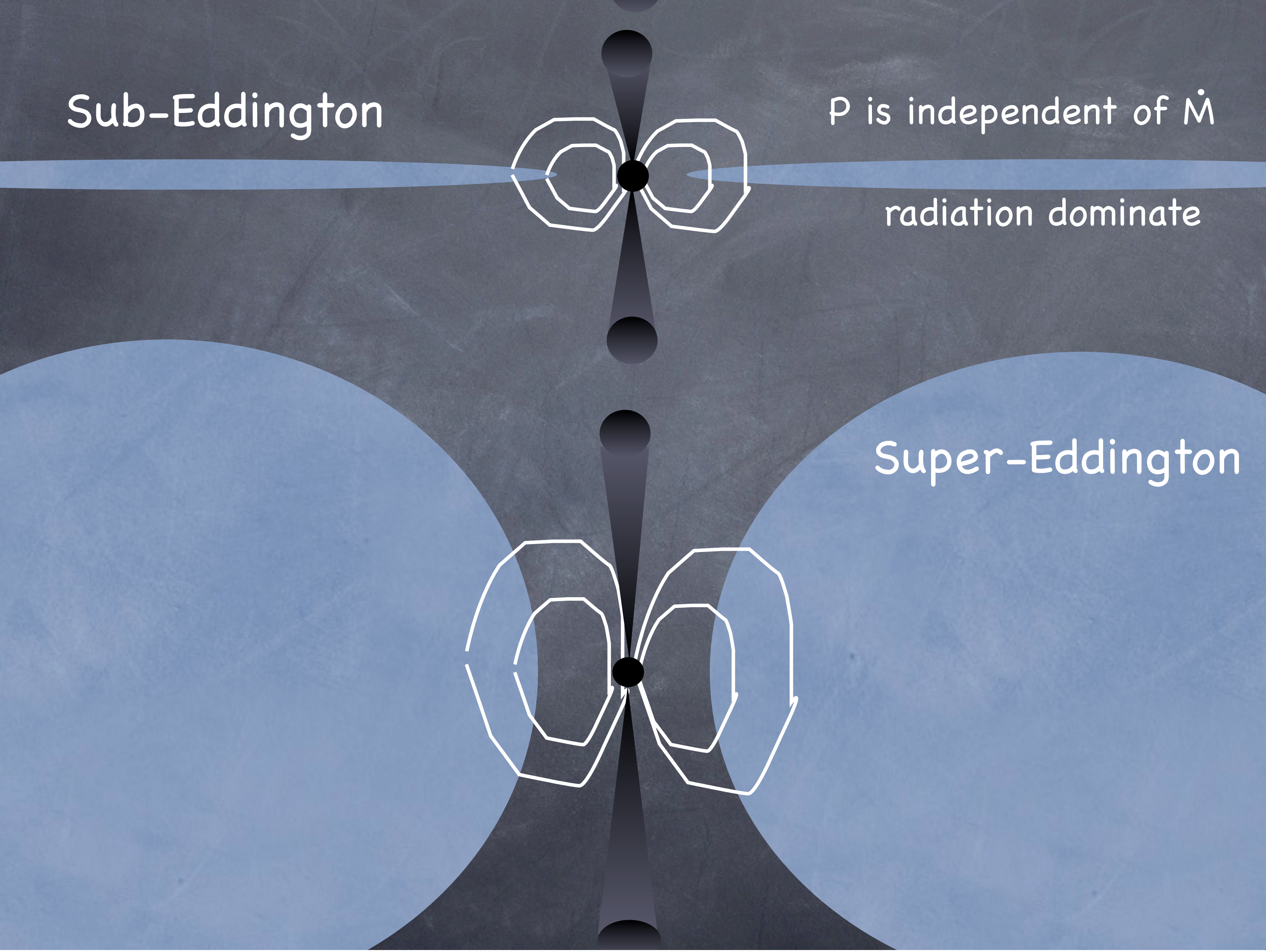


2×10^5 sec - onset of $t^{-5/3}$ decay

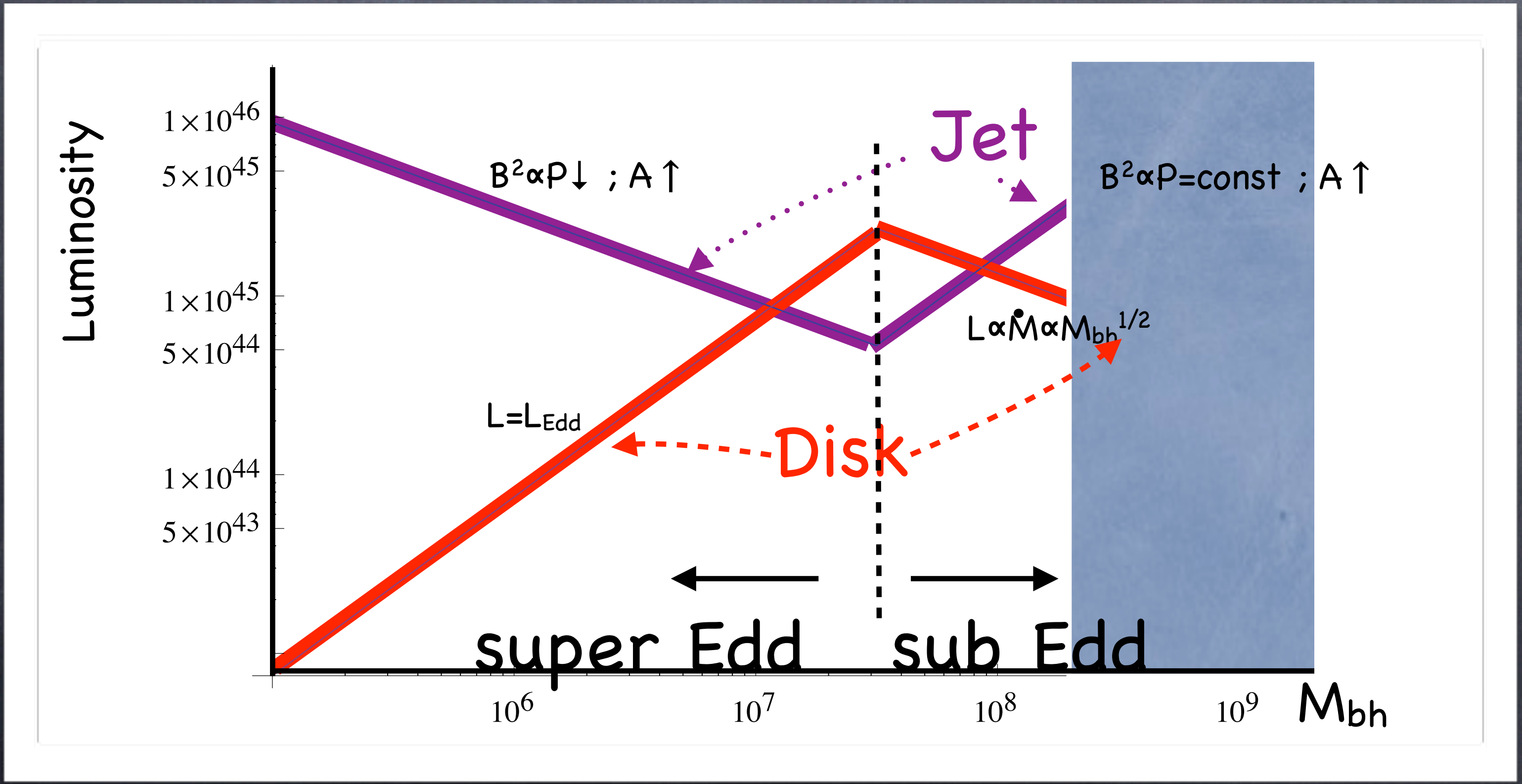


Why Jet?

- Blandford Znajek Jet power is deterimined by Magnetic field (B) on the horizon and the BH's area.
- B is determined by P (Pressure around ISCO)
- P depends on accretion mode - super or sub Eddington which depends on on BH mass M_{BH} accretion rate $\dot{M} \propto (M_*/M_{BH})^{1/2}$
- Thermal (UV) emission also depends on accretion mode.

