The Origin of Cosmic Fireworks

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Franck Genet, Eli Livne

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GRBs are the (electromagnetically) brightest objects in the Universe. Only ~8 orders of magnitude less then the theoretically maximal * luminosity (c^5/G)~10^{59} erg/sec .

$$\frac{Mc^2}{GM/c^3}$$

* Up to relativistic corrections.

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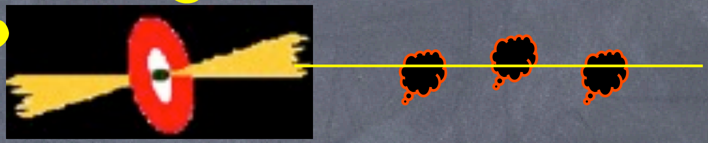
- **Determining the high redshift history of the universe ?**



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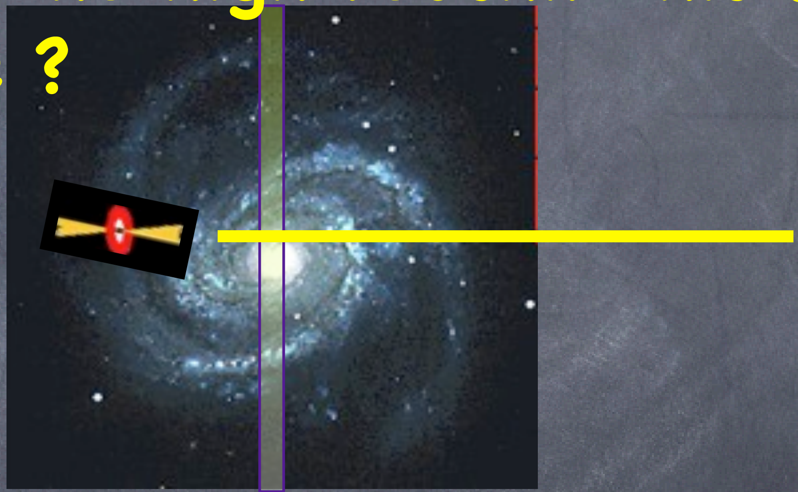

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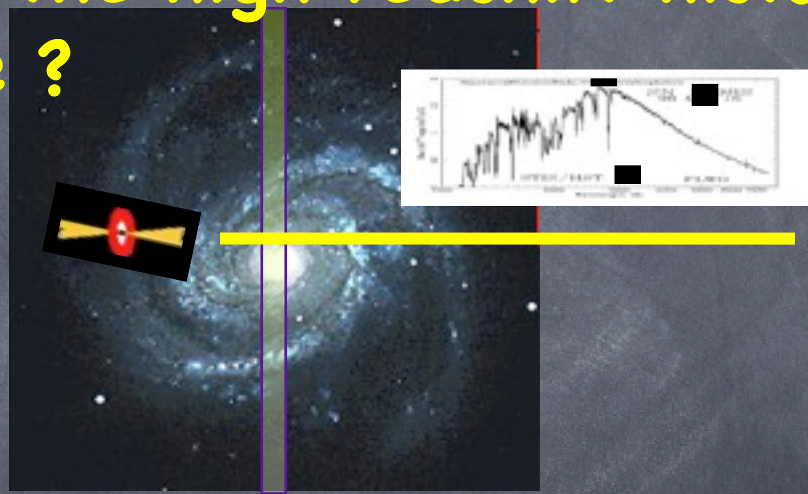

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- Determining the high redshift history of the universe ?
- Destroy Life on Earth (mass extinction) ??

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- Determining the high redshift history of the universe ?
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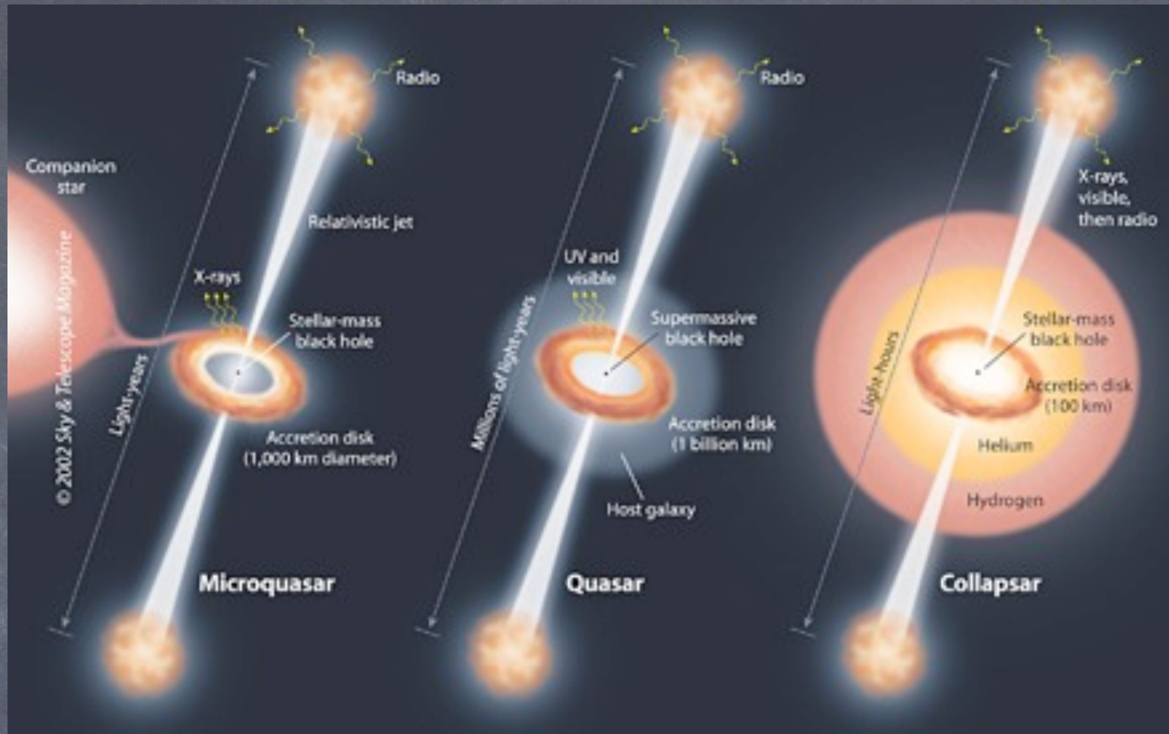
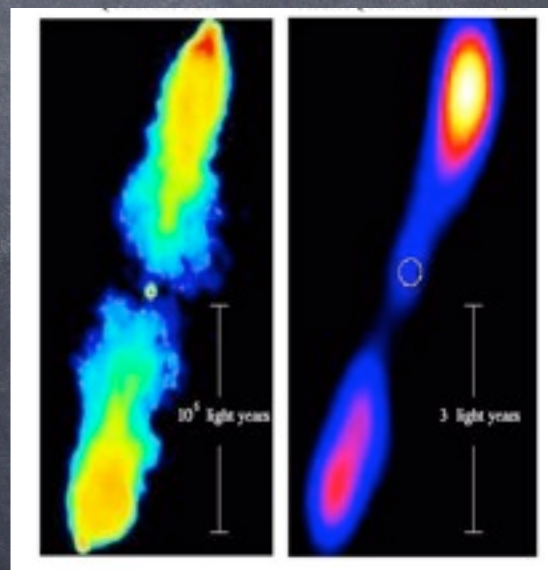
- Creat Life on Earth (trigger planet formation)?


The M87 Jet


Radio
Radio
Companion star
Relativistic jet
X-rays
Stellar-mass black hole
Accretion disk (1,000 km diameter)
Light-years
© 2002 Sky & Telescope Magazine
Microquasar
UV and visible
Supermassive black hole
Accretion disk (1 billion km)
Host galaxy
Millions of light-years
Quasar
X-rays, visible, then radio
Stellar-mass black hole
Accretion disk (100 km)
Helium
Hydrogen
Light-hours
Collapsar


3 light years

Properties

- Duration 0.01-1000s

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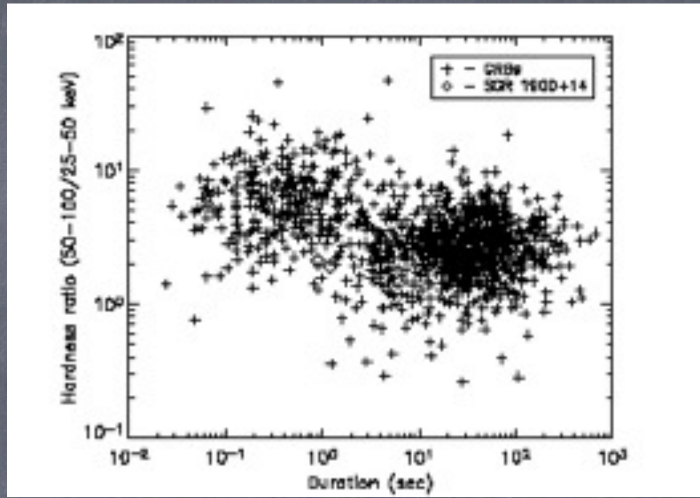

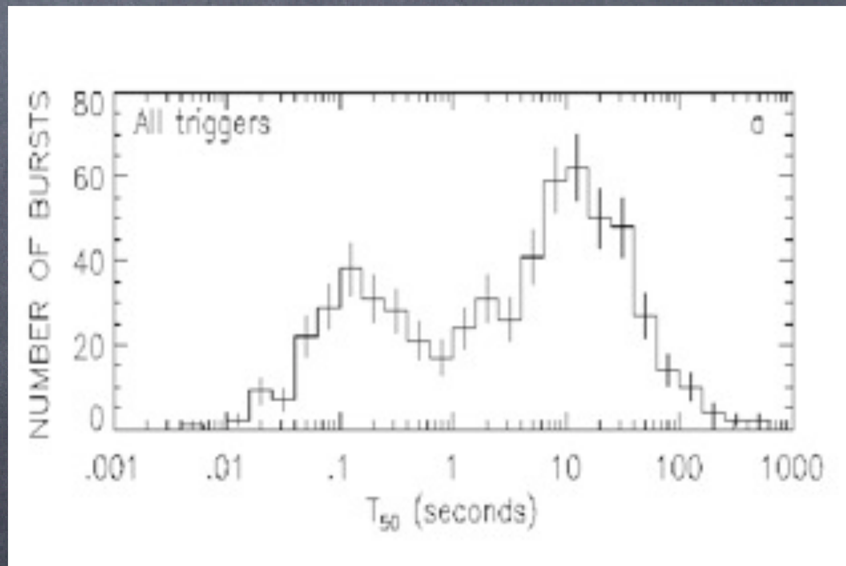

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- ~10keV - 10 MeV

  (non thermal spectrum)

  (very high energy tail,

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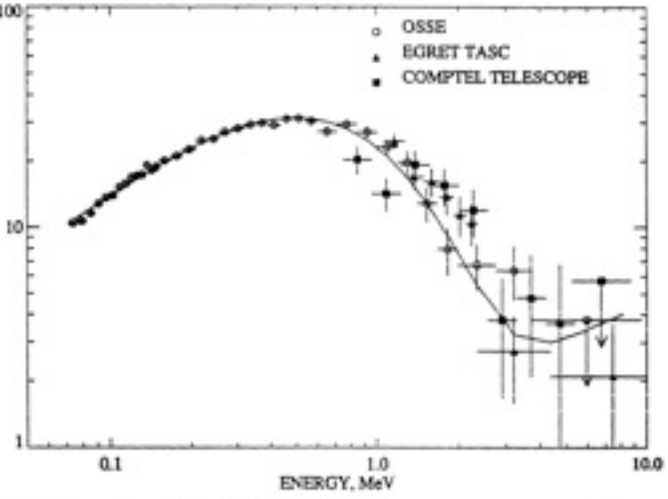

Figure 9 The spectrum of GB 910601 observed over a wide energy range, as measured by three experiments on *CGRO* (Share et al 1994). A typical broad spectrum with a peak power at about 600 keV is seen. (The fitted spectral up-turn above 4 MeV is not significant.)

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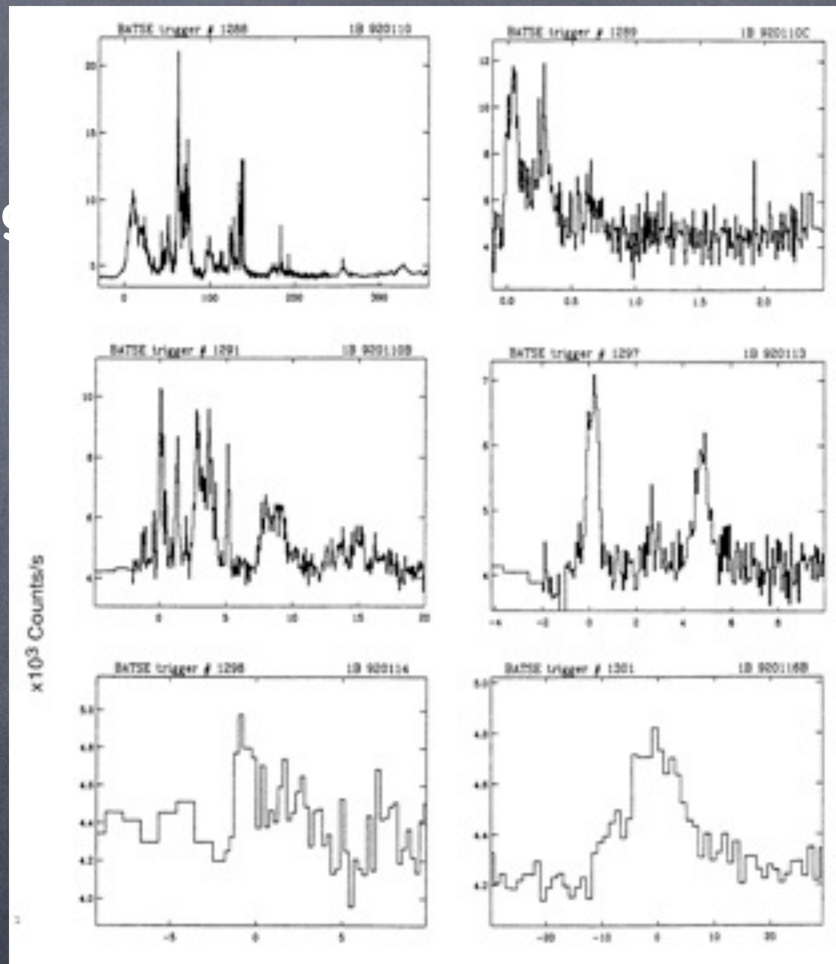

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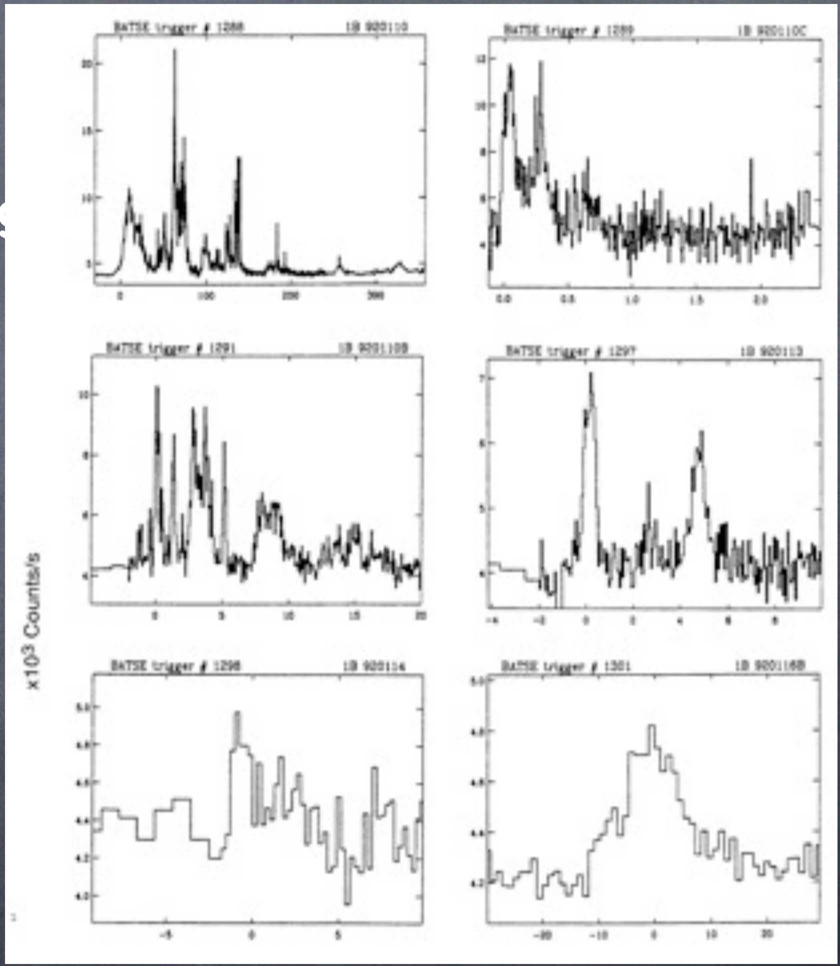
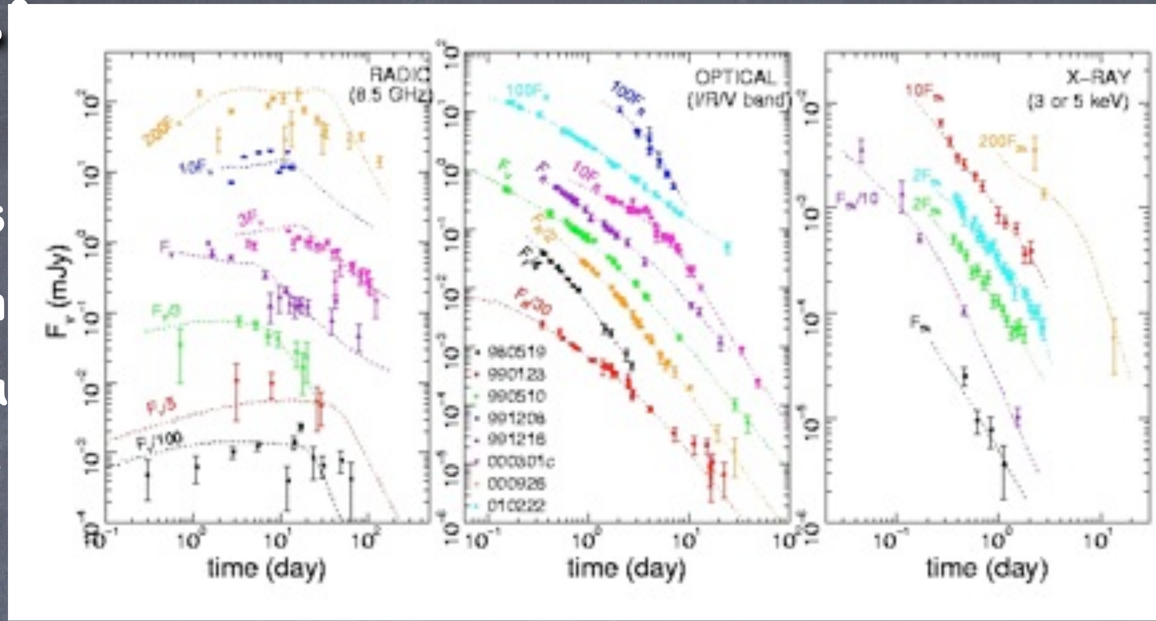


Propert



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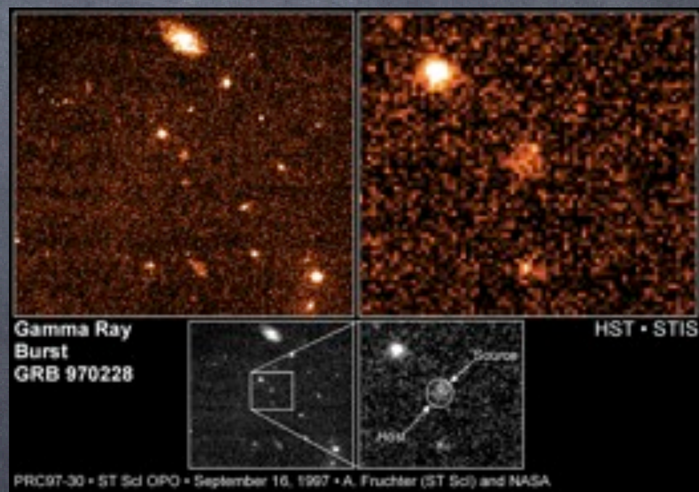
- Followed by multiwavelength
  Afteglow



What is the origin of GRBs?

