Transiet Relatvisitc Explosions

Tsvi Piran

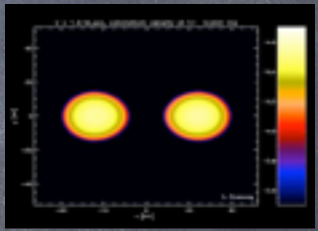
The Hebrew University, Jerusalem

Omer Bromberg, Franck Genet, Julian Krolik, Eli Livne, Ehud Nakar, Martin Obergaulinger, Stephan Rosswog, Re'em Sari

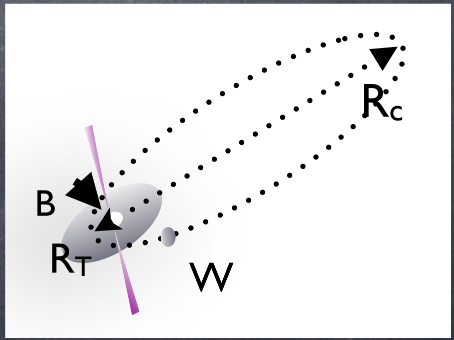
Bologna 2013

A Tale of Three Explosions

- The origin of Gamma Ray Bursts
- Radio Flares from Neutron star mergers



- Tidal Disruption Events



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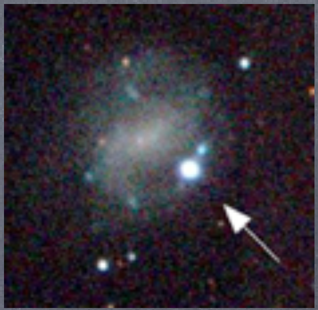

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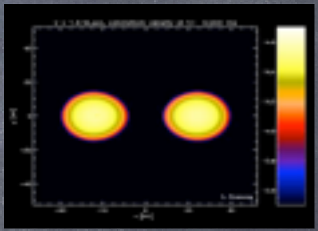

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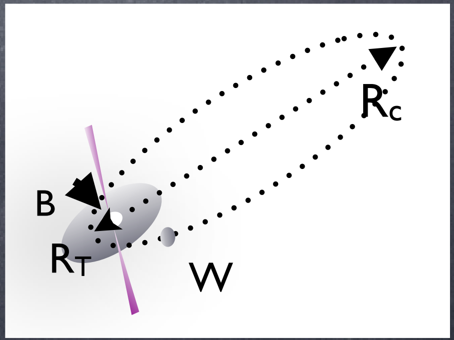

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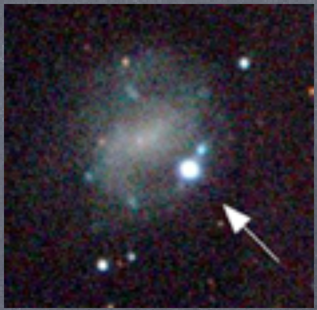

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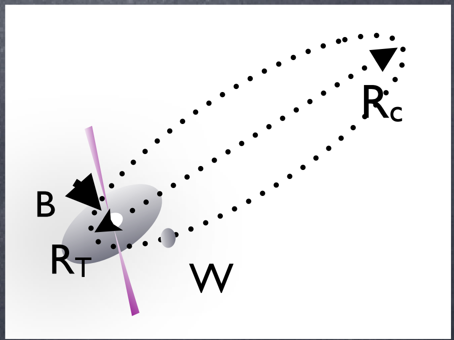
- Tidal Disruption Events



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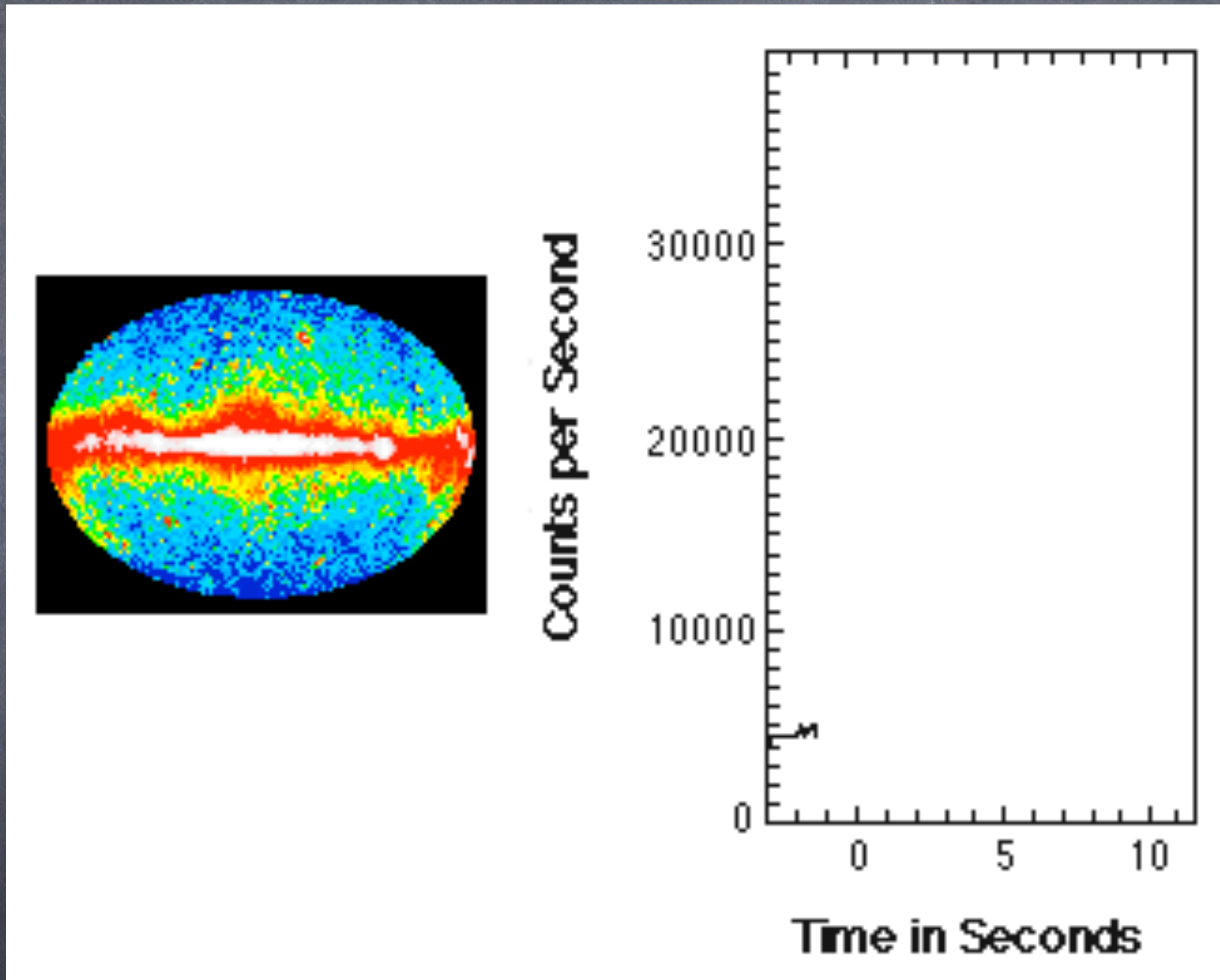
GRBs are the (electromagnetically) brightest objects in the Universe. Only ~8 orders of magnitude less then the theoretically maximal * luminosity (c^5/G)~10^{59} erg/sec .

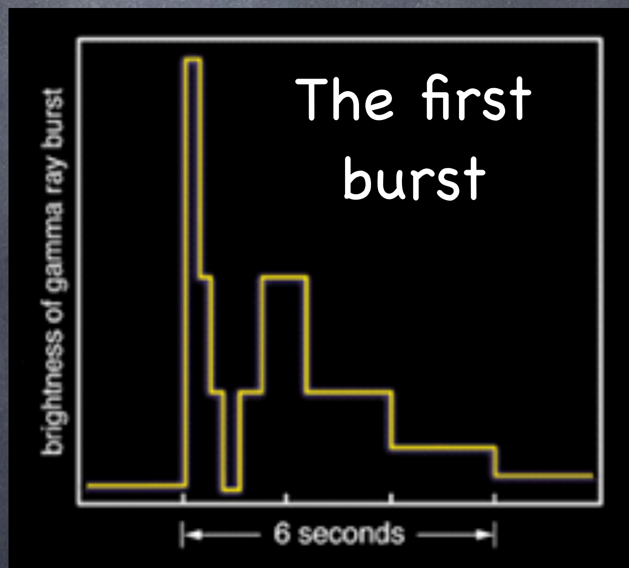
$$\frac{Mc^2}{GM/c^3}$$

* Up to relativistic corrections.


Counts per Second
30000
20000
10000
0
0
5
10
Time in Seconds

The Vela Satellites

GRBs were discovered accidentally at the late 60ies by the Vela satellites, defense sattelites built to monitor the outer space treaty that forbade nuclear explosions in space. At that time - the late sixties - it was considered "impolite" to launch a spy sattelite.

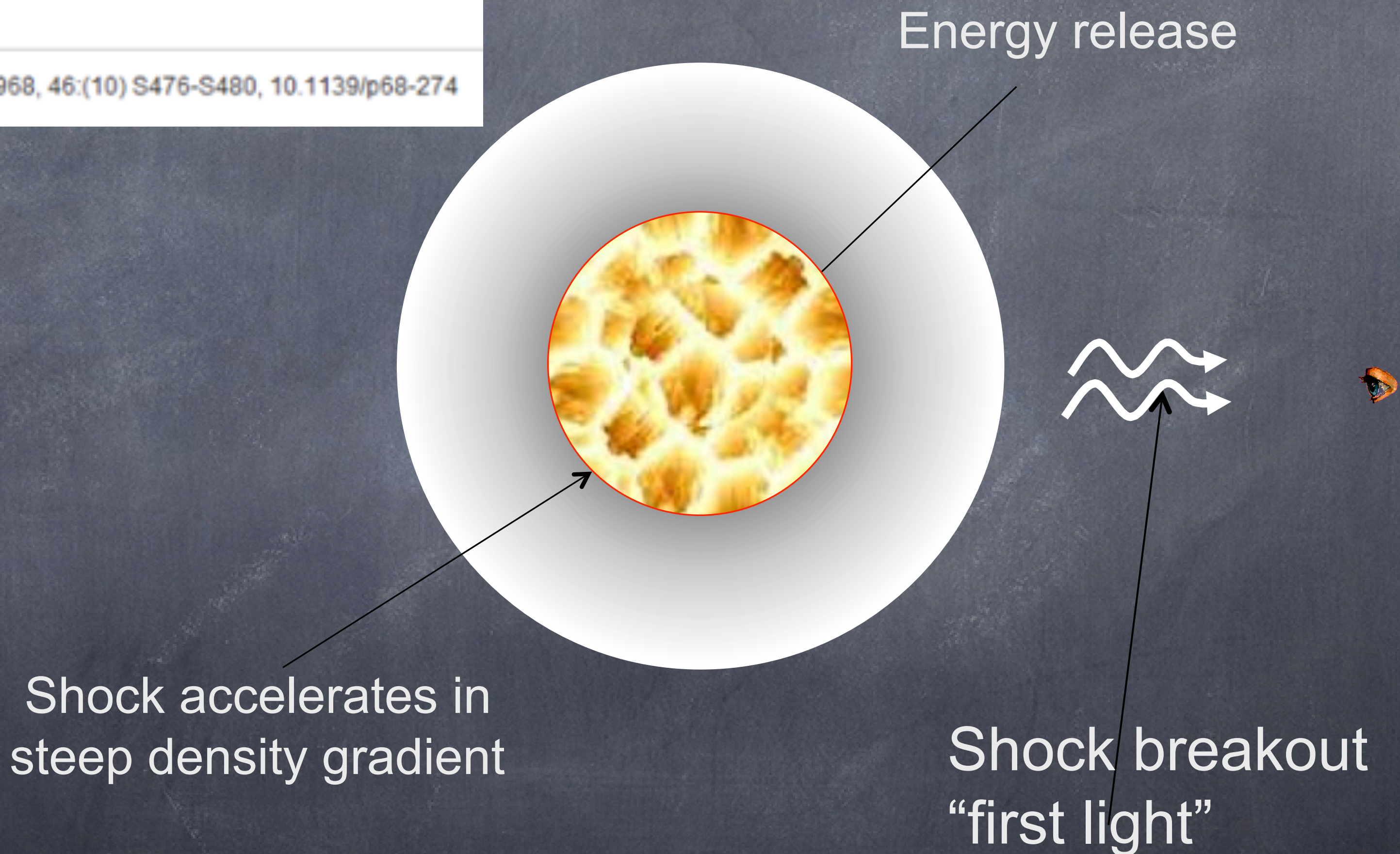


An invited prediction ?

Prompt gamma rays and X rays from supernovae

Stirling A. Colgate

Canadian Journal of Physics, 1968, 46:(10) S476-S480, 10.1139/p68-274



Properties

- Duration 0.01-1000s

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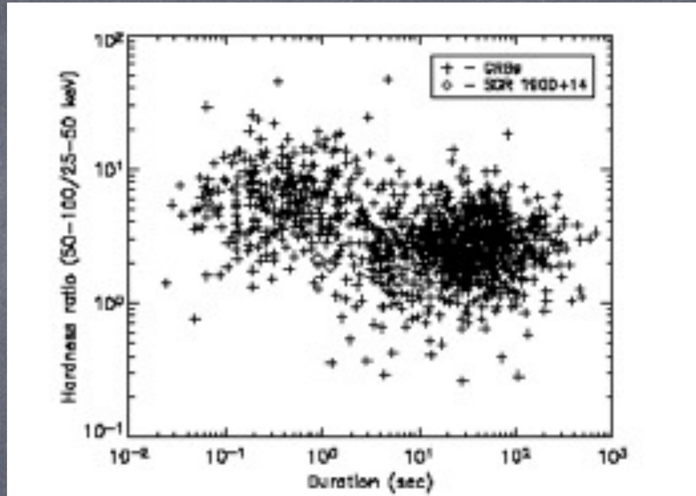
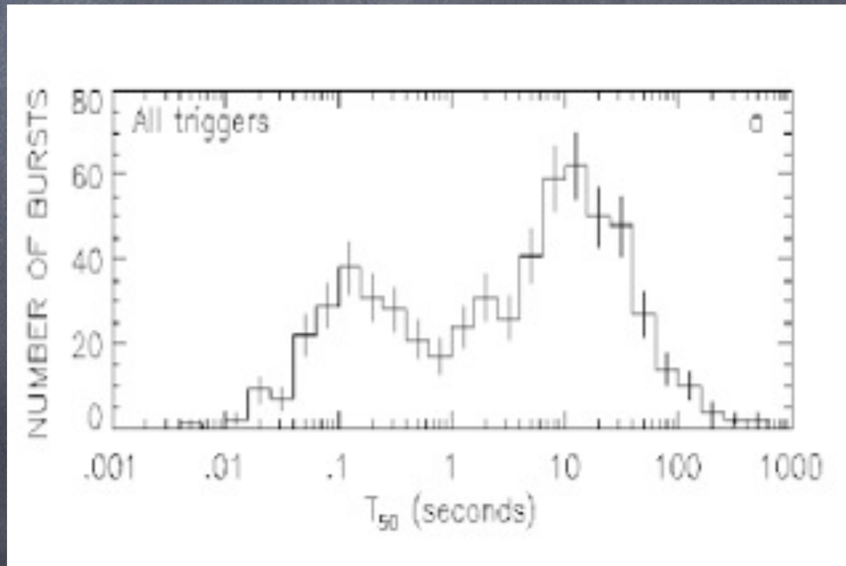
  Two populations (long and short)





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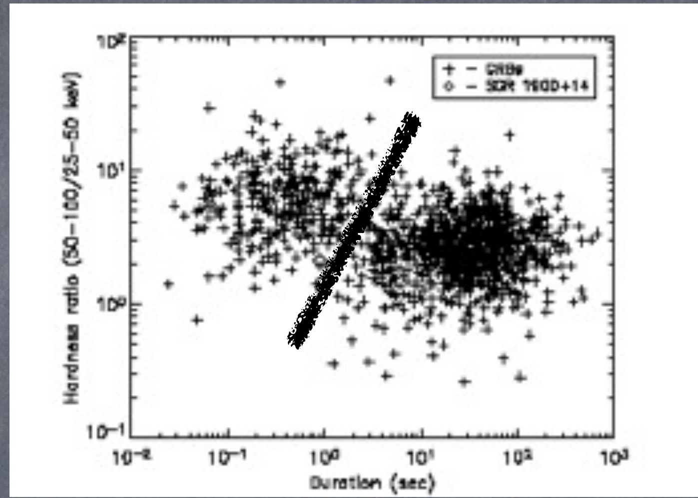

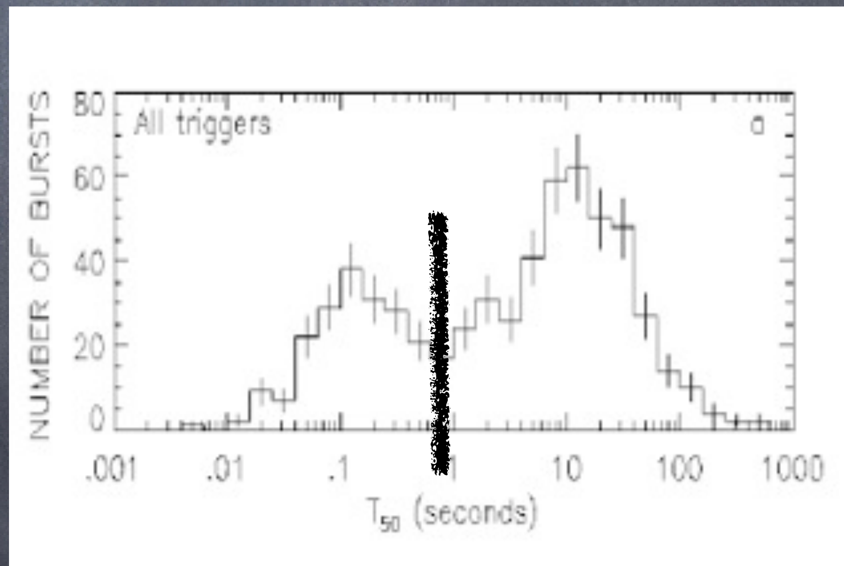

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  (non thermal spectrum)
  (very high energy tail,
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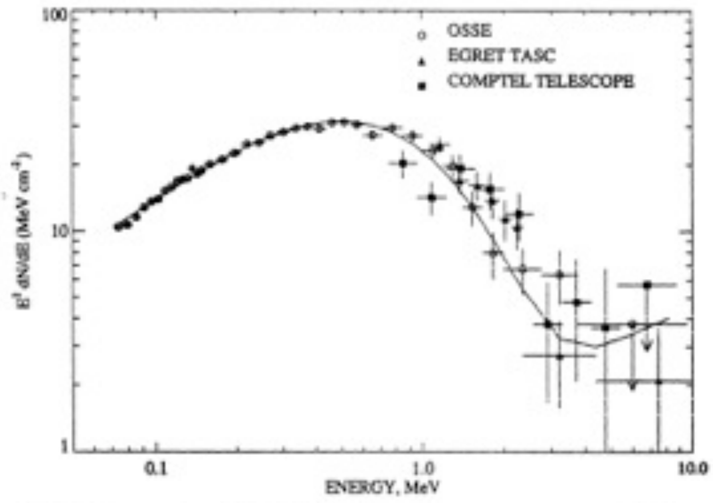

Figure 9 The spectrum of GB 910601 observed over a wide energy range, as measured by three experiments on *CGRO* (Share et al 1994). A typical broad spectrum with a peak power at about 600 keV is seen. (The fitted spectral up-turn above 4 MeV is not significant.)

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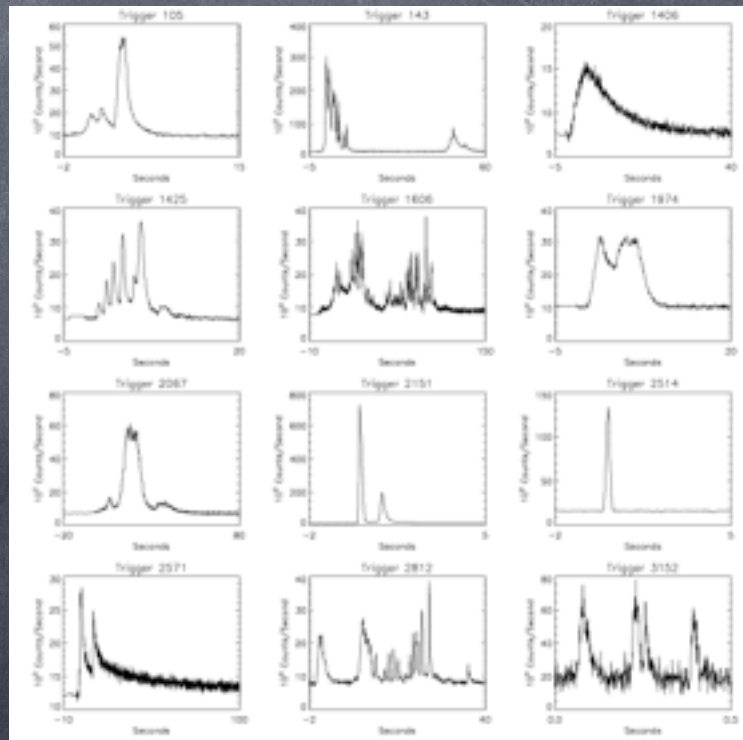

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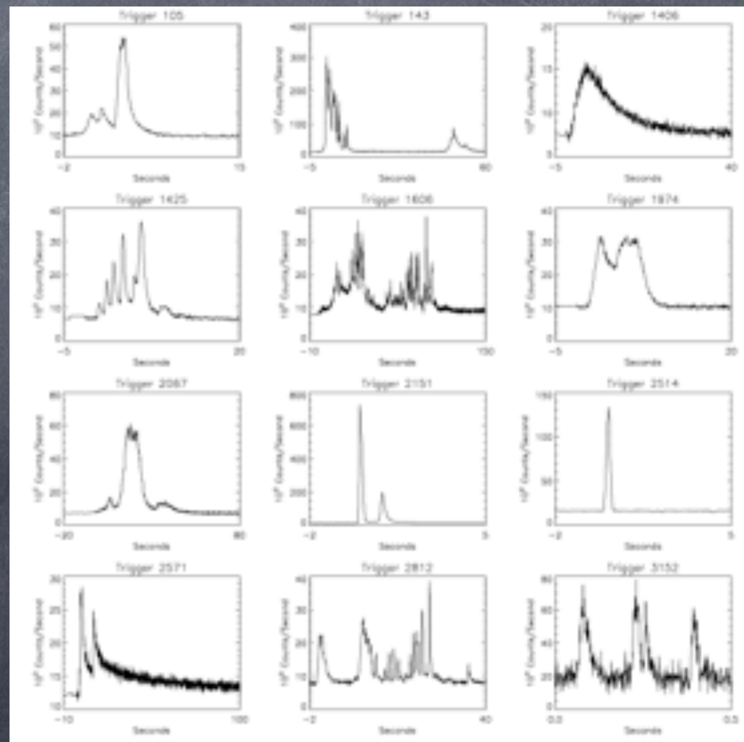

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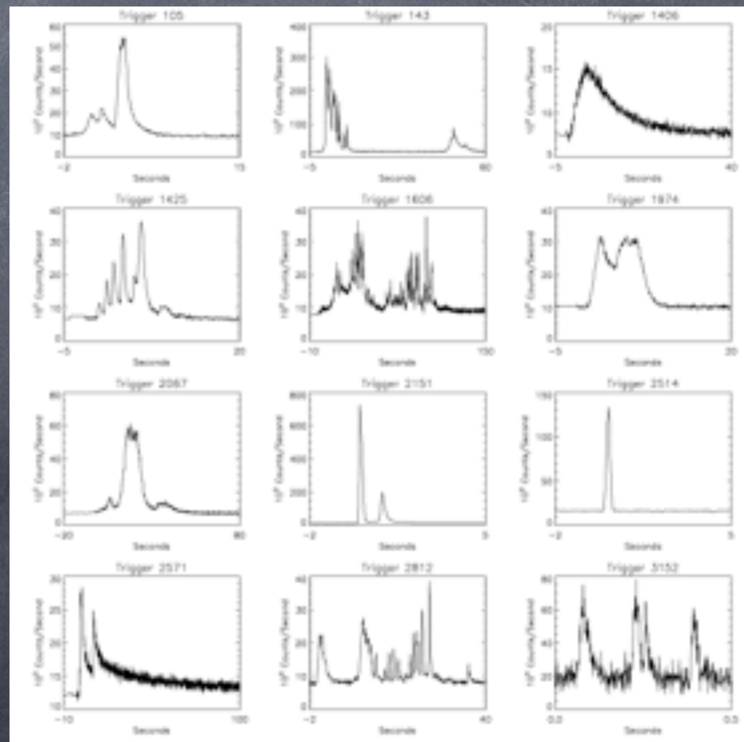

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- Rapid variability

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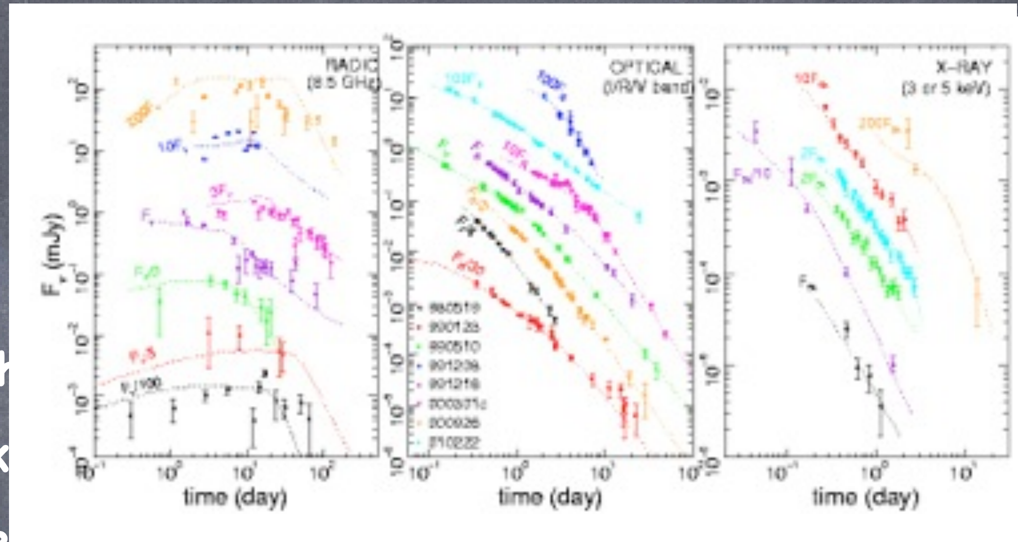
- Typical energy ~10^{52} ergs
- Followed by multiwavelength

  Afteglow



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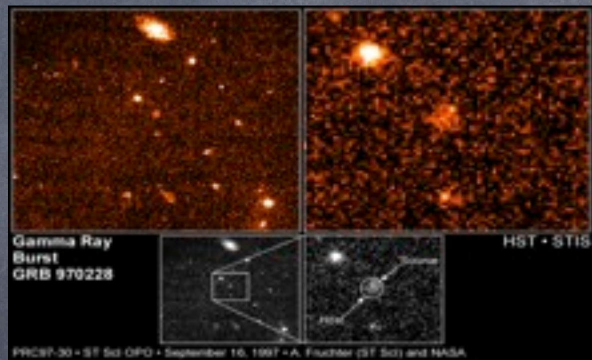
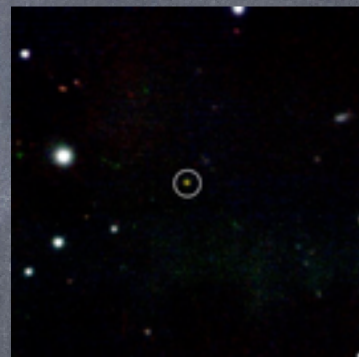
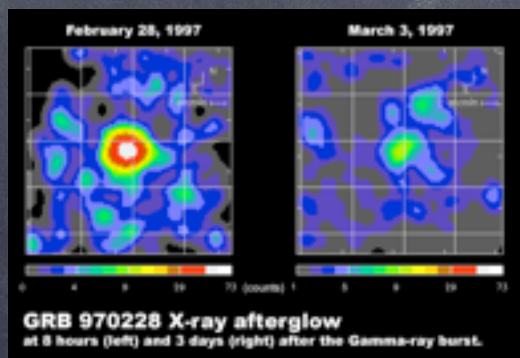
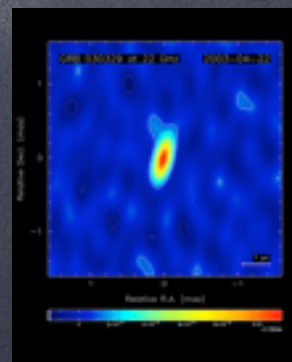








What makes a GRB?