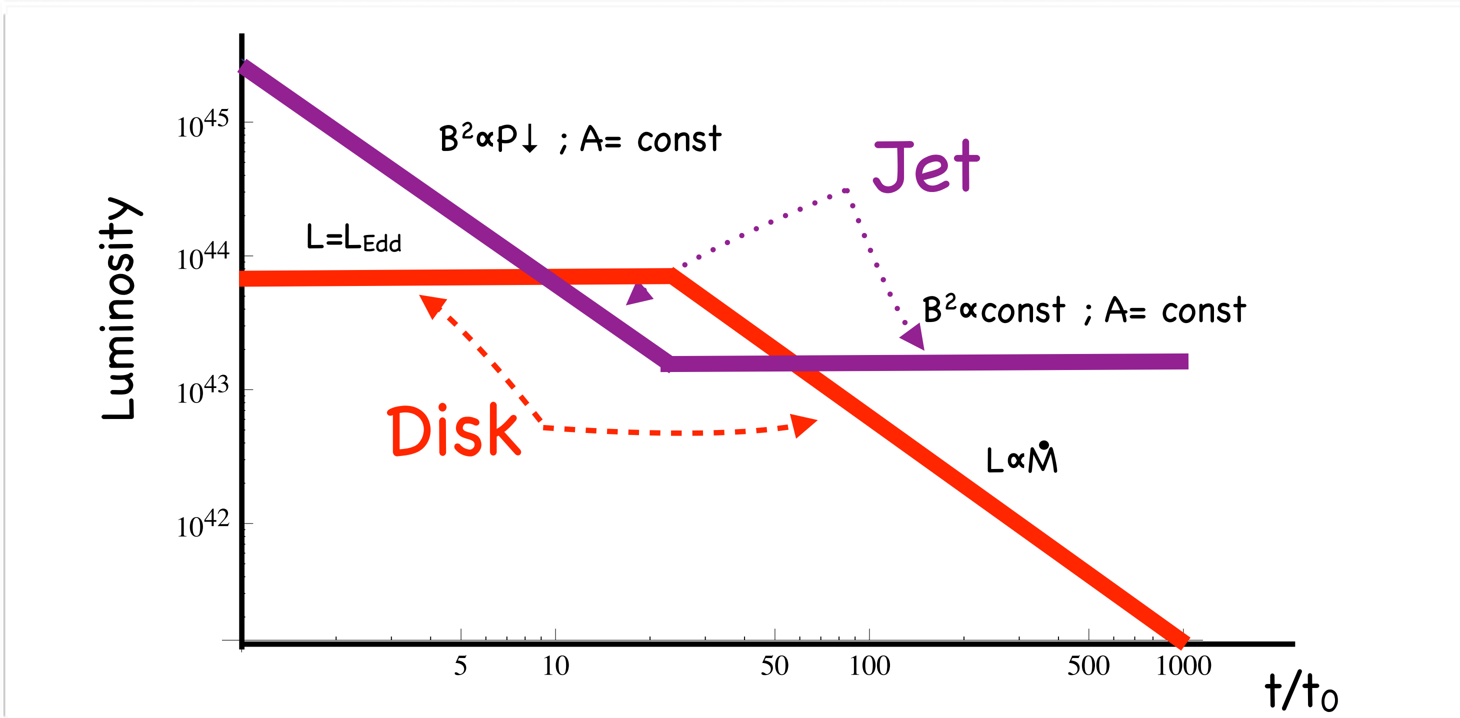

Sub-Eddington
P is independent of $\dot{M}$
radiation dominate
Super-Eddington

Jet (non thermal) vs Disk (thermal UV) Luminsoity

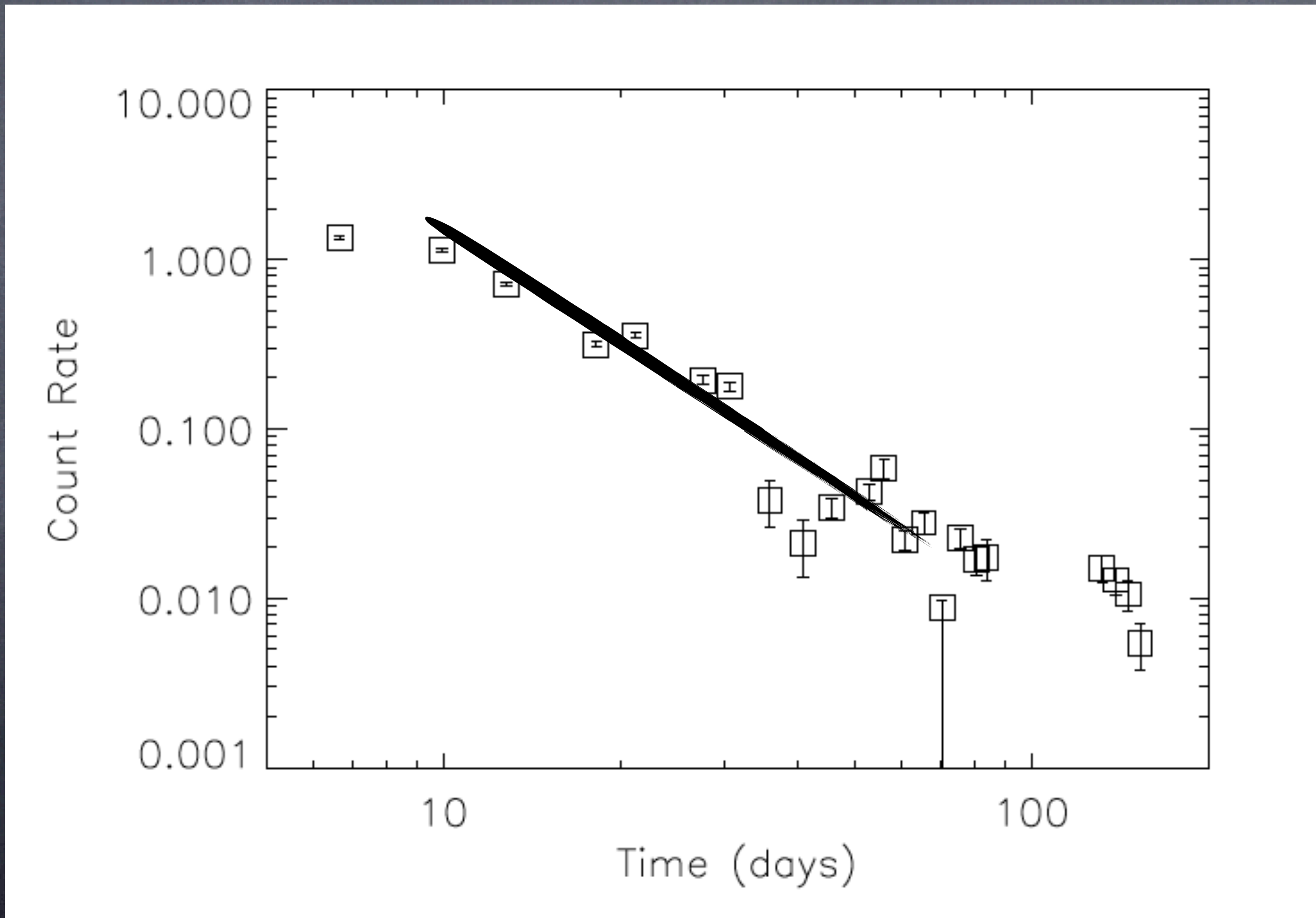


Light curves