The (long) GRB-Supernova connection

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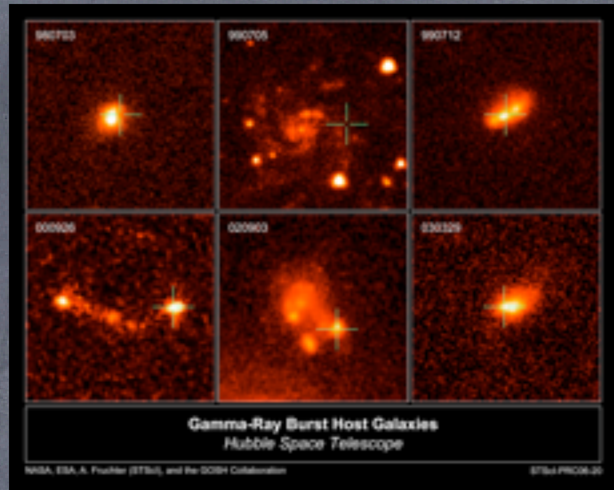
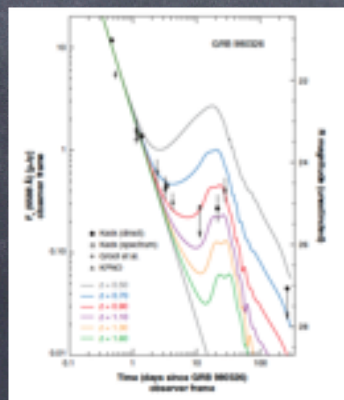
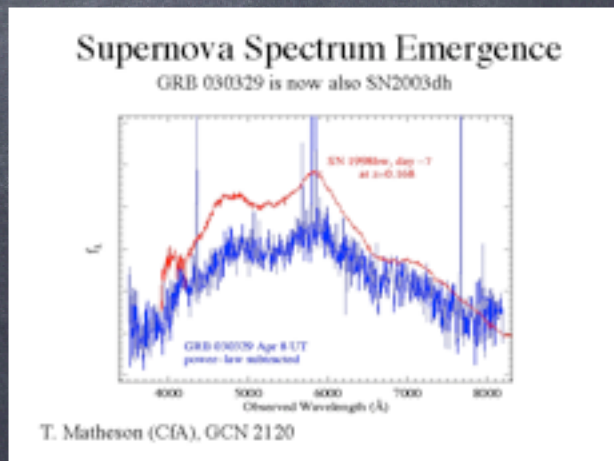
- Observational indications
  - Long GRBs arise in star forming regions (Paczynski 1997)
  - **Association with Sne (Ibc) Galama et al. 1998**
  - SN bumps.
  - **GRB030329-SN 2003dh**

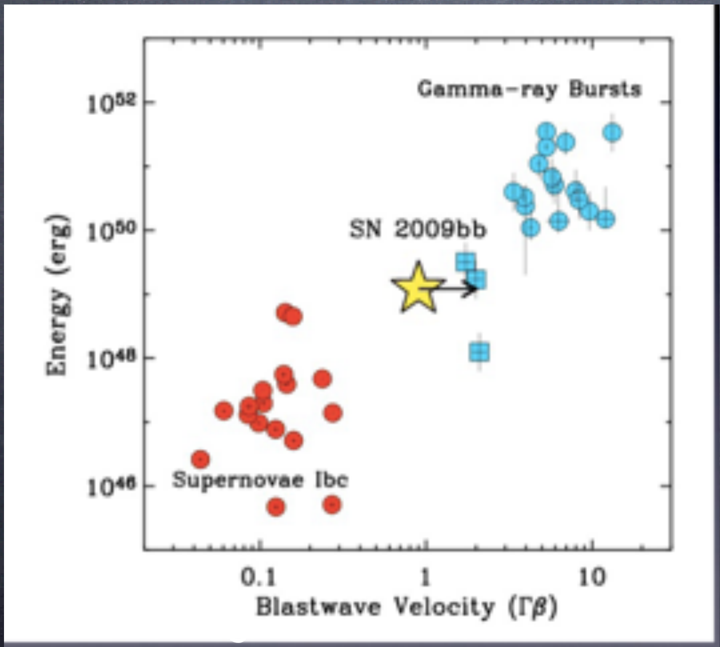


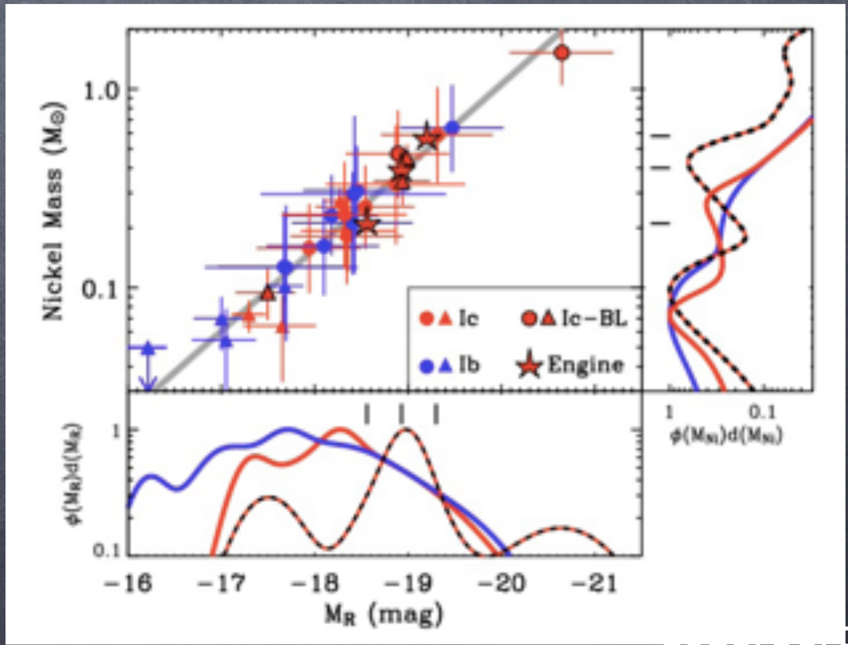




SNe of GRBs

- Very bright (Hypernova) - but not unique
- Broad lines (high velocity outflow >0.1c)
- Possibly engine driven (Soderberg)

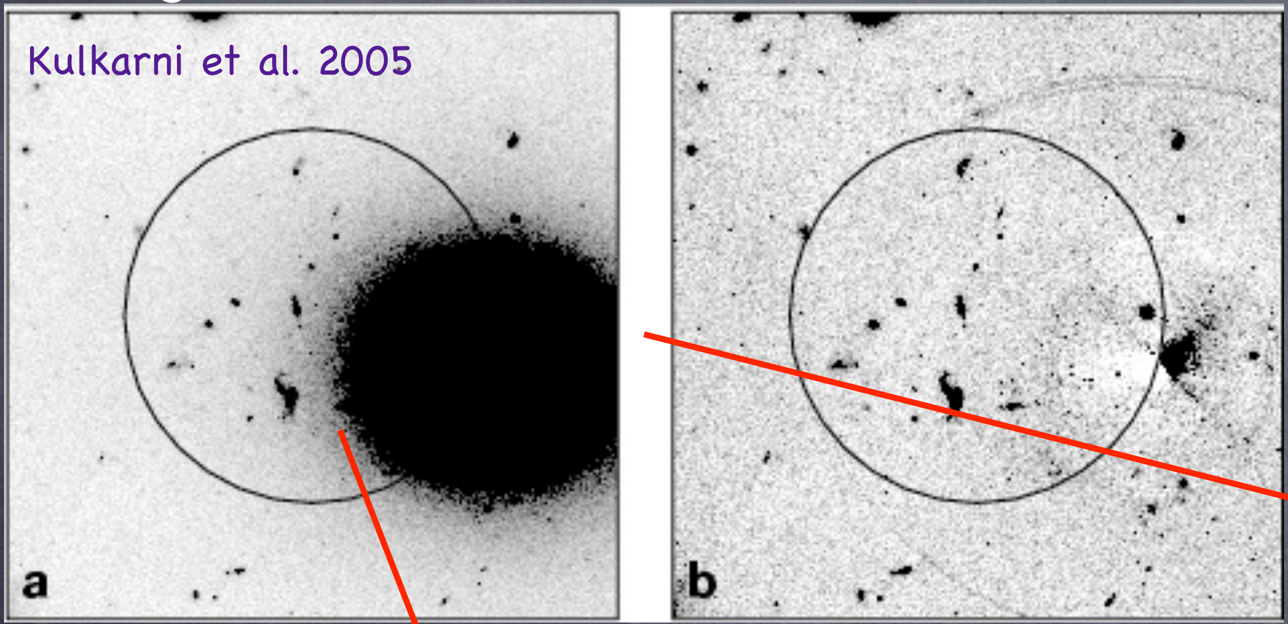




Short GRBs - e.g. GRB 050509b

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

(but also contains >10 higher redshift galaxies); No optical/radio afterglow



IF elliptical host

⇓

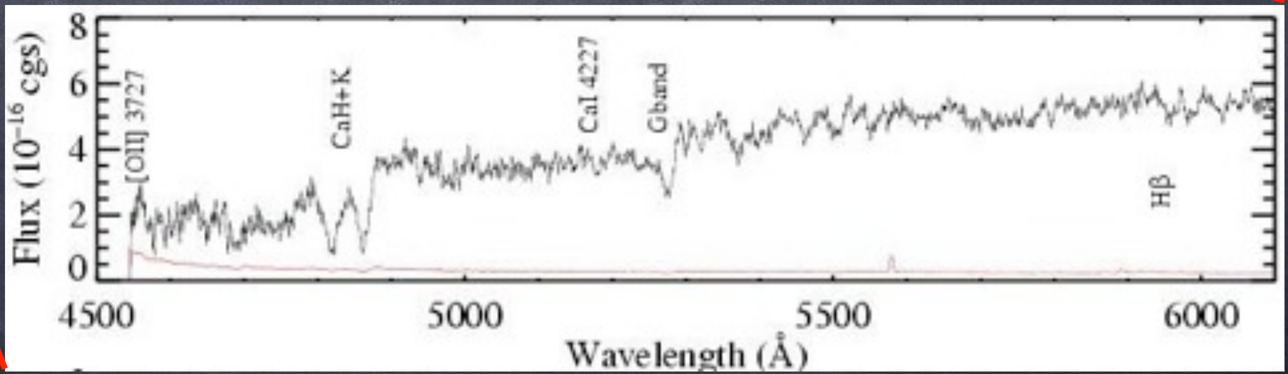
Progenitors related to an old stellar population

Bloom et al. 2005

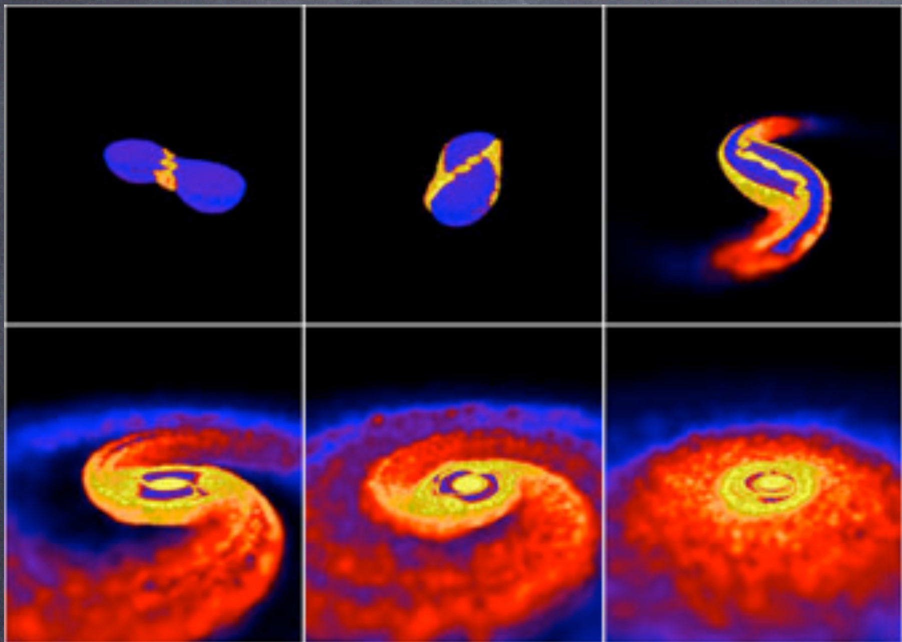
Castro-Tirado et al. 2005

Gehrels et al. 2005

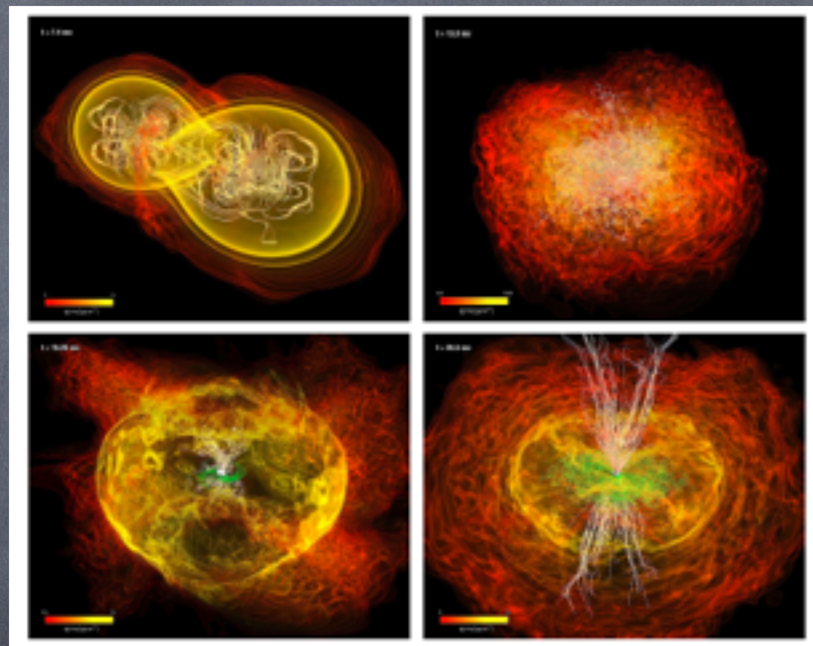
Hjorth et al. 2005



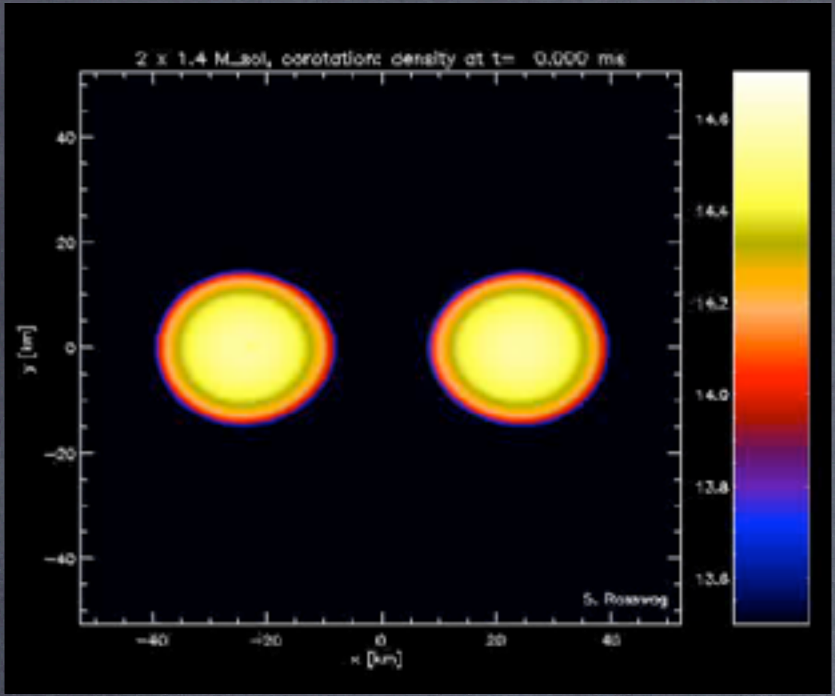
Neutron star mergers as progenitors of short GRBs (Eichler Livio Piran, Schramm, 1988)

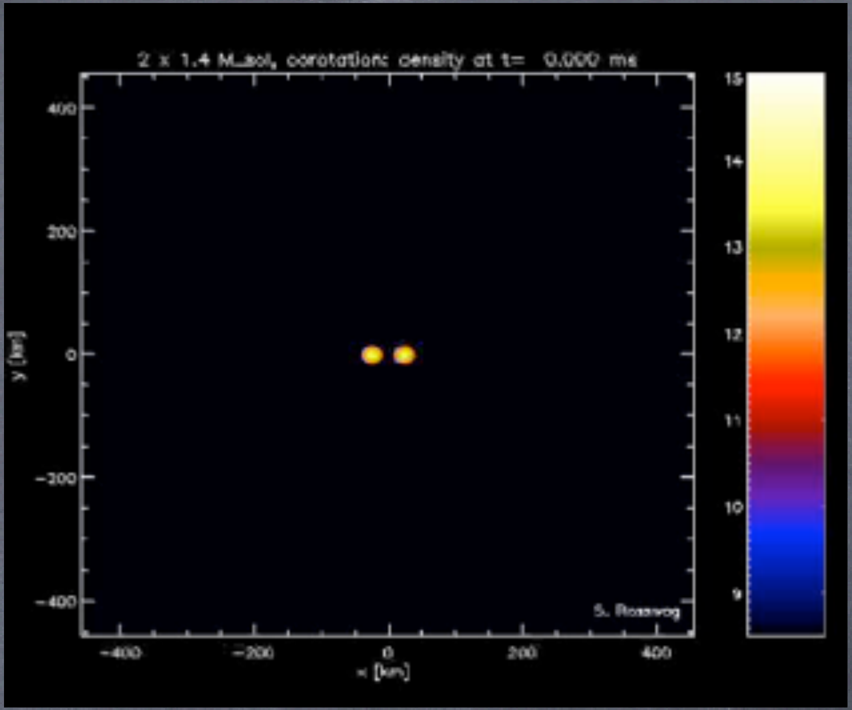


NS merger simulations Price & Rosswog 2007

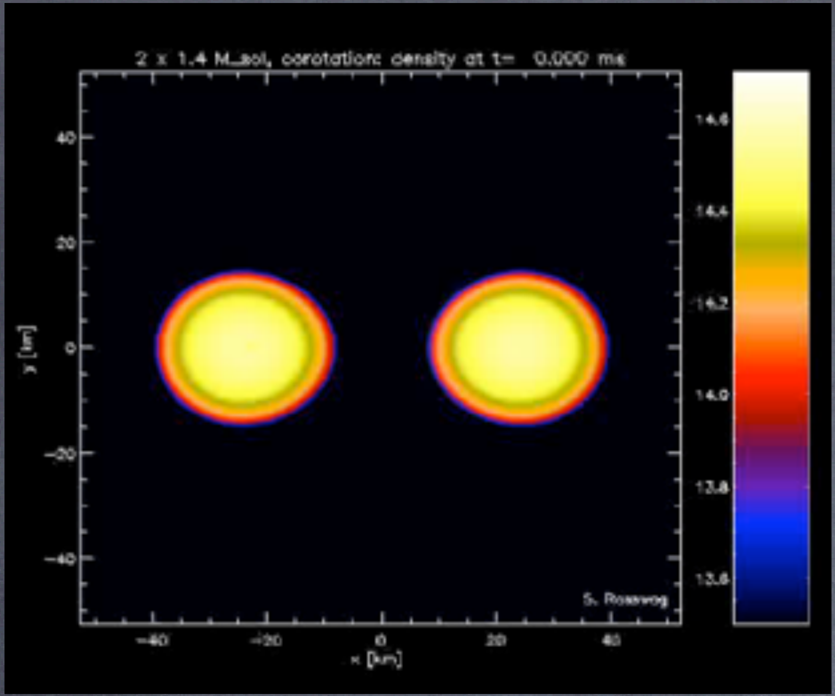


Magnetic field jet arising from NS merger Rezolla et al., 2011





Price & Rosswog



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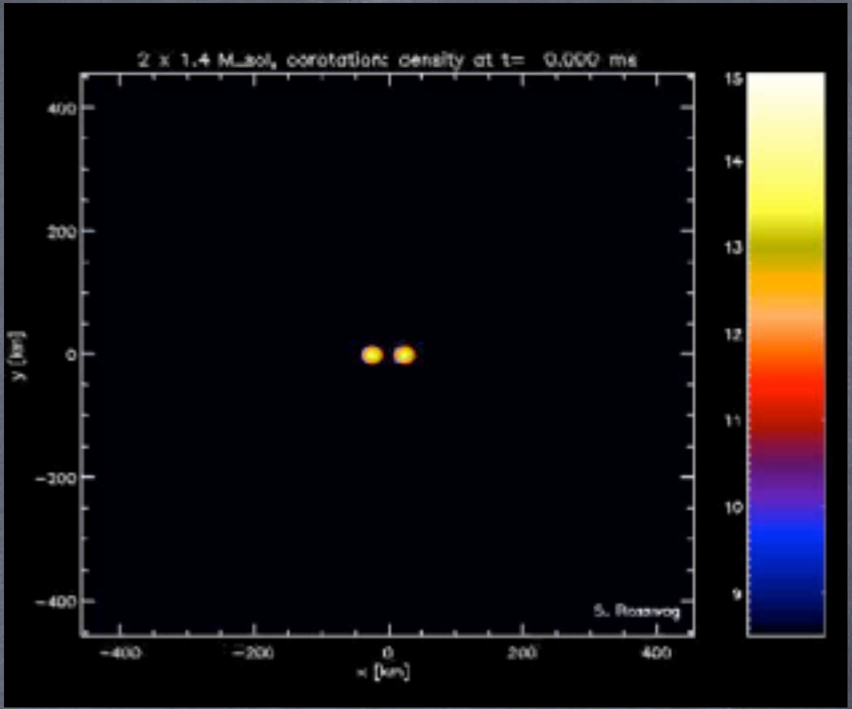
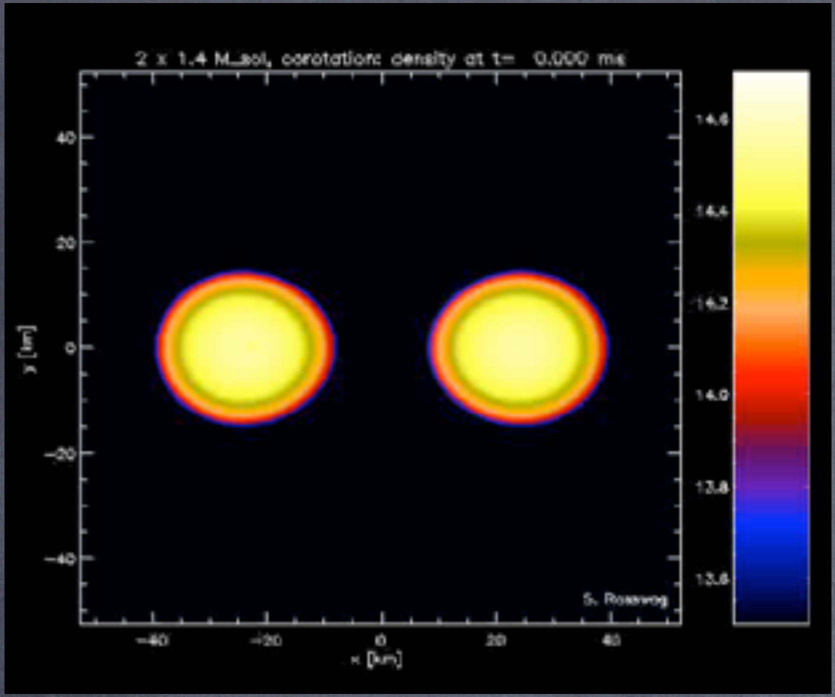
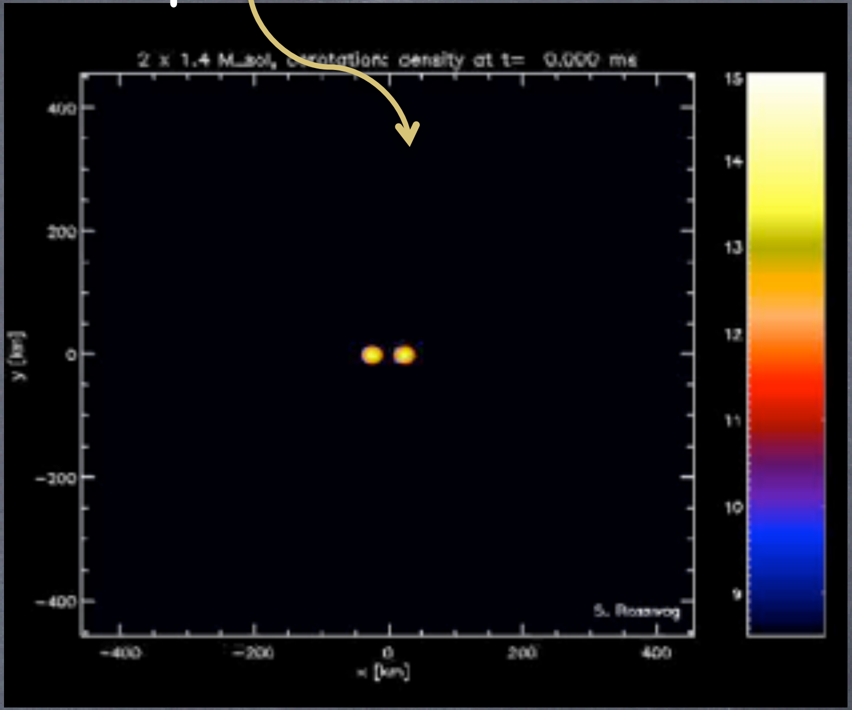