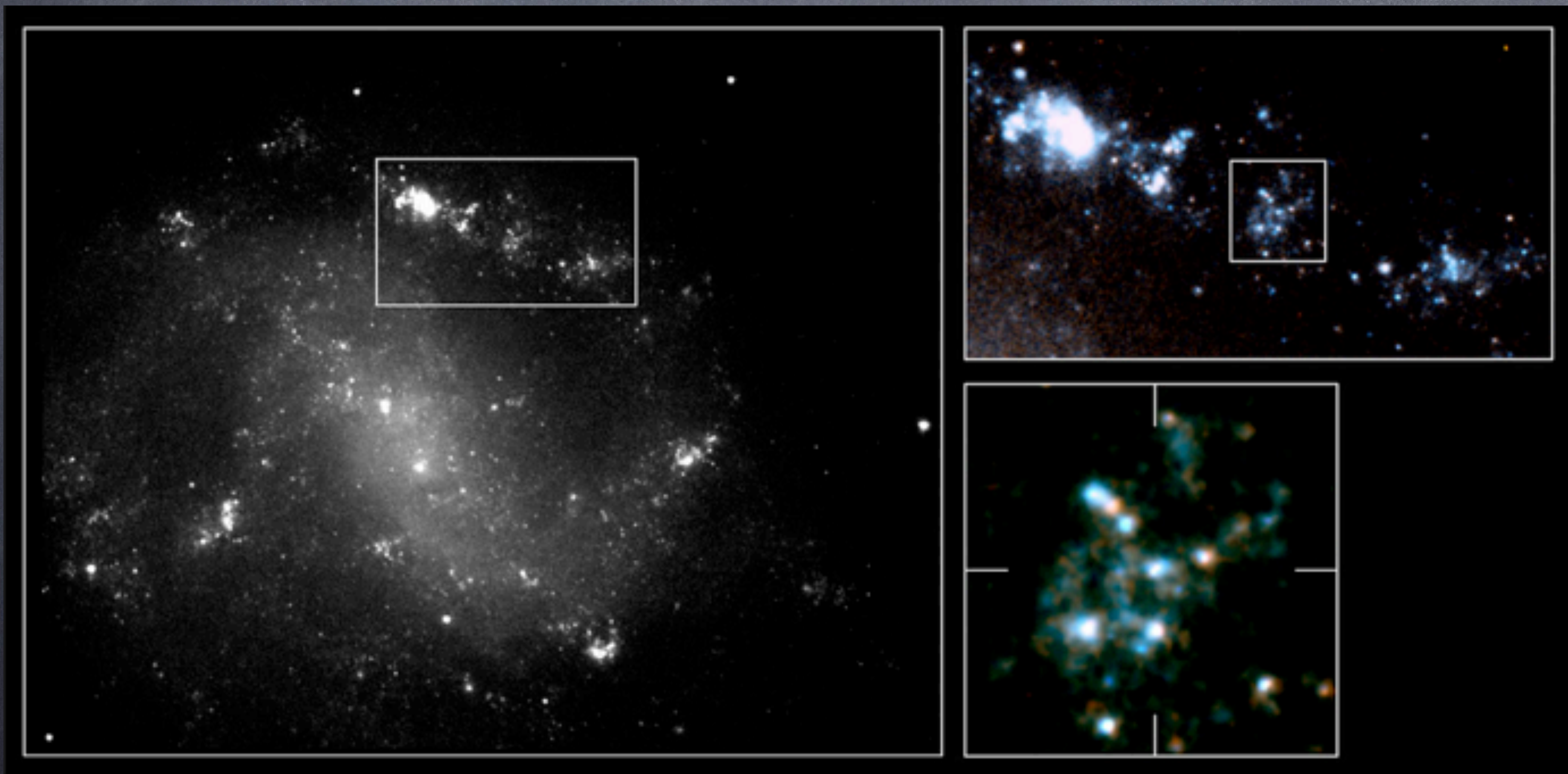
Energy, Energy, Energy + Time

- $E \approx 10^{51}$-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 of two

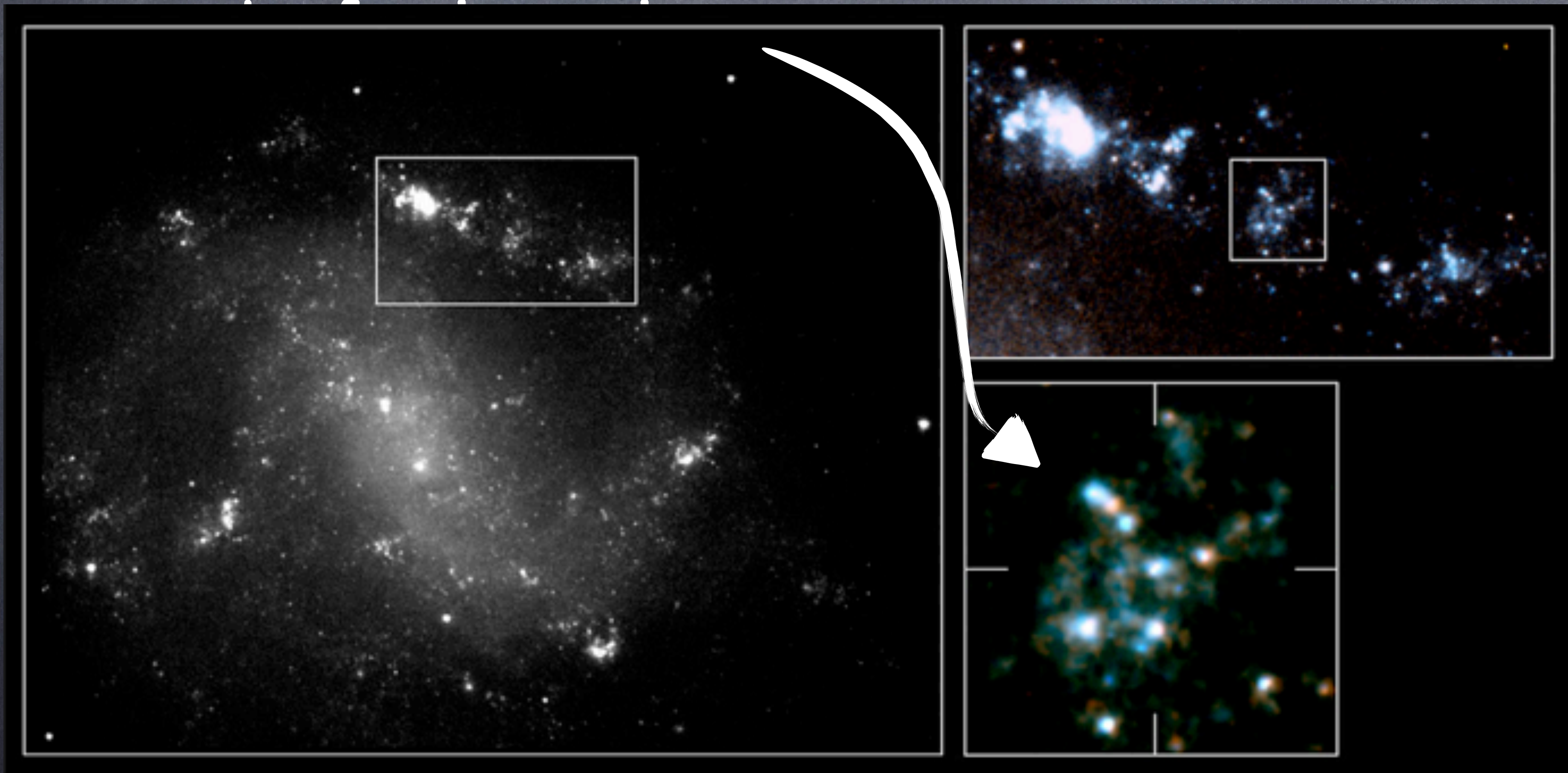
  compact objects

The (long) GRB-Supernova connection



The (long) GRB-Supernova connection

- **Observational indications**
  - **Long GRBs arise in**



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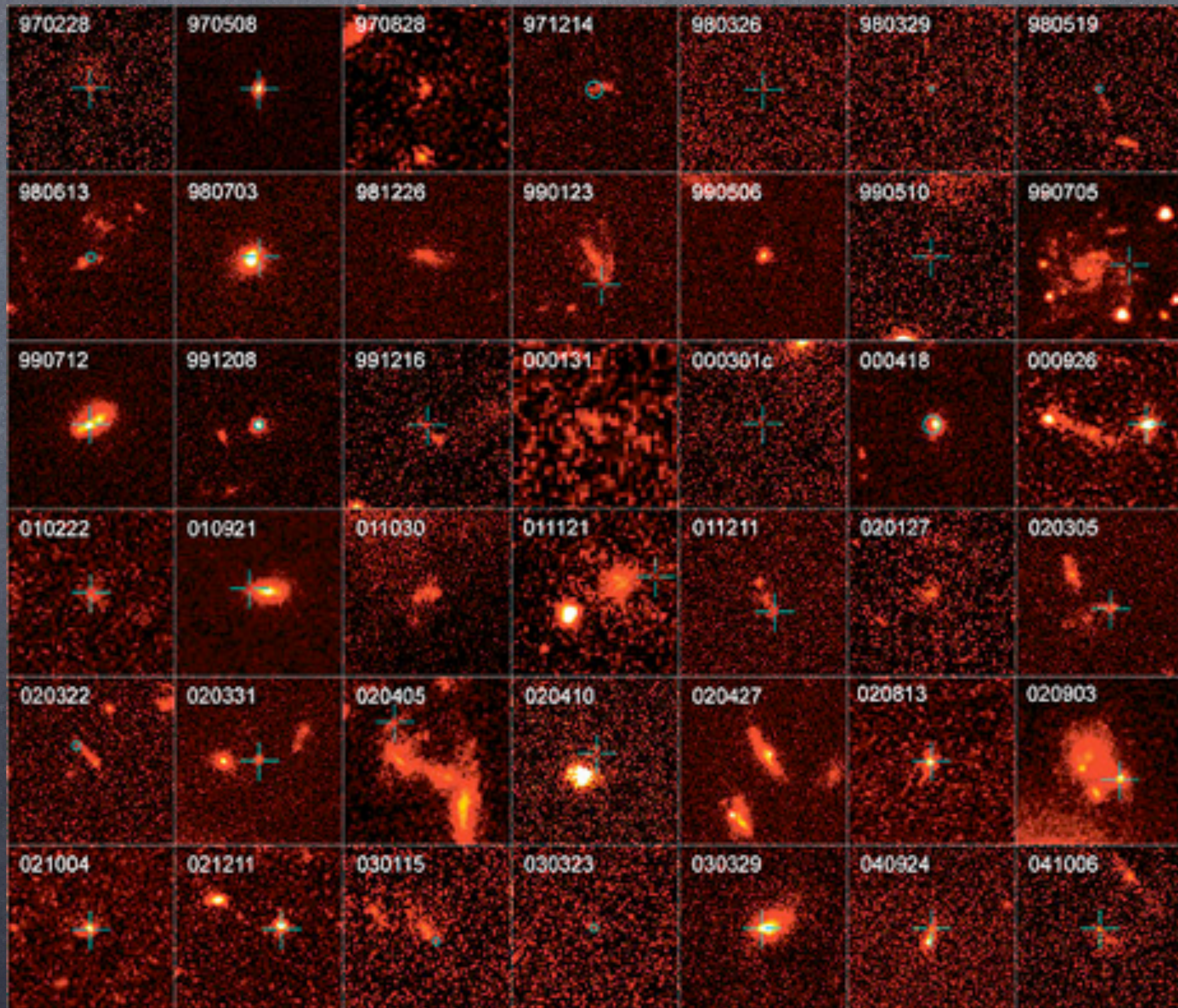
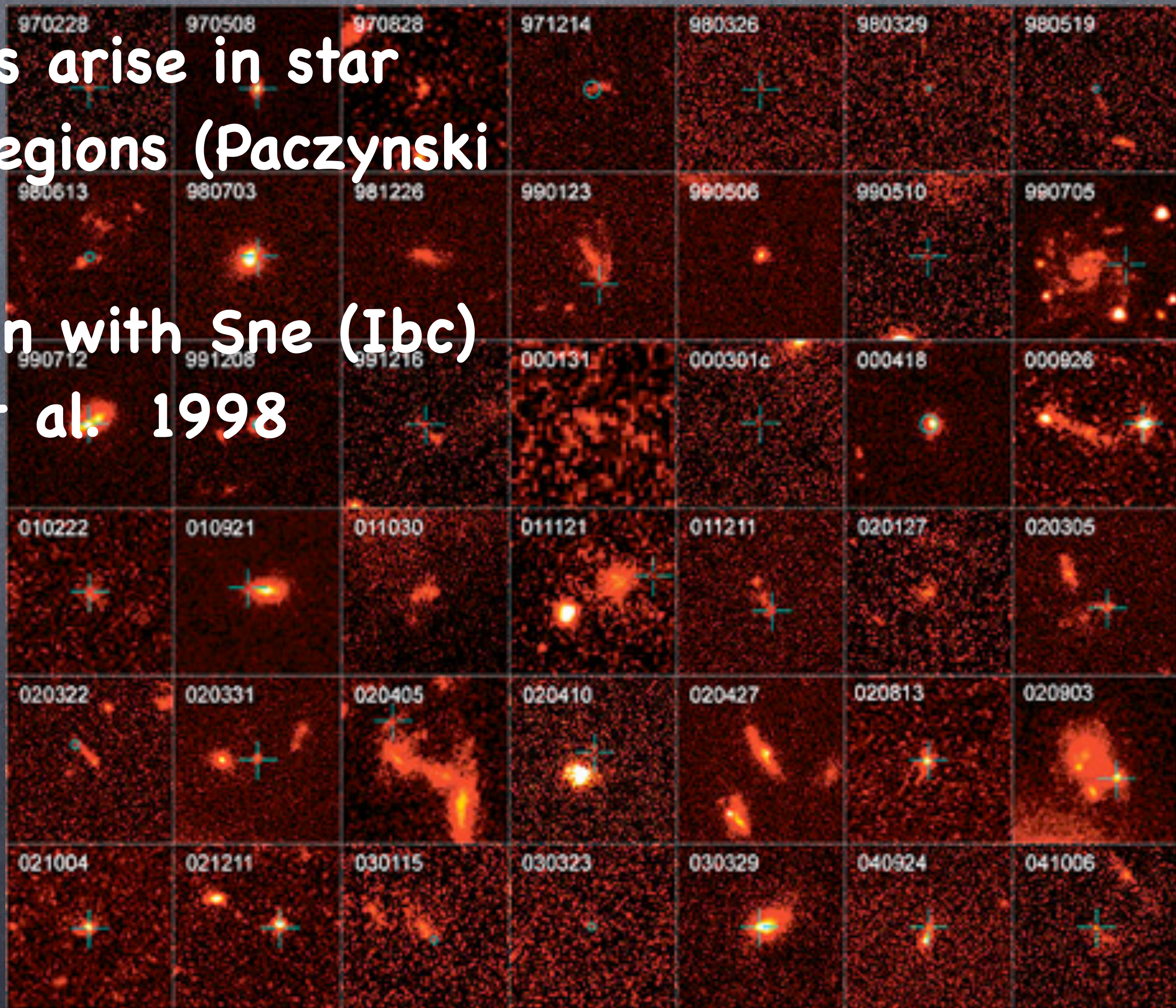


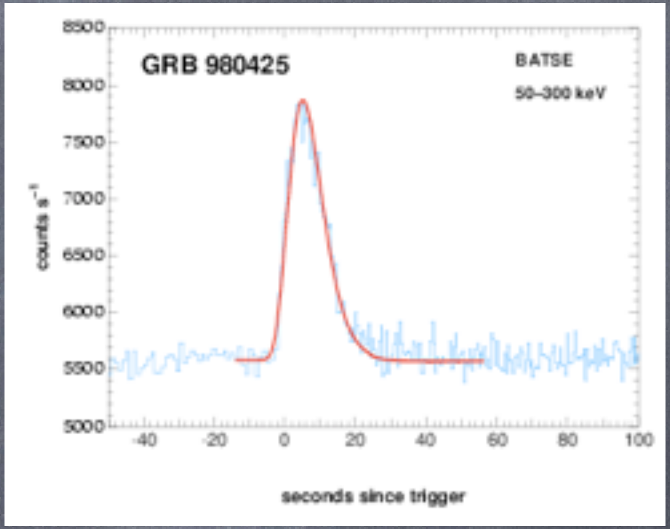
The (long) GRB-Supernova connection

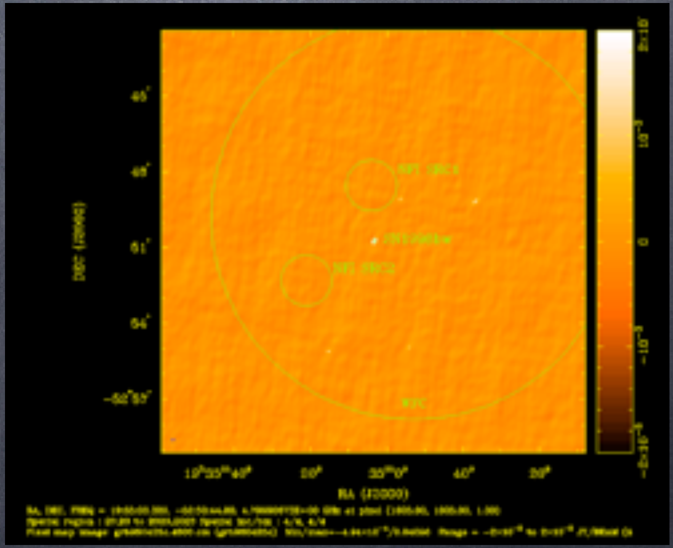
- **Observational indications**
  - **Long GRBs arise in star forming regions (Paczynski 1997)**
  - **Association with Sne (Ibc) Galama et al. 1998**



Supernova 1998bw-GRB980425

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





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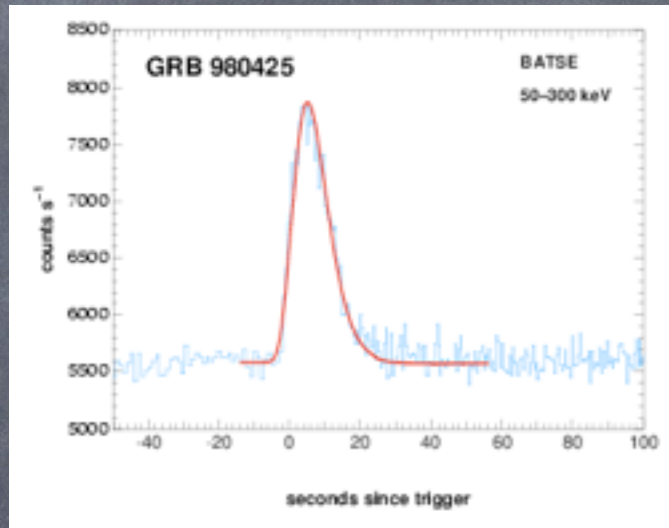

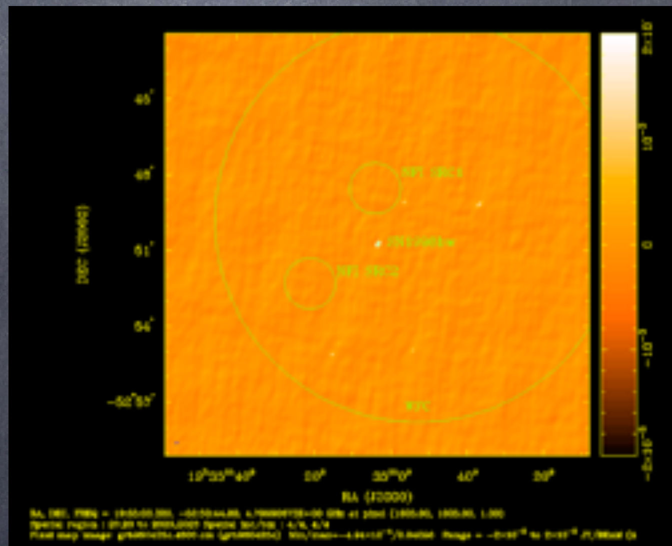

The Smoking Gun

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

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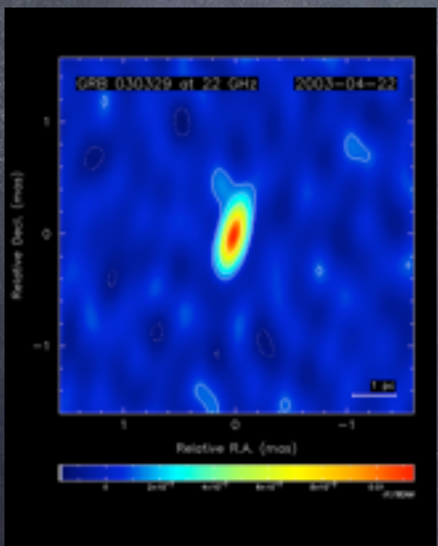

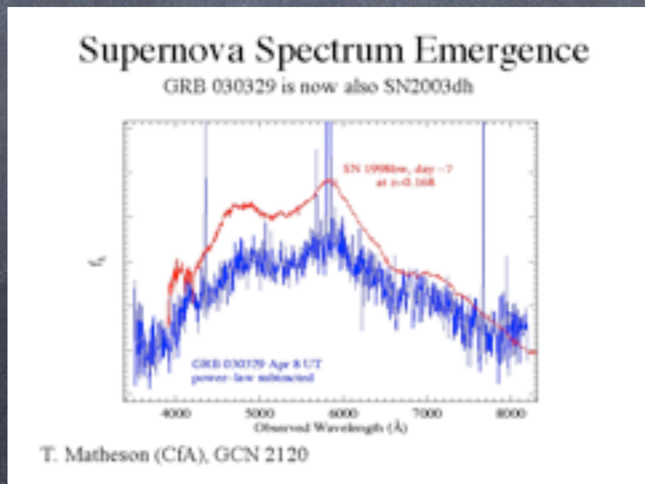

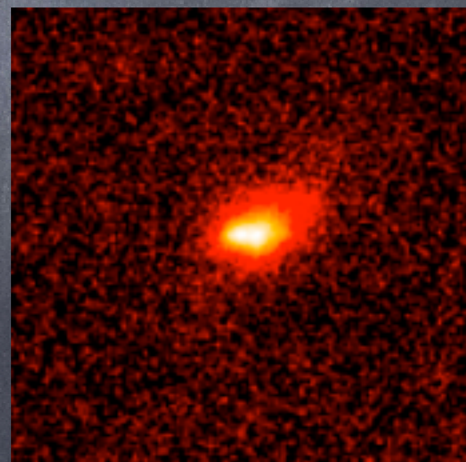

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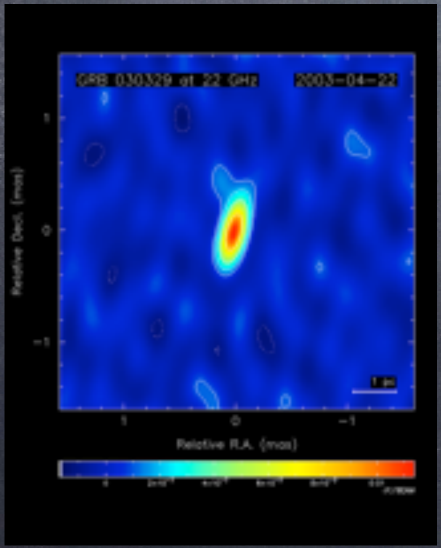
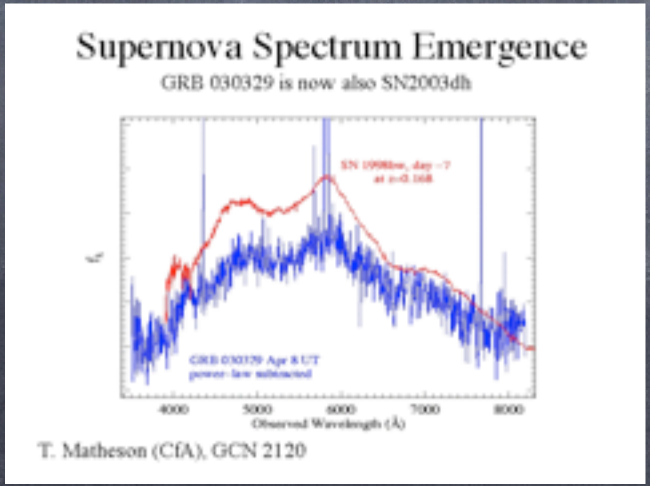
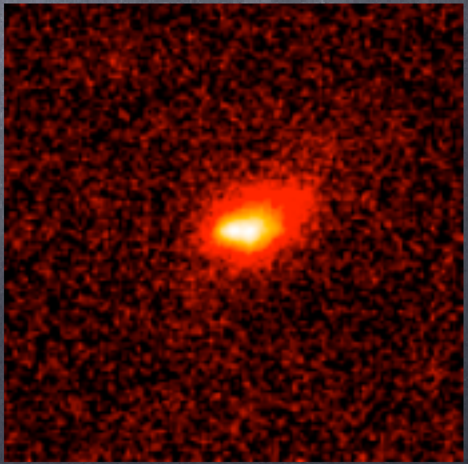
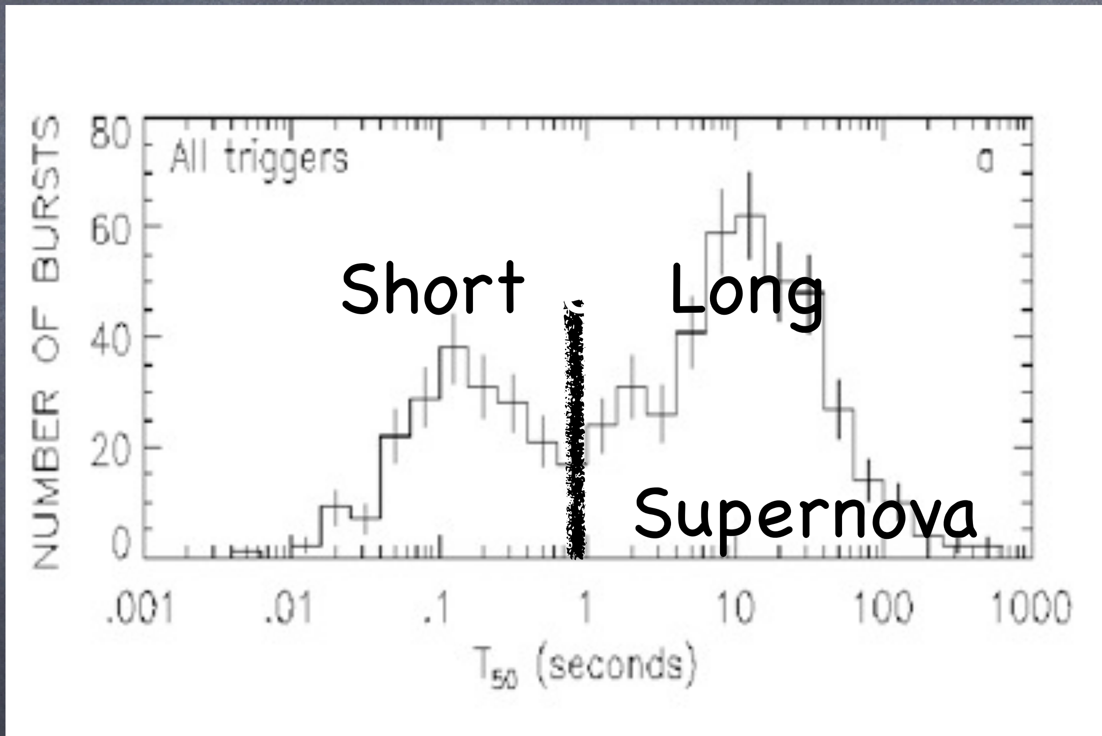