$t_0 \simeq 1 \times 10^7 (\mathcal{M}_* M_{BH,6})^{1/2}$ s,



The x-ray light curve of Swift J2508



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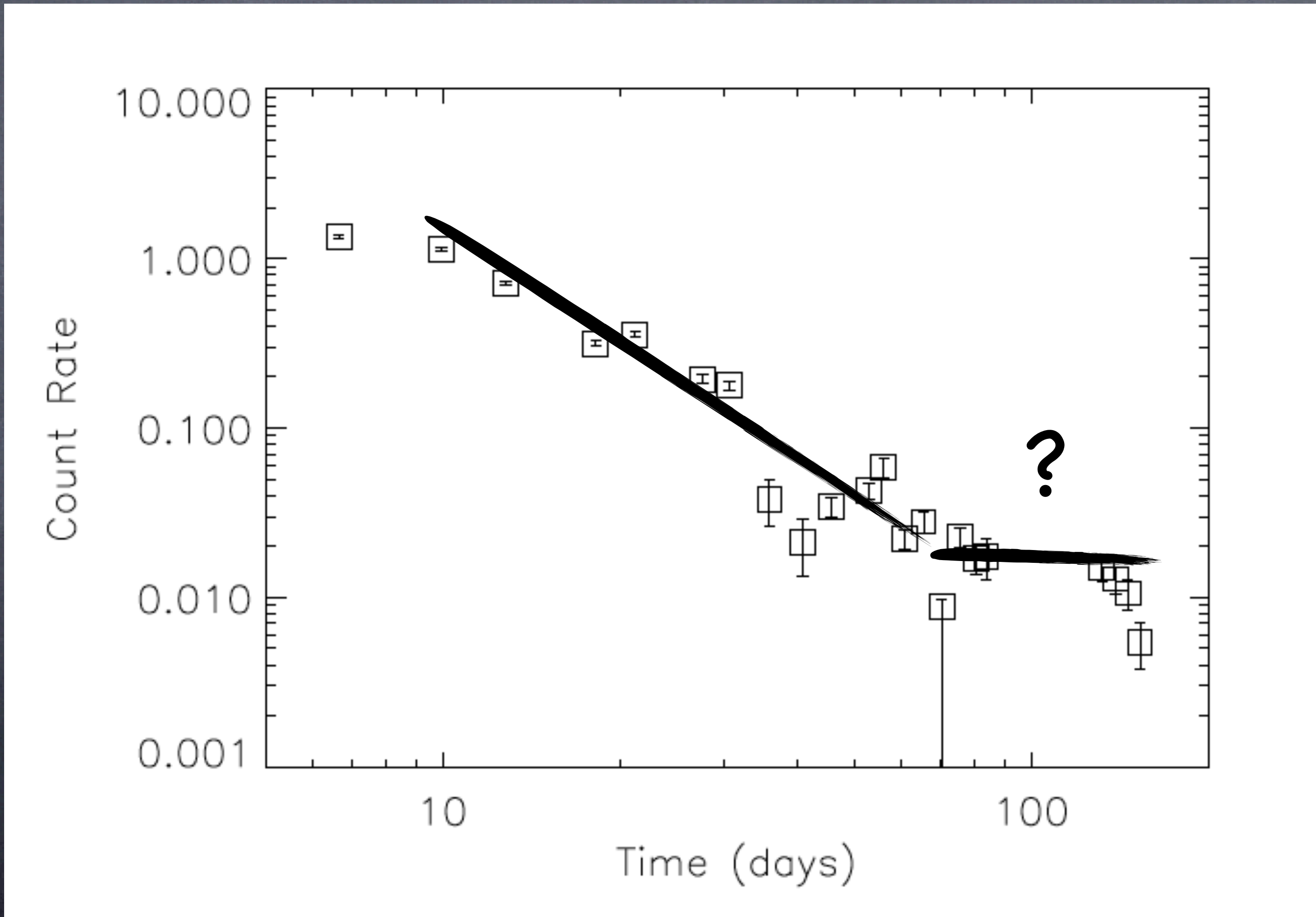
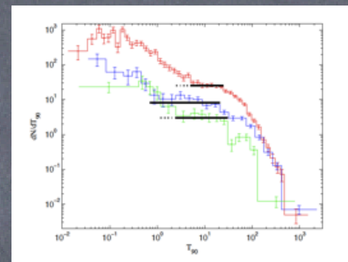