Price & Rosswog

R process material





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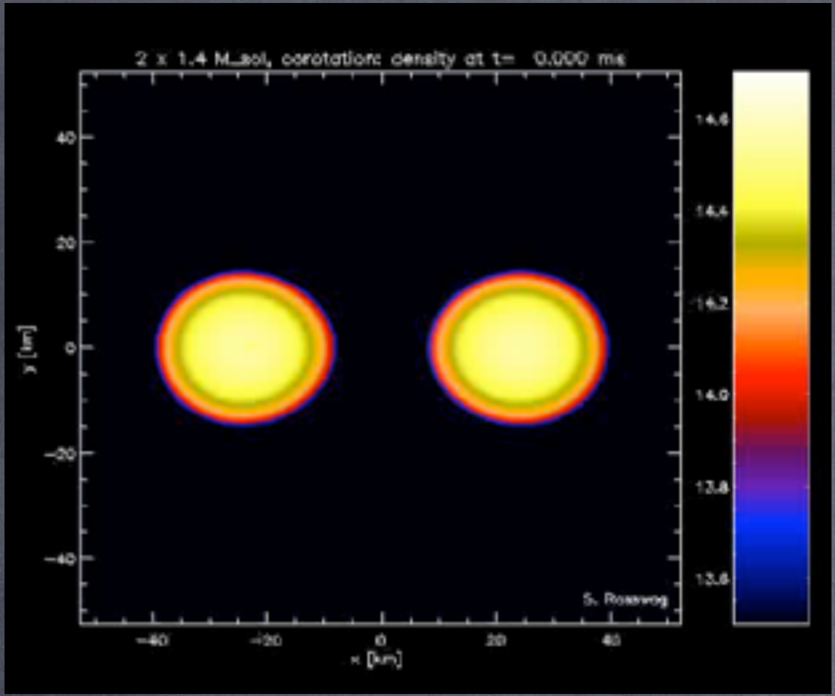
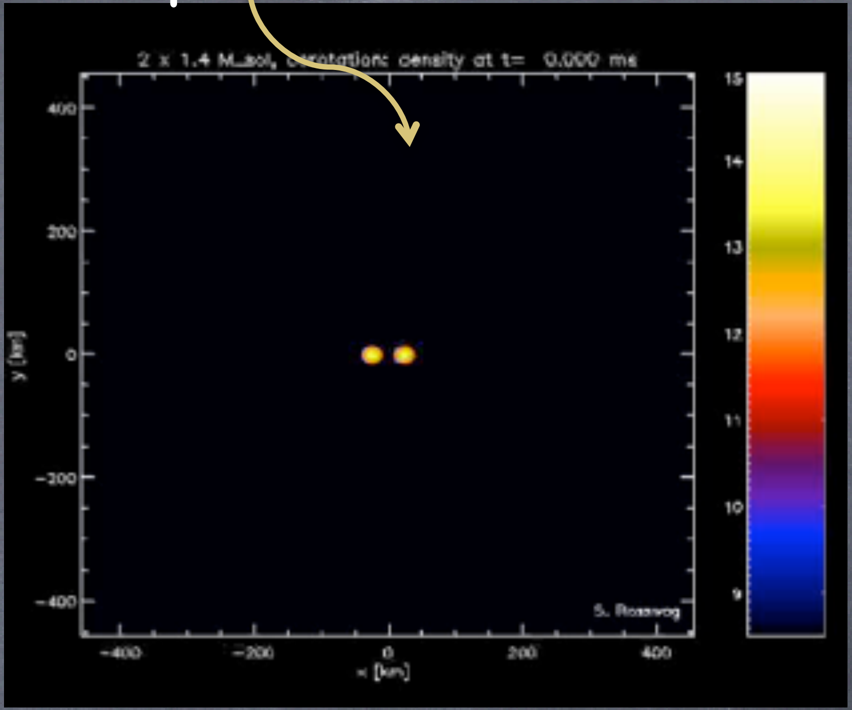




Price & Rosswog

Confirmation only with detection of Gravitational radiation

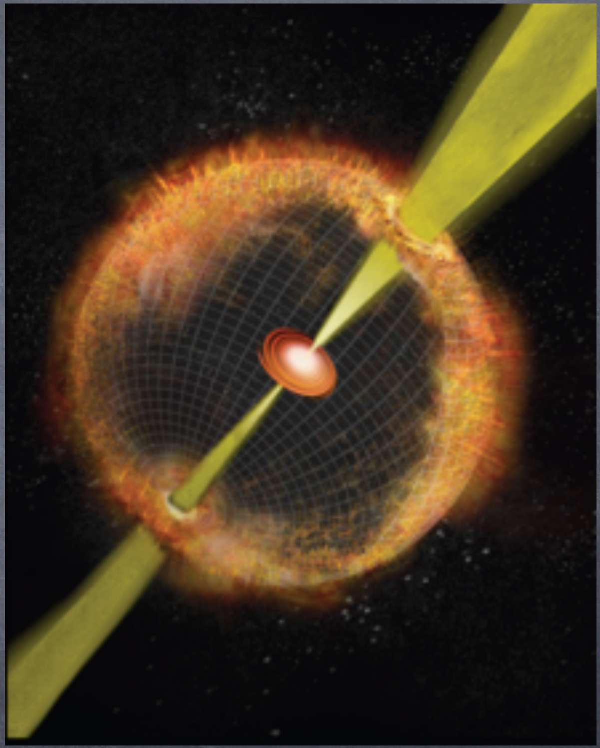
Prologue

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
(Woosley 1993, MacFadyen & Woosley 1998)



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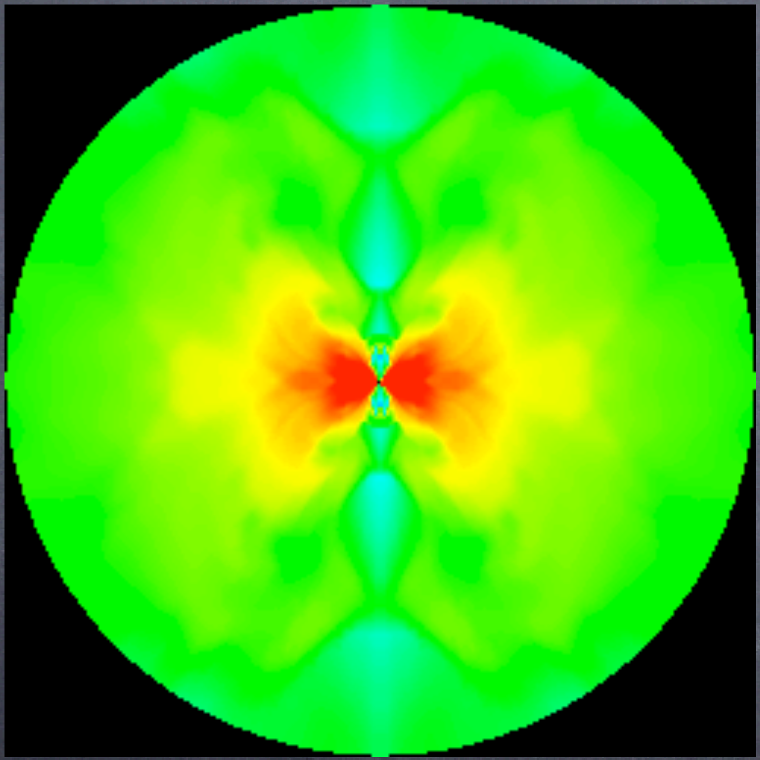

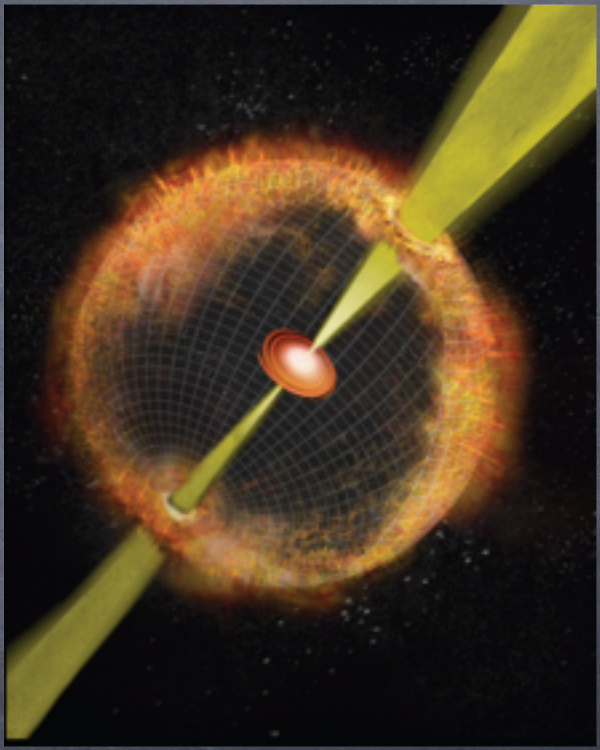

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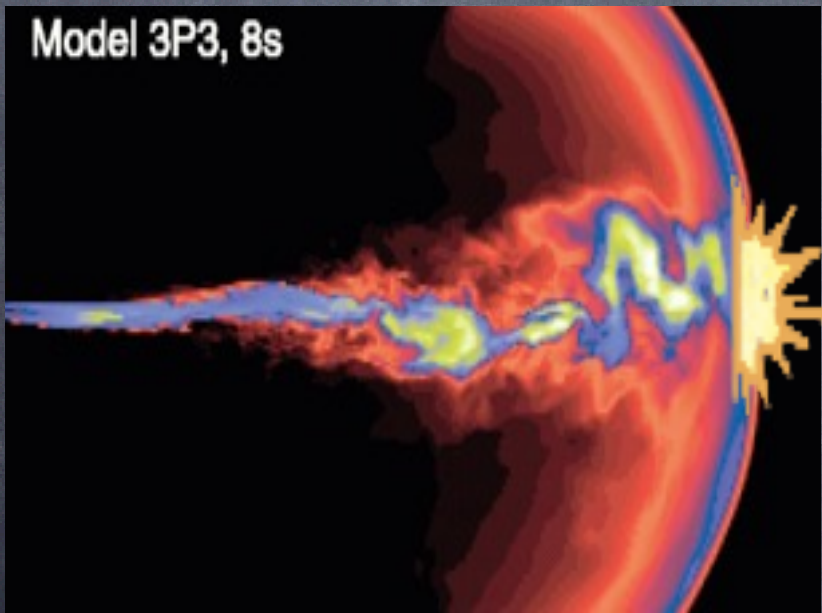
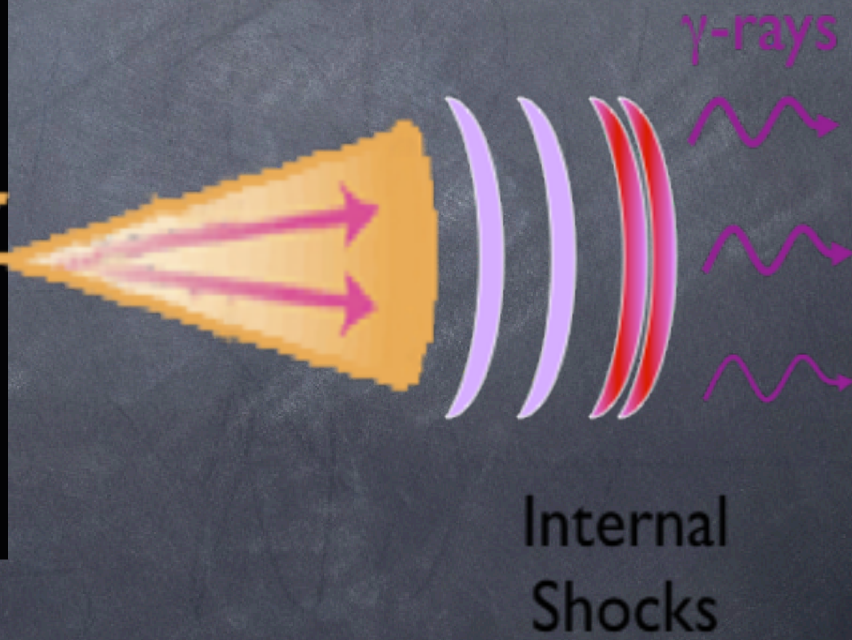
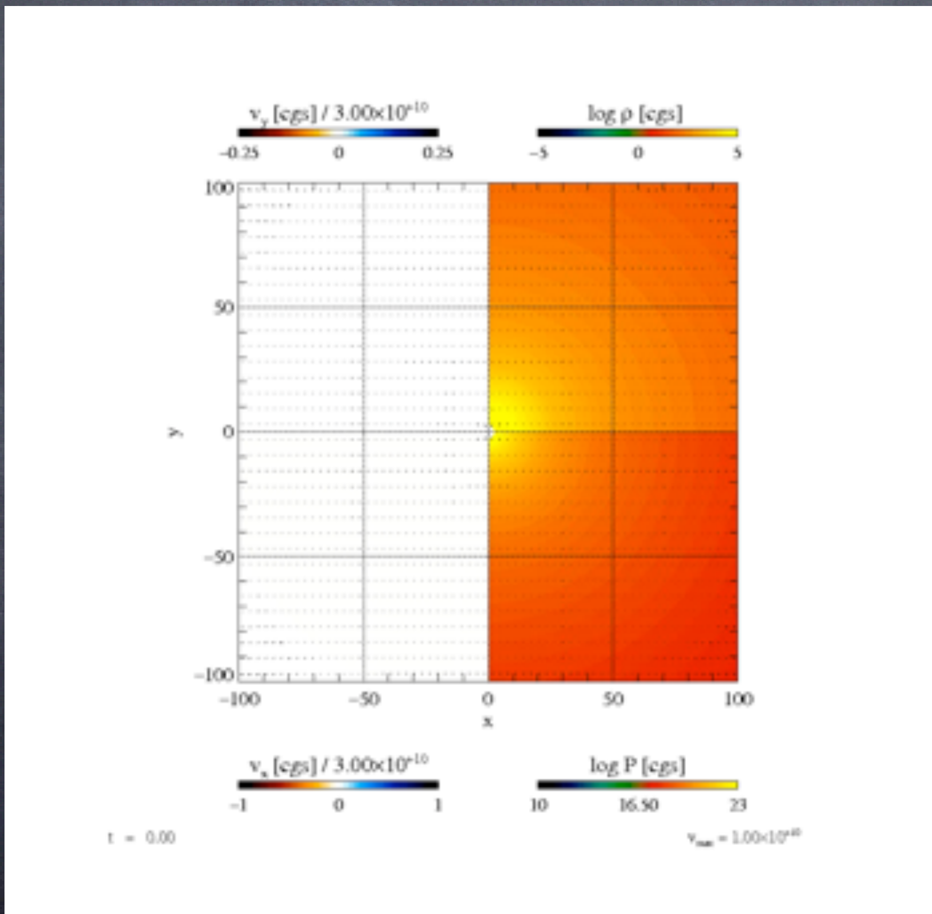


Zhang, Woosley & MacFadyen 2004



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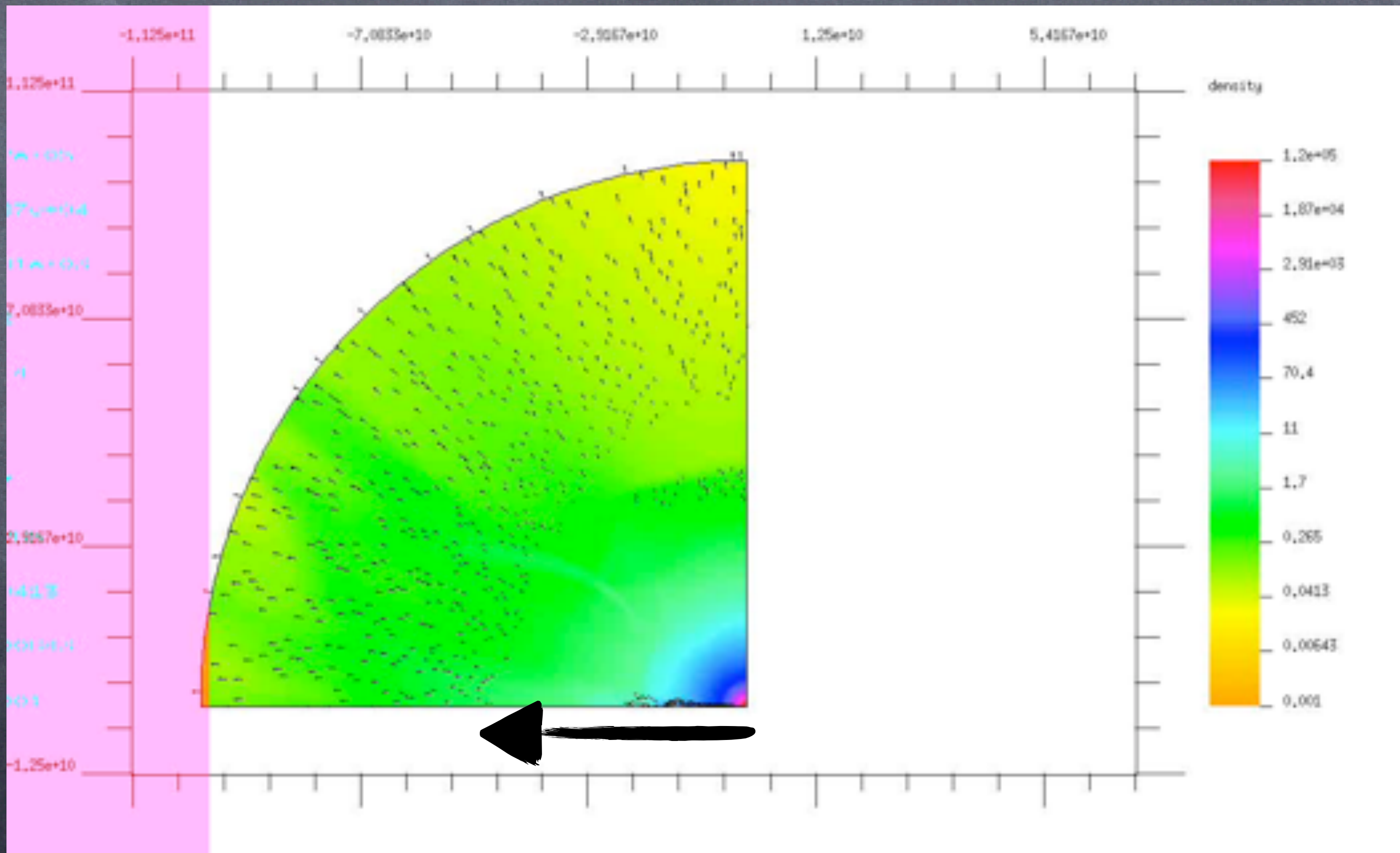
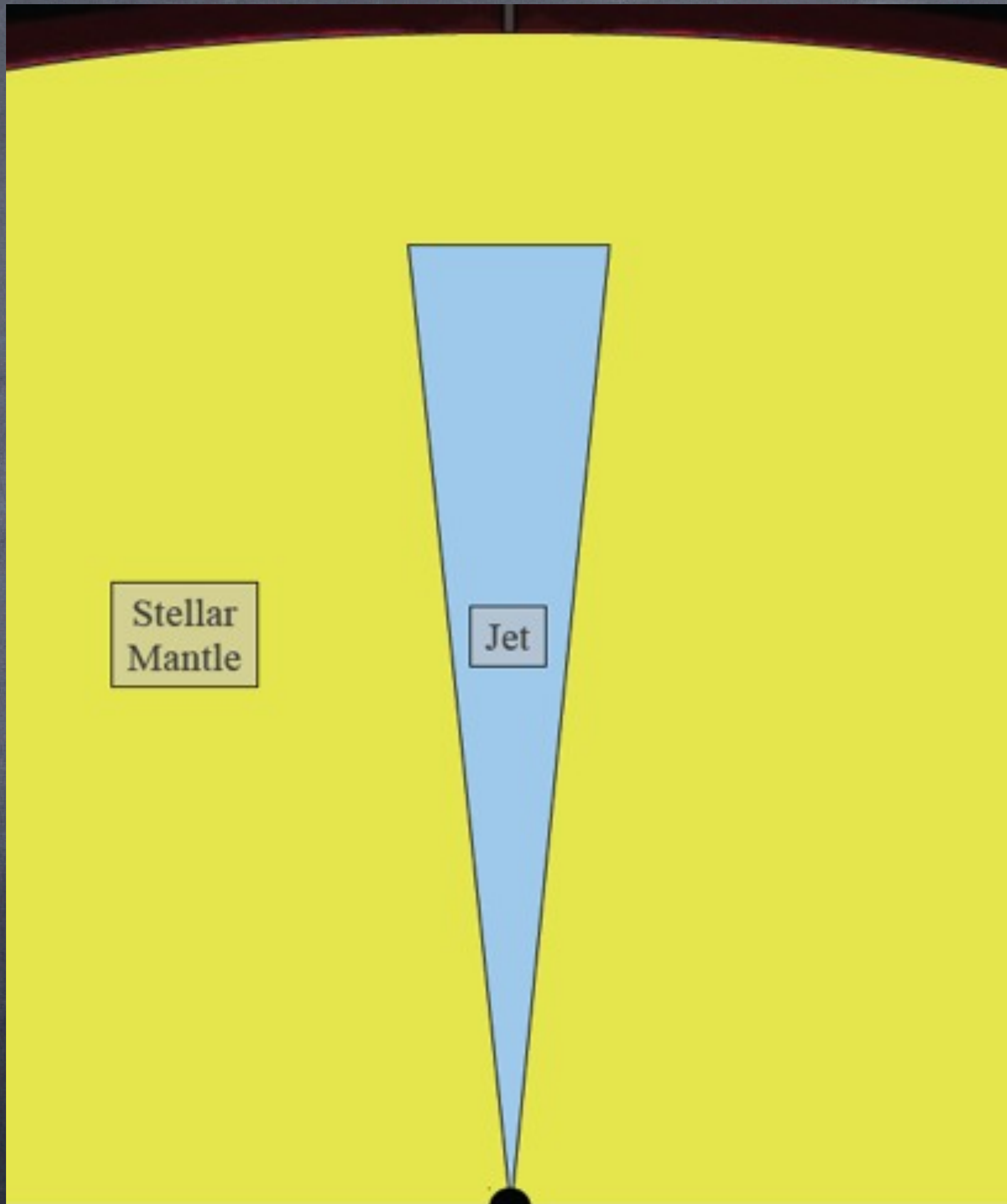
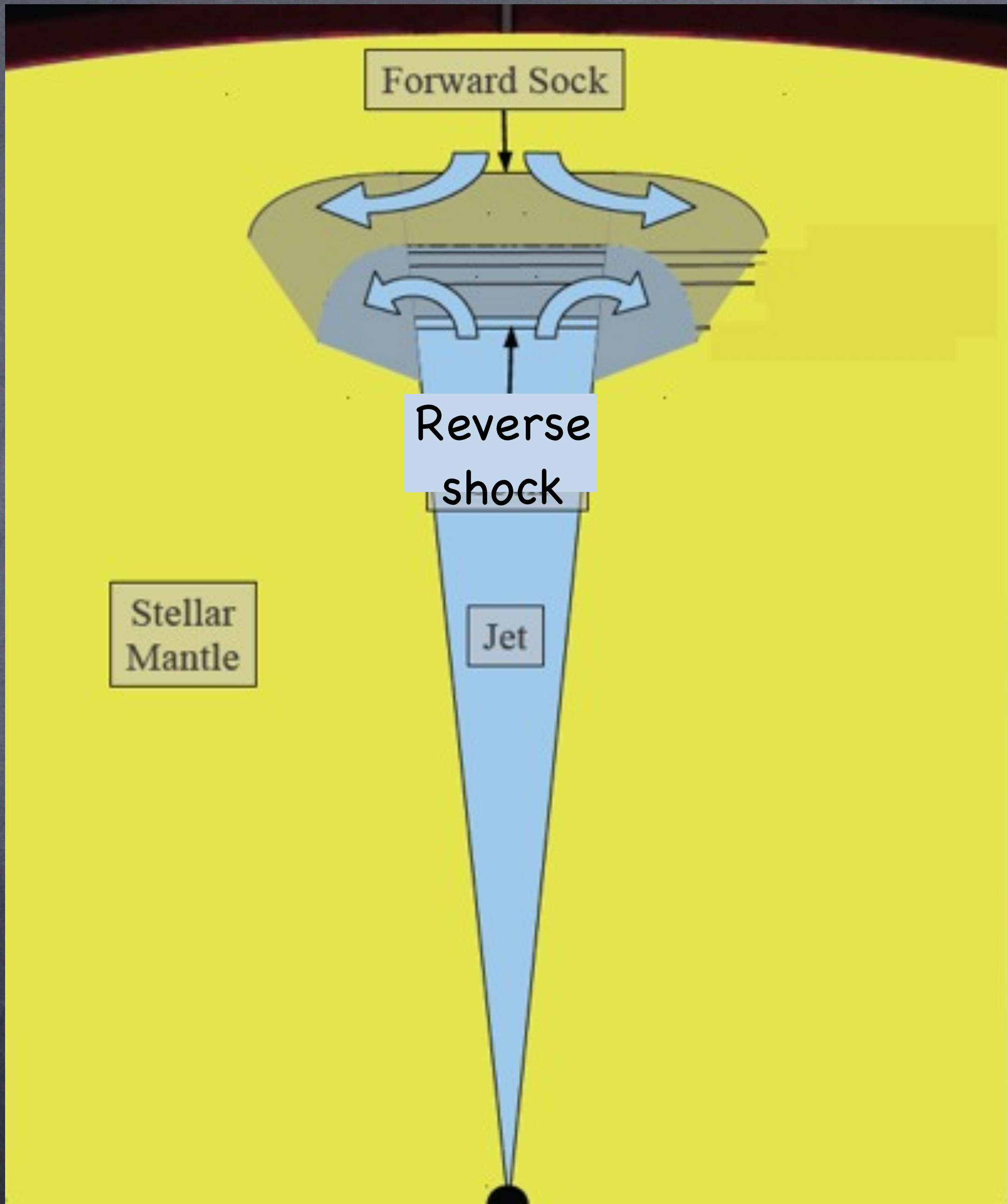
Opening angle of 15^o degrees at 2000 km into a star of 15 solar masses and solar metallicity. Constant energy injection rate, 5 * 10^{50}erg /s, through the entire run of the model. Lorentz factor at injection 7