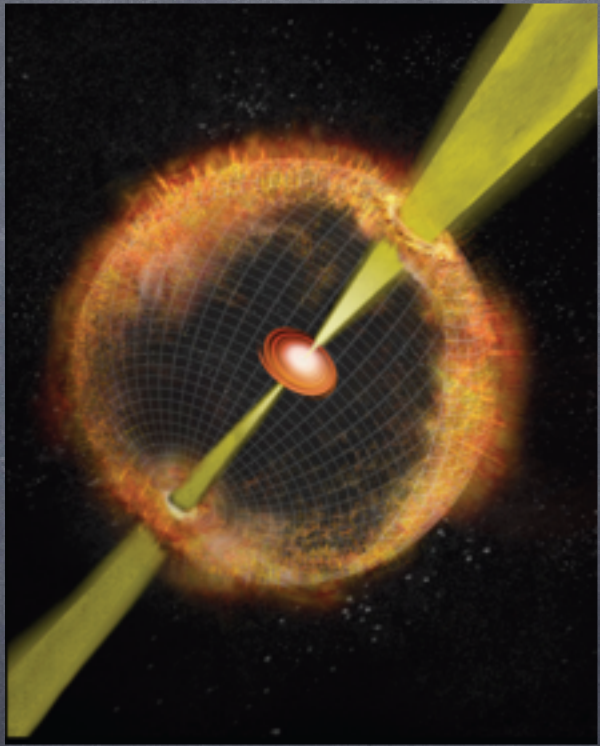
- Recently also GRB101219B - SN 2010ma

Two Types of GRBs



The Collapsar Model

(MacFadyen & Woosley 1998)



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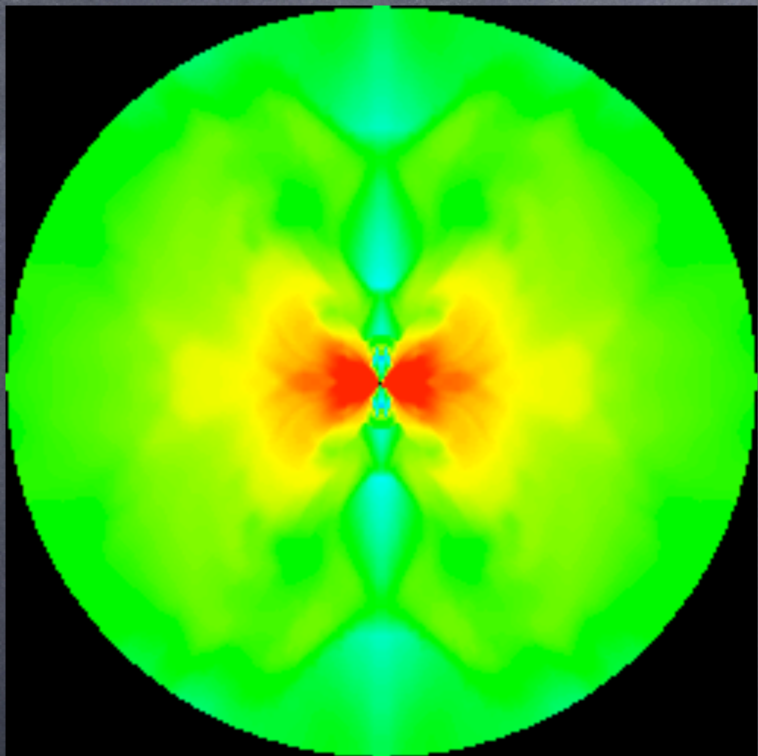
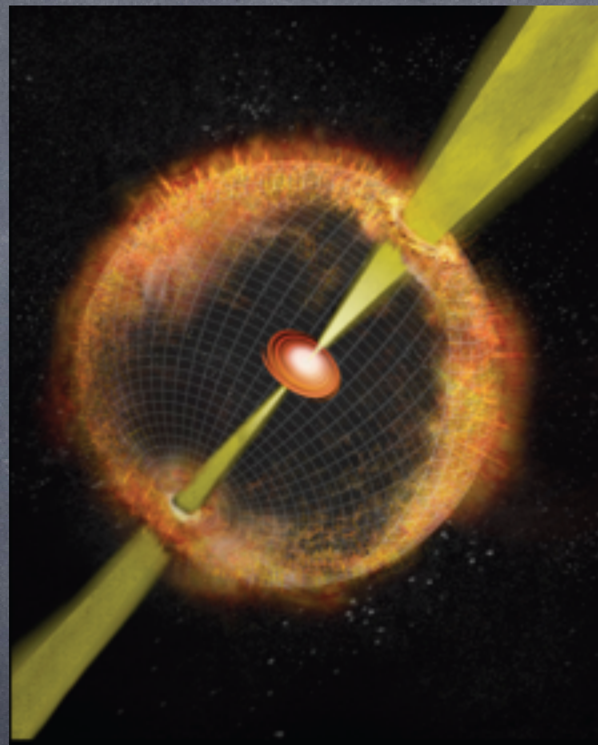
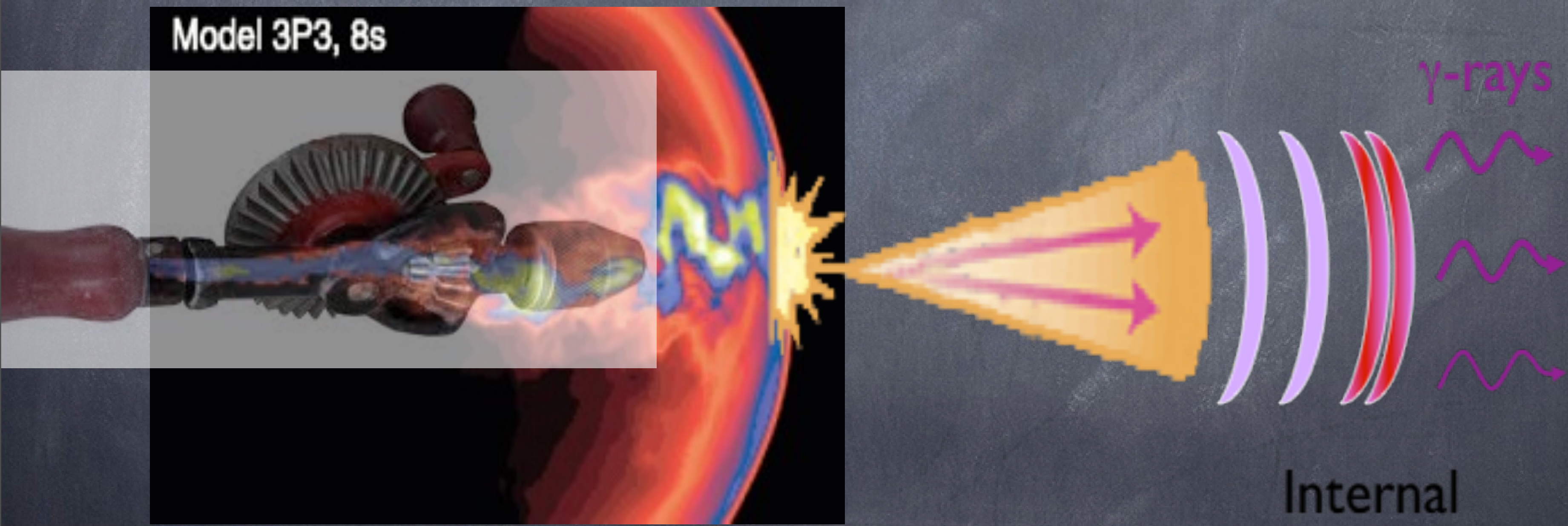


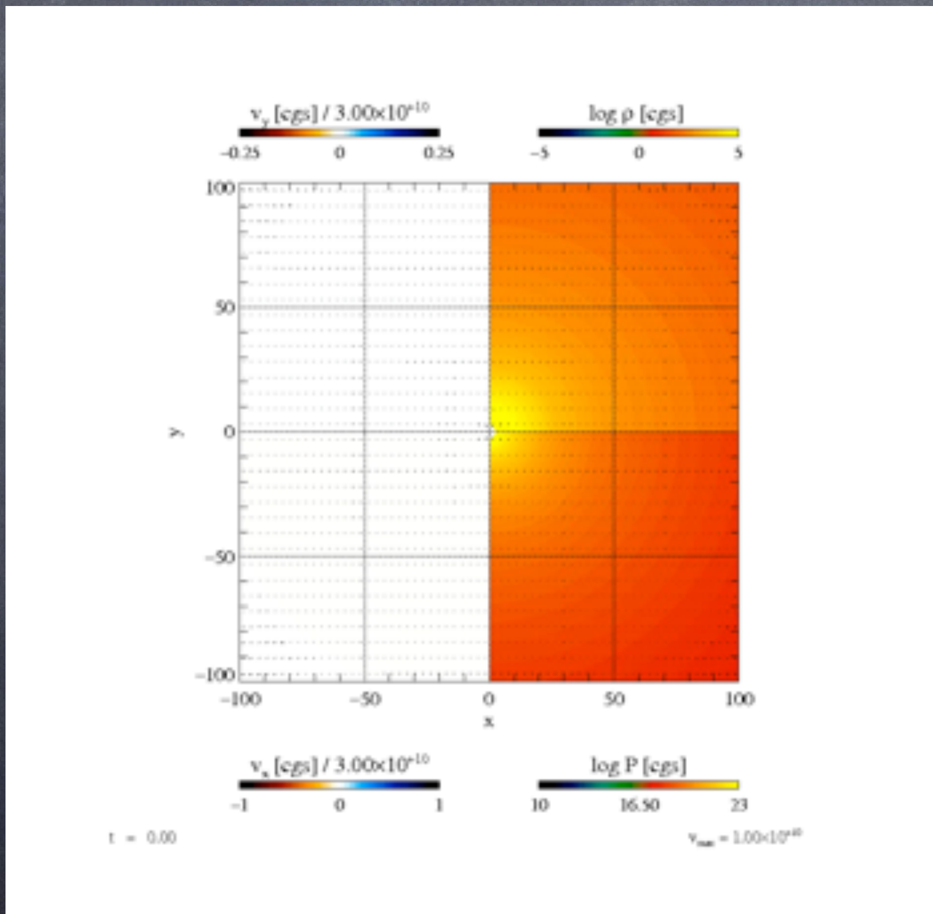


The Jet drills a hole in the star Model



Zhang, Woosley & MacFadyen 2004

Jet Simulations
(Obergaulinger, Piran + 12)



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

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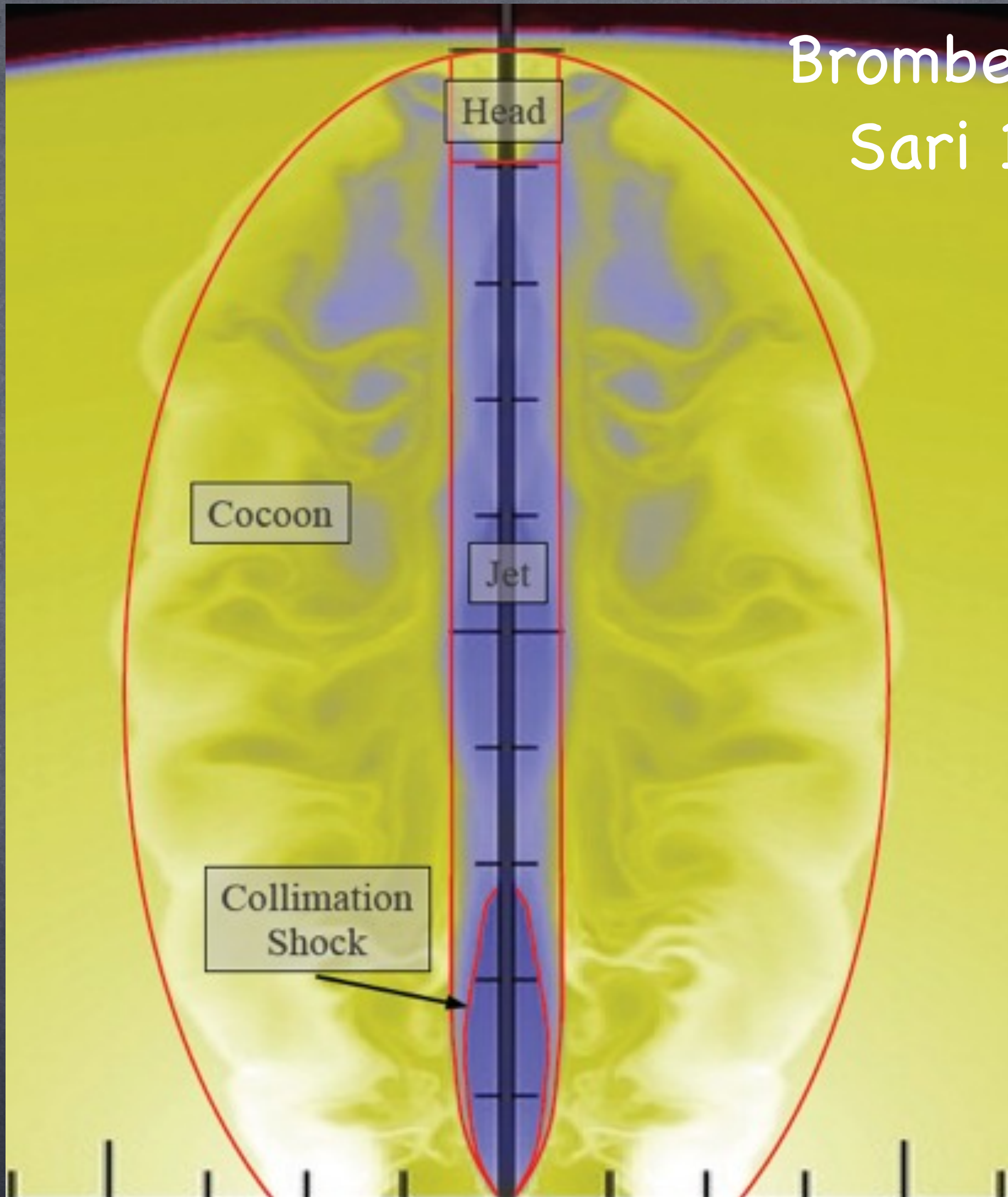
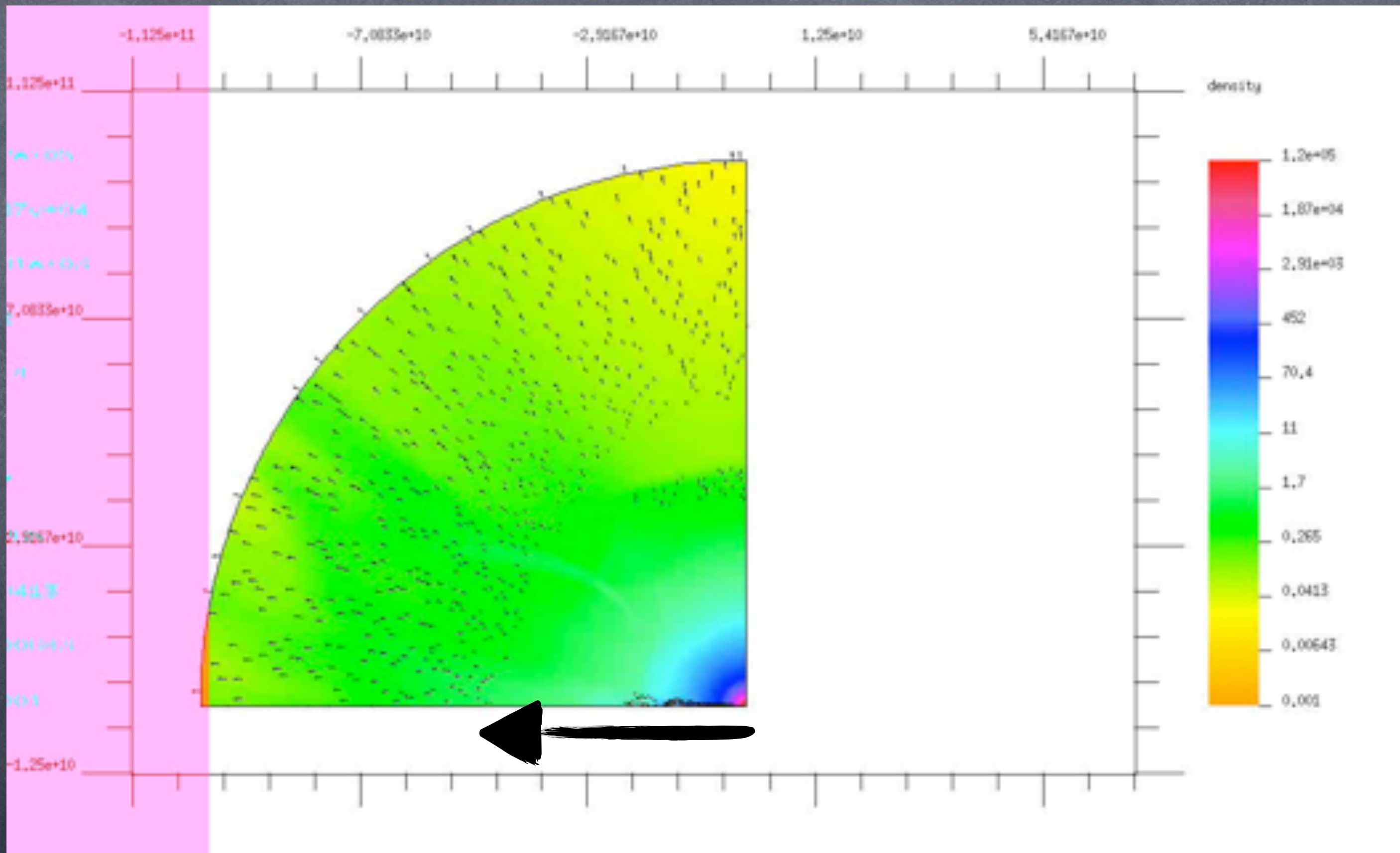


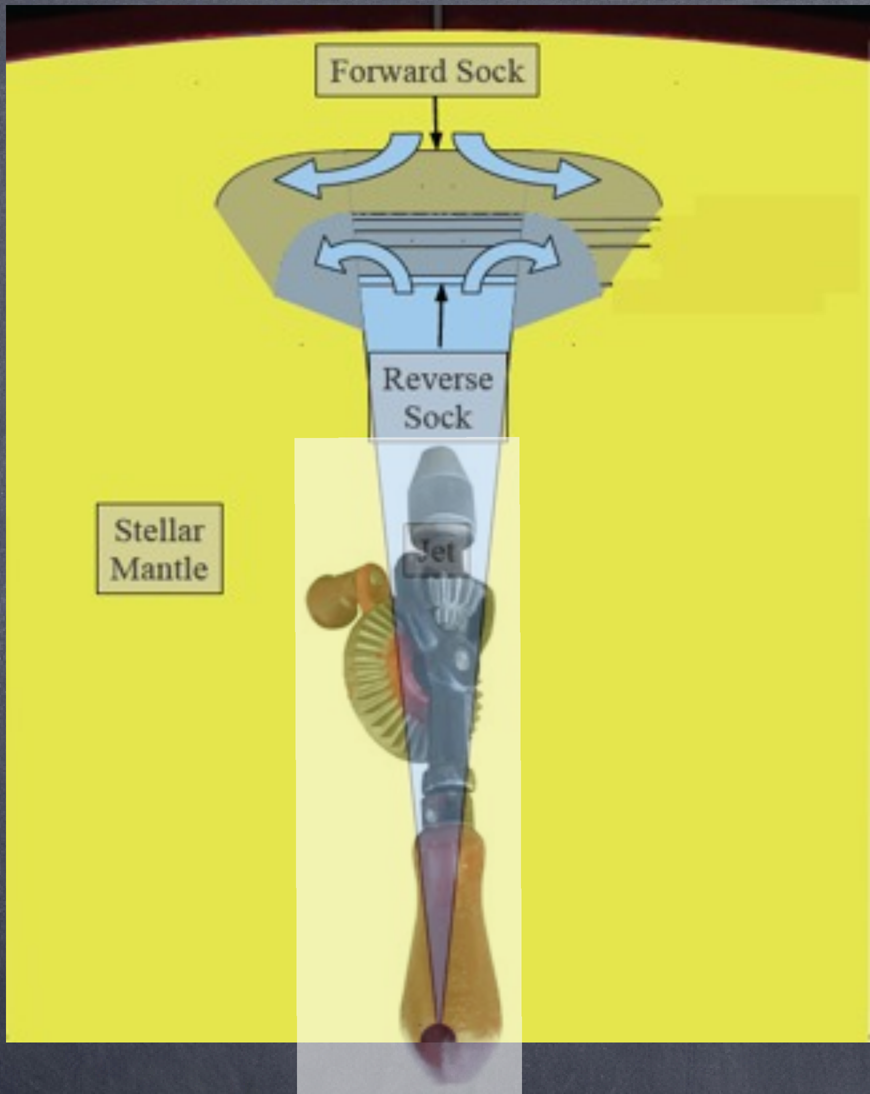
Bromberg Nakar, TP, Sari 11 ApJ 2011

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

Genet, Livne, Obergaulinger & TP 2011

About one solar mass is ejected non spherically

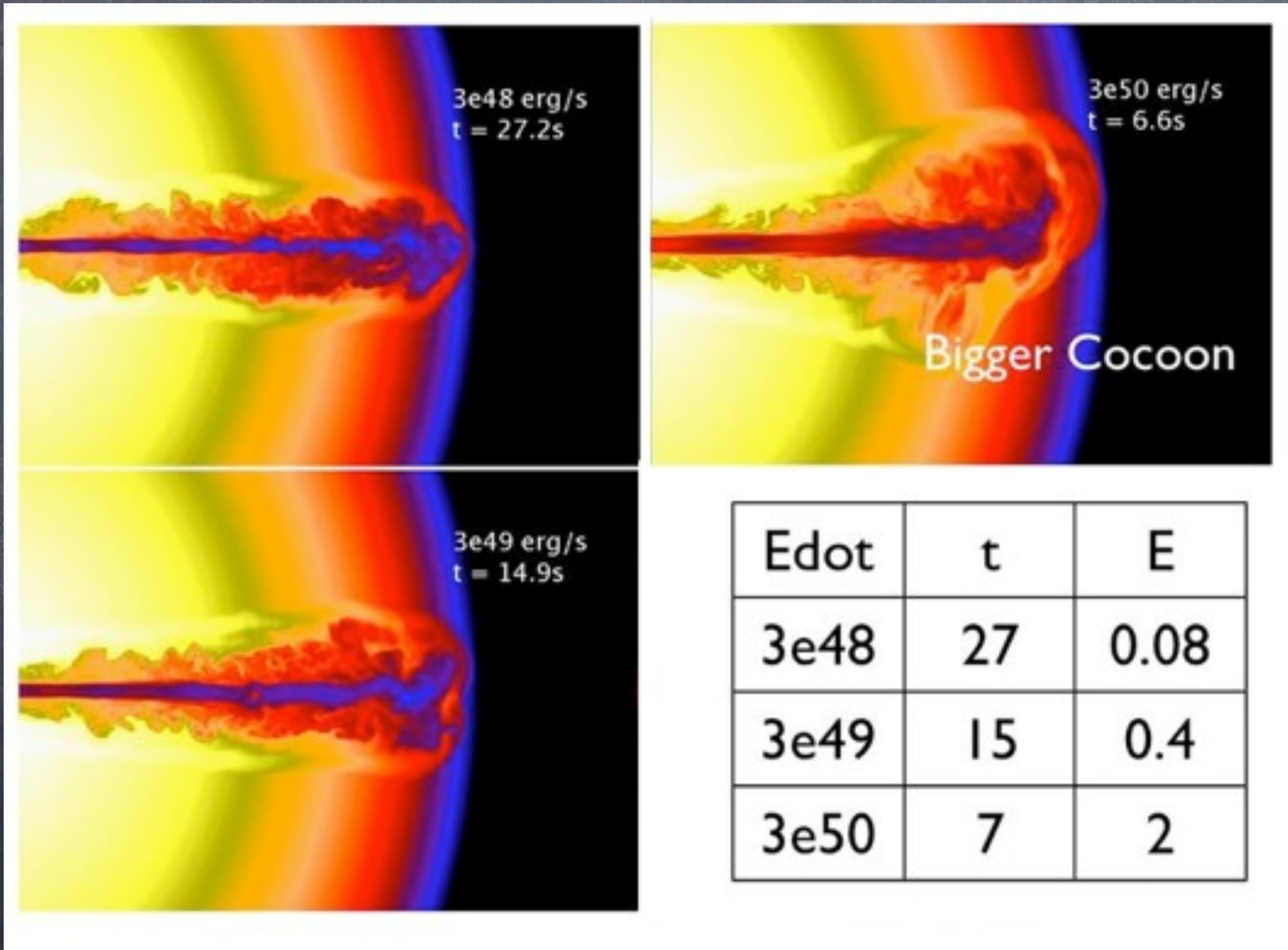




Bromberg Nakar, TP, Sari 11 ApJ 2011

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

Comparison with simulations



Edot	t	E
3e48	27	0.08
3e49	15	0.4
3e50	7	2

$$t_b \propto L^{-1/3}$$

Zhang et al., 04

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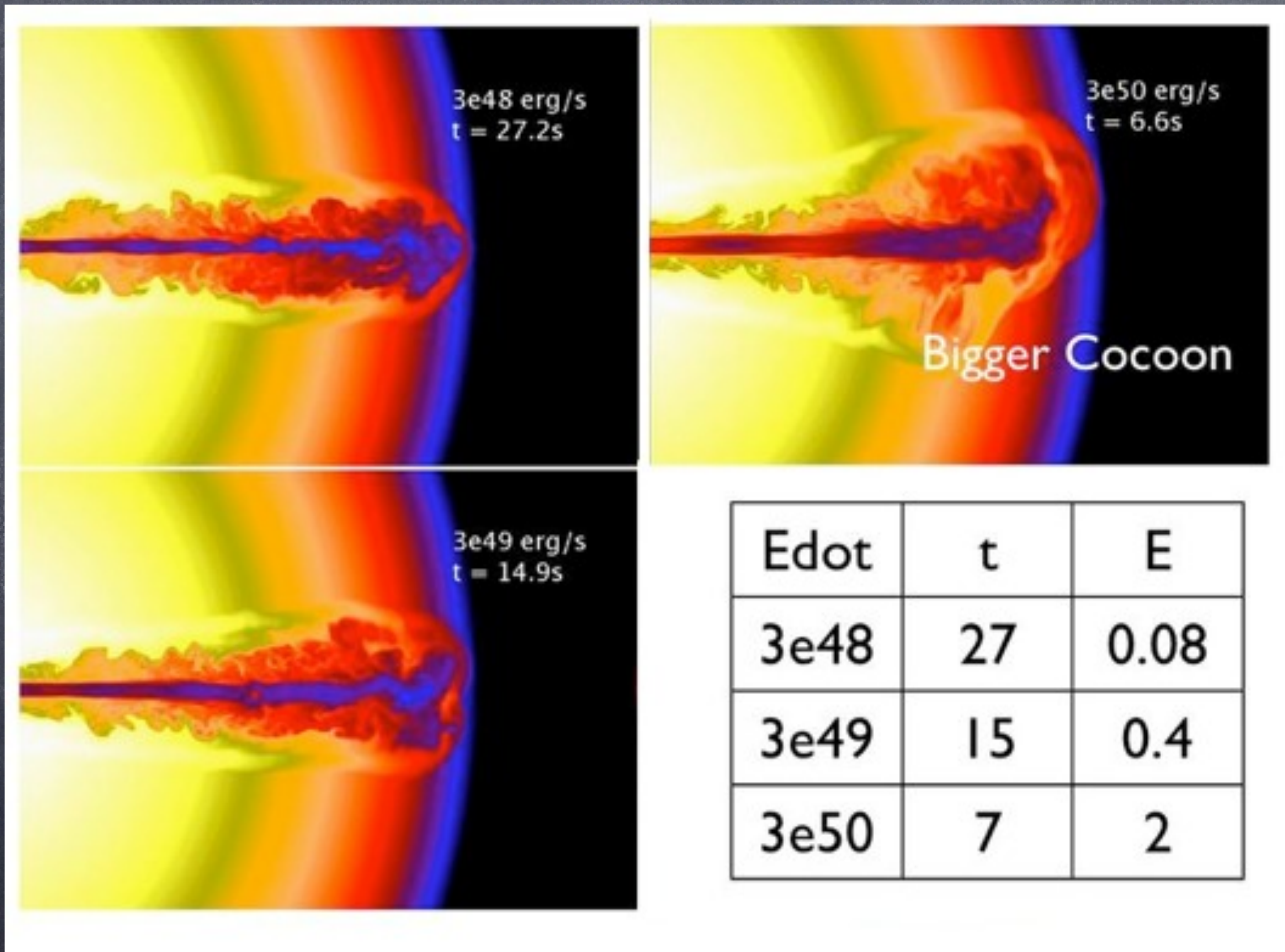