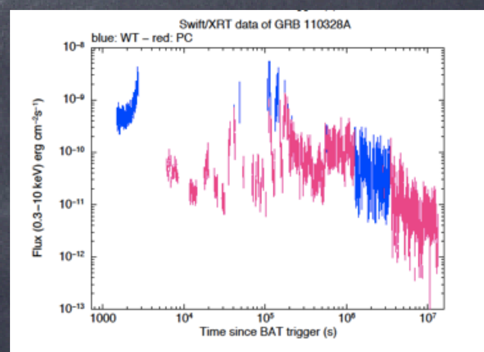
Can we apply a similar reasoning to Neutrino Dominated Accretion Disks in GRBs?

Kawanaka & TP in preparation 2011

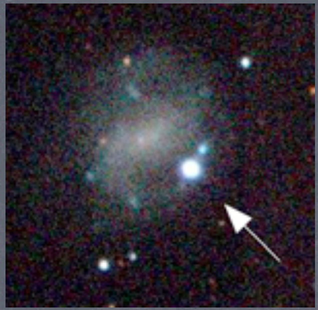
Summary

- There is a third population of GRBs - low luminosity GRBs - llGRBs - that arise from a different physica mechanism
- The observed plateau in the duration distribution of LGRBs show that LGRBs arise from Collapsars!
- A large fraction (~1/3) of Swift short GRBs are Collapsars (only those with less than 0.7 sec are clearly Non-Collapsars).
- Strong Radio Flares shold follow Neutron Star mergers
- Swift J1644 was a disruption of a WD
- Super Edd -> Jets -> x-rays in TDEs





Summary



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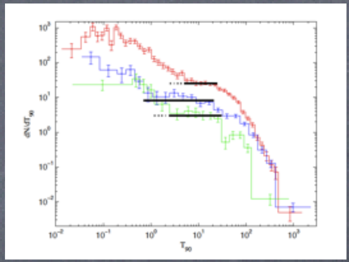

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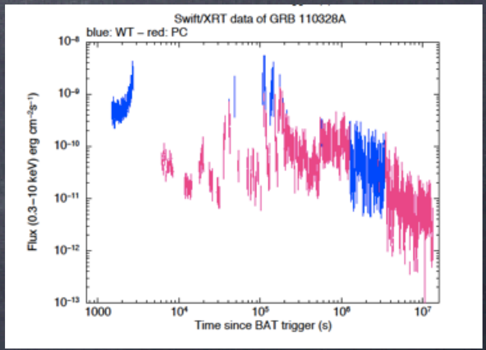

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