Disruption of the Stellar envelope by the jet – Genet, Livne, Obergaulinger & TP 2011

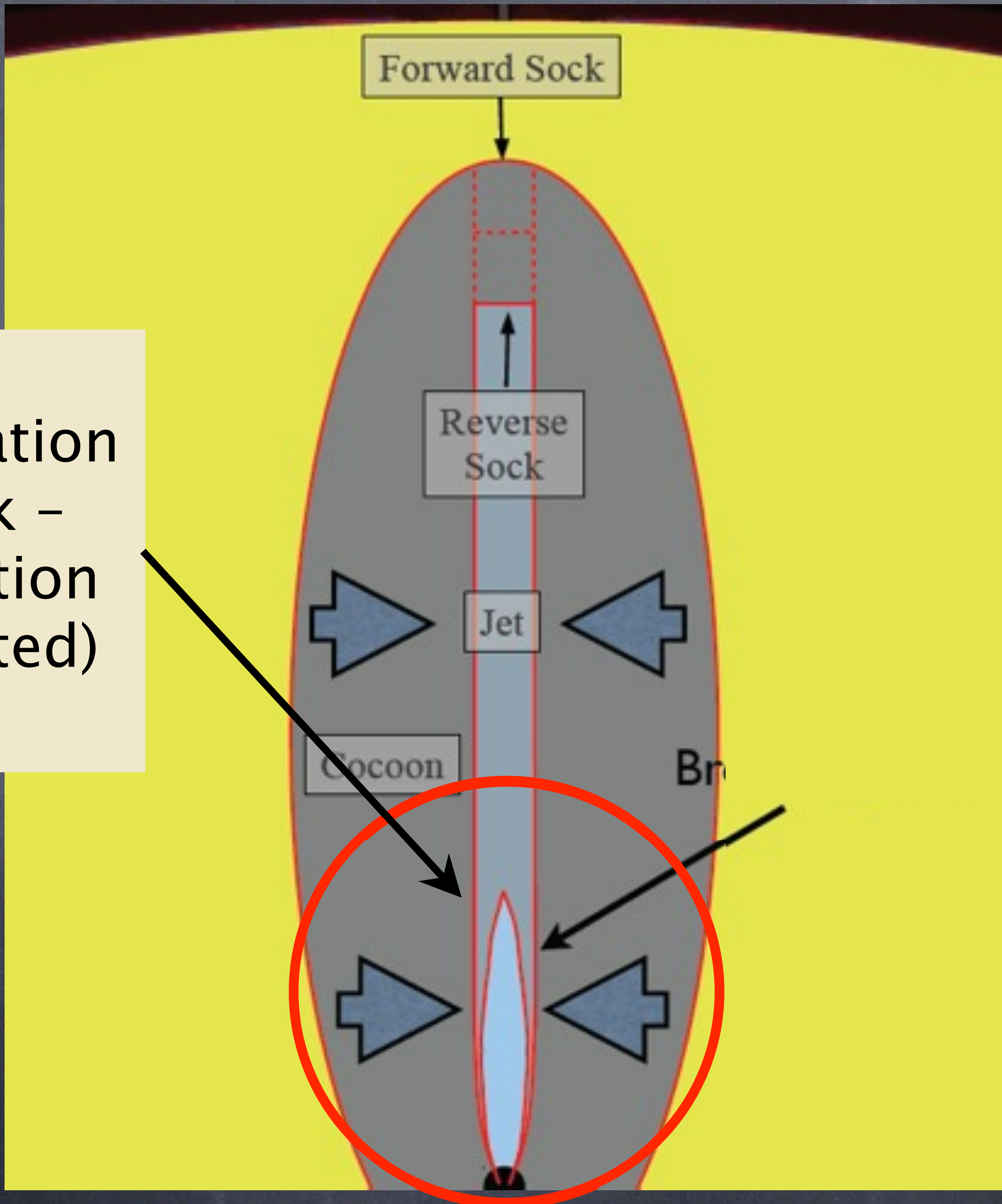
About one solar mass is ejected non spherically

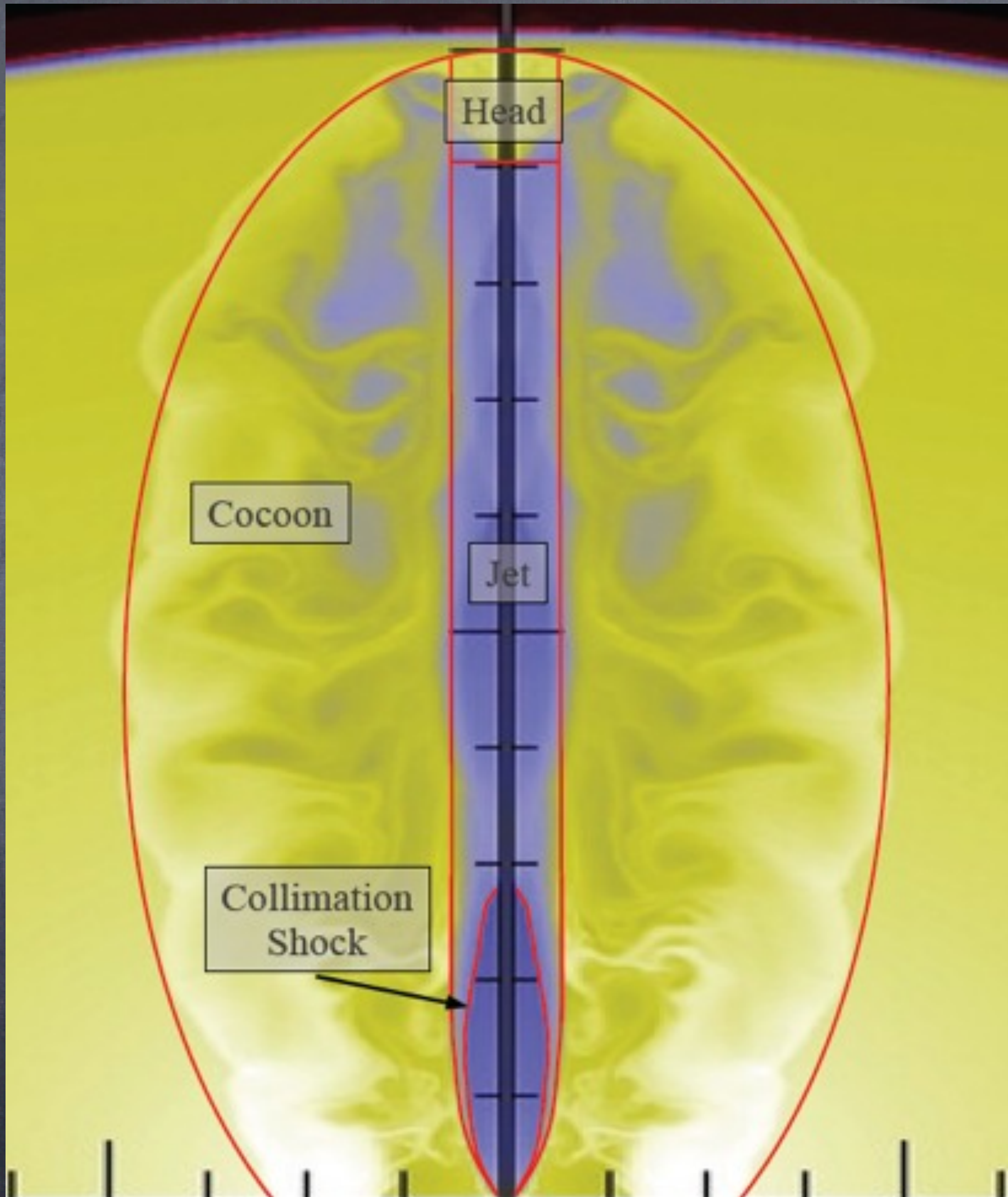



Stellar
Mantle
Jet


Forward Sock
Reverse shock
Stellar Mantle
Jet

Collimation Shock – (Radiation mediated)




Head
Cocoon
Jet
Collimation
Shock

Jet breakout time

(Bromberg Nakar, TP, Sari 11 ApJ in press)

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

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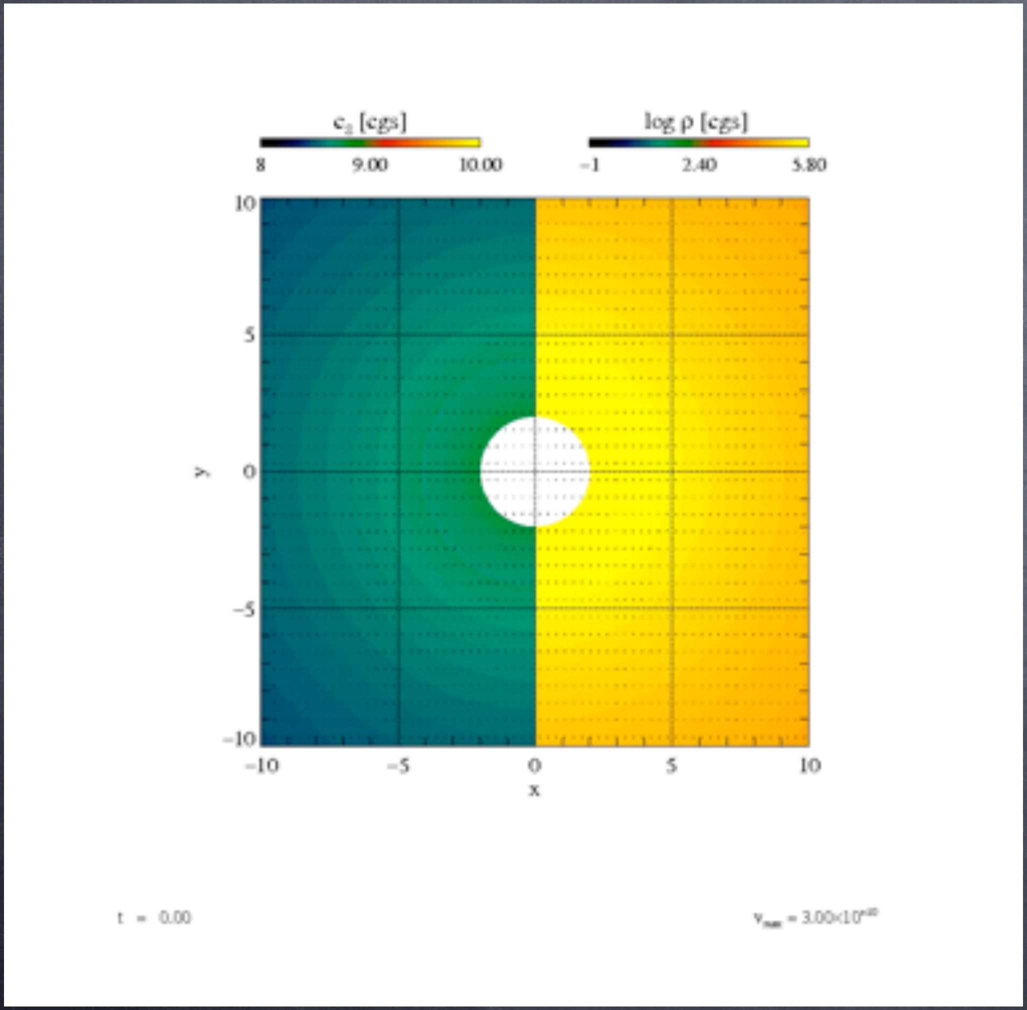
The engine must be active until the jet's head breaks out!*

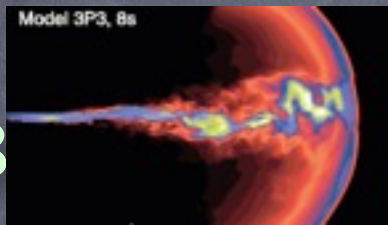
Jet Simulations - A Failed Jet (Obergaulinger, Piran + 11)



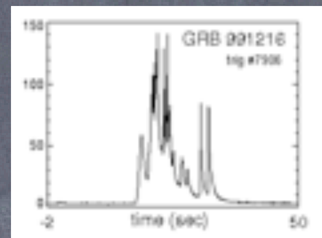
Opening angle of 15° degrees at 2000 km into a star of 15 solar masses and solar metallicity. Constant energy injection rate, 5 * 10^{50}erg/s, for 2 seconds.

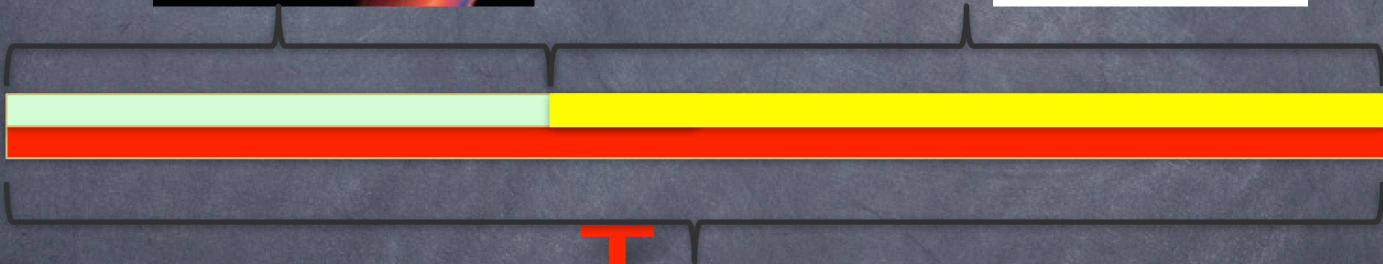
$$T_{engine} = T_B + T_{90}$$

T_B



T_{90}





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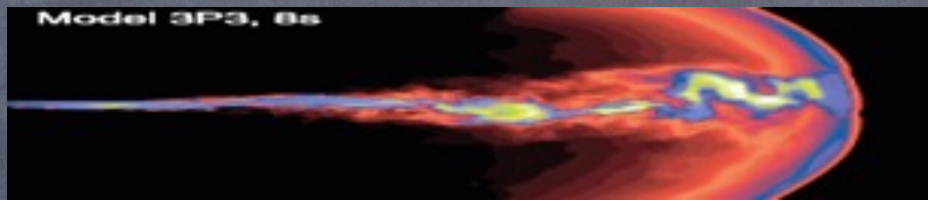

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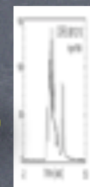

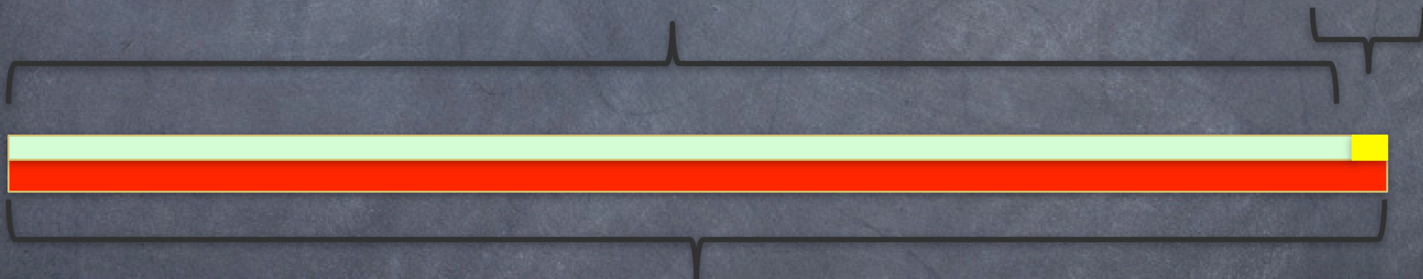

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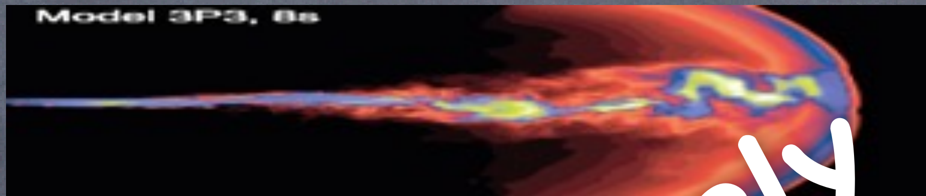
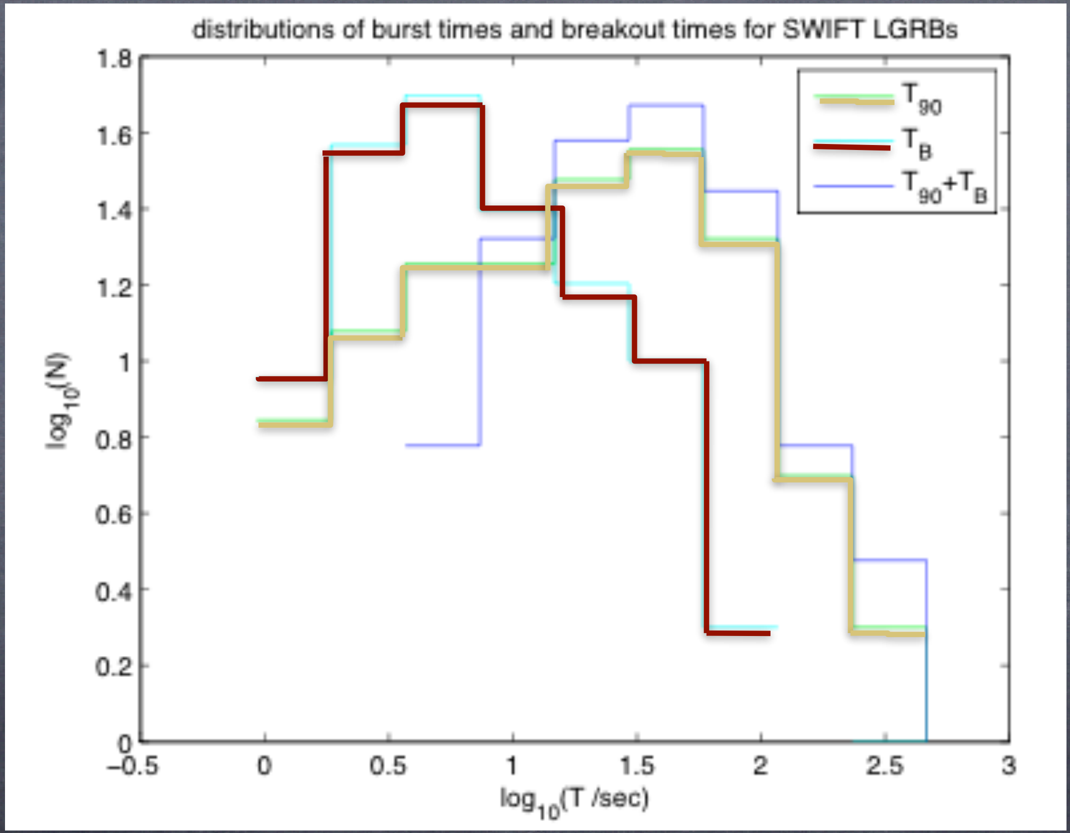