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T
25
12
6

Zhang et al., 04

Jet breakout time

(Bromberg Nakar, TP, Sari 11 ApJ 2011)

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

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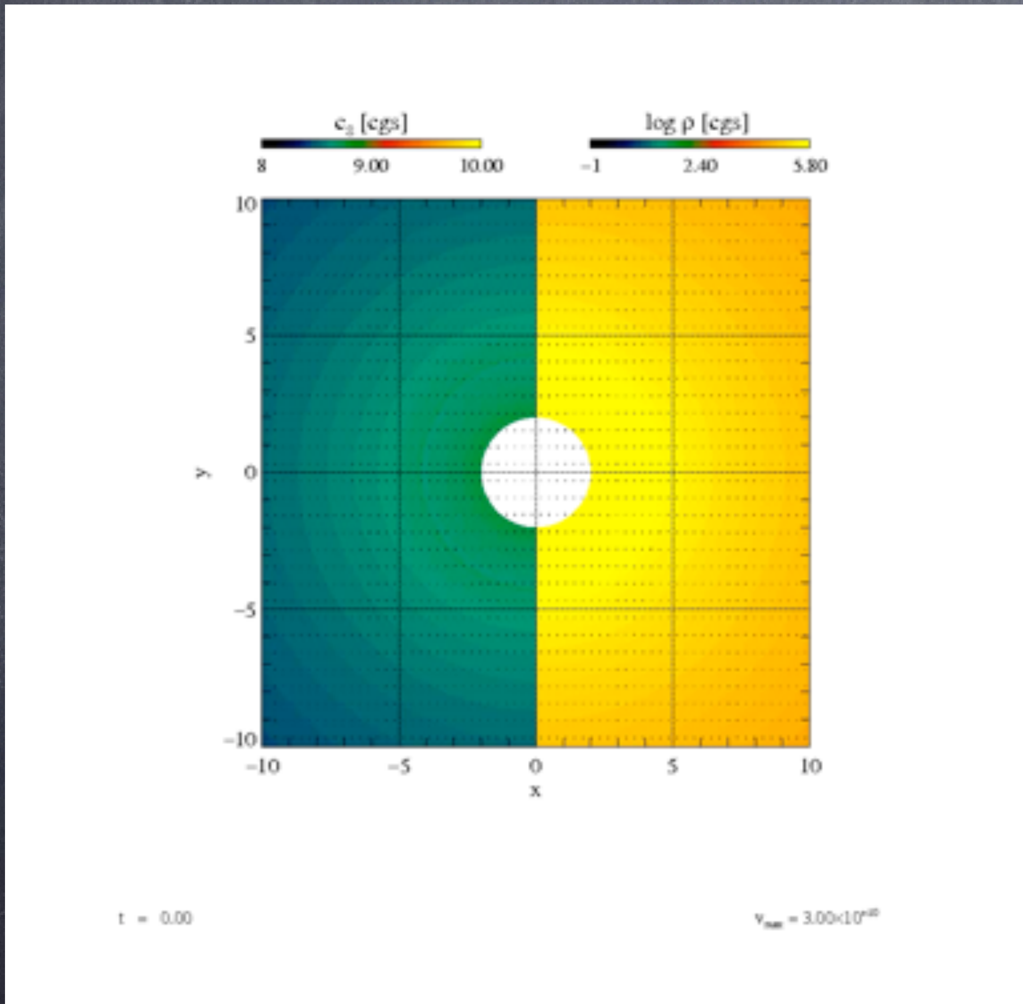
The engine must be active until the jet's head breaks out!*

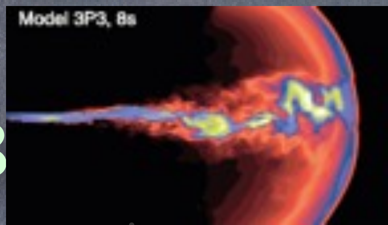
Jet Simulations - A Failed Jet (Obergaulinger, Piran + 11)



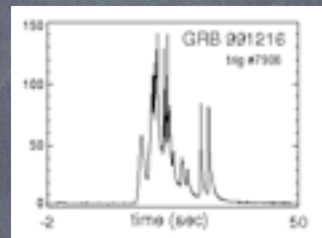
Opening angle of 15° degrees at 2000 km into a star of 15 solar masses and solar metallicity. Constant energy injection rate, $5*10^{50}$erg/s, for 2 seconds.

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

T_B



T_{90}



T_{engine}

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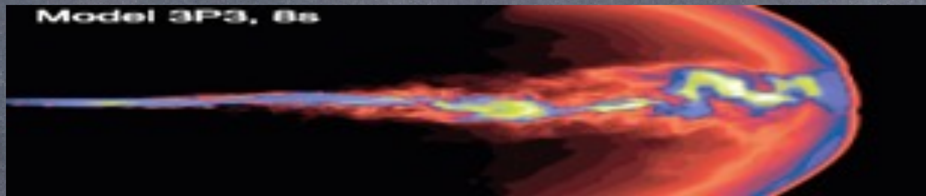
T_B



T_{90}

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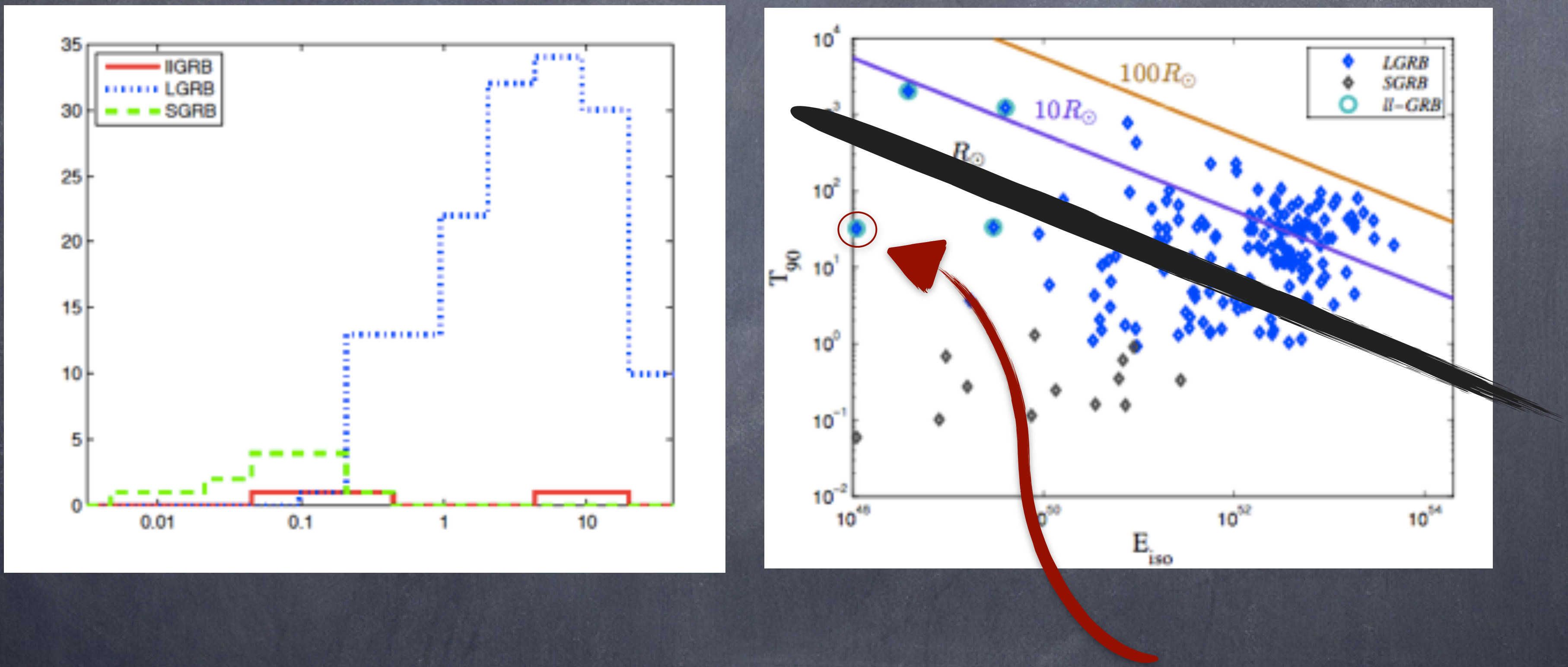
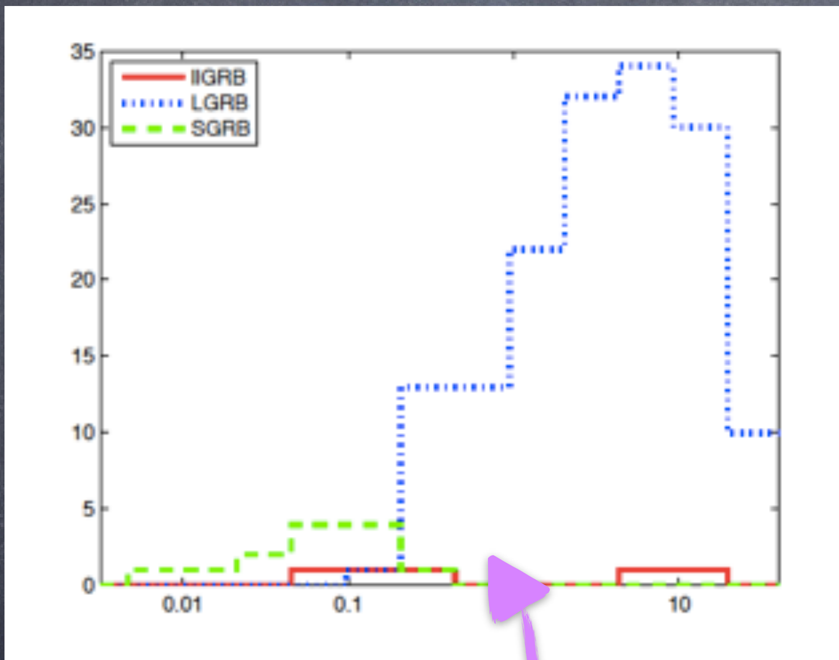
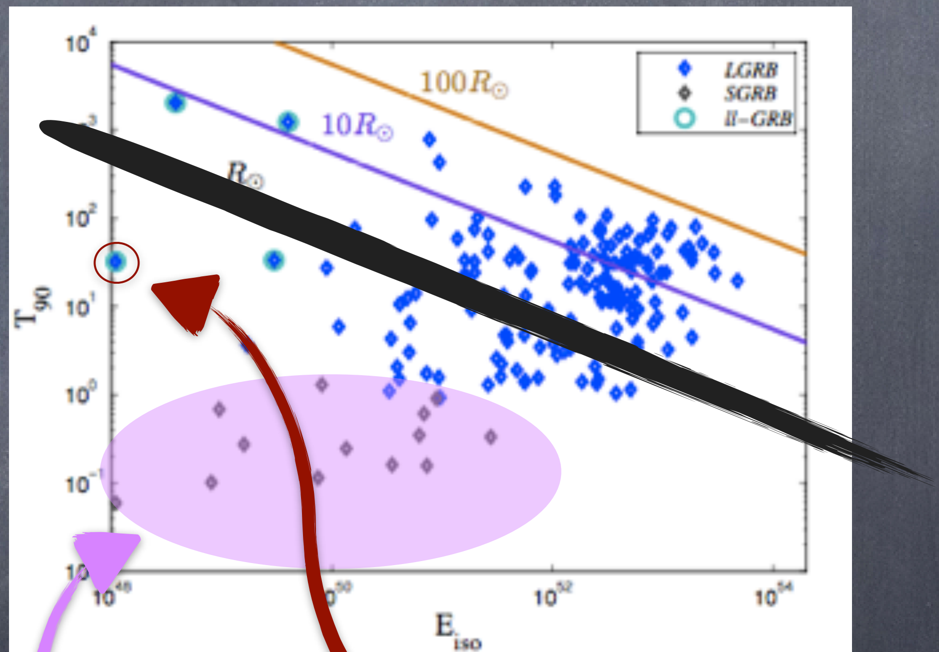


llGRB
LGRB
SGRB
0.01
0.1
1
10
LGRB
SGRB
ll-GRB
$100R_\odot$
$10R_\odot$
$R_\odot$
T_{90}
E_{iso}

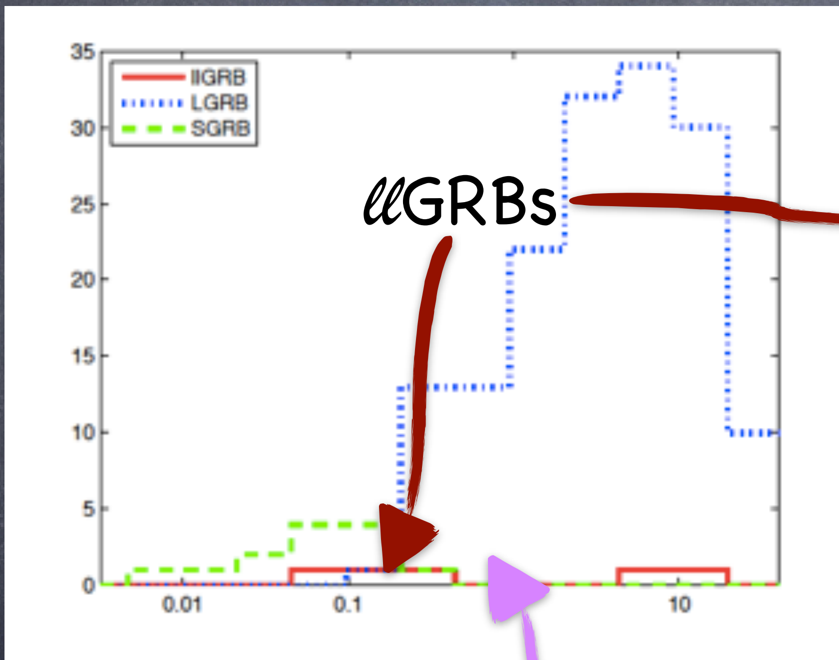
98bw

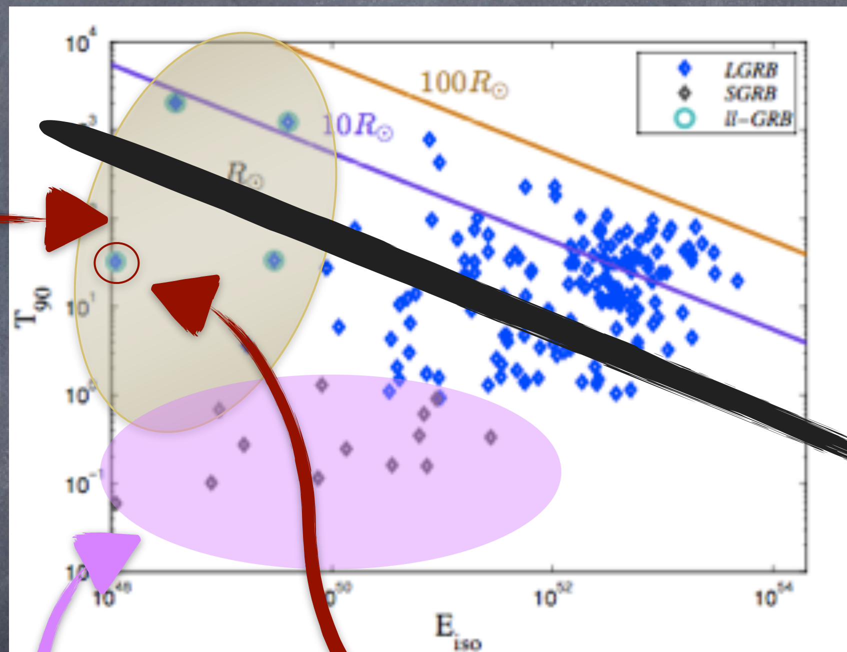




Short
GRBs

98bw

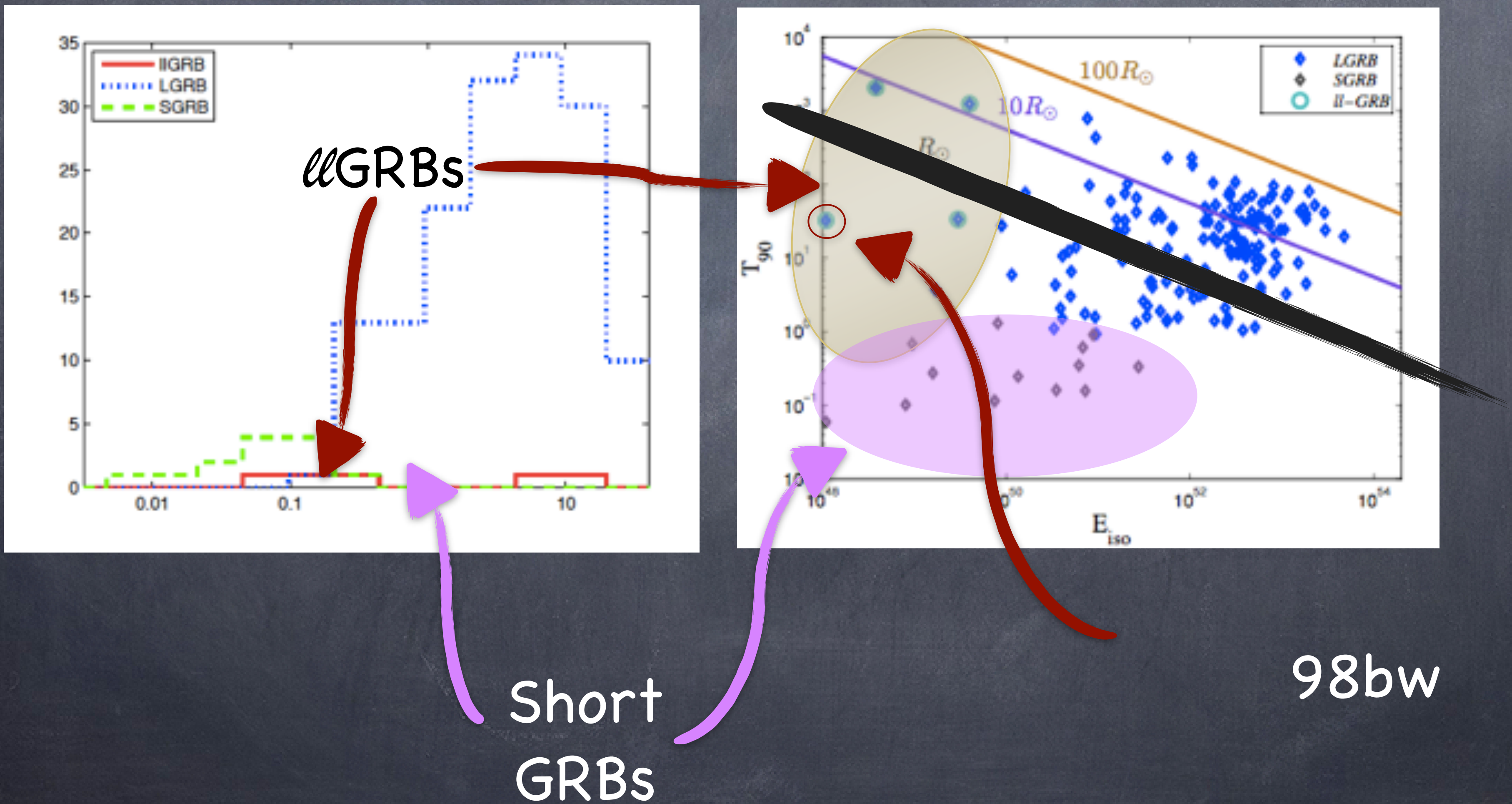




Short GRBs

98bw

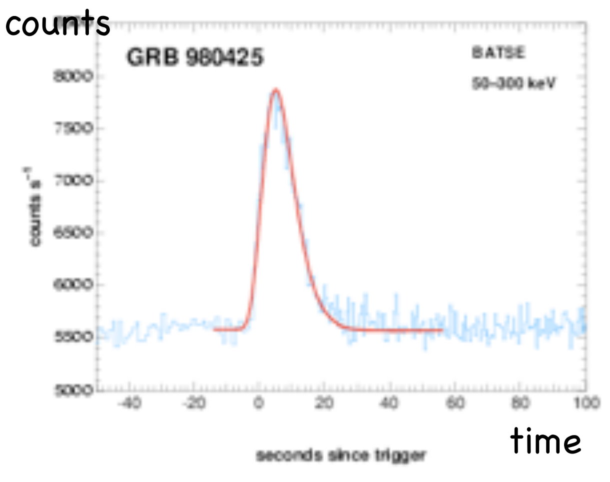
Low luminosity GRBs - ℓℓGRBs Don't arise from Collapsars

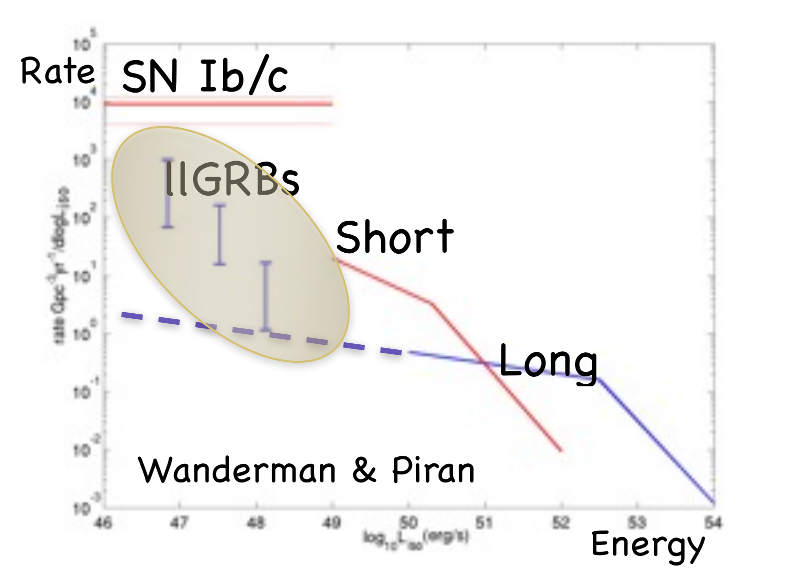


Low Luminosity GRBs - $\ell\ell$GRBs

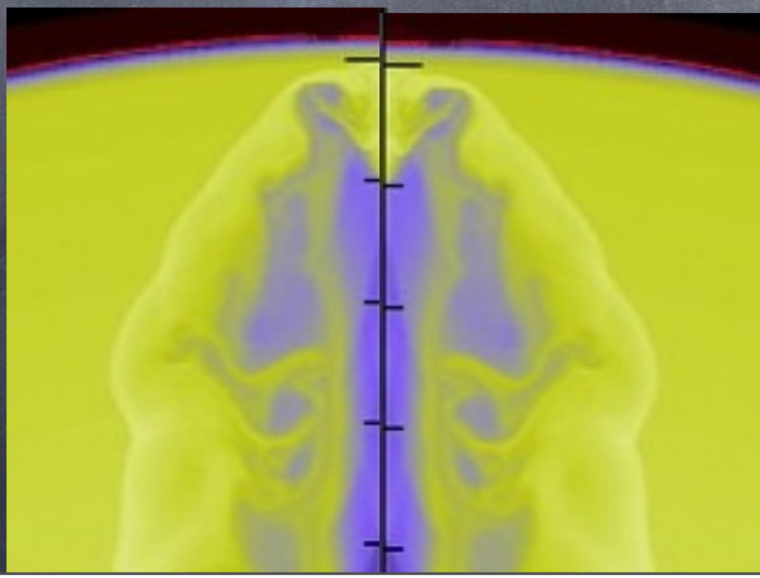
Bromberg Nakar, TP, 11 ApJL 2011

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



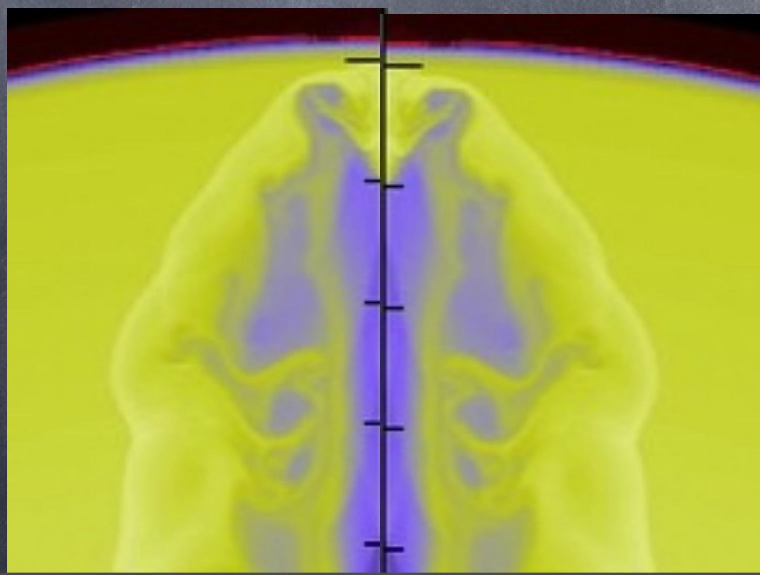


What makes a $\ell\ell$GRBs?



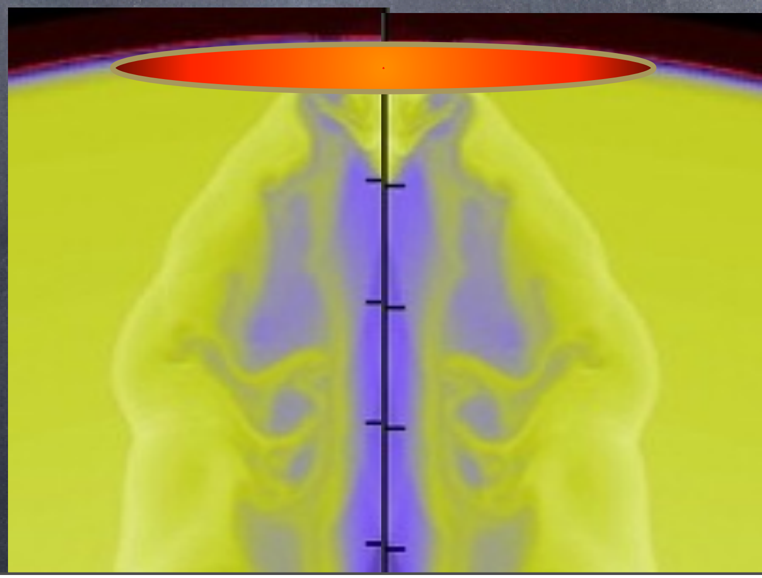
What makes a $\ell\ell$GRBs?

- 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

llGRBs

?