T_{90}

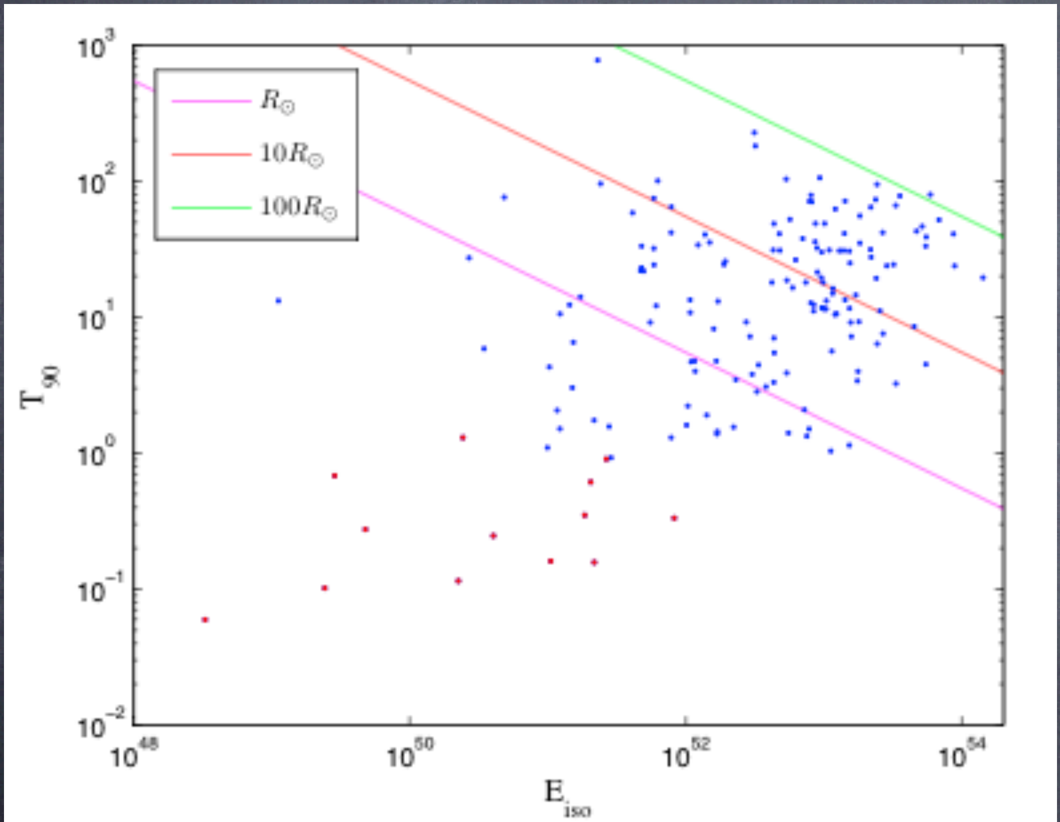
Unlikely

T_{engine}

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



Distribution of T_{90} for Swift Bursts vs Energy



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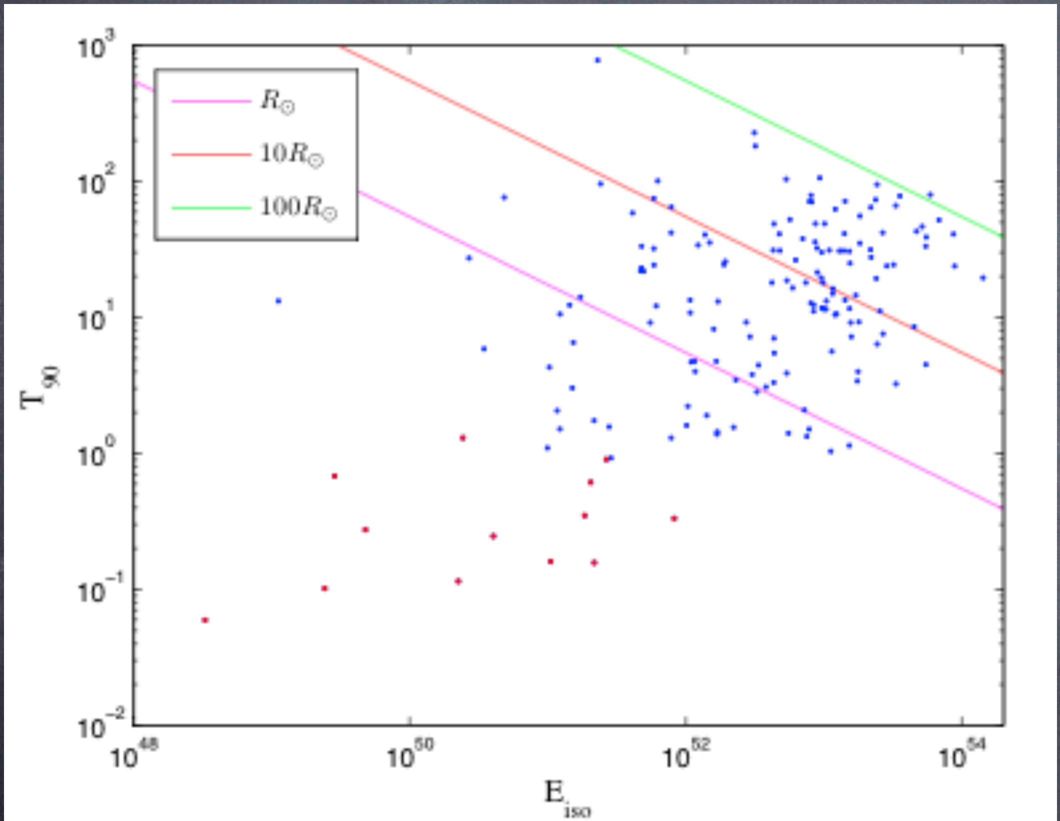

$T_{90} > T_B$ → LGRBs must have small progenitors (e.g. WR stars who lost their H envelope)

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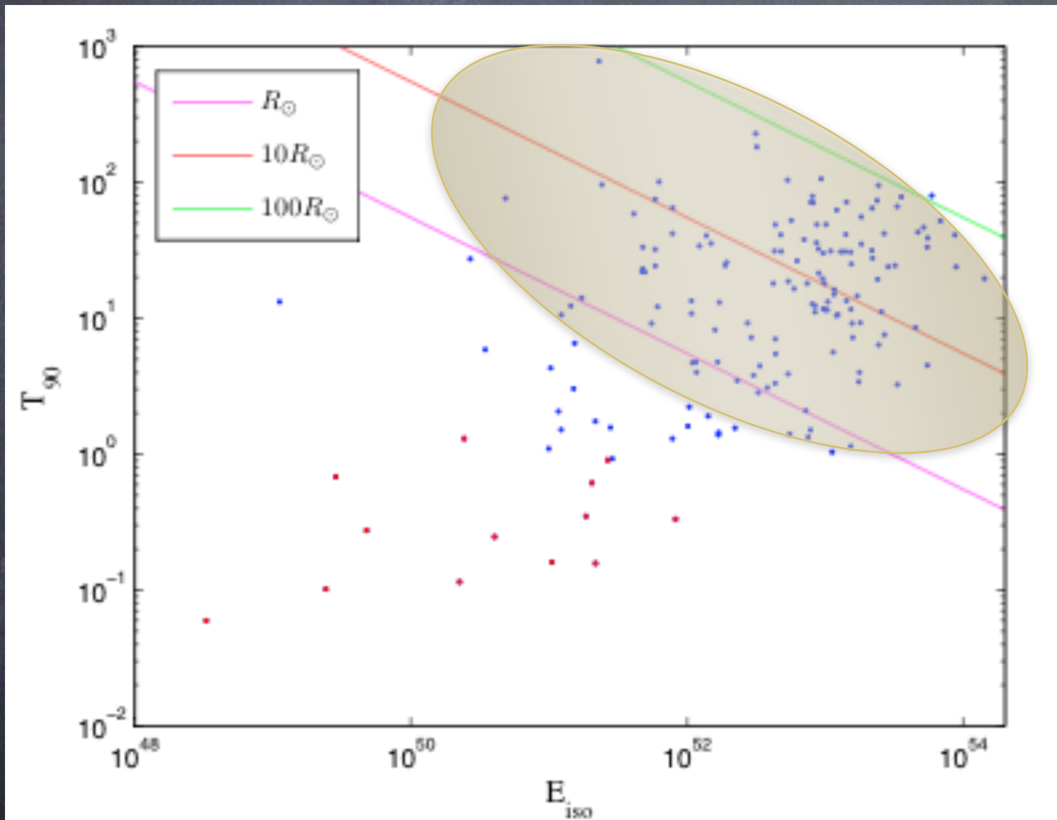

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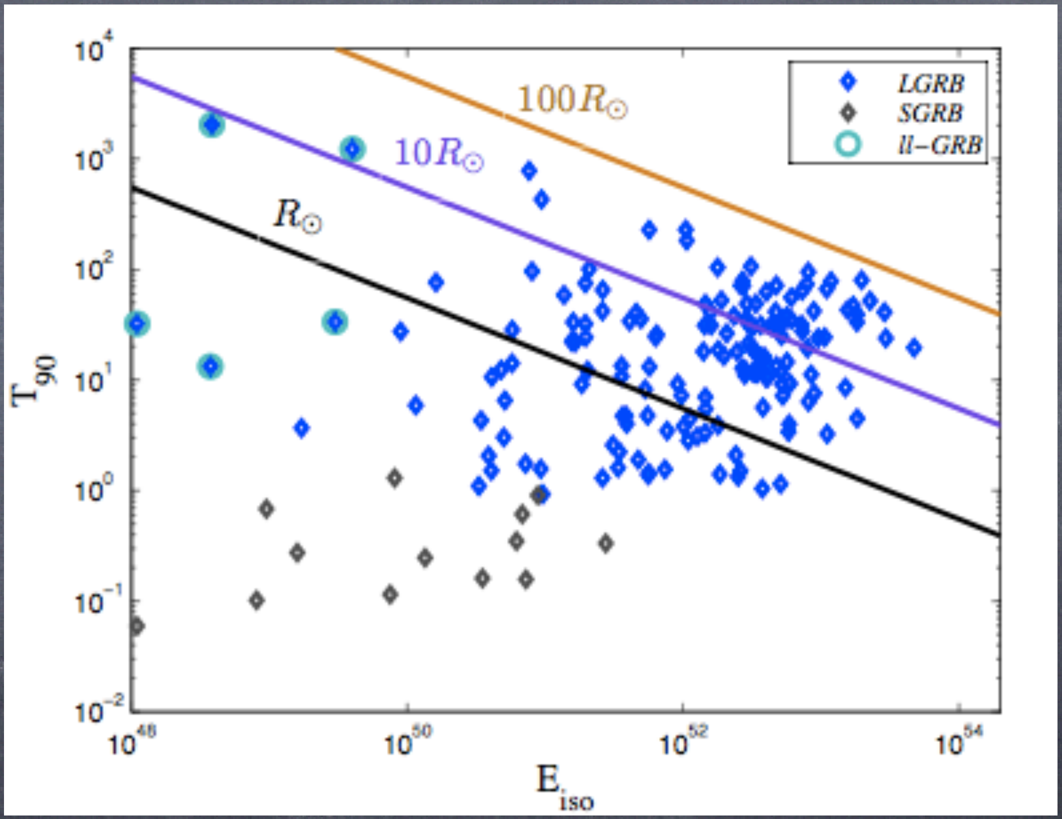

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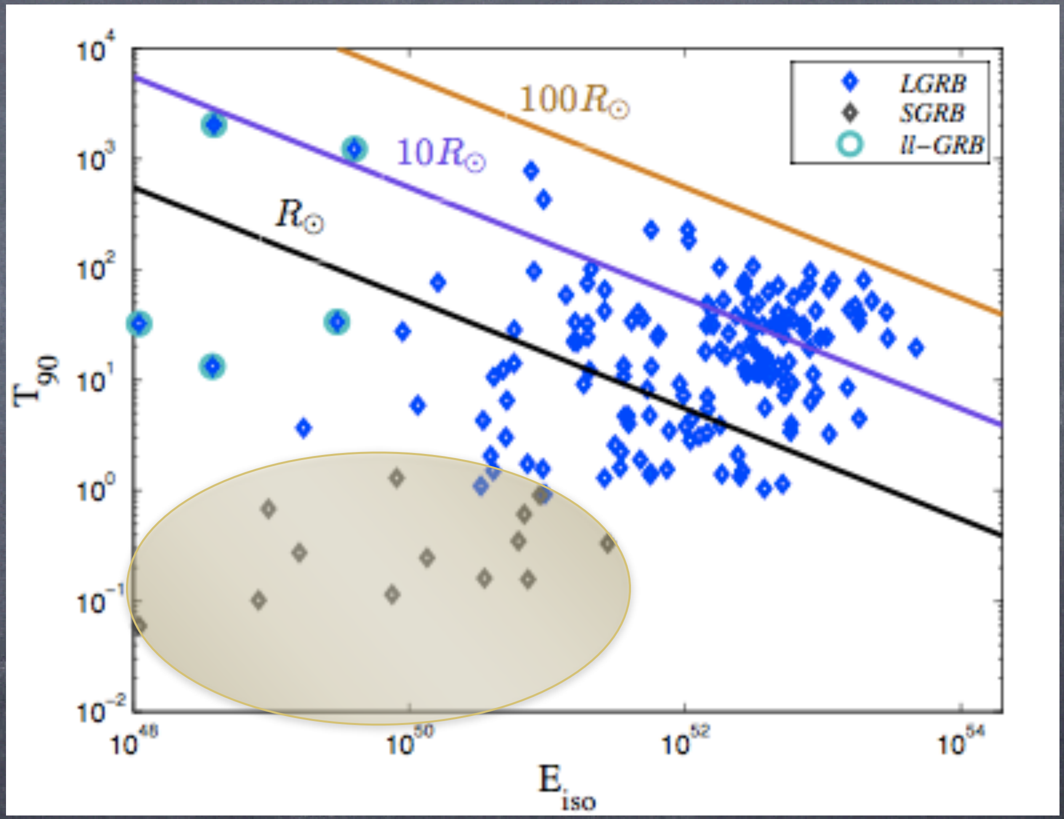
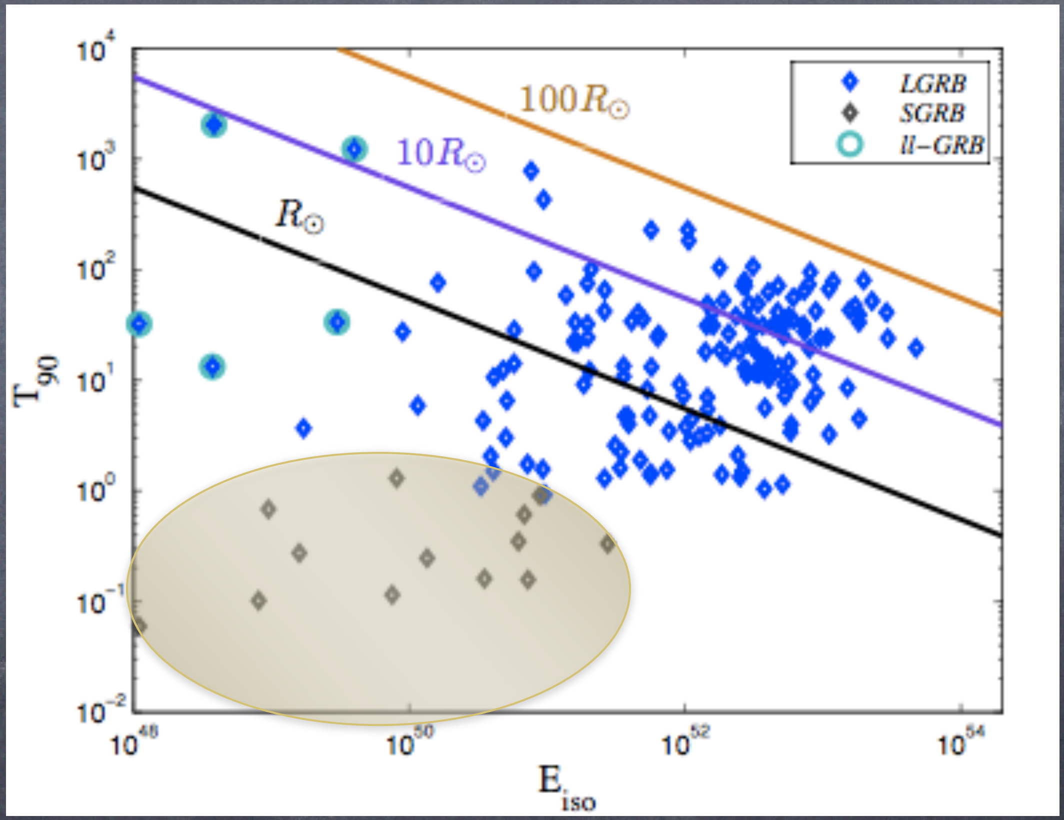


Distribution of T_{90} for Swift Bursts vs Energy

Short GRBs Cannot be produced in Collapsars



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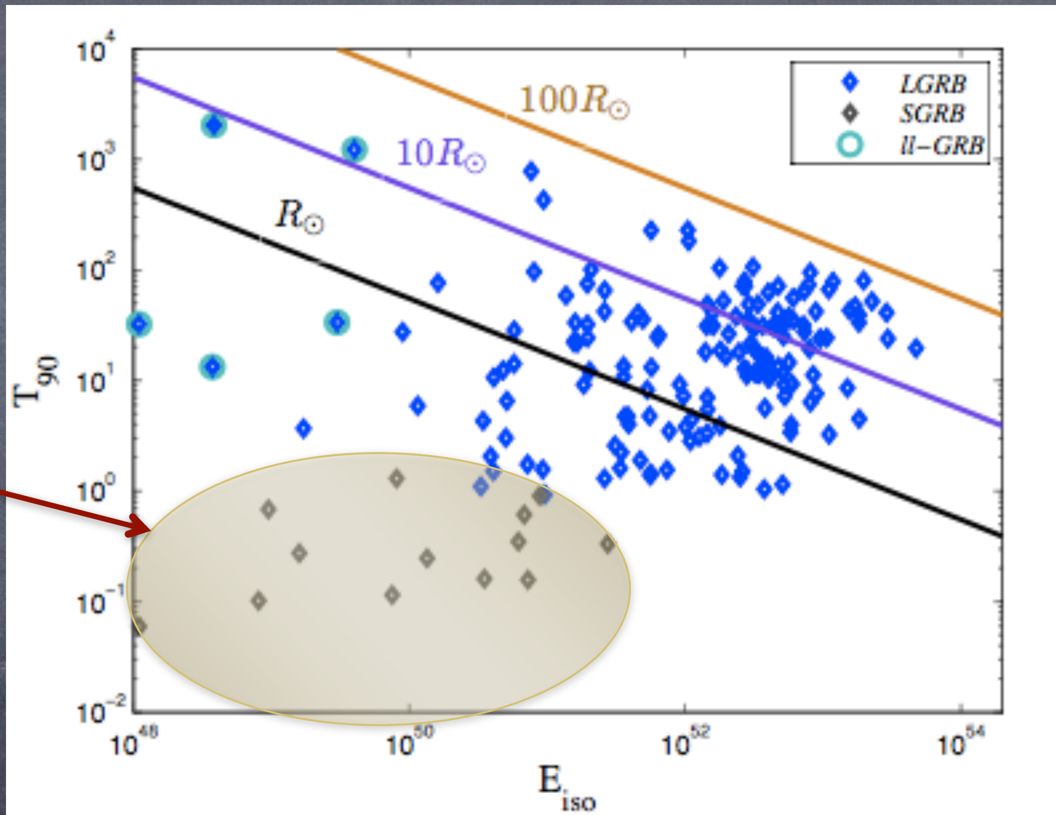
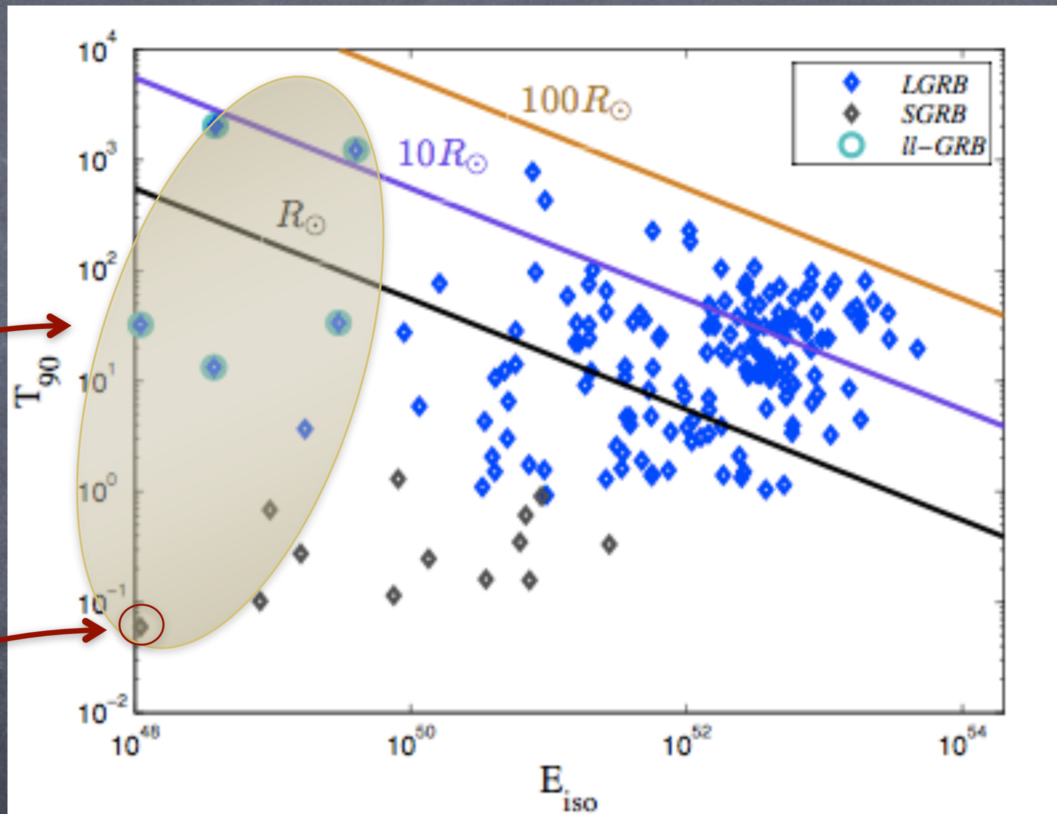


Distribution of T_{90} for Swift Bursts vs Energy

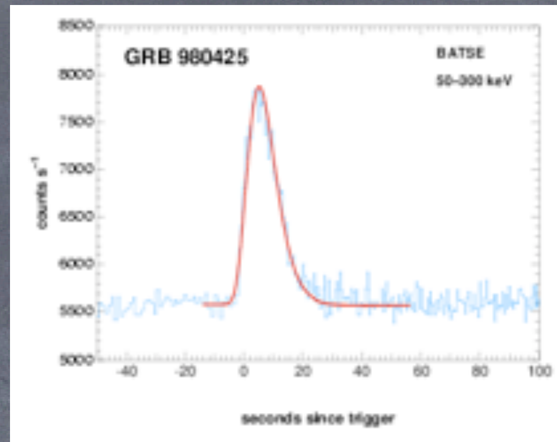
Low luminosity GRBs - llGRBs

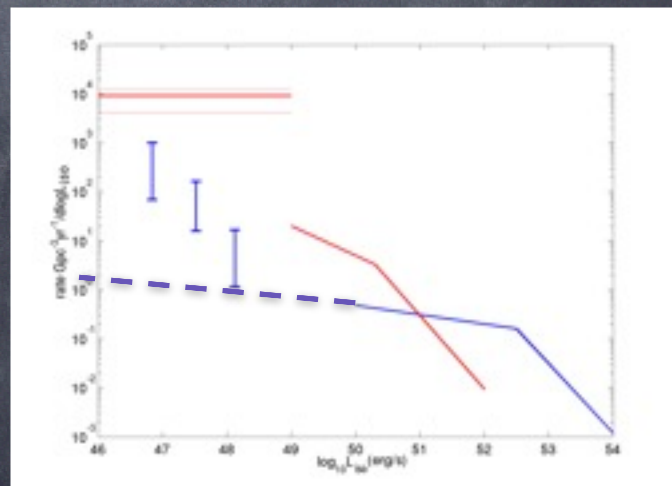
98bw



Low Luminosity GRBs - *ll*GRBs

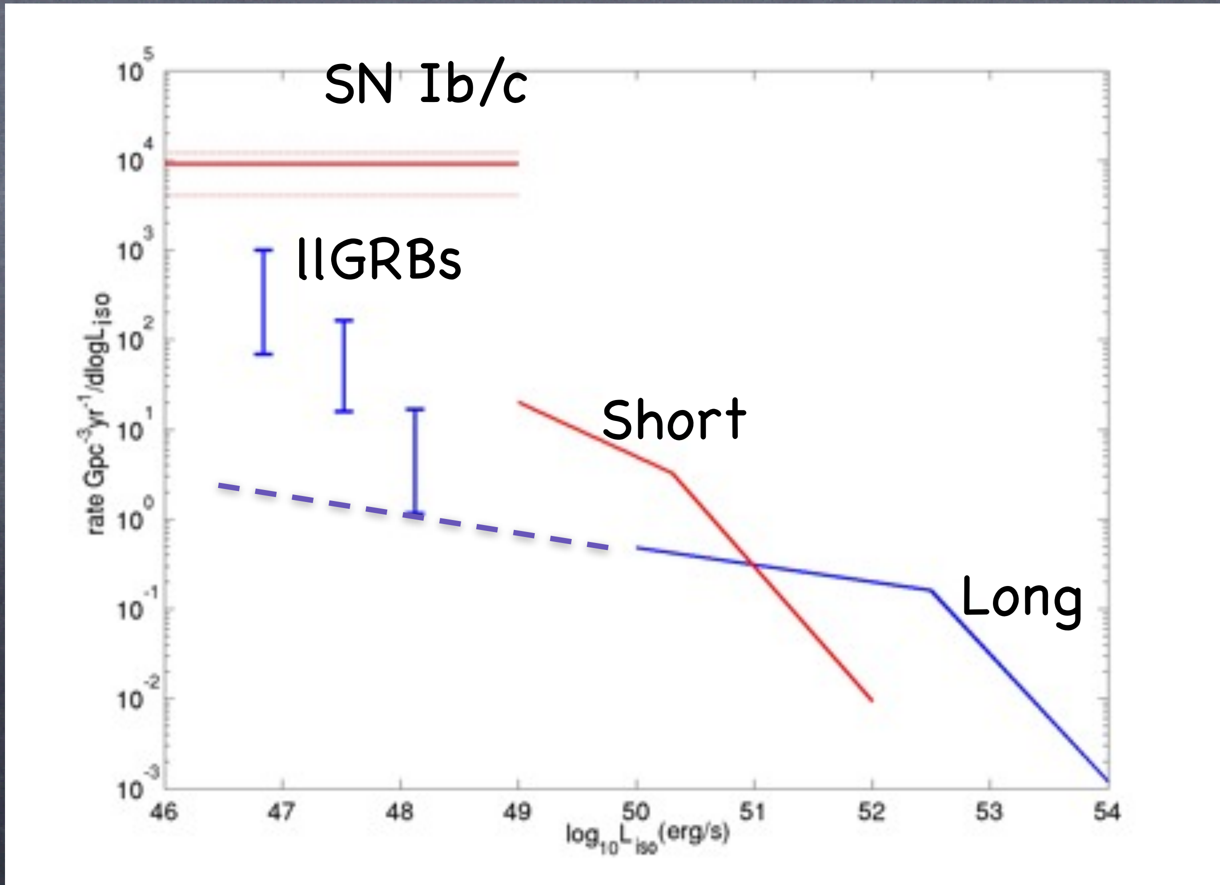
- Low luminosity GRBs:
  - $E_{iso} \sim 10^{48}$-10^{49} ergs
  - **Smooth** single peaked light curve.
  - **Soft** Emission (E_{peak} <150 keV)
  - $T_{90} \sim$ 10-1000 sec **Wide** opening angle θ>20º (otherwise rate will exceed type Ibc)
  - <u>**All GRBs associated with SNe apart from GRB 030329 are llGRBs**</u>





The local GRB rate and luminosity function (Wanderman & Piran)

The rate of llGRBs is comparable to the rate of type Ibc broad line Sne (Soderberg et al., 2006)



Almost ALL GRBS accompanied by SNe are *ll*GRBs

ℓℓGRBs associated with SNe

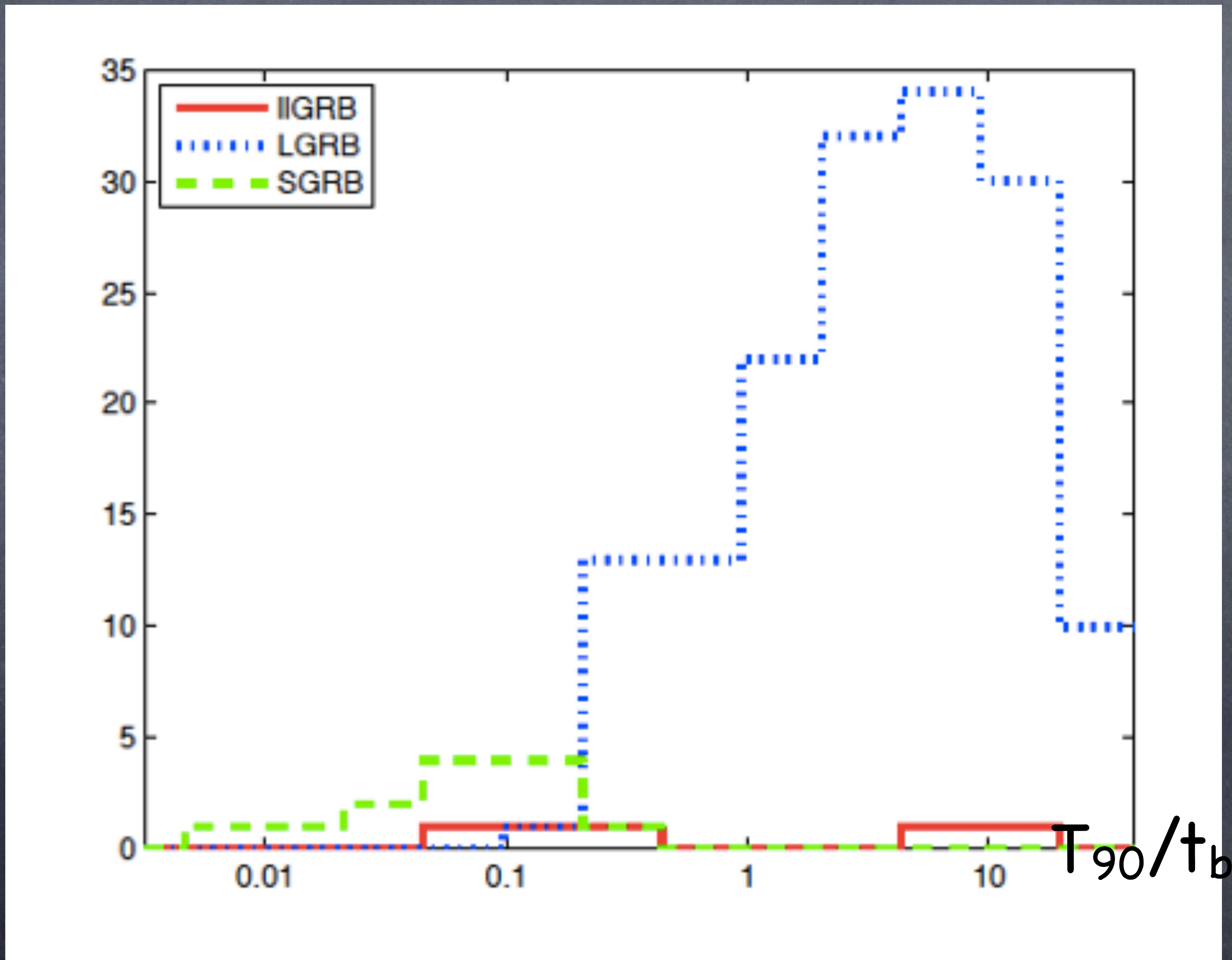
GRB/SN	z	E_{iso} [ergs]	T_{90} [s]	L_{iso} [erg/s]	$M/M_{\odot}$ [ergs]	$E_{iso}/E_{iso,min}$
GRB 980425/SN 1998bw	0.0085	10^{48}	35	$3 \cdot 10^{46}$	11	0.07
GRB 031203/SN 2003lw	0.105	$1 \cdot 10^{50}$	37	$2.7 \cdot 10^{48}$	13	0.3
GRB 051109B/ ?	0.08	$< 1.3 \cdot 10^{49}$	15	$9 \cdot 10^{47}$	?	0.08
GRB 060218/SN 2006aj	0.033	$4 \cdot 10^{49}$	2100	$2 \cdot 10^{46}$	24	2.7
GRB 100316D/SN 2010bh	0.0593	$4 \cdot 10^{49}$	1300	$3 \cdot 10^{46}$	?	2.3
GRB 030329/SN 2003dh	0.168	$8 \cdot 10^{51}$	25	$3.2 \cdot 10^{50}$	8	1.2

$$E_{iso,\min} = 10^{48}\ t_{10^3\,\mathrm{sec}}^{-2}\,\theta_{20^\circ}^{2}\,R_{11}^{2}\,M_{15\odot}\ ergs$$

- Only the longer bursts may originate from jets which break out of the star.
- Shorter duration low luminosity bursts cannot arise from a jet breaking out from a star!

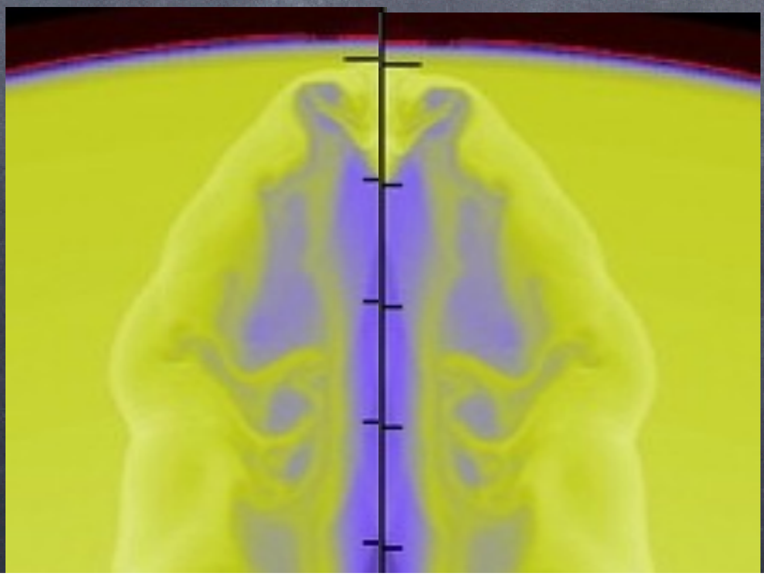
$\ell\ell$GRBs don't arise from Collapsars

(Bromberg Nakar, TP 11 ApJL in press)



What are *ll*GRBs?

- A weak jet which fail to break ("**a failed GRB**") lwhat we observe is the shock breakout form the stellar envelope.
- For a detailed model see Nakar & Sari, 2011.



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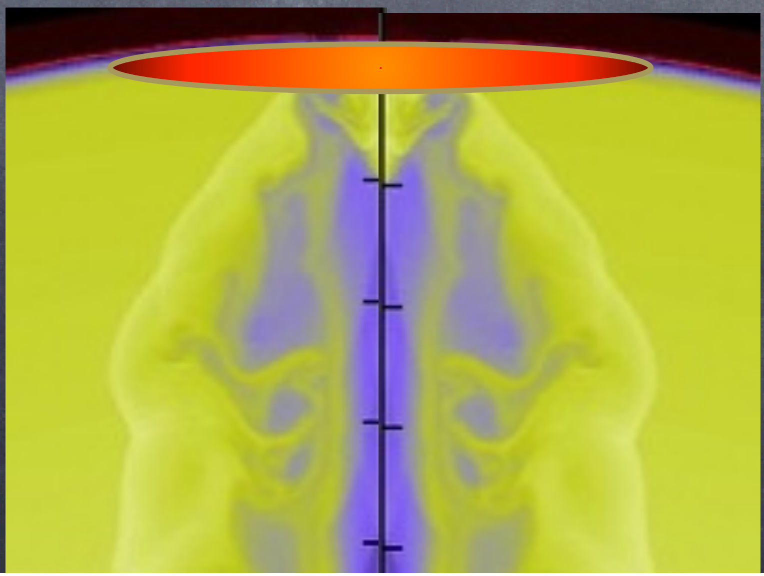

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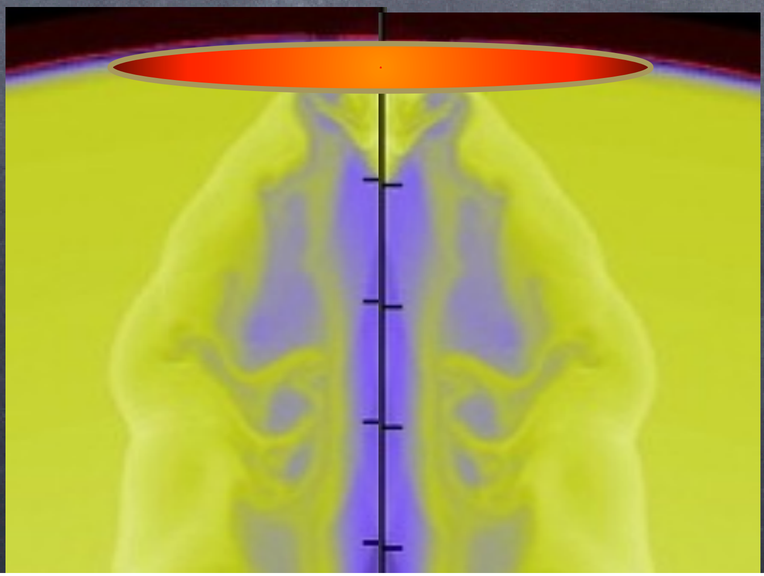

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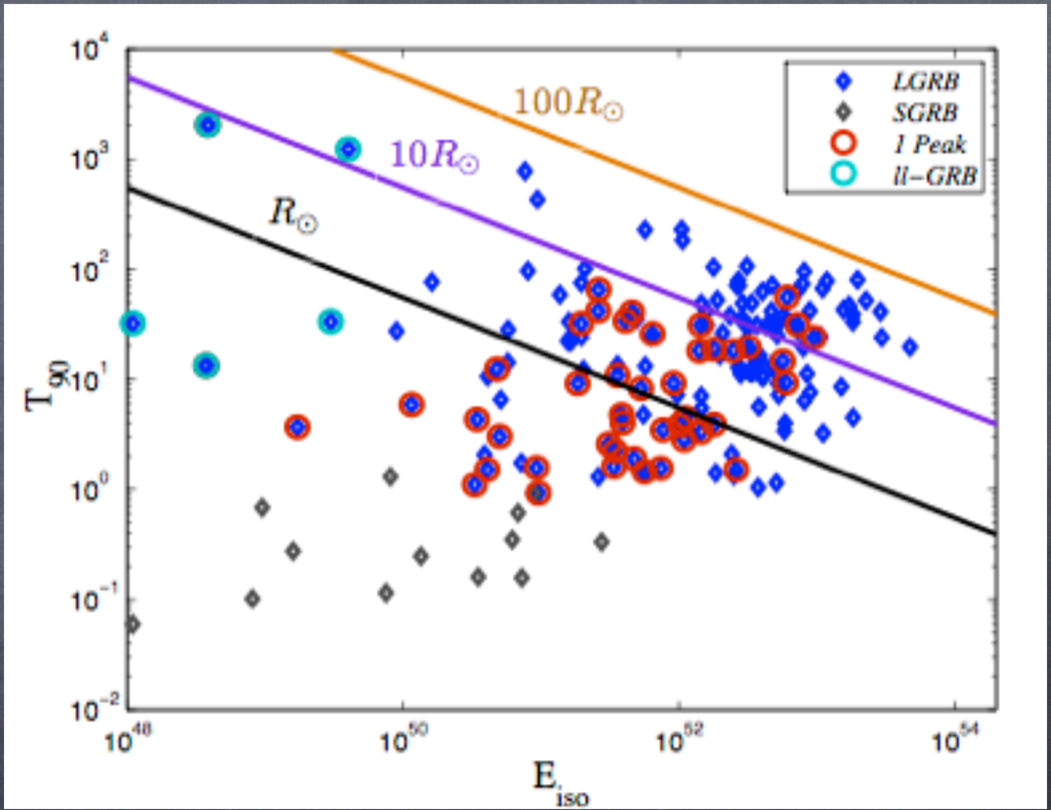

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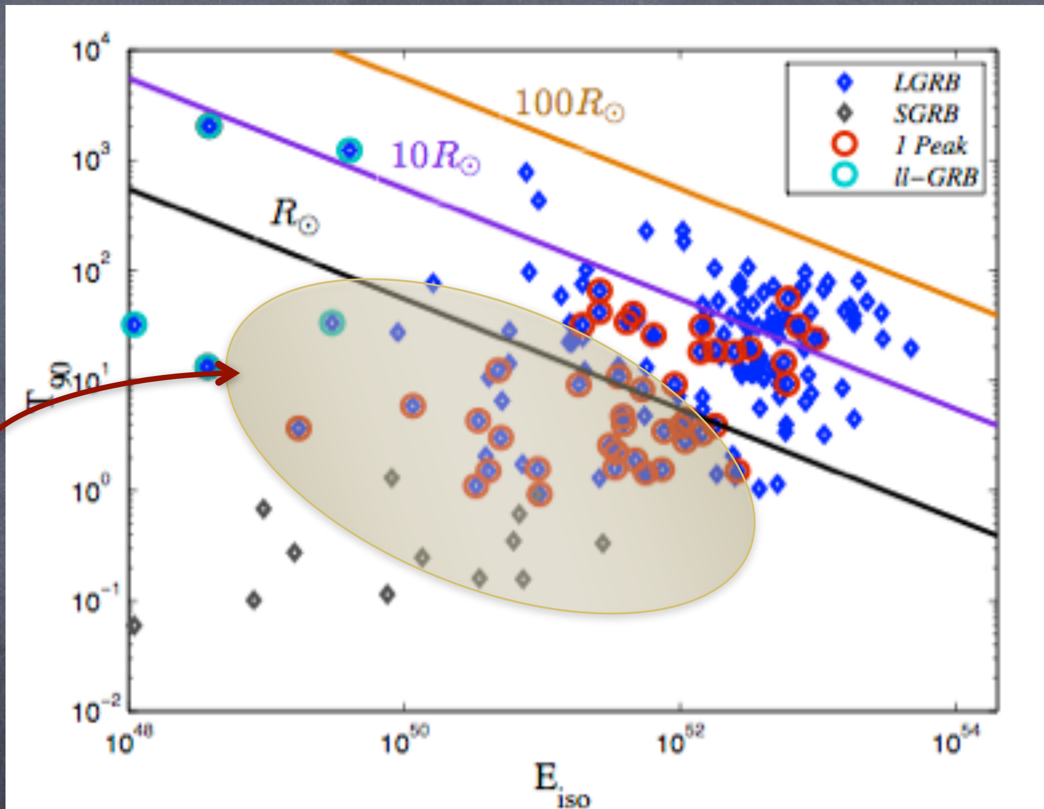
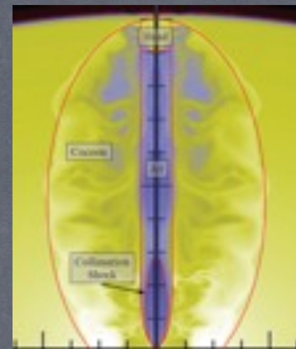


Are most single peaked GRBs llGRBs?

So:



So:

- Minimal break energy and minimal engine time are required for a jet to cross the stellar envelope.