A prediction of the Collapsar model

Observed duration

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

Engine time

Break out time

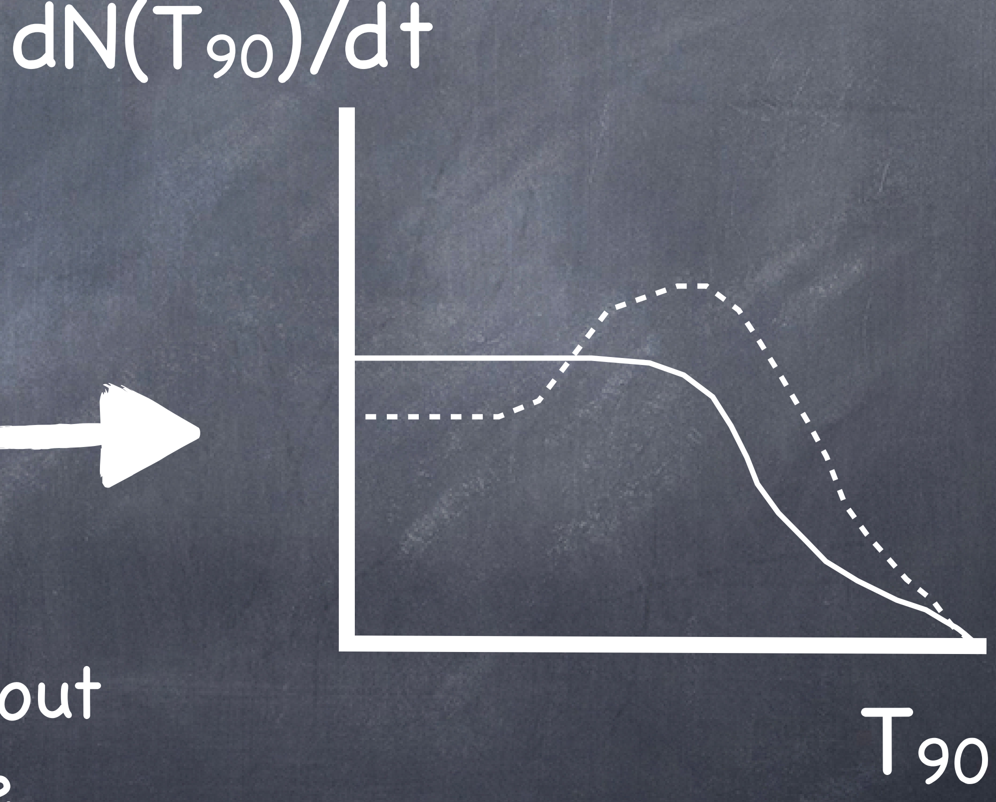
A prediction of the Collapsar model

Observed duration

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

Engine time

Break out time



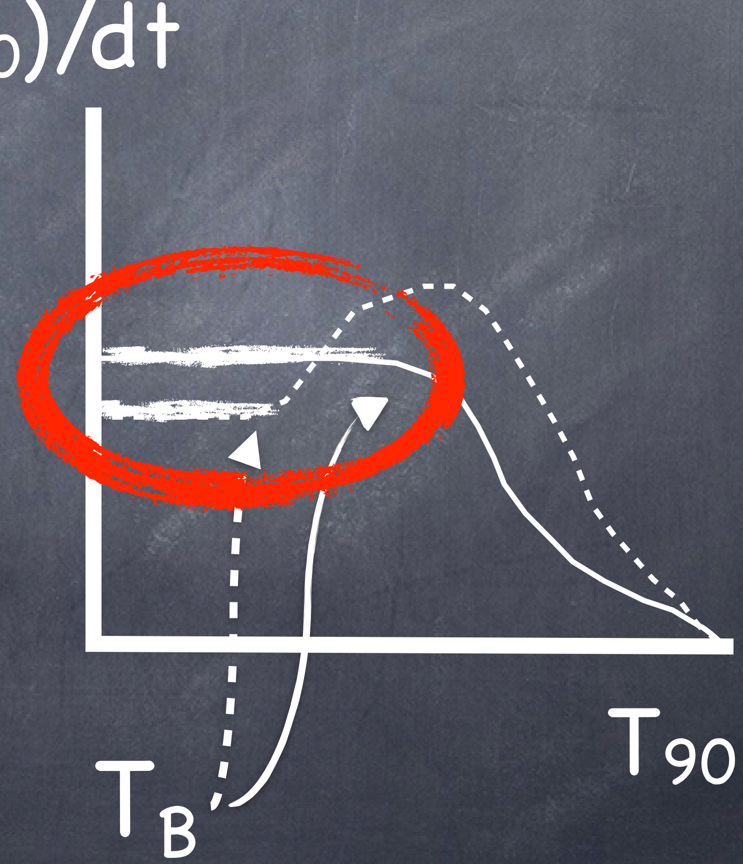
A prediction of the Collapsar model

Observed duration

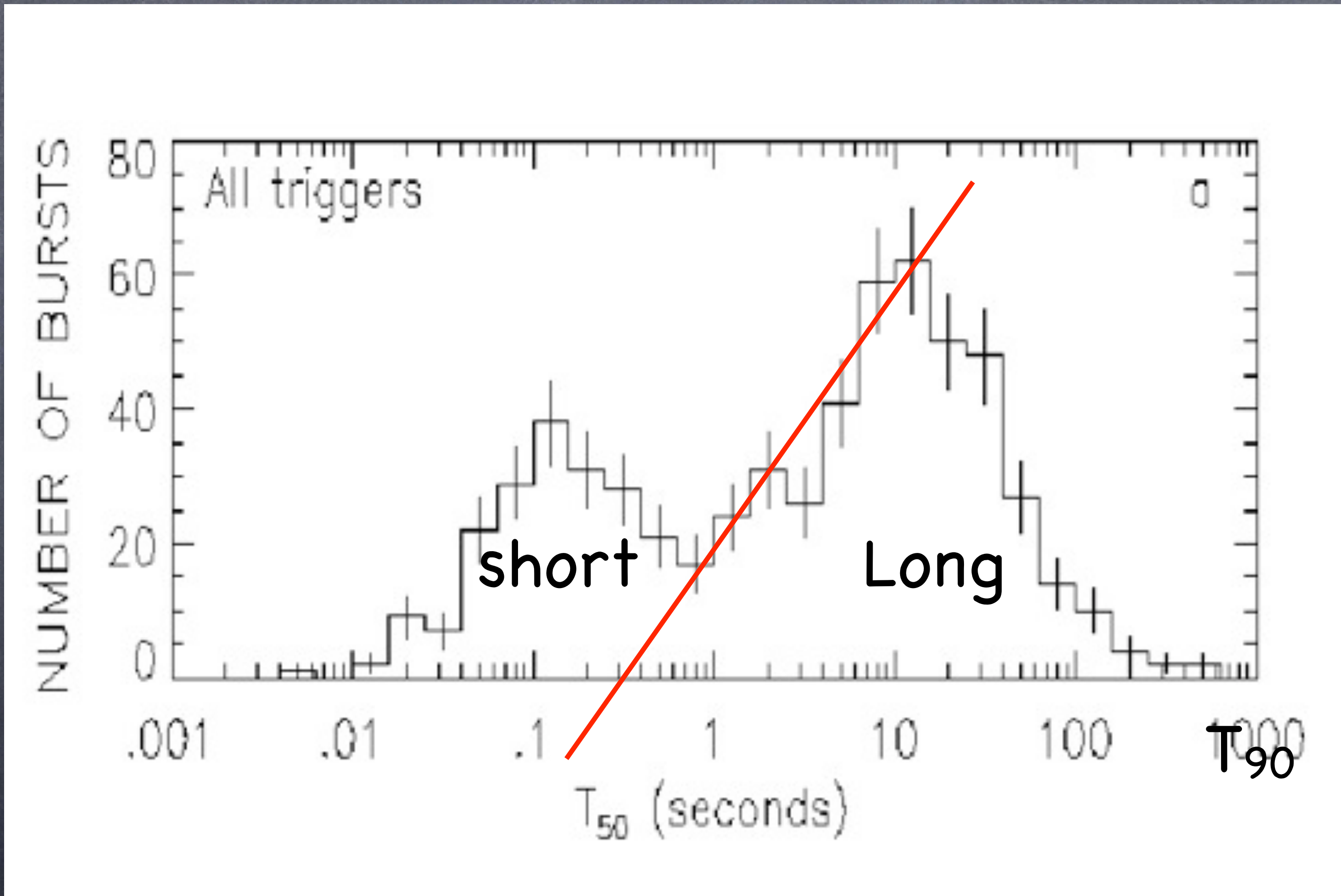
$$T_{90} = T_e - T_B$$

Engine time

Break out time

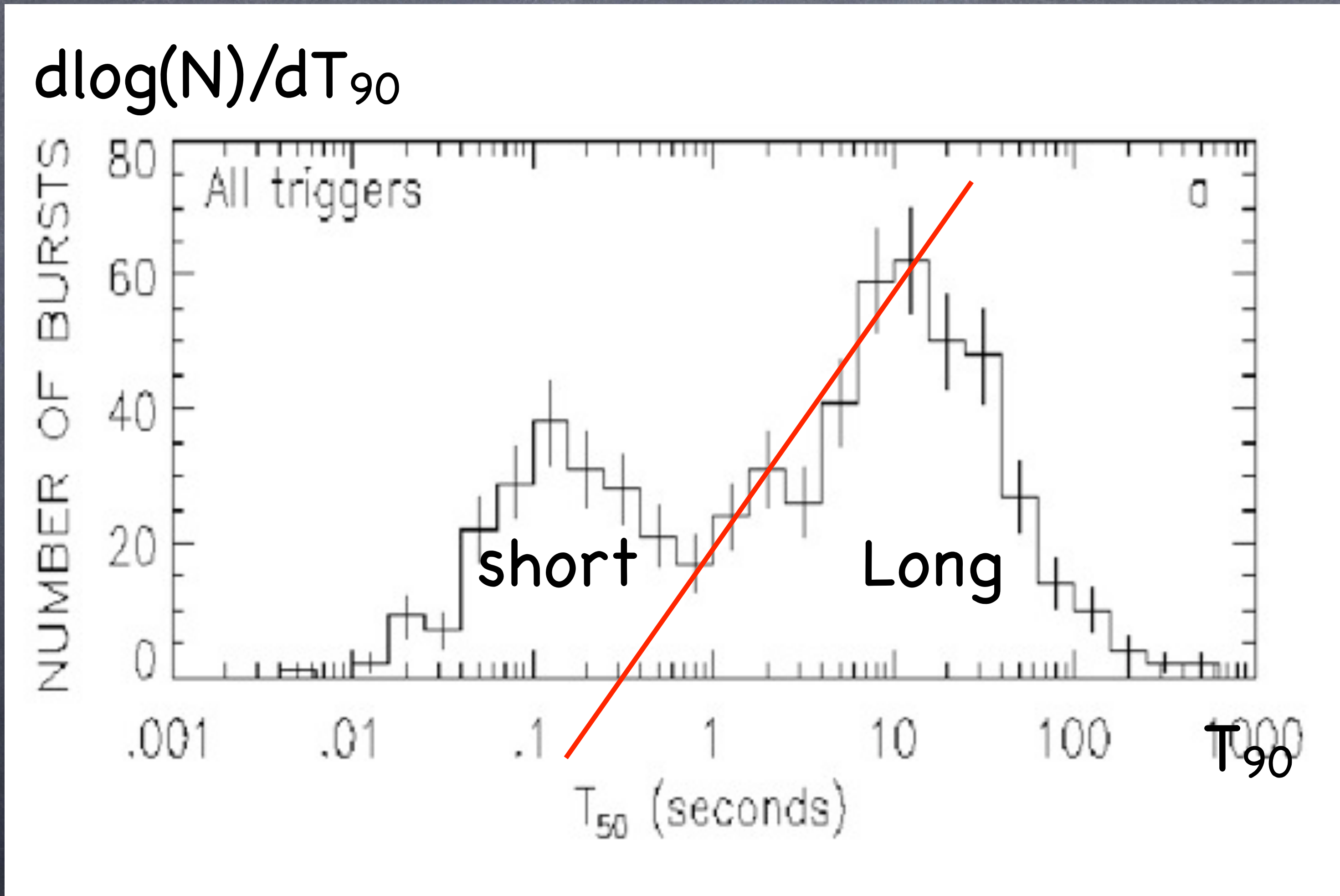


?



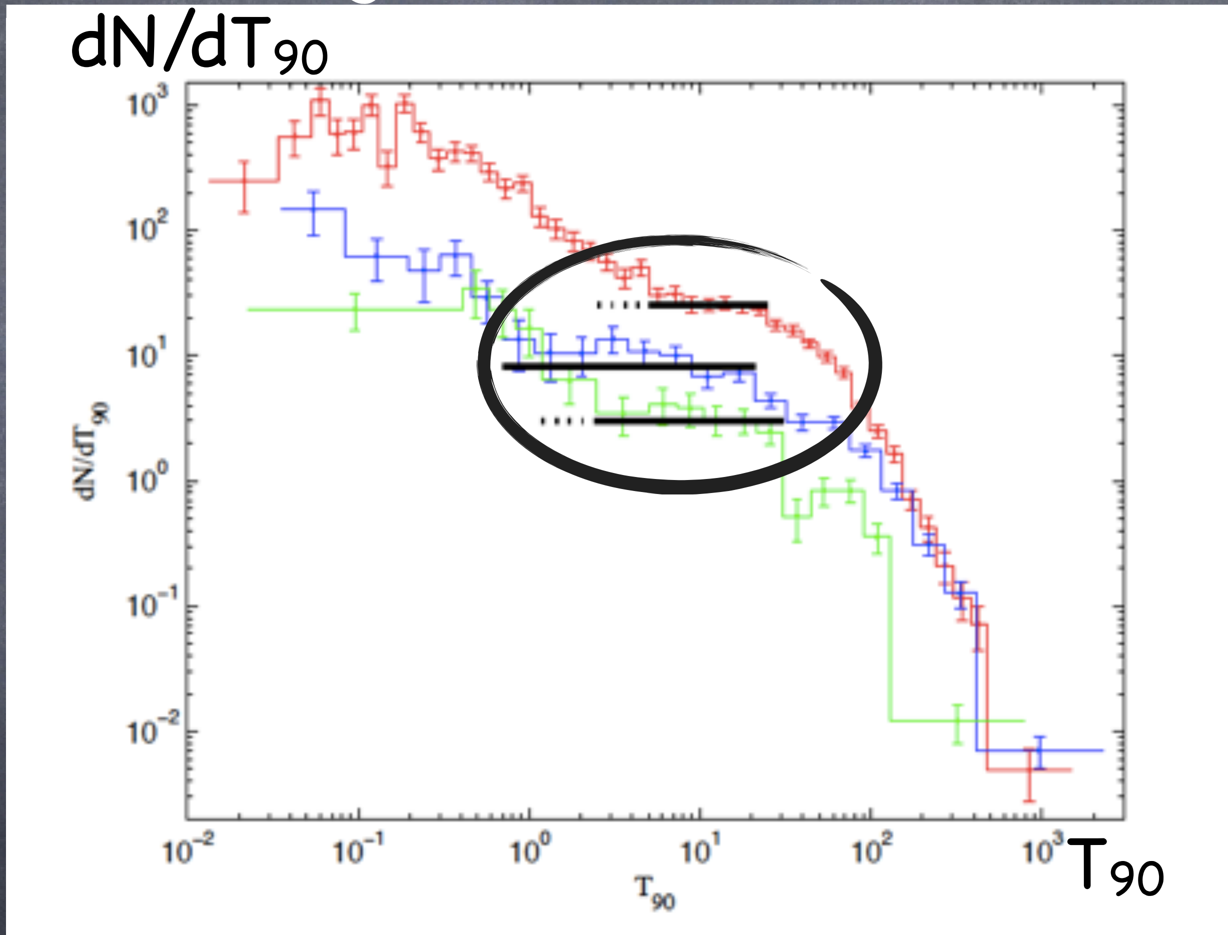
All triggers
a
NUMBER OF BURSTS
80
60
40
20
0
.001
.01
.1
1
10
100
1000
T₅₀ (seconds)
short
Long
T90

?


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)

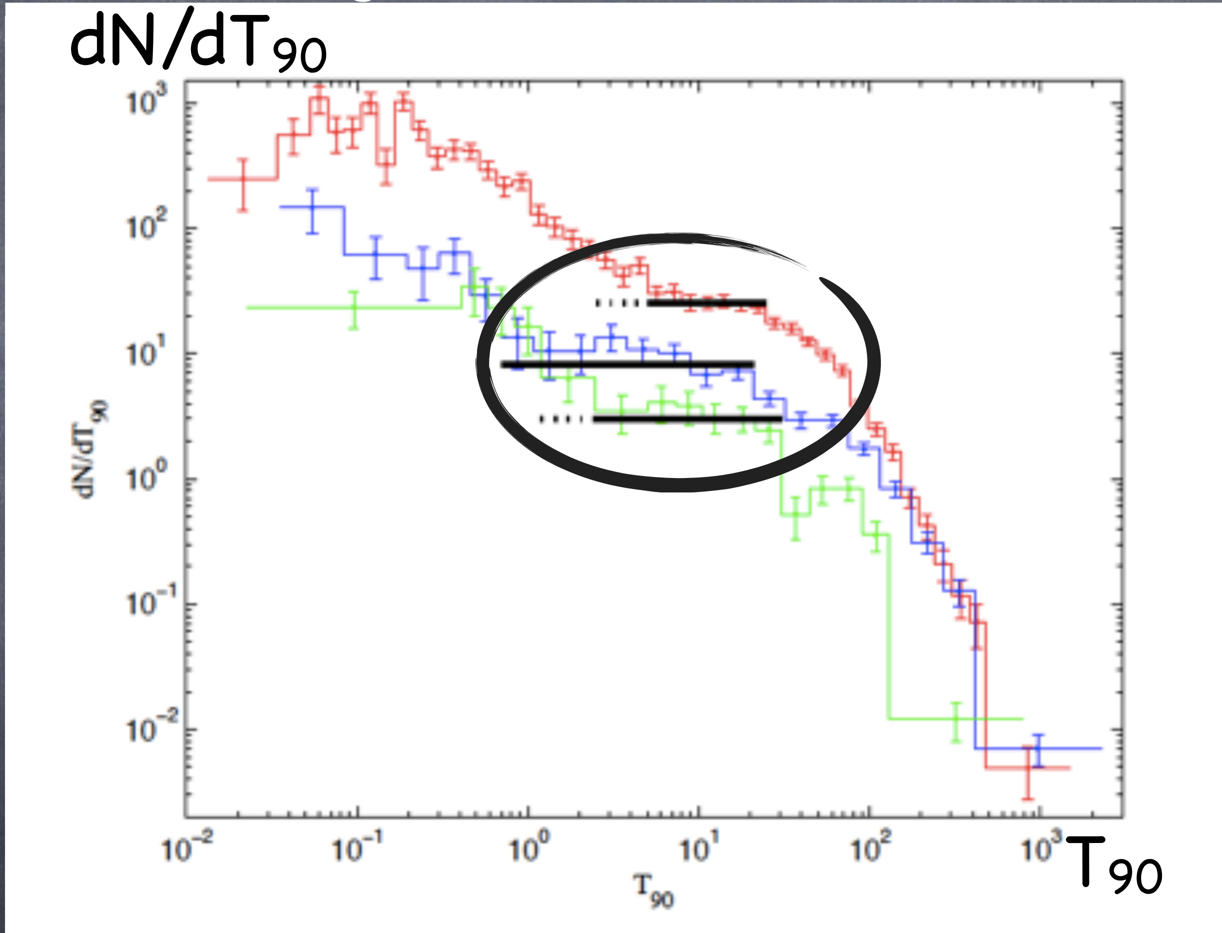
A second look

(Bromberg Nakar, TP & Sari, 2011)



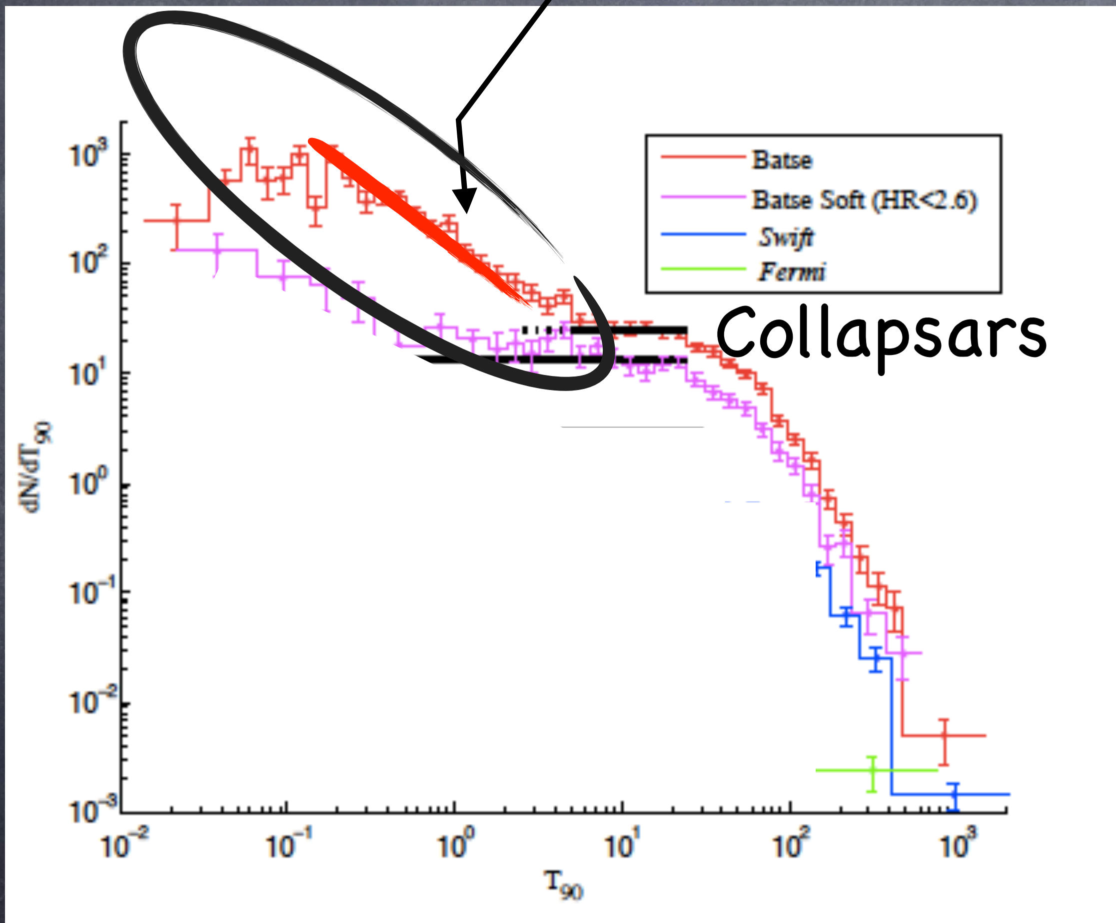
A second look

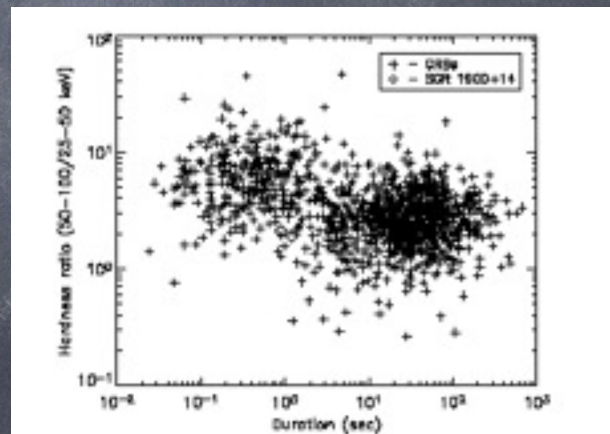
(Bromberg Nakar, TP & Sari, 2011)



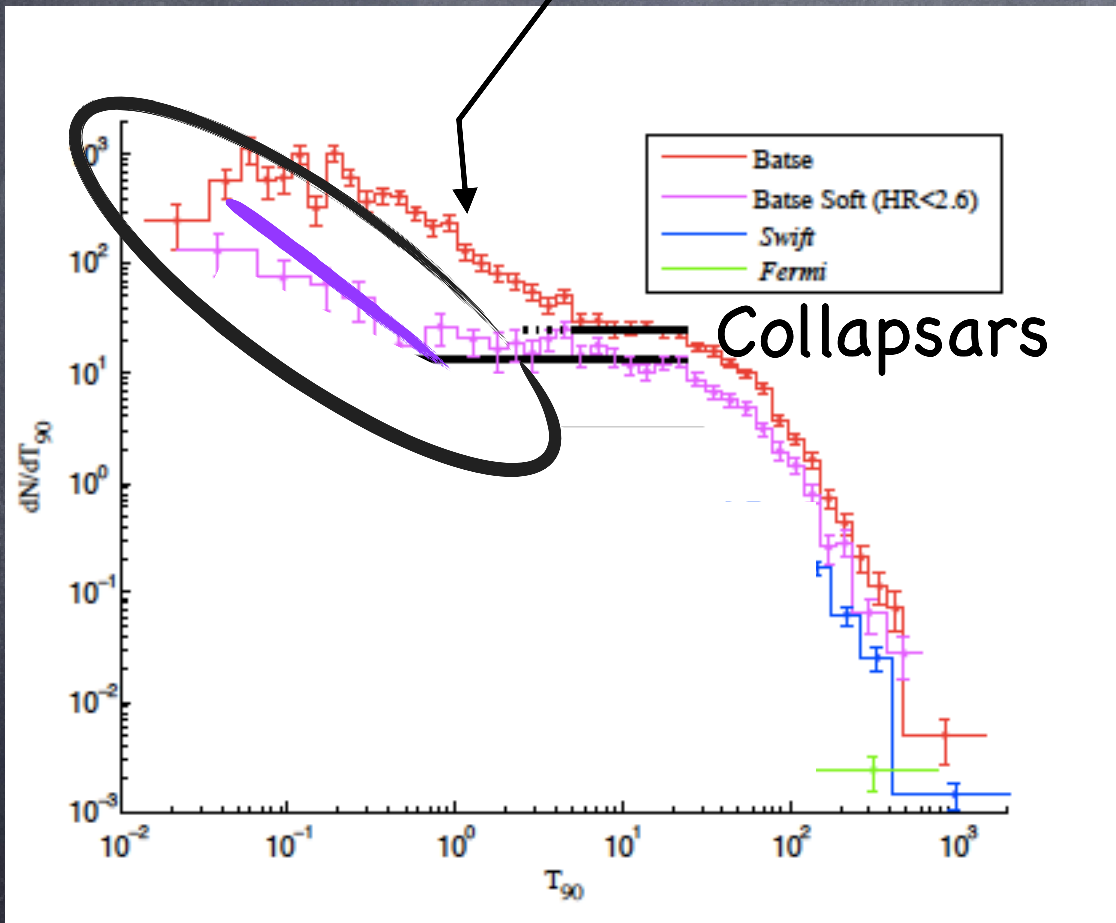
A direct observational proof of the Collapsar model.