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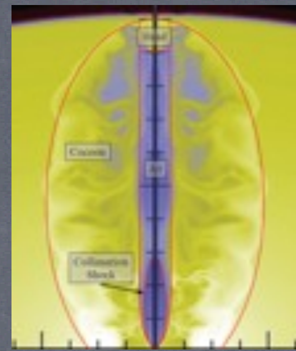

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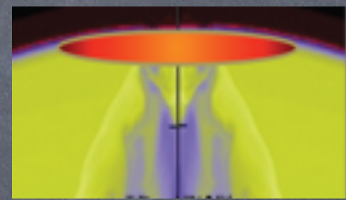

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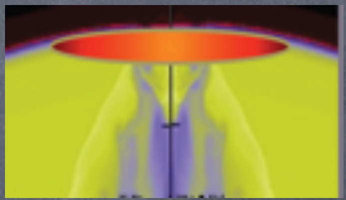

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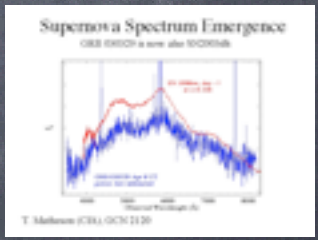

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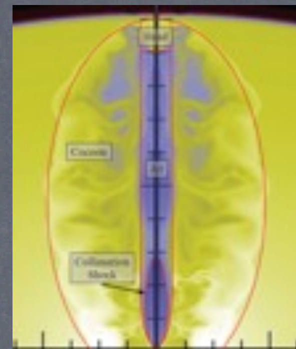

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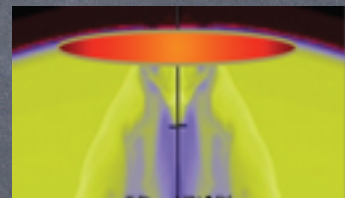

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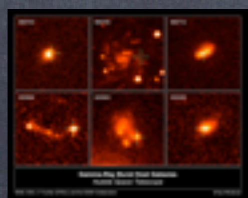
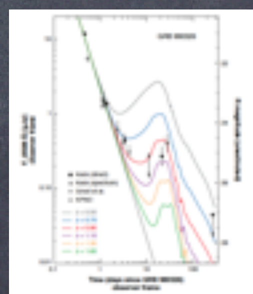
- But

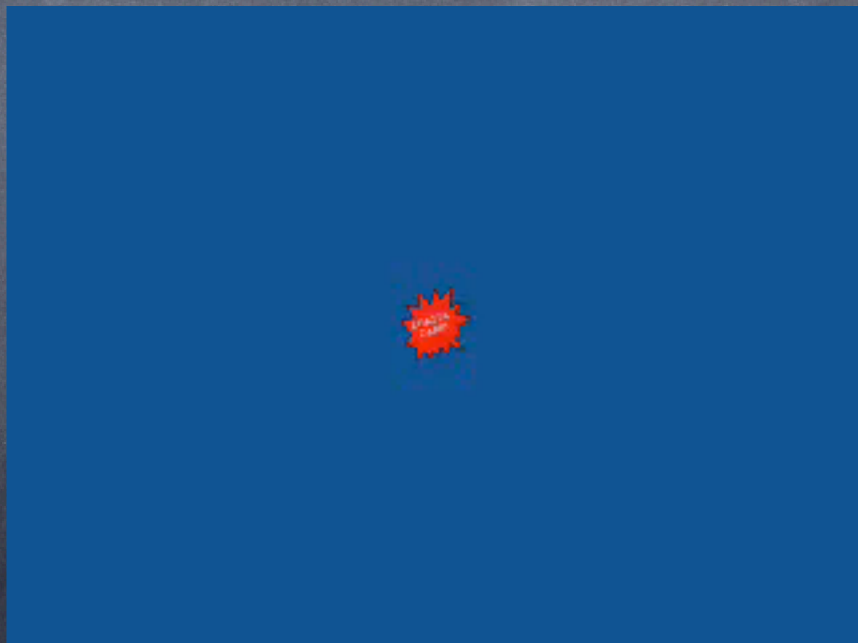
…

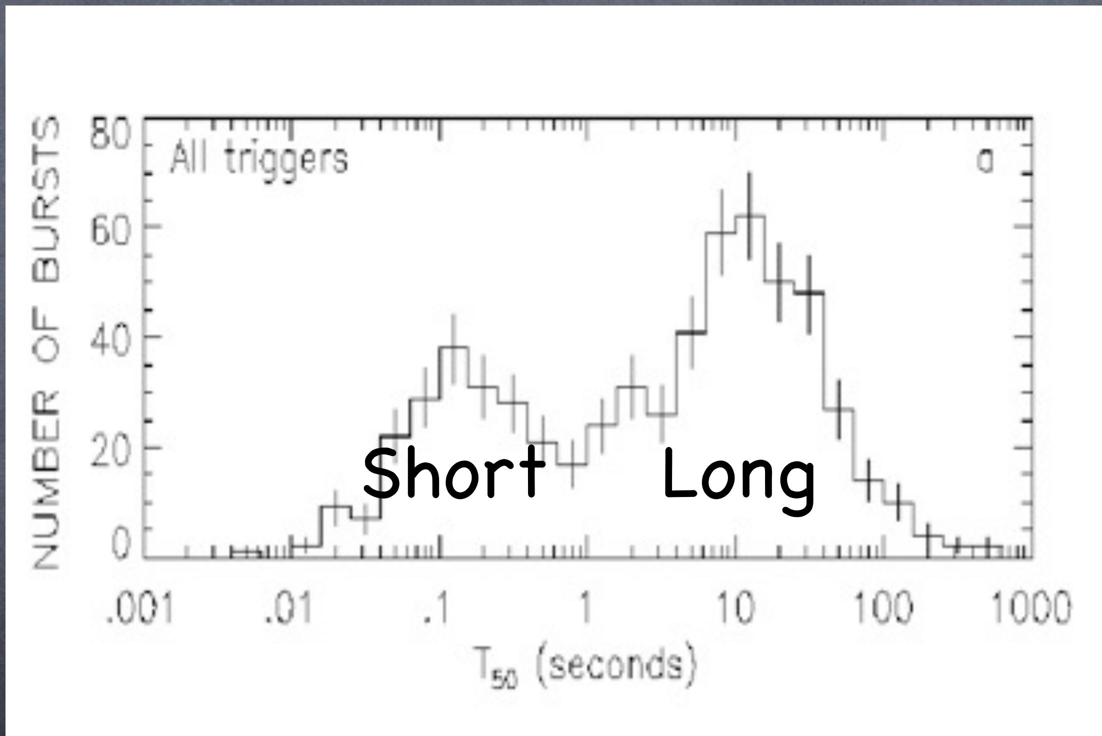




?

ΣΠΑΣΤΑ ΟΛΑ




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

Predictions of the Collapsar model

$$t_\gamma = t_e - t_b.$$

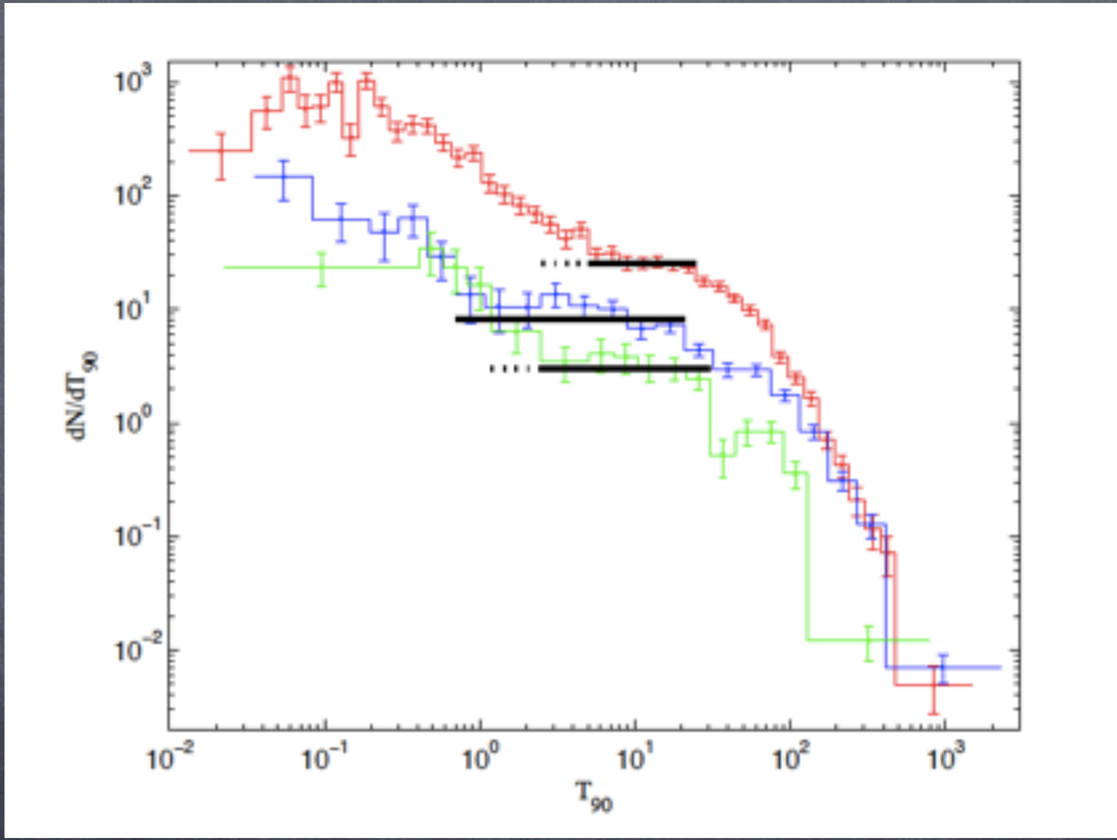
$$, \; p_\gamma(t_\gamma)dt_\gamma \; = \; p_e(t_b + t_\gamma)dt_\gamma$$

$$p_\gamma(t_\gamma) \approx \begin{cases} p_e(t_b) & t_\gamma \ll t_b \\ p_e(t_\gamma) & t_\gamma \gg t_b \end{cases},$$

Short Long

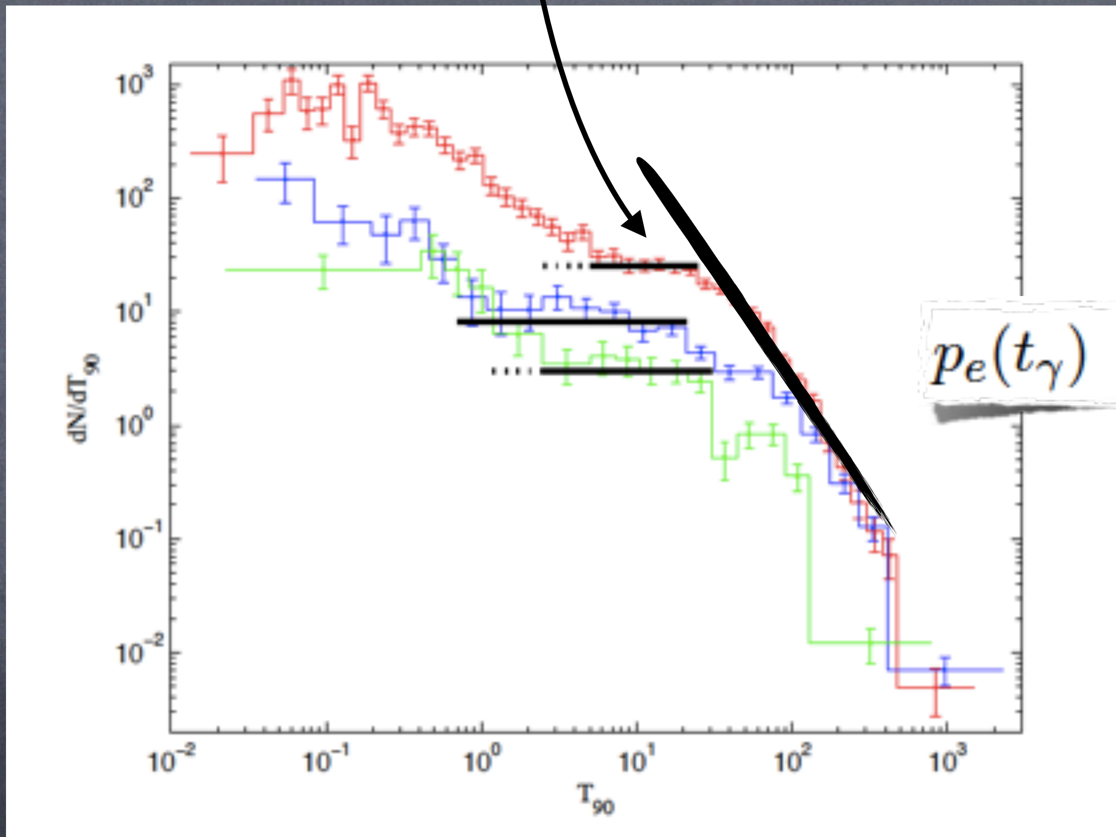
Short Long

A second look



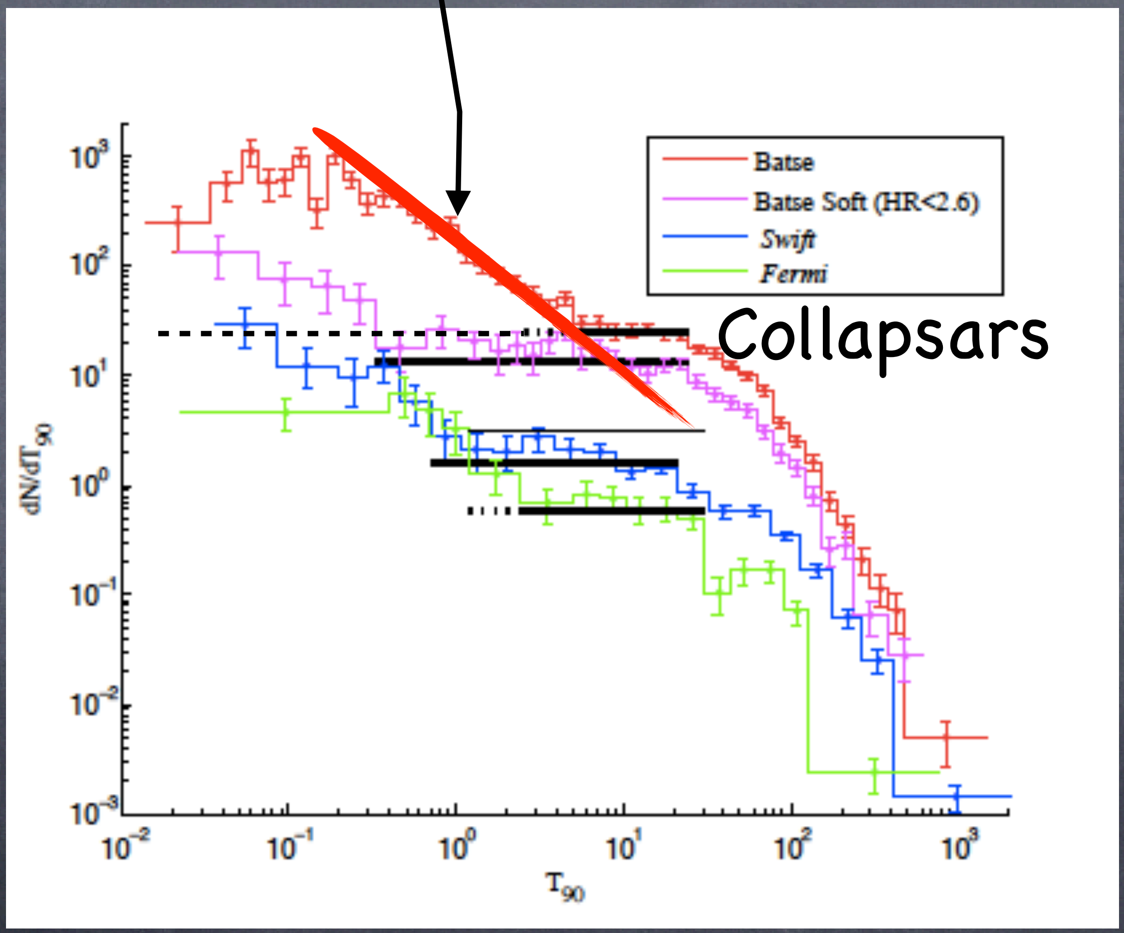
This provides the first direct observational proof of the Collapsar model.

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



$$p_e(t_\gamma) \quad t_\gamma \gg t_b$$

Short (Non-Collapsars) GRBs



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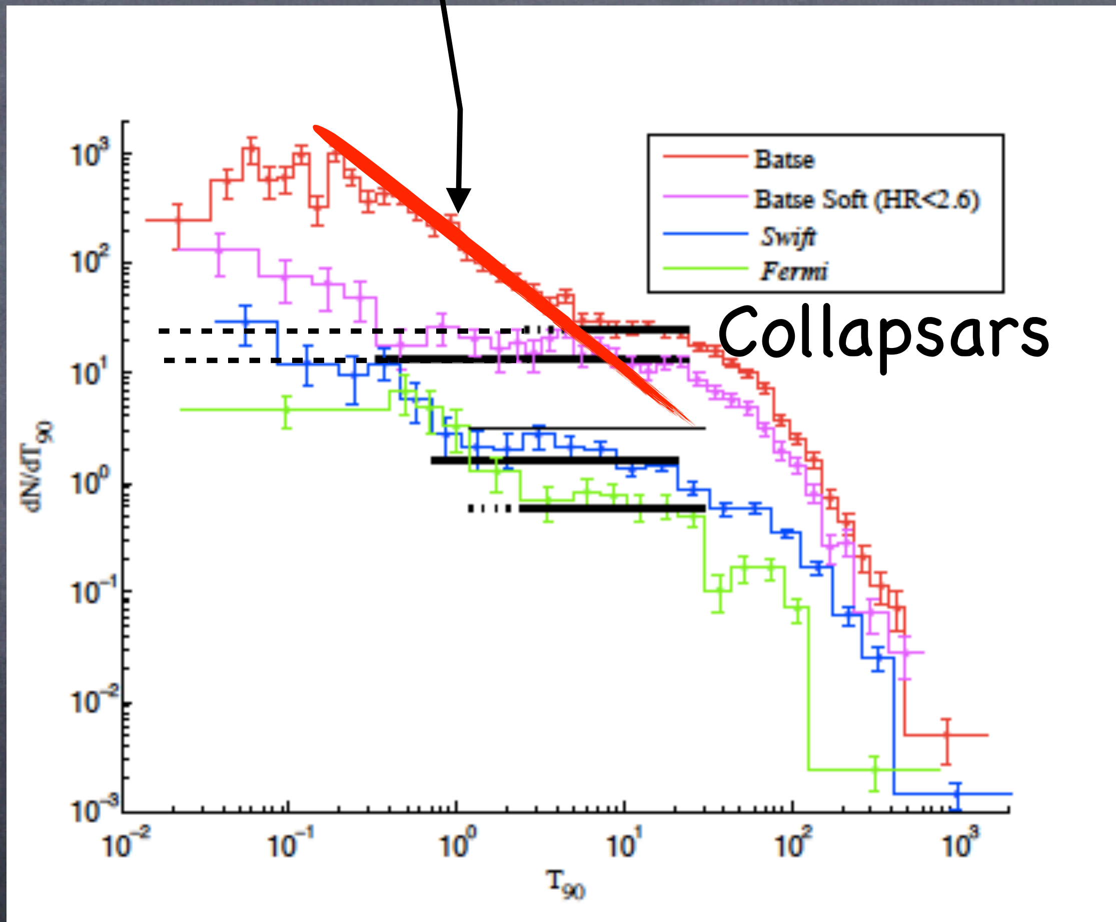

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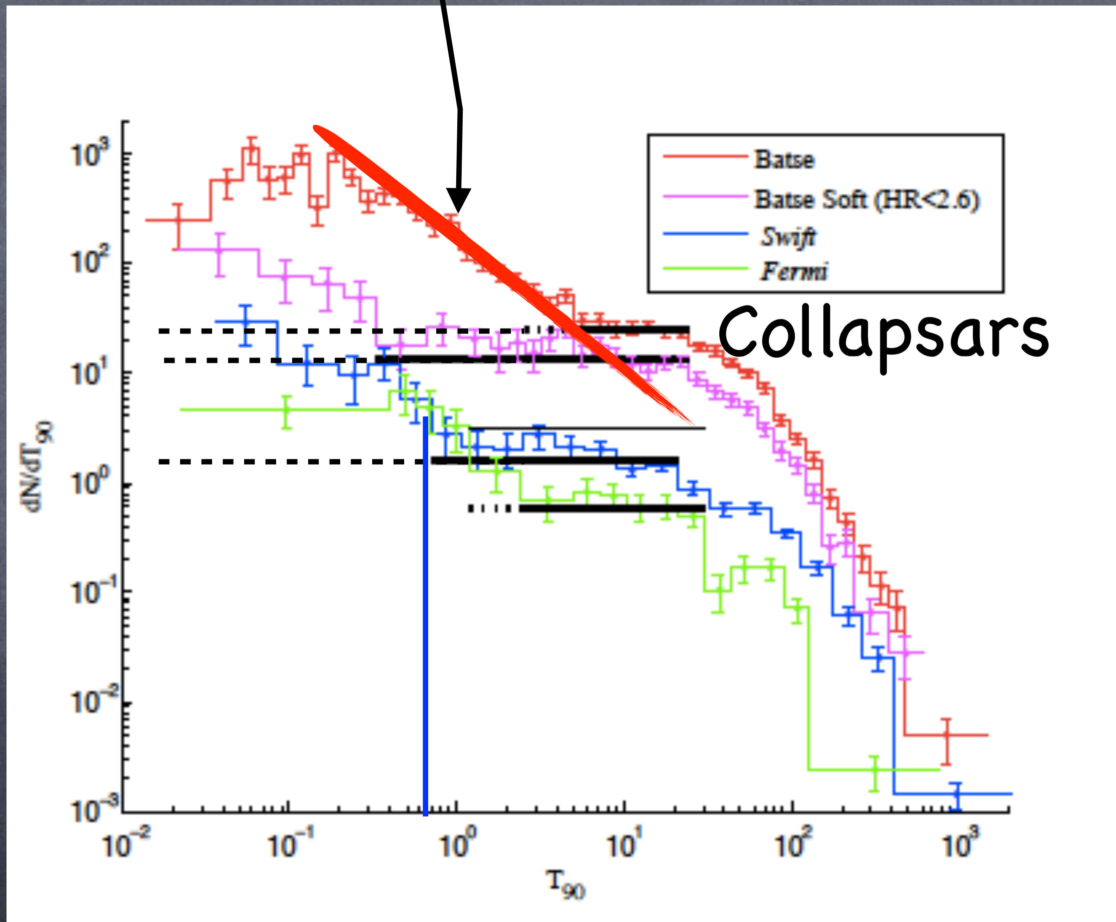

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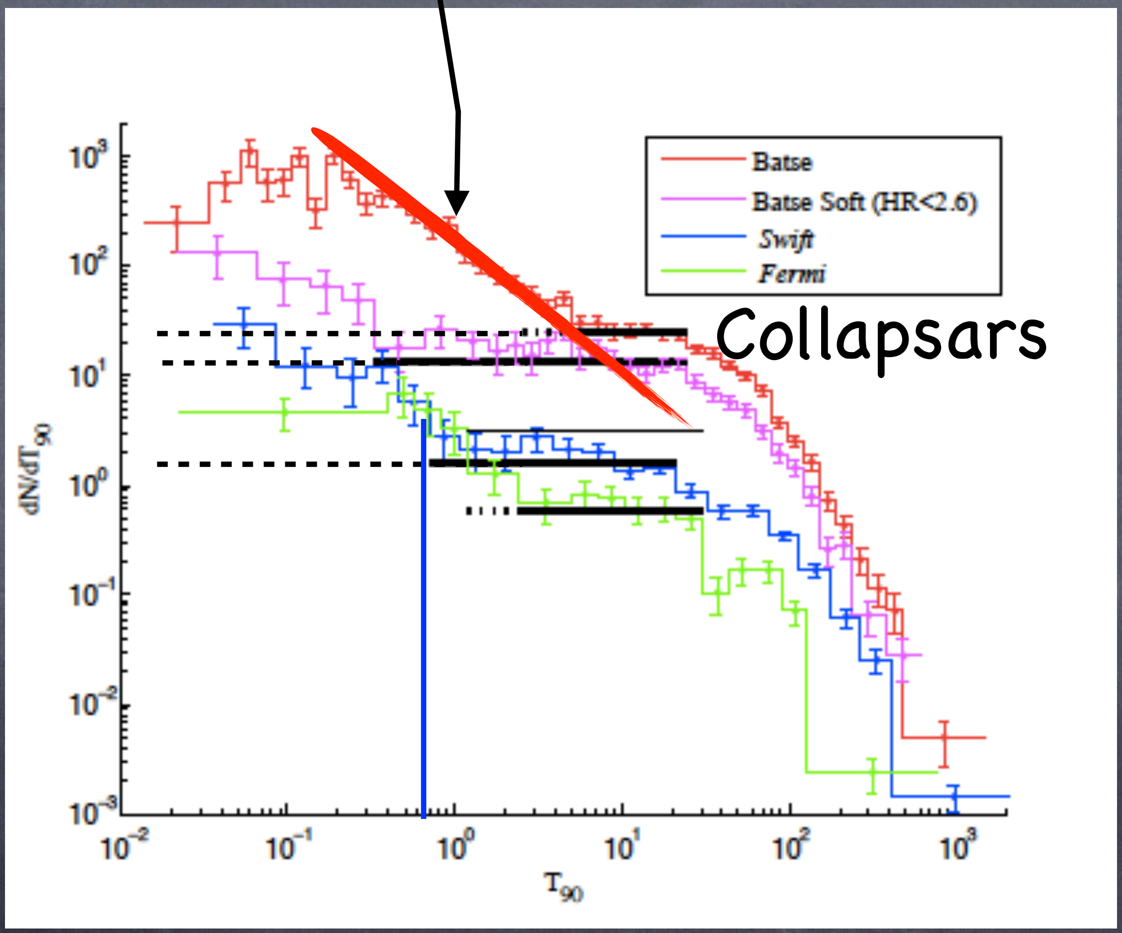

Short Swift jet with T_{90}>0.7sec are not short!