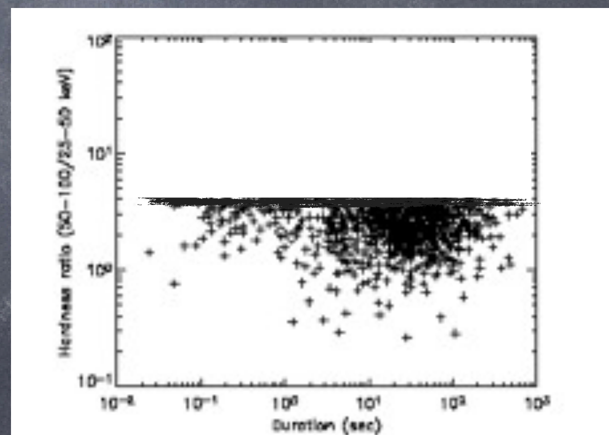
Short (Non-Collapsars) GRBs

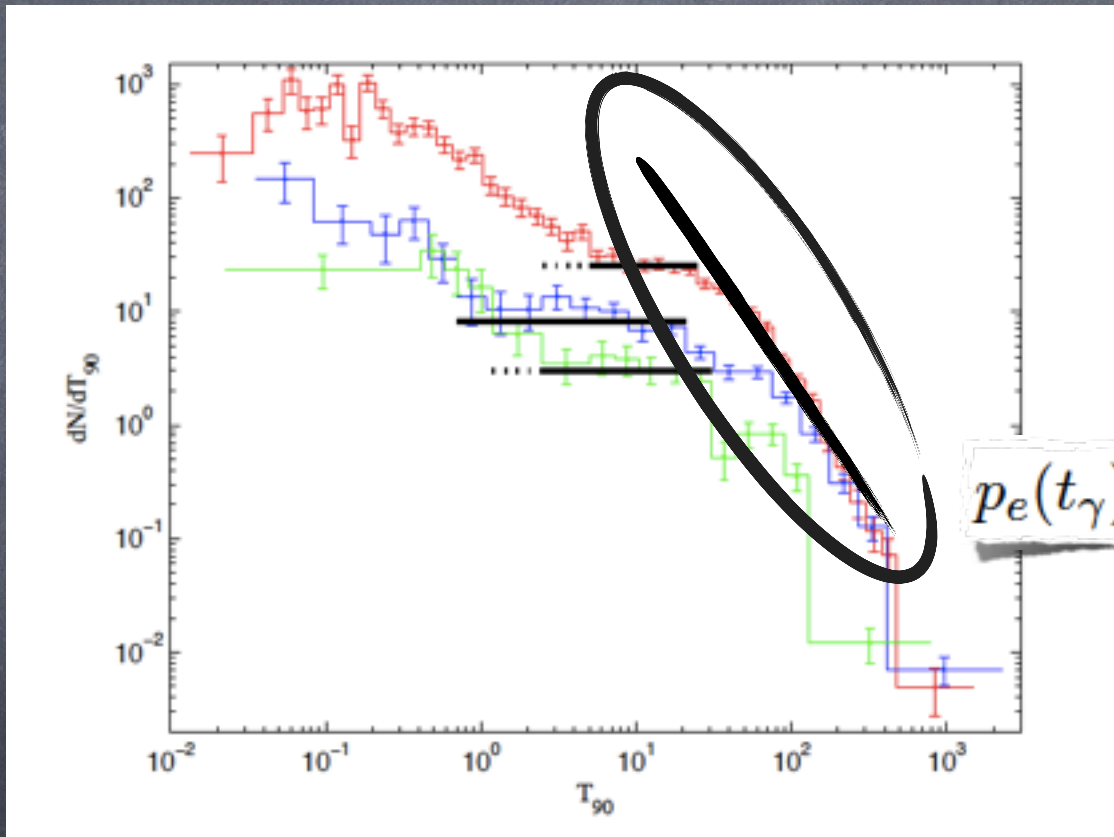




Short (Non-Collapsars) GRBs

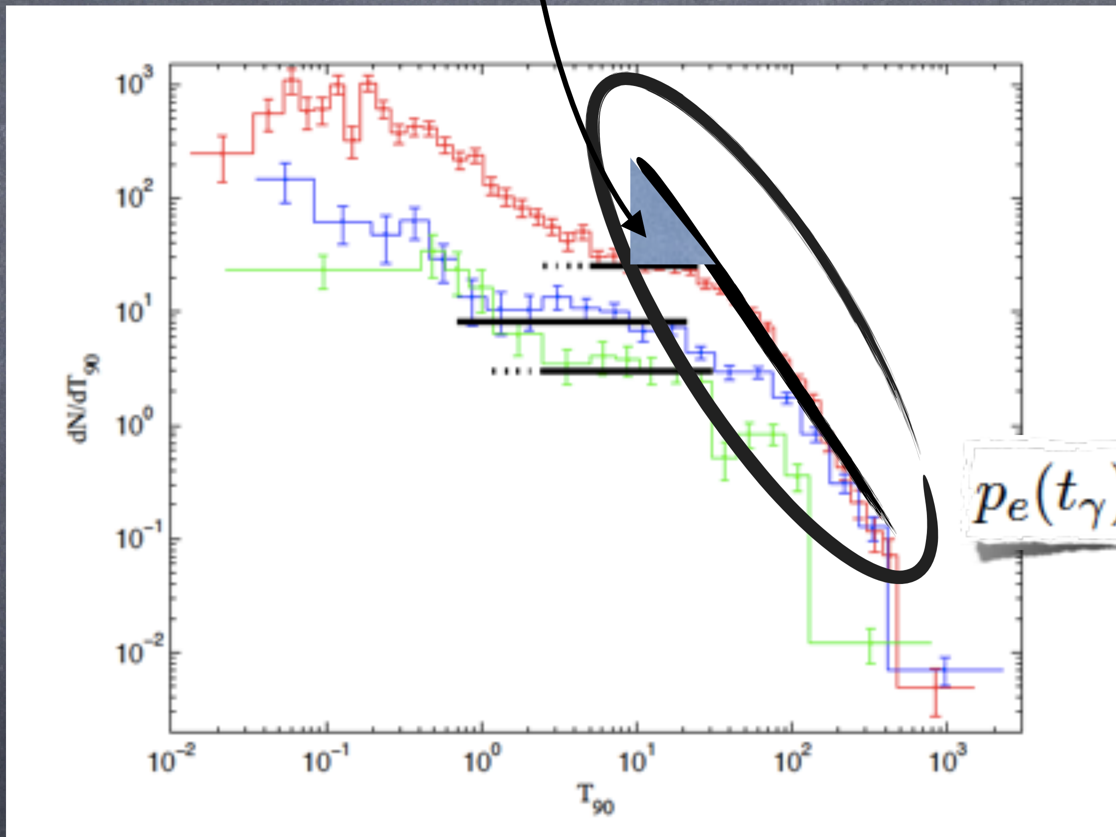






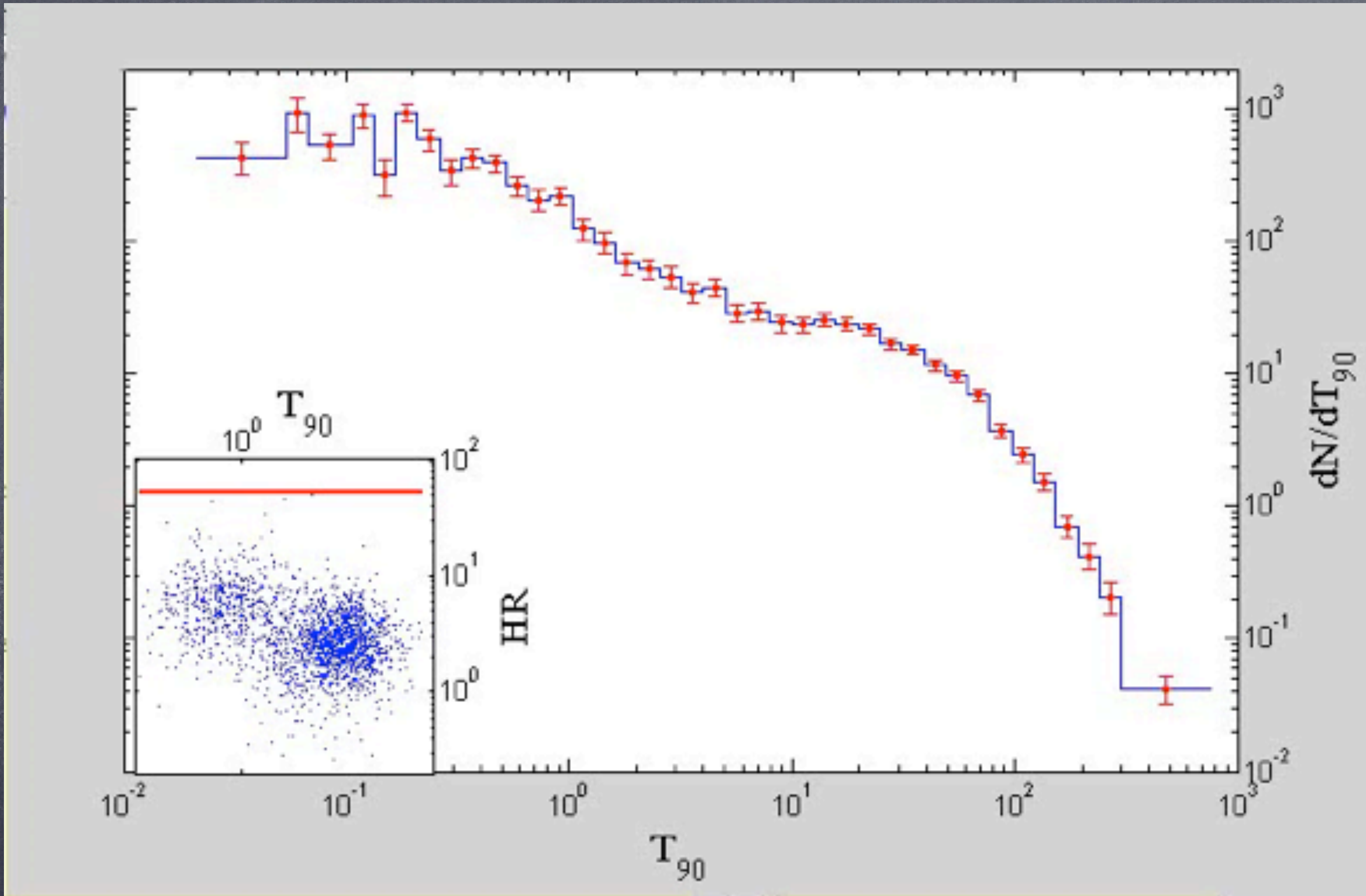
$p_e(t_\gamma) \quad t_\gamma \gg t_b$

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

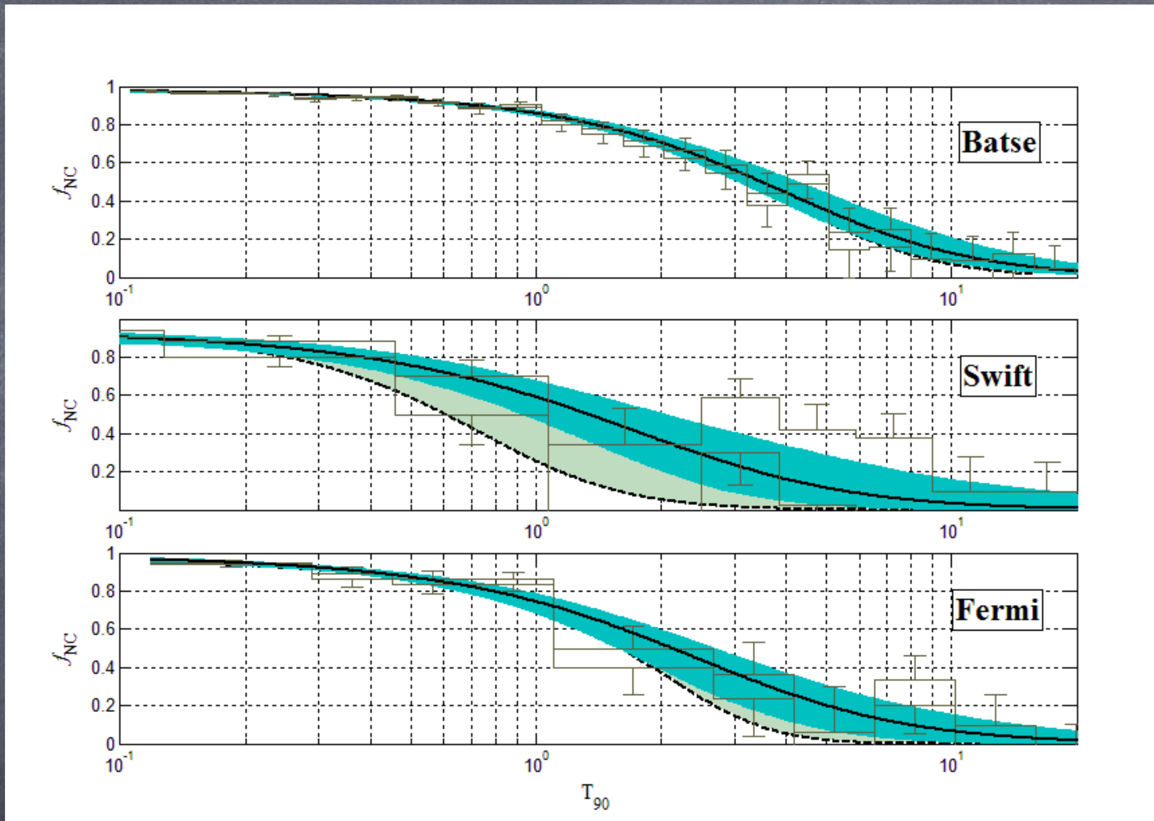


$p_e(t_\gamma) \quad t_\gamma \gg t_b$

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


T90
dN/dT90
HR
10^-2
10^-1
10^0
10^1
10^2
10^3

SGRB Fraction



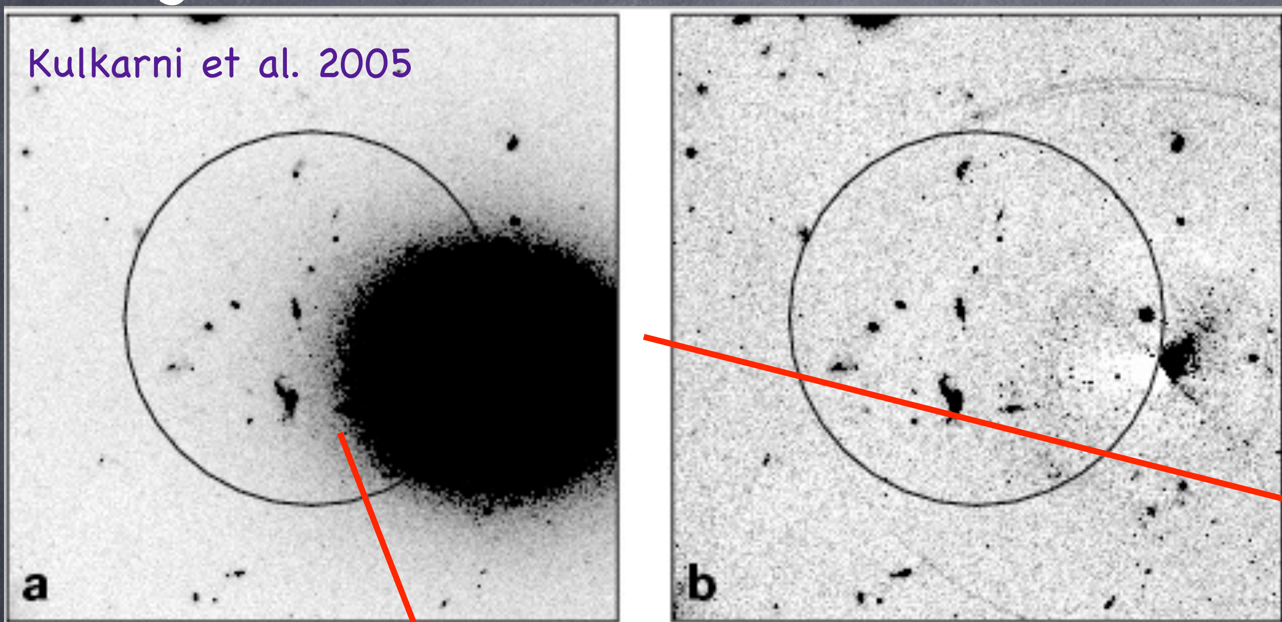
Bromberg et al , 2013

Summary

- GRBs don't follow the SFR
- Low luminosity GRBs are a different subgroup that forms with a different (third) physical mechanism.
- The rate of low luminosity GRBs is much higher than the rate of regular long or short GRBs
- The observed temporal distribution provides a first direct proof of the Collapsar model.
- Many short GRBs observed by Swift are wrongly classifeid as "short" - this has implications to both the rate of NS mergers and to the properties of these GRBs.

Short (non collapsar) GRBs

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

⇓

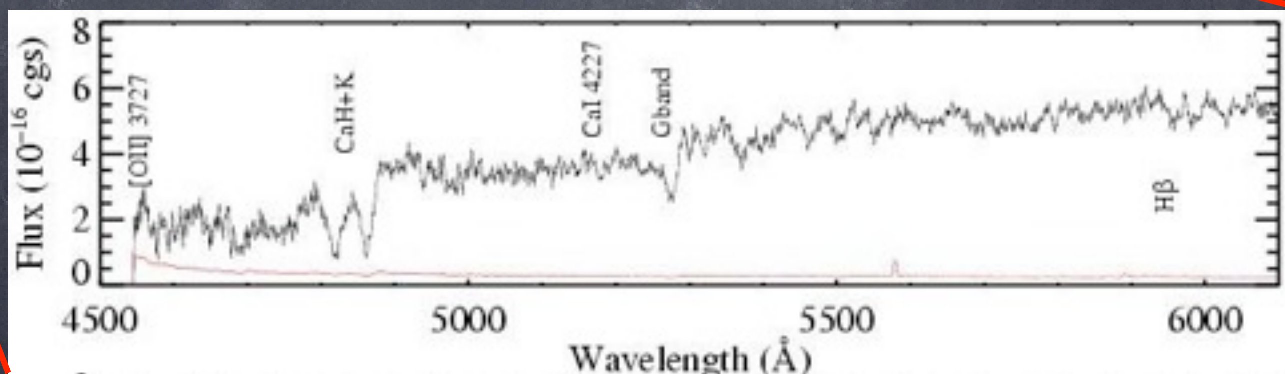
Progenitors related to an old stellar population

Bloom et al. 2005

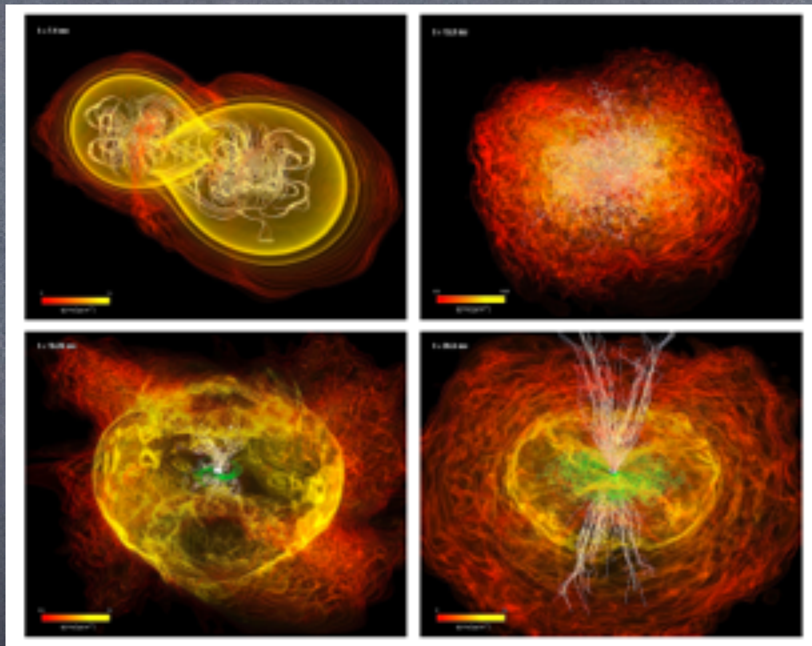
Castro-Tirado et al. 2005

Gehrels et al. 2005

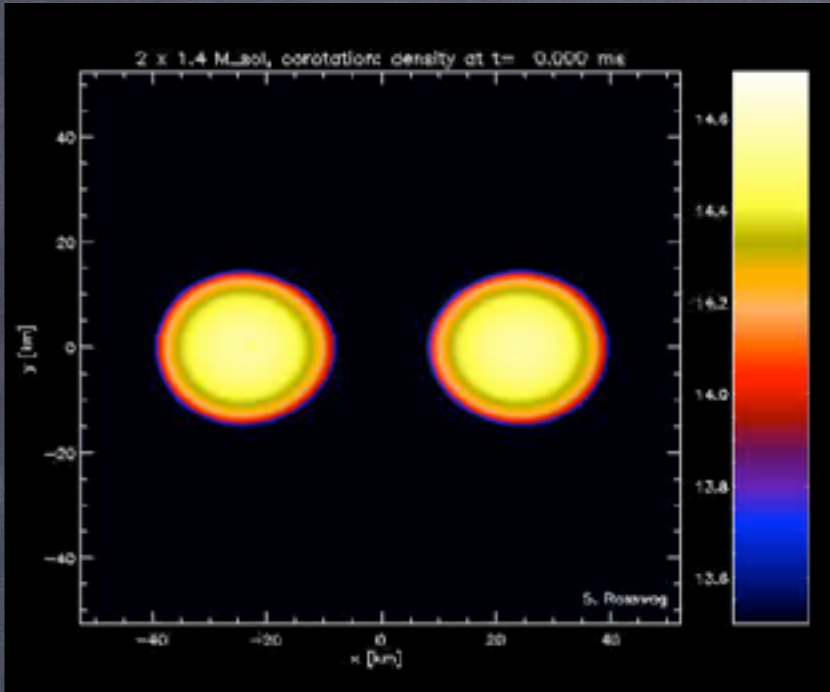
Hjorth et al. 2005

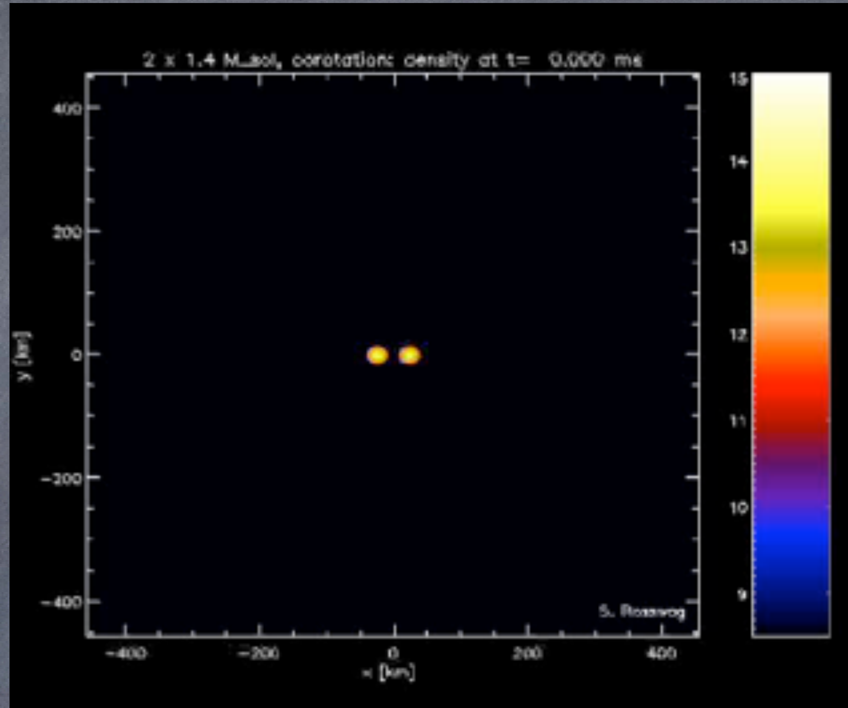


Neutron star mergers as progenitors of short GRBs (Eichler Livio, Piran, Schramm, 1988, Narayan, Paczynski & Piran 1992)

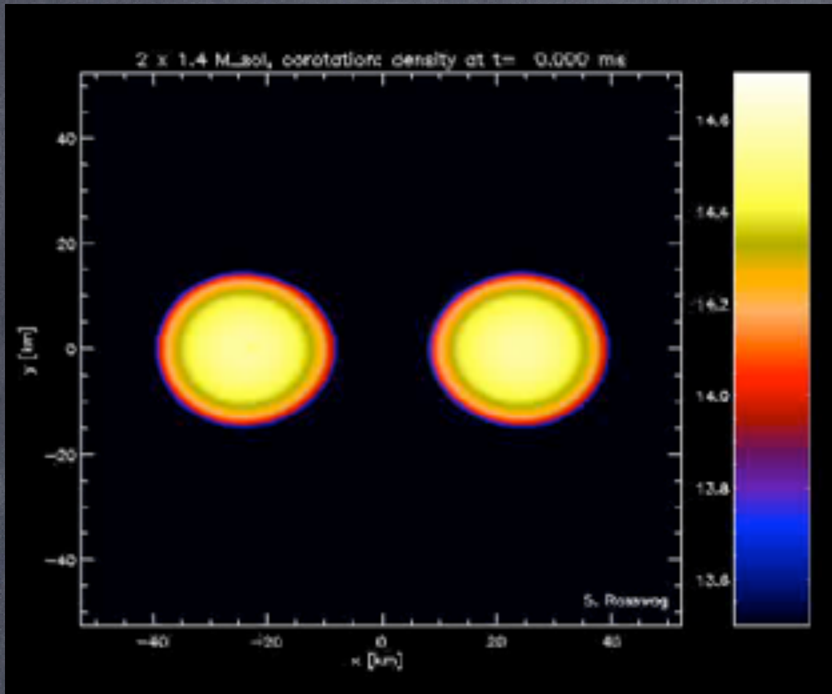


Magnetic field jet arising from NS merger Rezolla et al., 2011

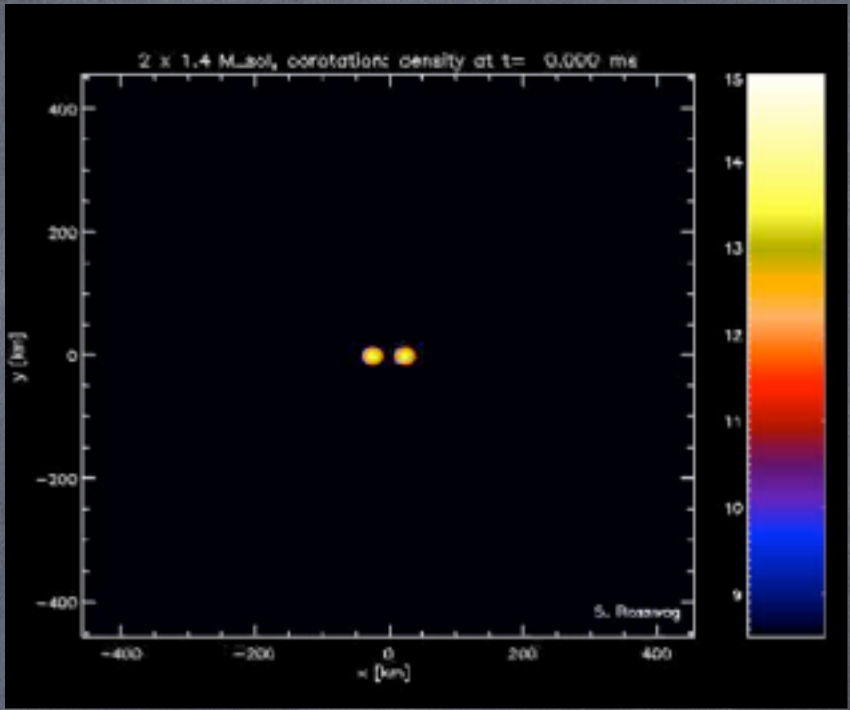




Price & Rosswog

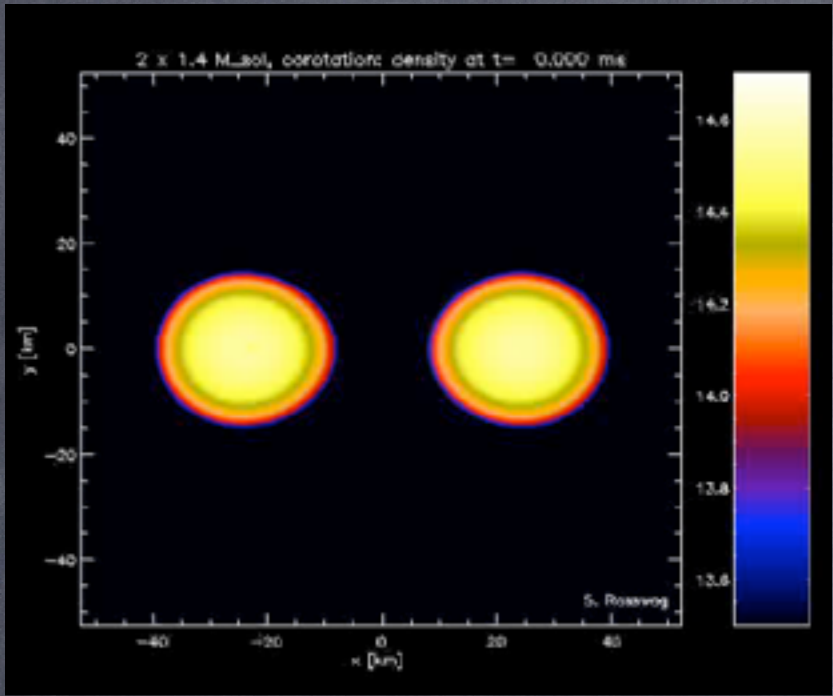


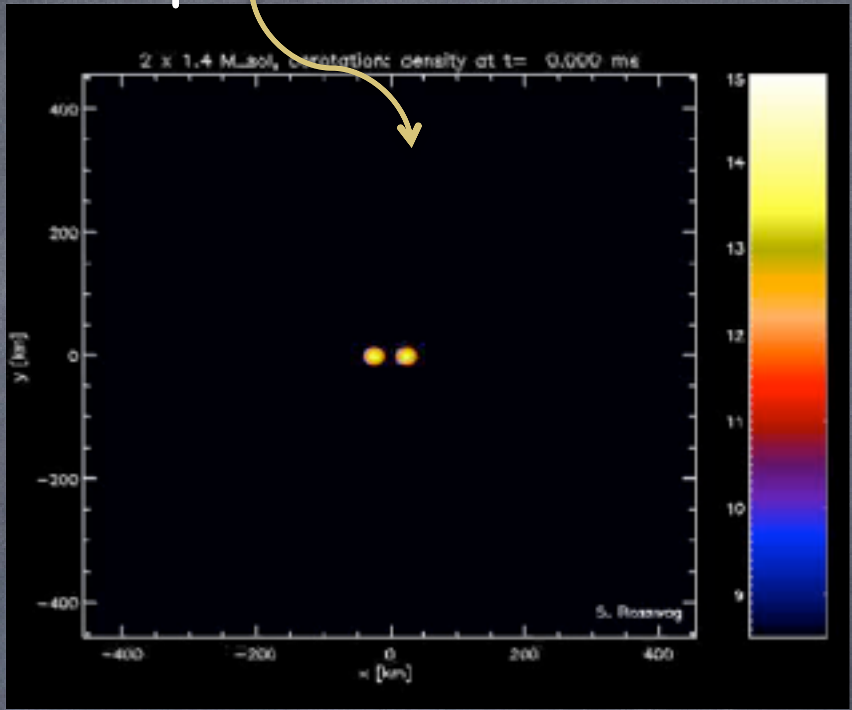
Price & Rosswog



Price & Rosswog

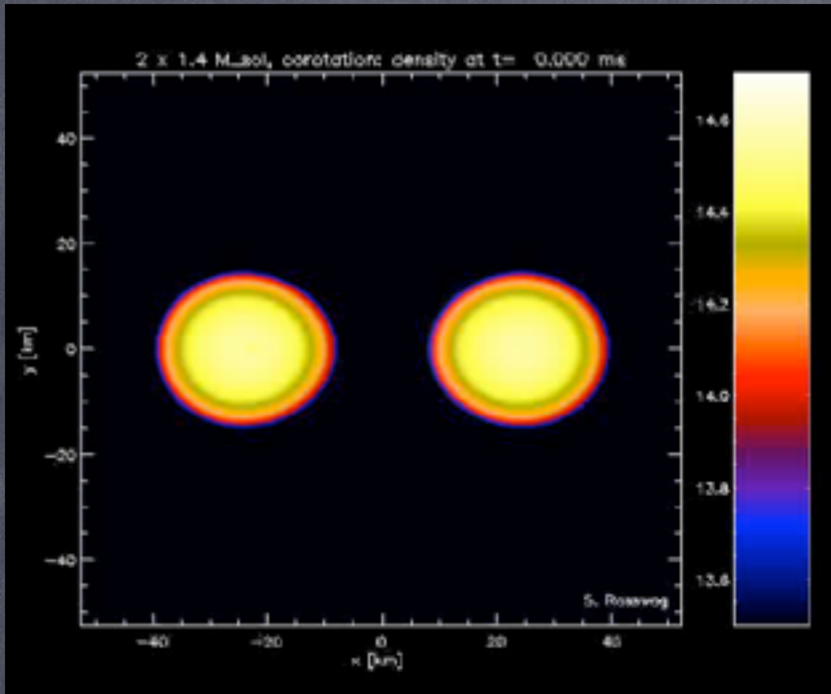
R process material

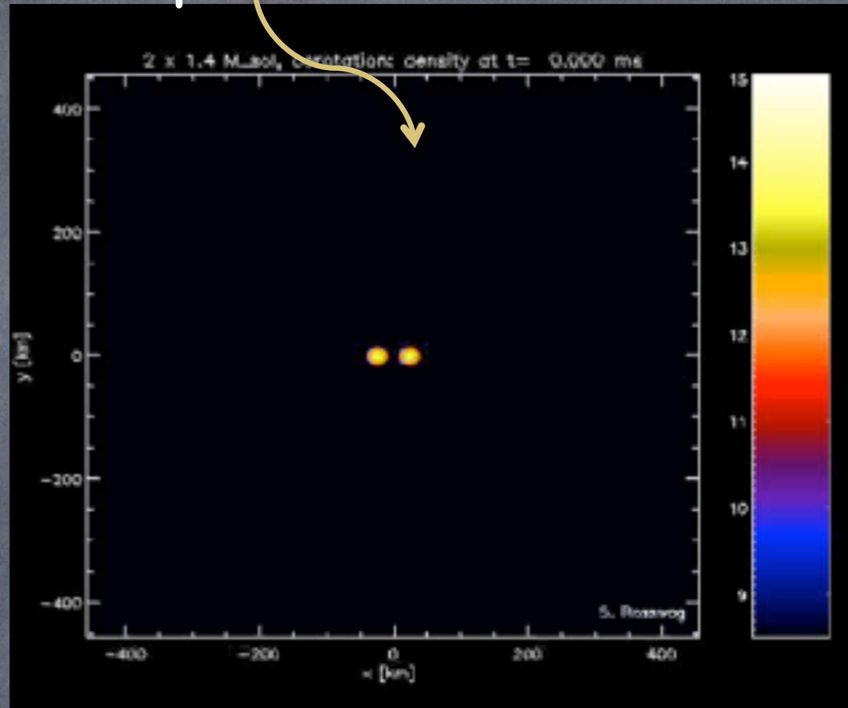




Price & Rosswog

R process material

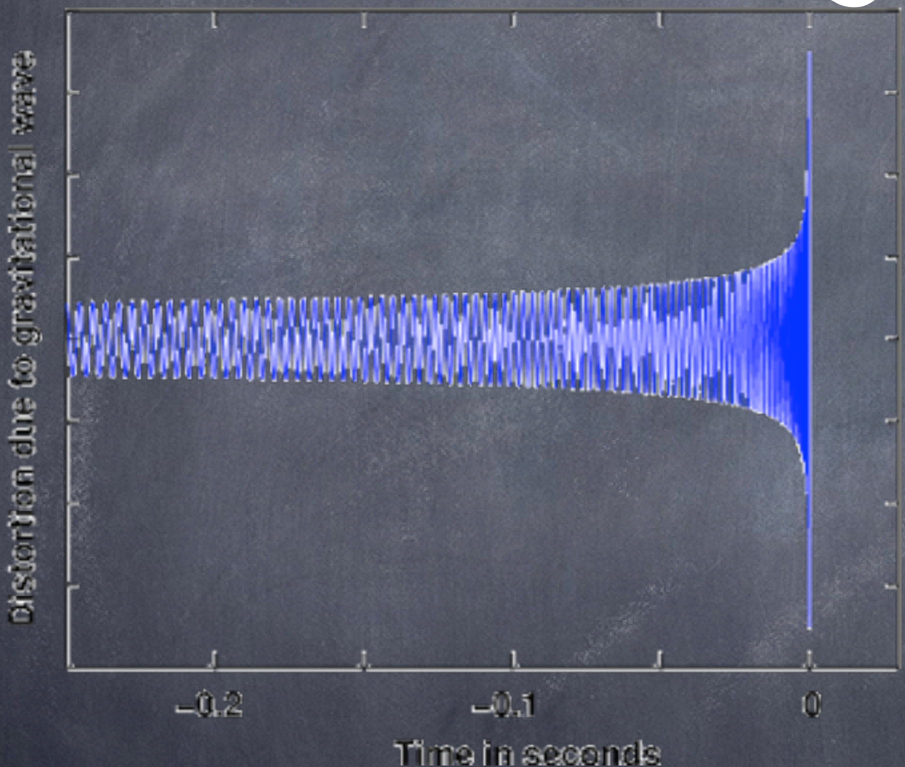




Price & Rosswog

Confirmation only with detection of Gravitational radiation

Short GRBs-NS Mergers ?

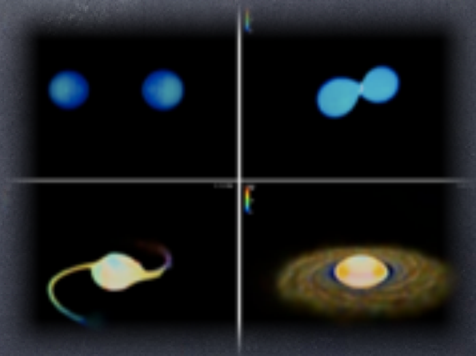


To be confirmation with detection of Gravitational radiation

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

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

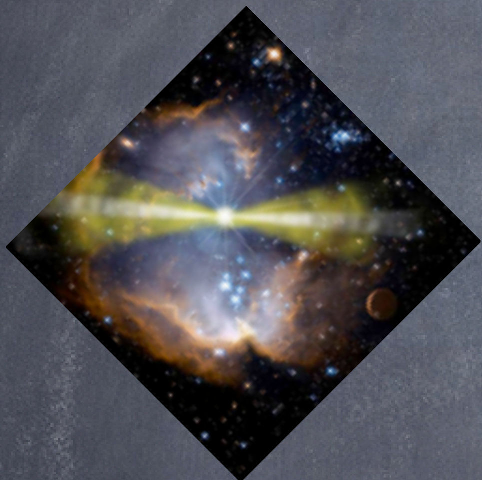
MNRASm 2013a,b

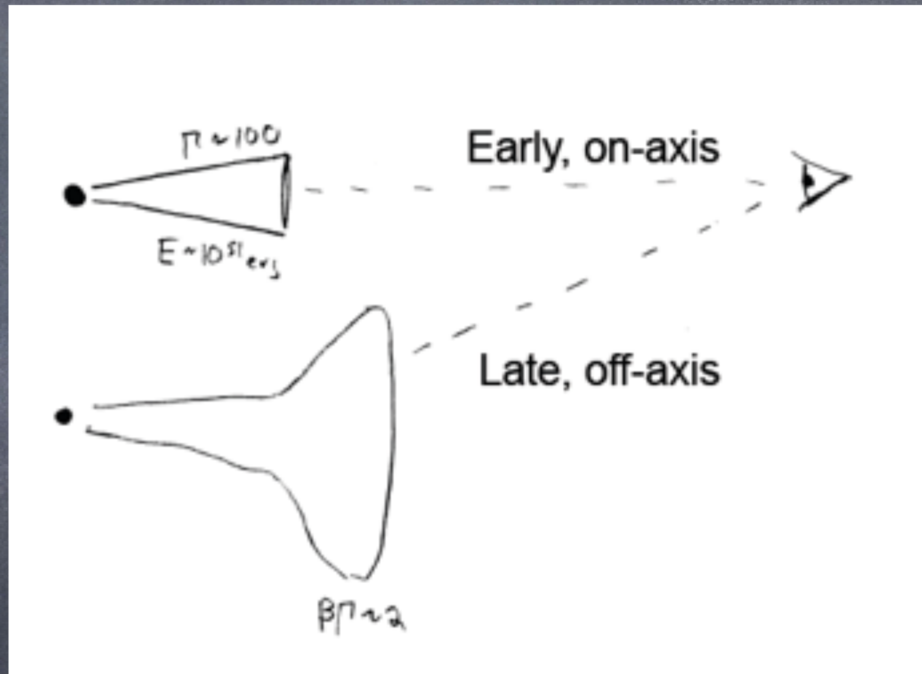


Why EM signal?

- Improves detectability (Kochaneck & Piran 1993)
- Essential for localization
- Much more physics

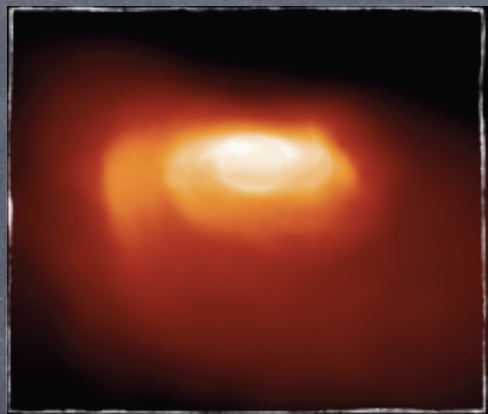
GRBs are beamed -> dificult to catch the GRB





Orpha afterglow will be too weak

Macronova
Paczynski & Li 1997

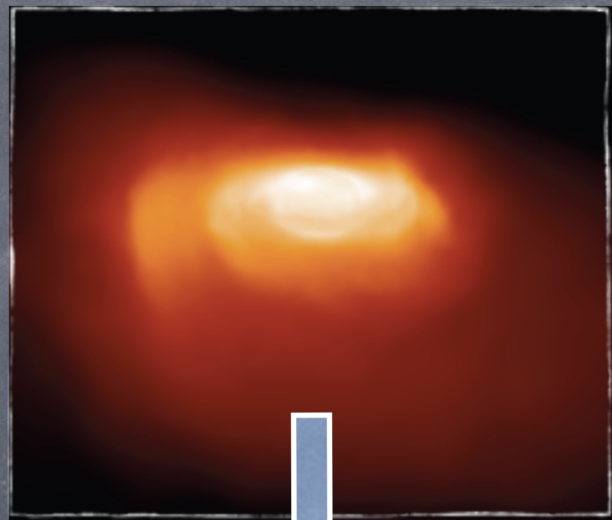


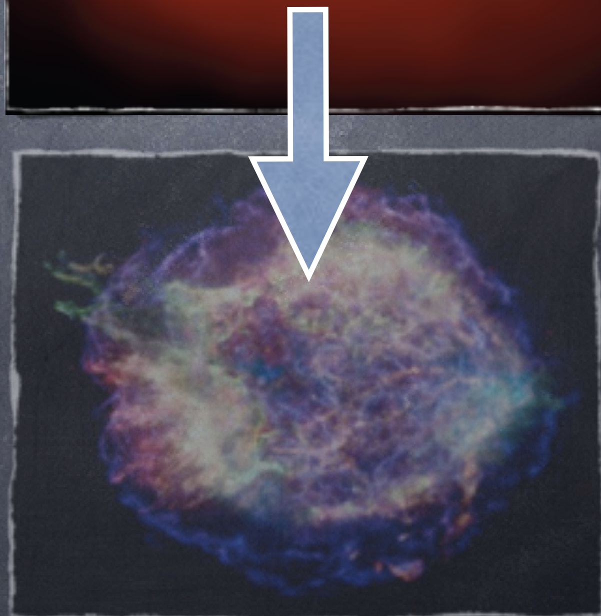
Numerous numerical simulations show that NS merger eject 0.1 $M_{\odot}$

Radio Flares

Nakar & Piran 2011

Interaction of the sub or mildly relativistic outflow with the ISM produces a long lived radio flare



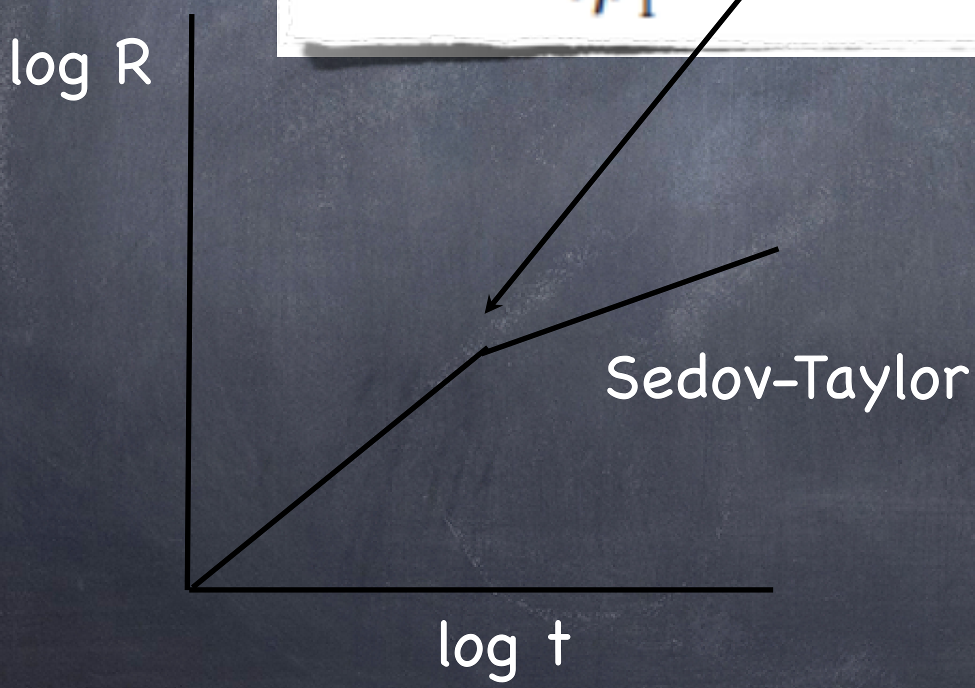


Supernova -> SNR

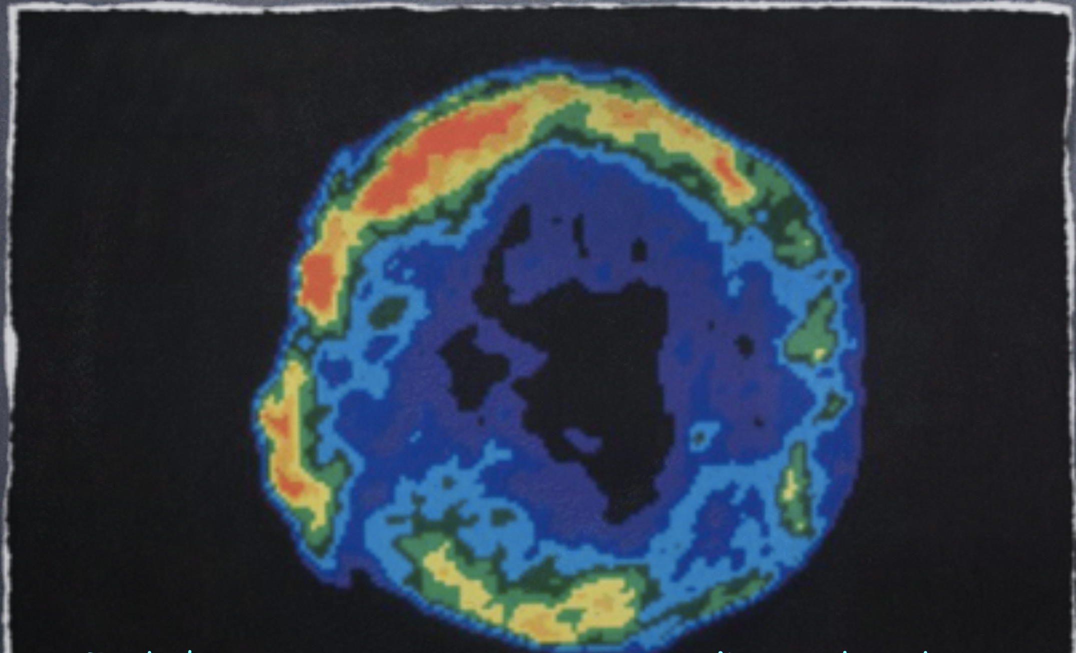
macronova -> Radio Flare

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 $\gamma > \gamma_m$

$p = 2.5 - 3$

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

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

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

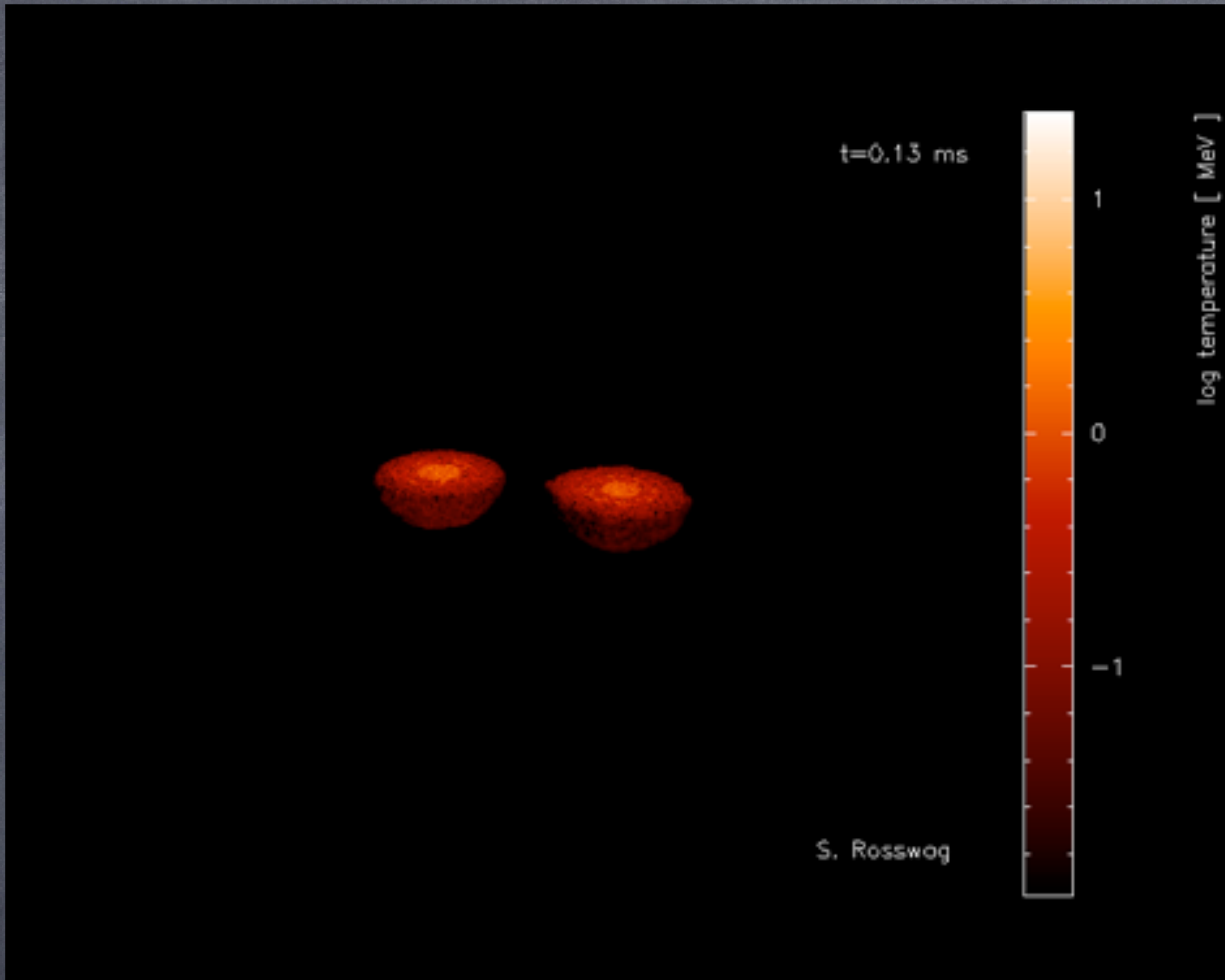
Frequency and Intensity

(Nakar & TP Nature, 2011)

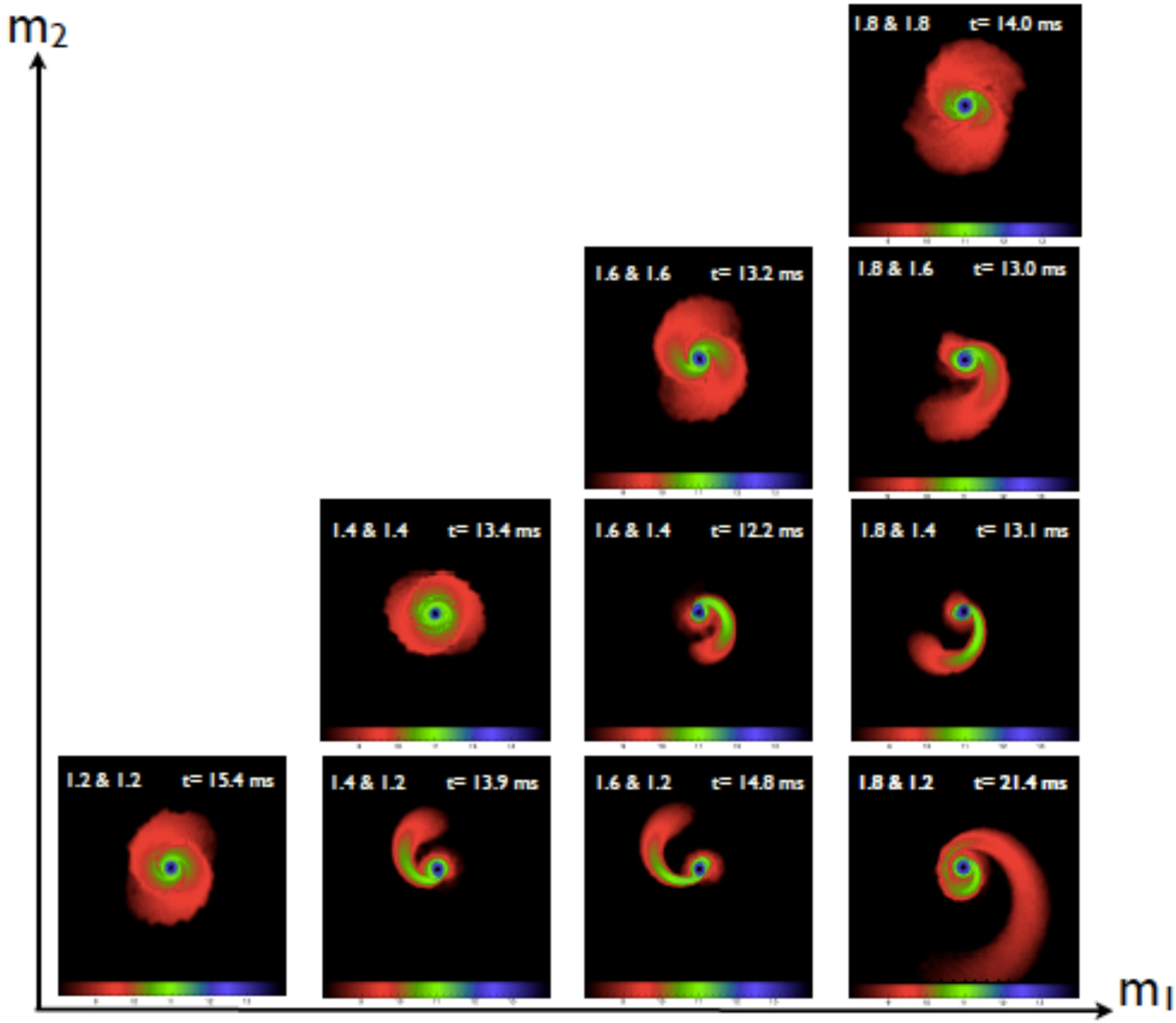
$$\nu_{m,dec} \equiv \nu_m(t_{dec}) \approx 1\ \mathrm{GHz}\ n^{1/2} \epsilon_{B,-1}^{1/2} \epsilon_{e,-1}^{2} (\Gamma_0 - 1)^{5/2},$$