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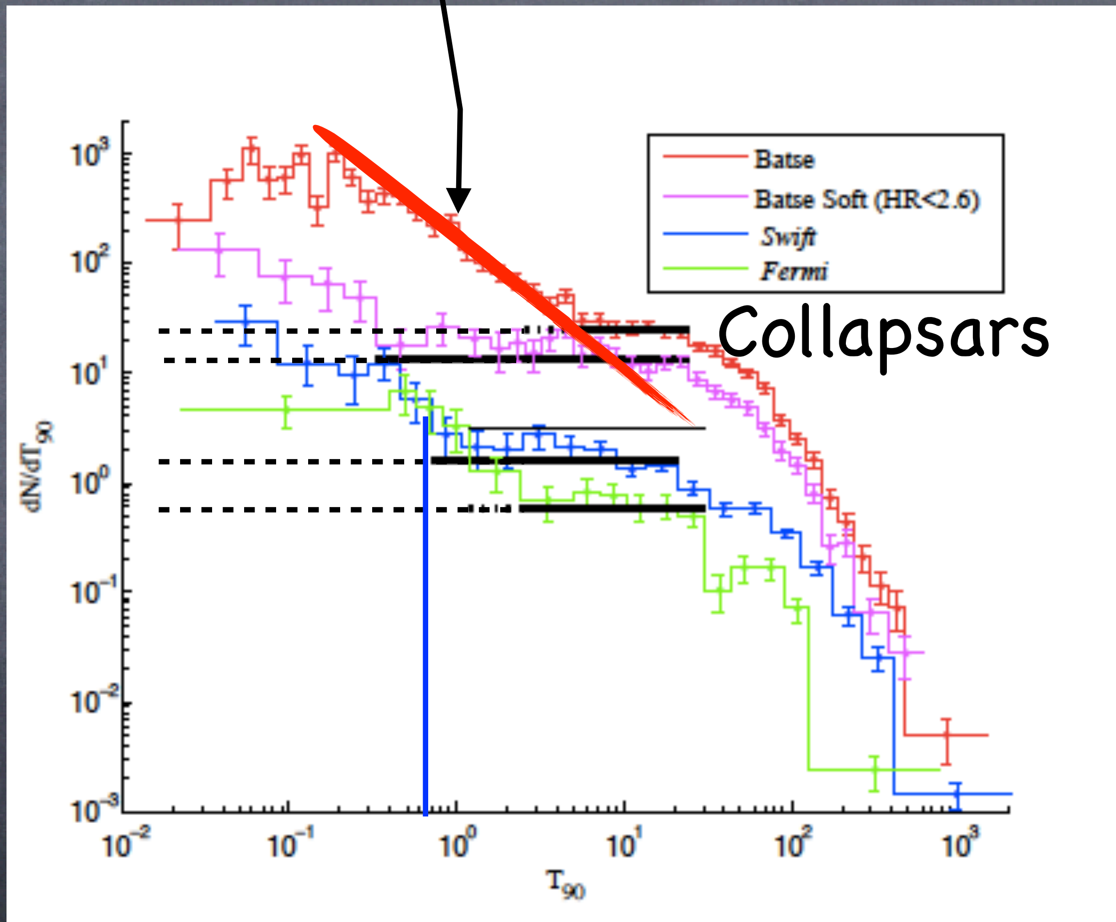
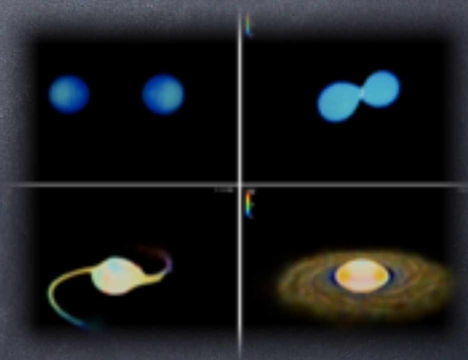


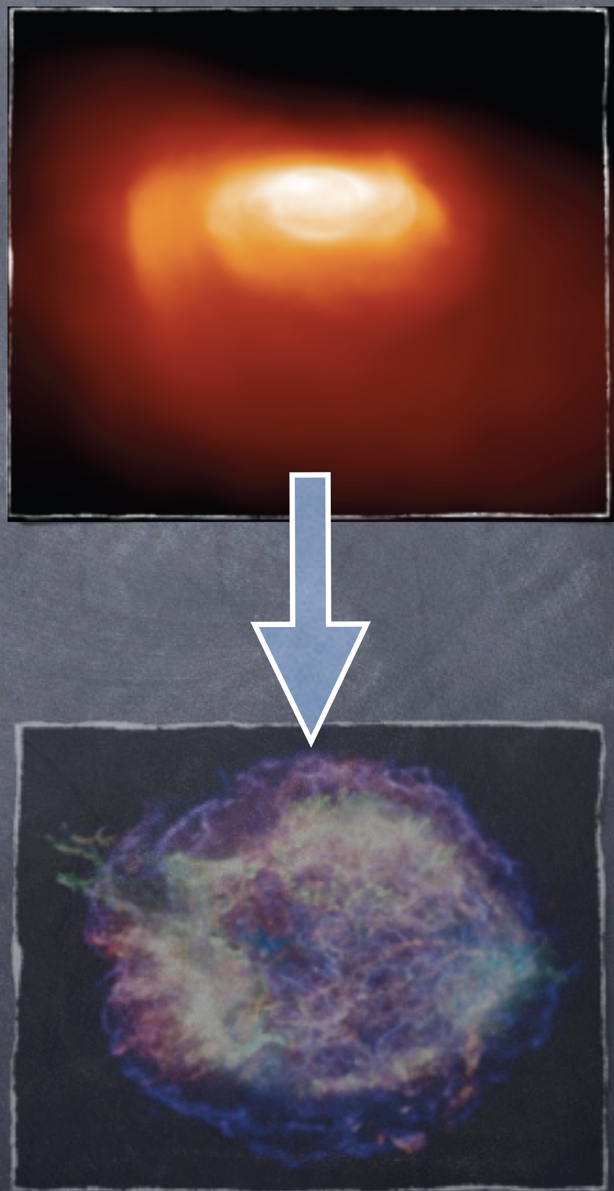
Short Swift jet with T_{90}>0.7sec are not short!

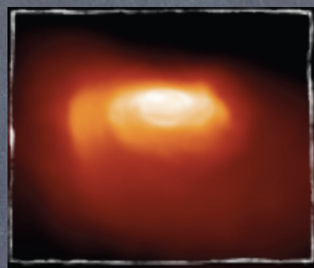
Determining the rate of NS merges from Radio Flares - Electromagnetic signals that follow the Gravitational Waves

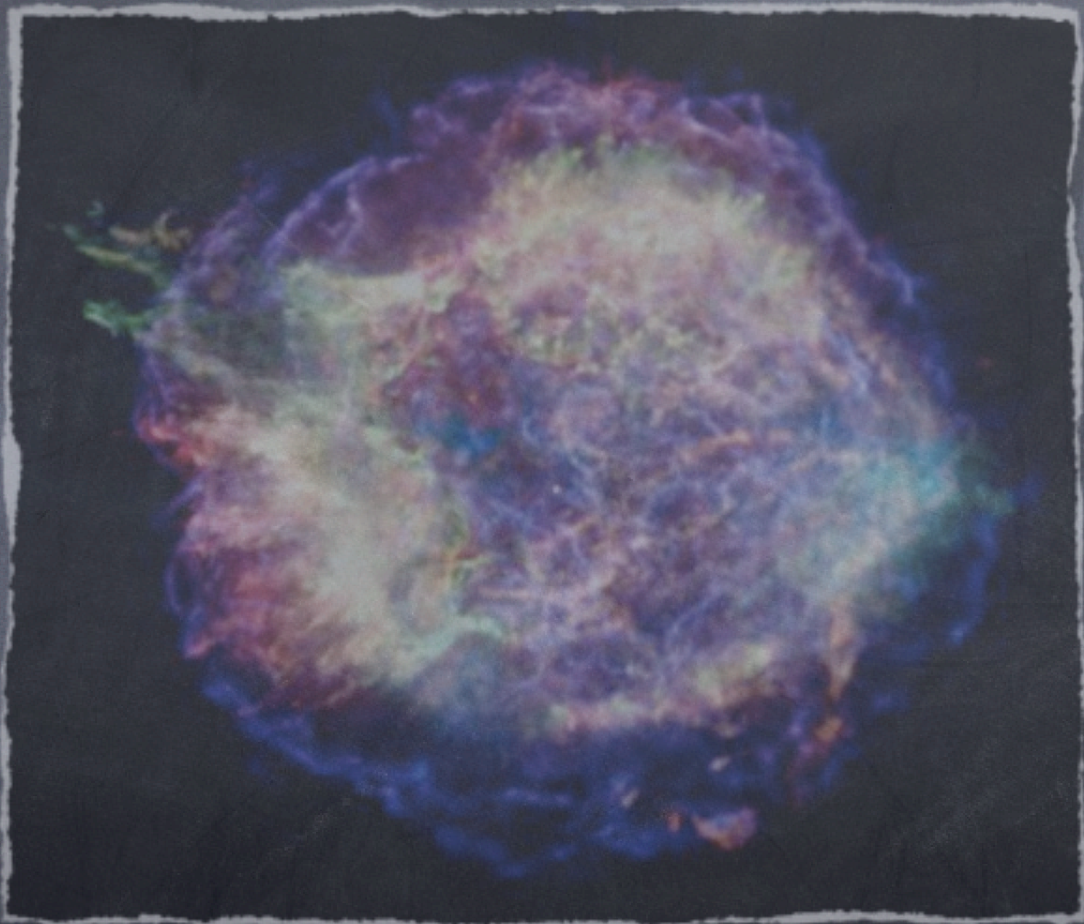


Basic ingredients of the Model

- Numerous numerical simulations show that NS merger eject Sub - or Mildly relativistic outflow with $E \sim 10^{49}$ erg
- Lorentz factor $(\Gamma-1) \approx 1$
- Interaction of the outflow with the ISM

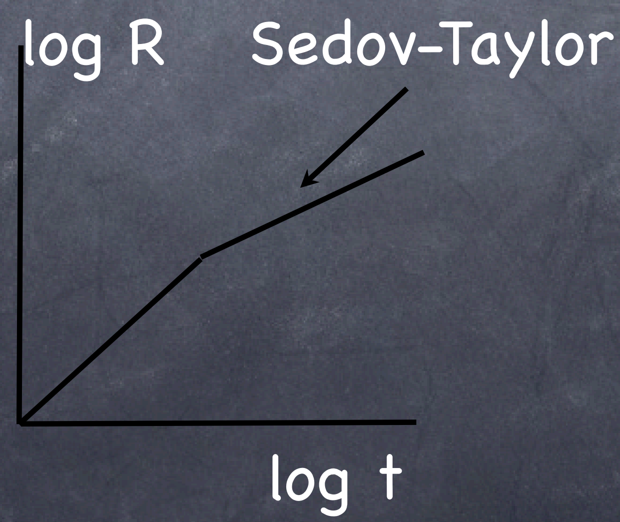




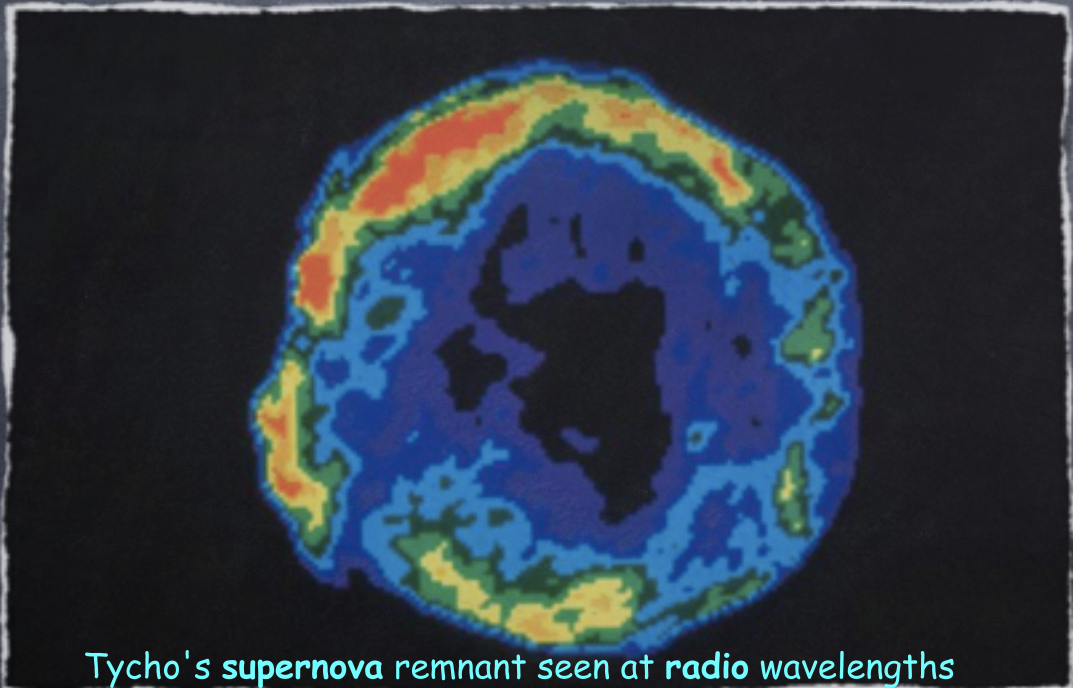


Dynamics

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



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 $\gamma > \gamma_m$

$p = 2.5 - 3$

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

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

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

Frequency and Intensity

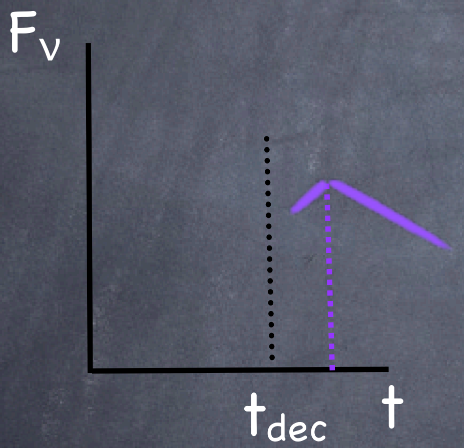
(Nakar, TP 11 Nature in press)

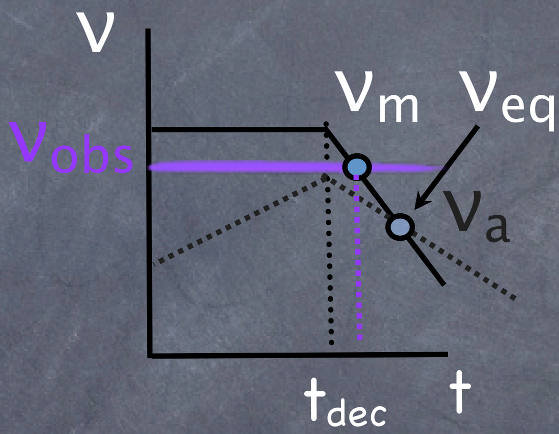
$$\nu_{m,dec} \equiv \nu_m(t_{dec}) \approx 1\ \mathrm{GHz}\ n^{1/2} \epsilon_{B,-1}^{1/2} \epsilon_{e,-1}^{2} (\Gamma_0 - 1)^{5/2},$$

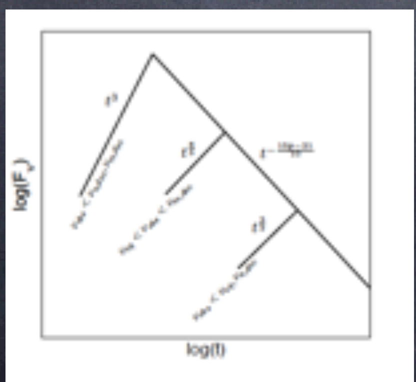
$$F_{\nu_{obs},peak}[\nu_{obs} > \nu_{m,dec},\ \nu_{a,dec}] \approx$$

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

The light curve







Text

$$\nu_{eq} = 1\ \mathrm{GHz}\ E_{49}^{1/7} n^{4/7} \epsilon_{B,-1}^{2/7} \epsilon_{e,-1}^{-1/7}$$

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

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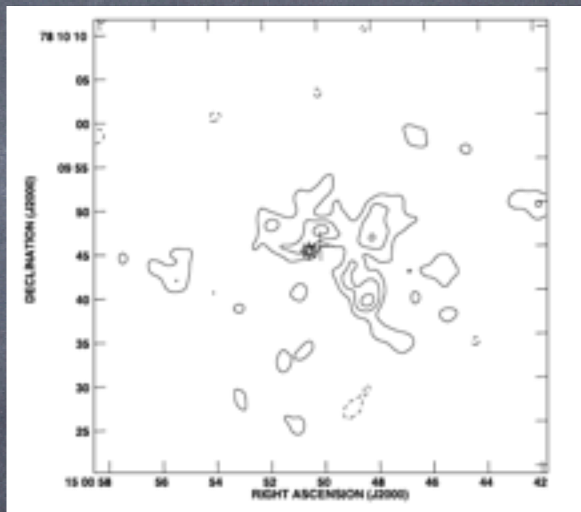
Detectability

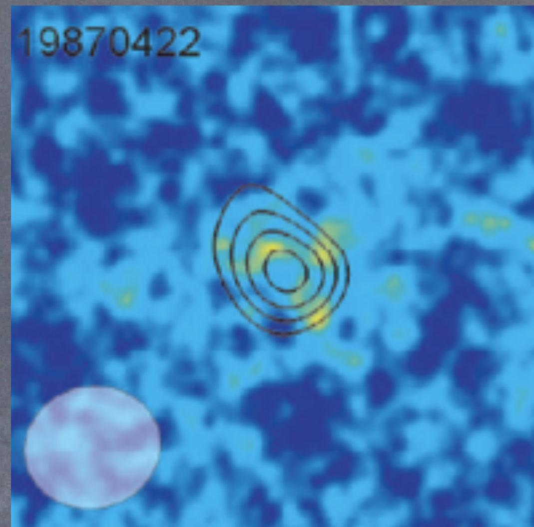
Table 1 | Observing radio flares

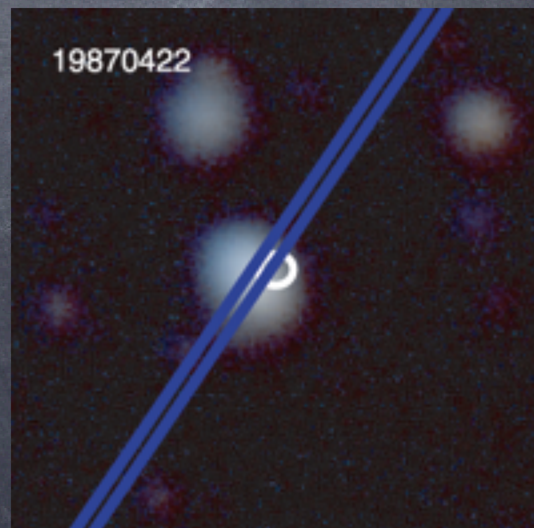
Radio facility	Observing frequency (GHz)	Field of view (deg^2)	One-hour r.m.s.* (μJy)	One-hour detection horizon† $\beta_i \approx 1$, $E_{49} = 1$, $n_0 = 1$	$\beta_i \approx 1$, $E_{49} = 10$, $n_0 = 1$	$\beta_i = 0.2$, $E_{49} = 10$, $n_0 = 1$, $p = 2.5$	Ten-hour detection horiz $\beta_i \approx 1$, $E_{49} = 1$, $n_0 = 10^{-3}$, $p = 2$
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

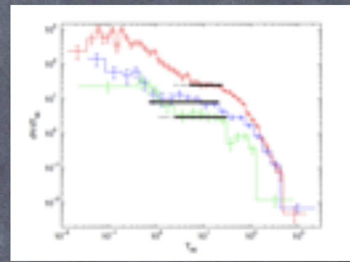






Summary

- llGRBs associated with most observed GRB-SNe are not from Collapsars!
- However, the observed plateau in the duration distribution of LGRBs show that LGRBs arise from Collapsars!



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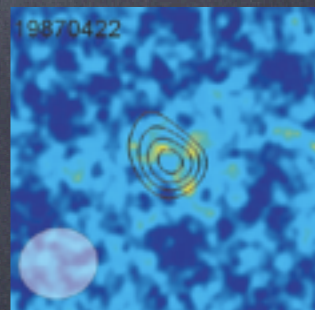

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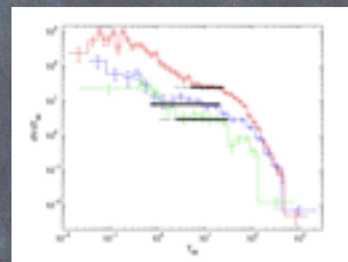

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