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

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

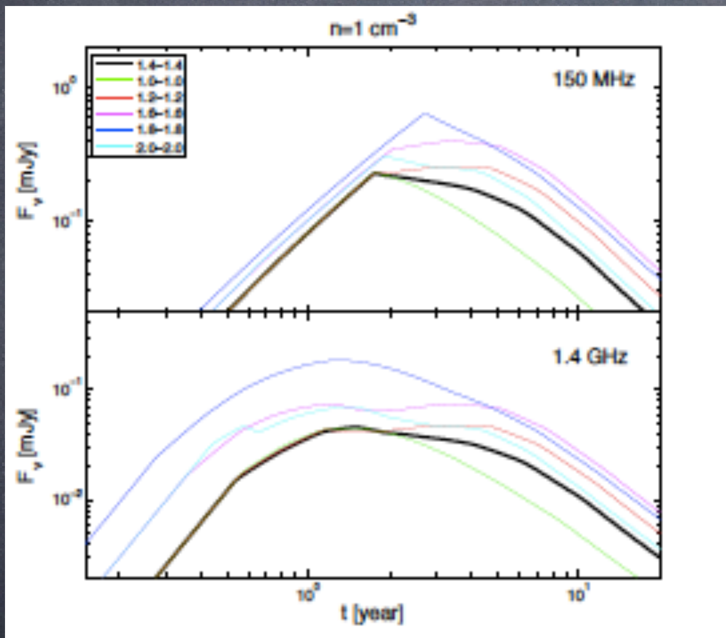


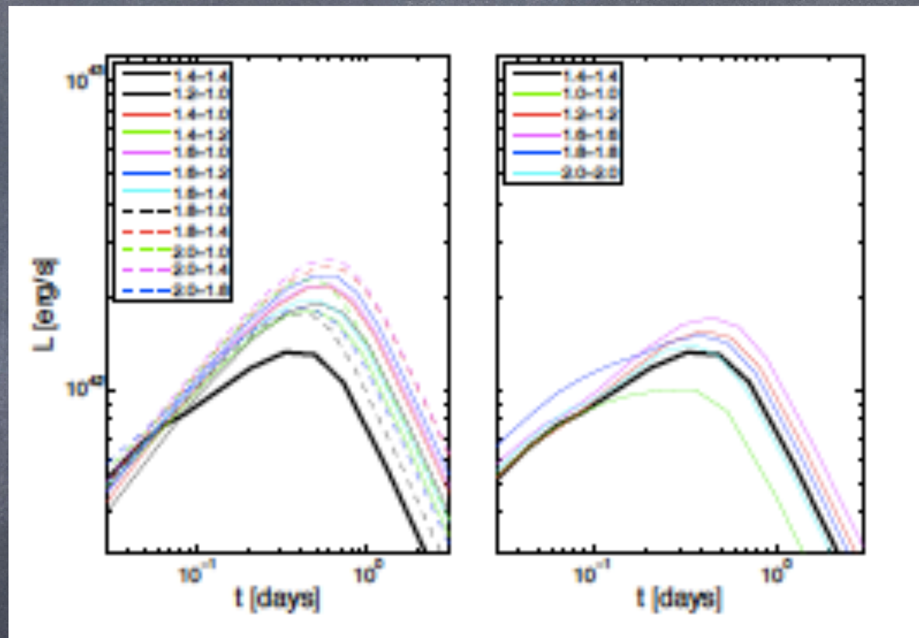
Rosswog, TP, Nakar 13, TP, Nakar, Rosswog 13



m2
m1
1.8 & 1.8 t= 14.0 ms
1.6 & 1.6 t= 13.2 ms
1.8 & 1.6 t= 13.0 ms
1.4 & 1.4 t= 13.4 ms
1.6 & 1.4 t= 12.2 ms
1.8 & 1.4 t= 13.1 ms
1.2 & 1.2 t= 15.4 ms
1.4 & 1.2 t= 13.9 ms
1.6 & 1.2 t= 14.8 ms
1.8 & 1.2 t= 21.4 ms

Radio Flares and Macronova





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

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

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

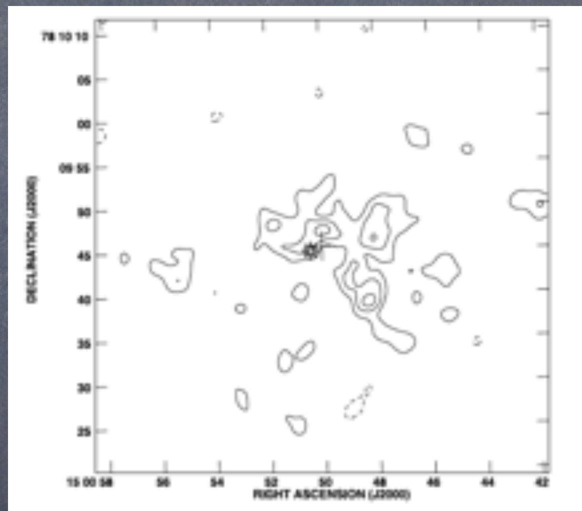
Detectability

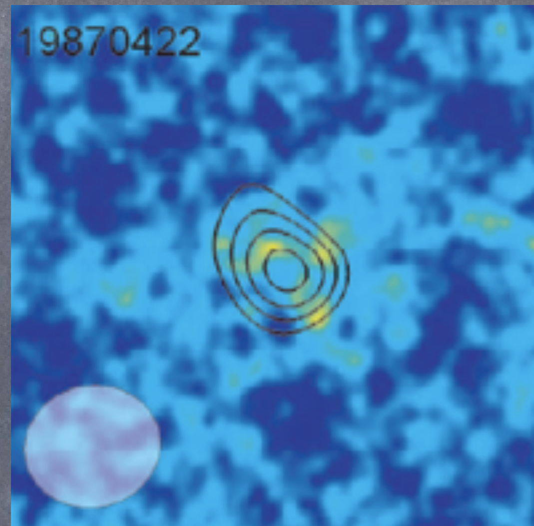
Table 1 | Observing radio flares

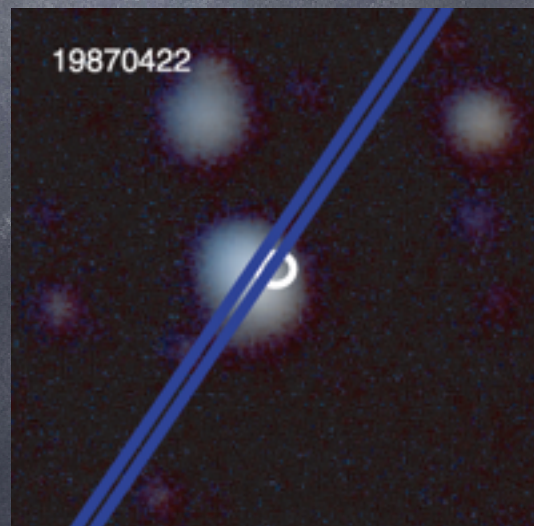
Radio facility	Observing frequency (GHz)	Field of view (deg^2)	One-hour r.m.s.* (μJy)	One-hour detection horizon†			Ten-hour detection horiz
				$\beta_i \approx 1$, $E_{49} = 1, n_0 = 1$	$\beta_i \approx 1$, $E_{49} = 10, n_0 = 1$	$\beta_i = 0.2, E_{49} = 10$, $n_0 = 1, p = 2.5$	$\beta_i \approx 1,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



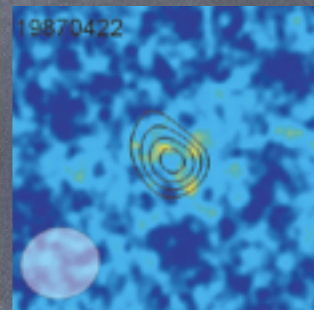




ERROR!

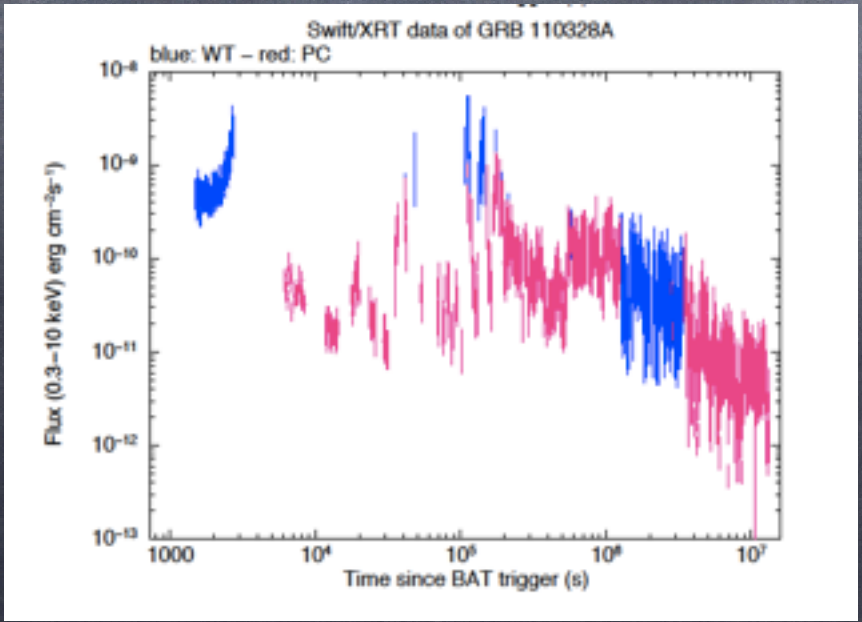
Summary

- Search for long lived Radio Flares may discover the rate ot Neutron star mergers with implications to short GRBs and the detection of Gravitational Radiation

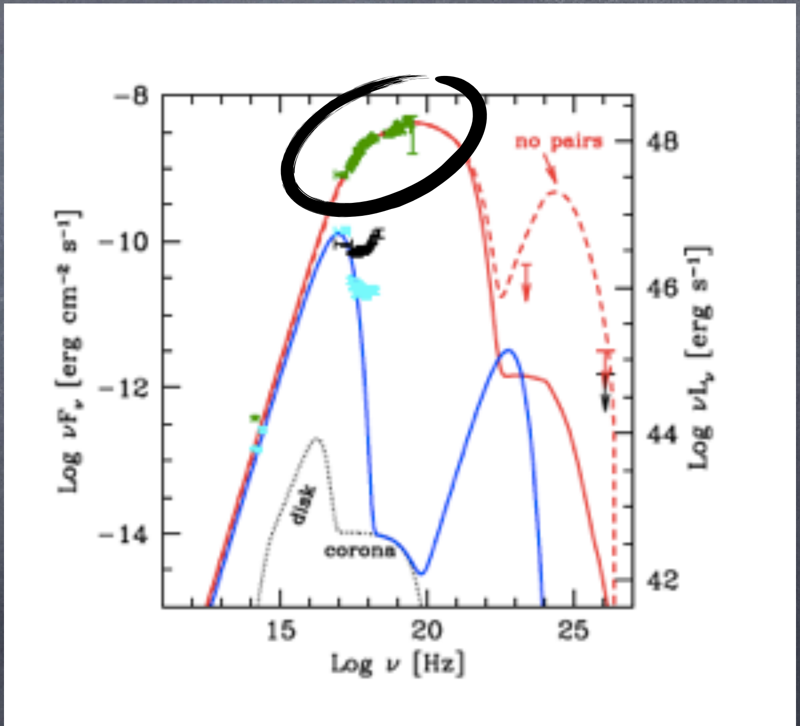


III. TIdal Disruption Events - Swift J1644 (GRB110328) and J2058

TP + Julian Krolik (ApJ. 11,12)

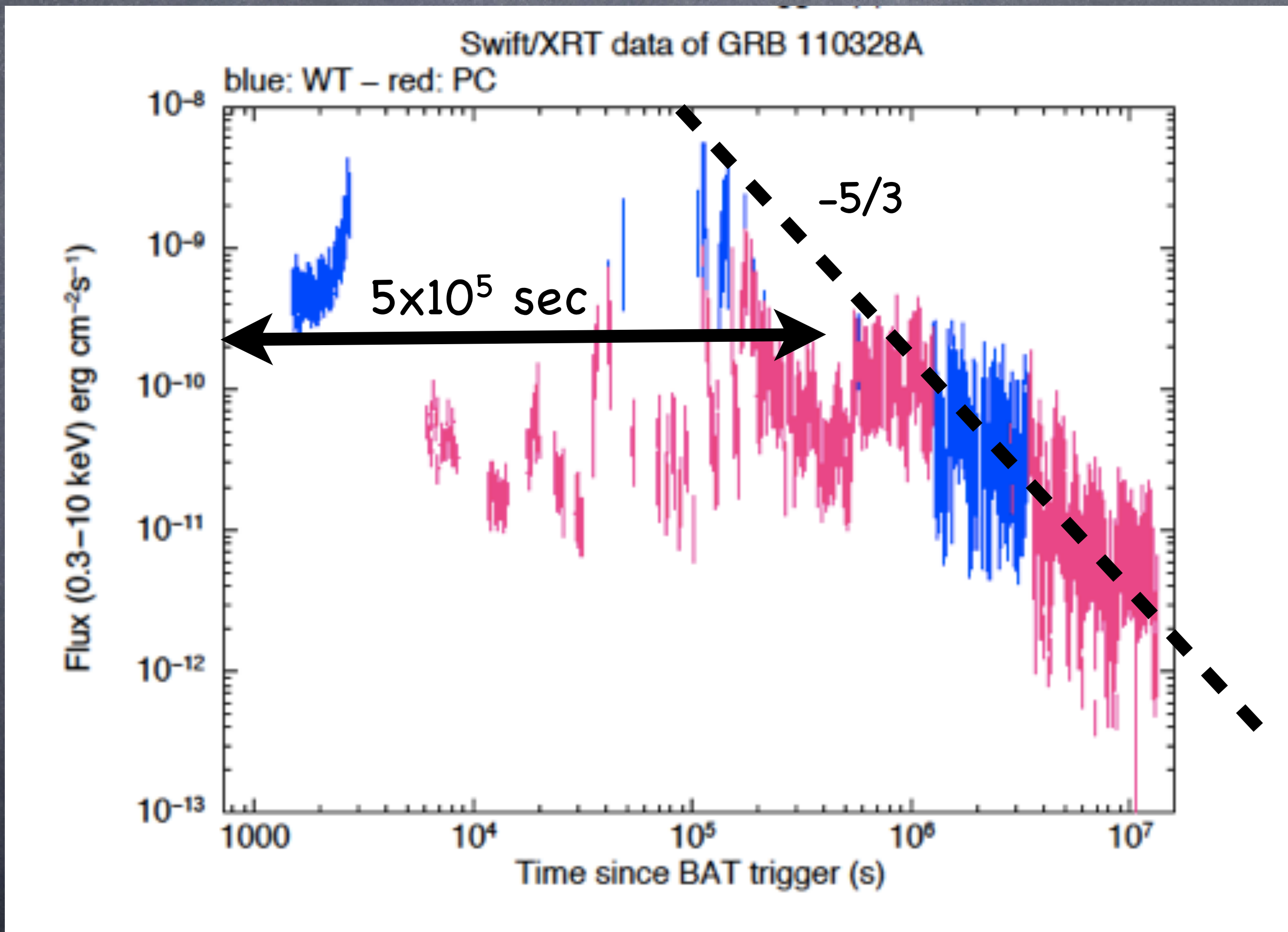


Why X-rays?

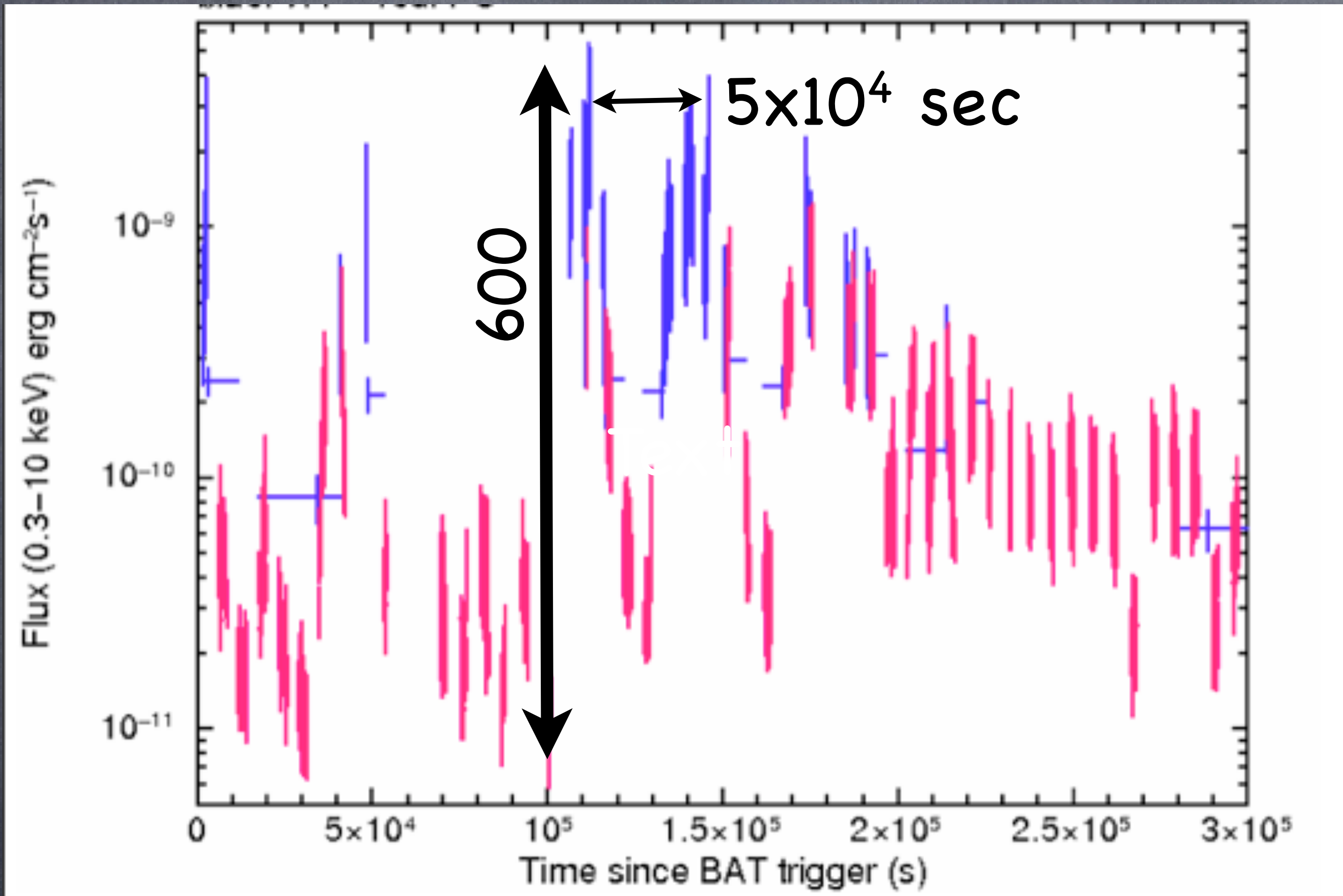


no pairs
disk
corona
Log νF_ν [erg cm^{-2} s^{-1}]
Log νL_ν [erg s^{-1}]
Log ν [Hz]
−8
−10
−12
−14
48
46
44
42
15
20
25

Ligth Curve

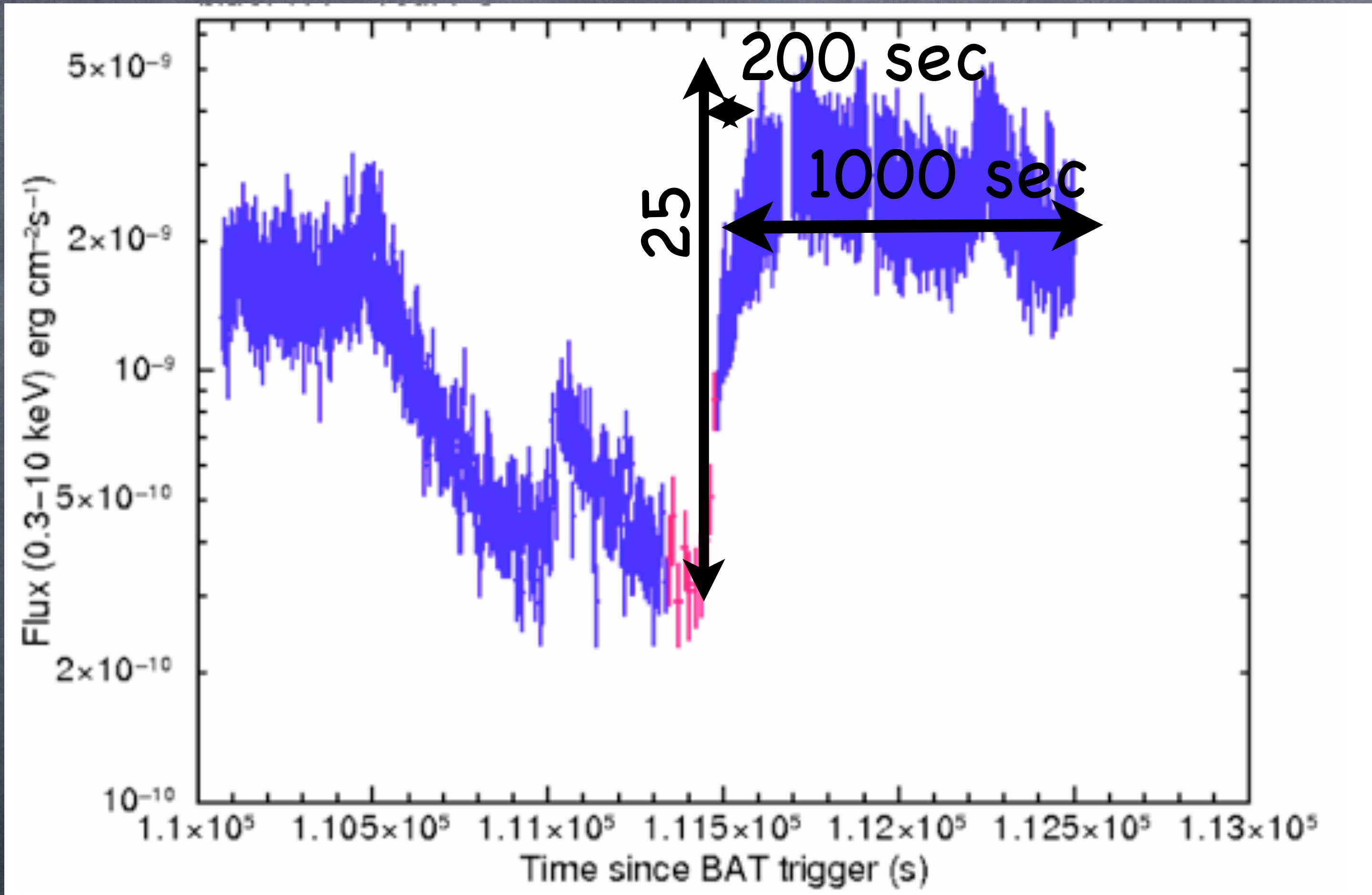


Swift/XRT data of GRB 110328A
blue: WT – red: PC
Flux (0.3–10 keV) erg cm⁻²s⁻¹)
Time since BAT trigger (s)
5x10^5 sec
-5/3



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

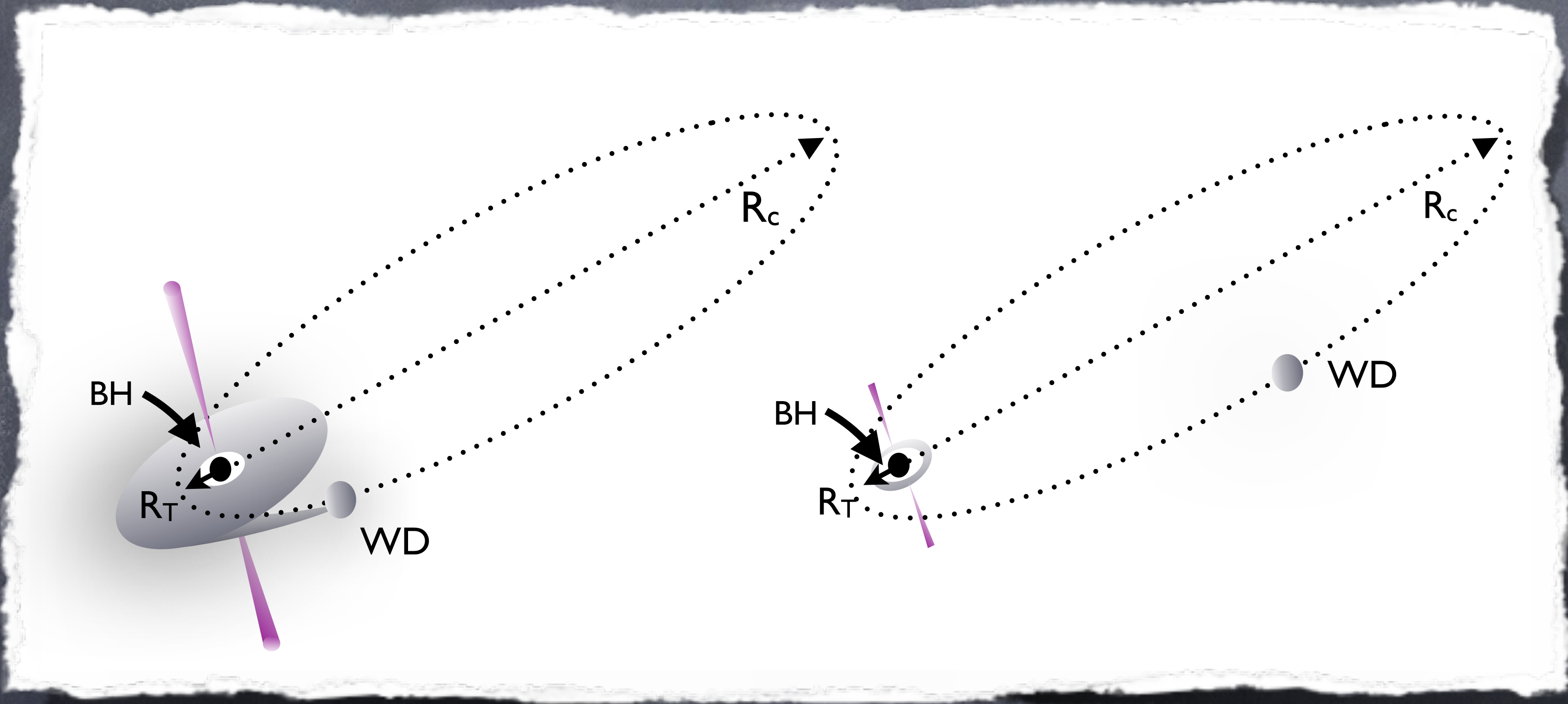
A tidal disruption of a main sequence star

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



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

Thursday, January 31, 13

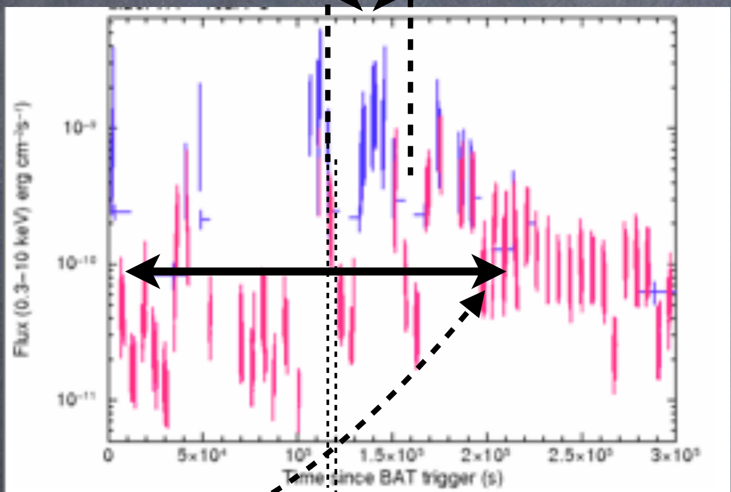
For a White Dwarf

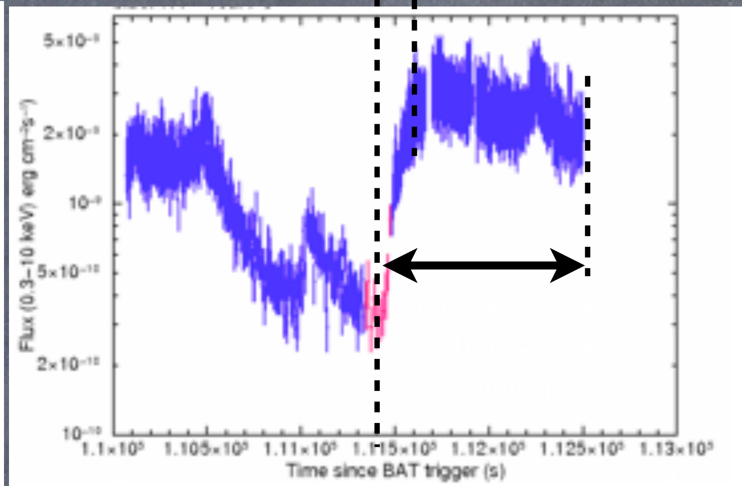
$P_{orb}(R_T) \approx 1/\sqrt{(G\rho)} \approx 6$ sec

- 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

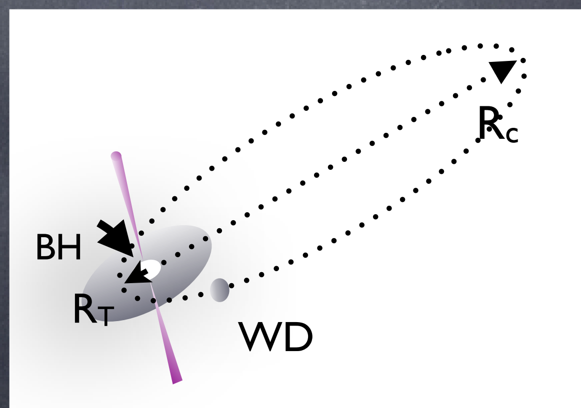
5x10^4 sec- orbital period of WD remnant

200 sec rise time - a few RT orbits



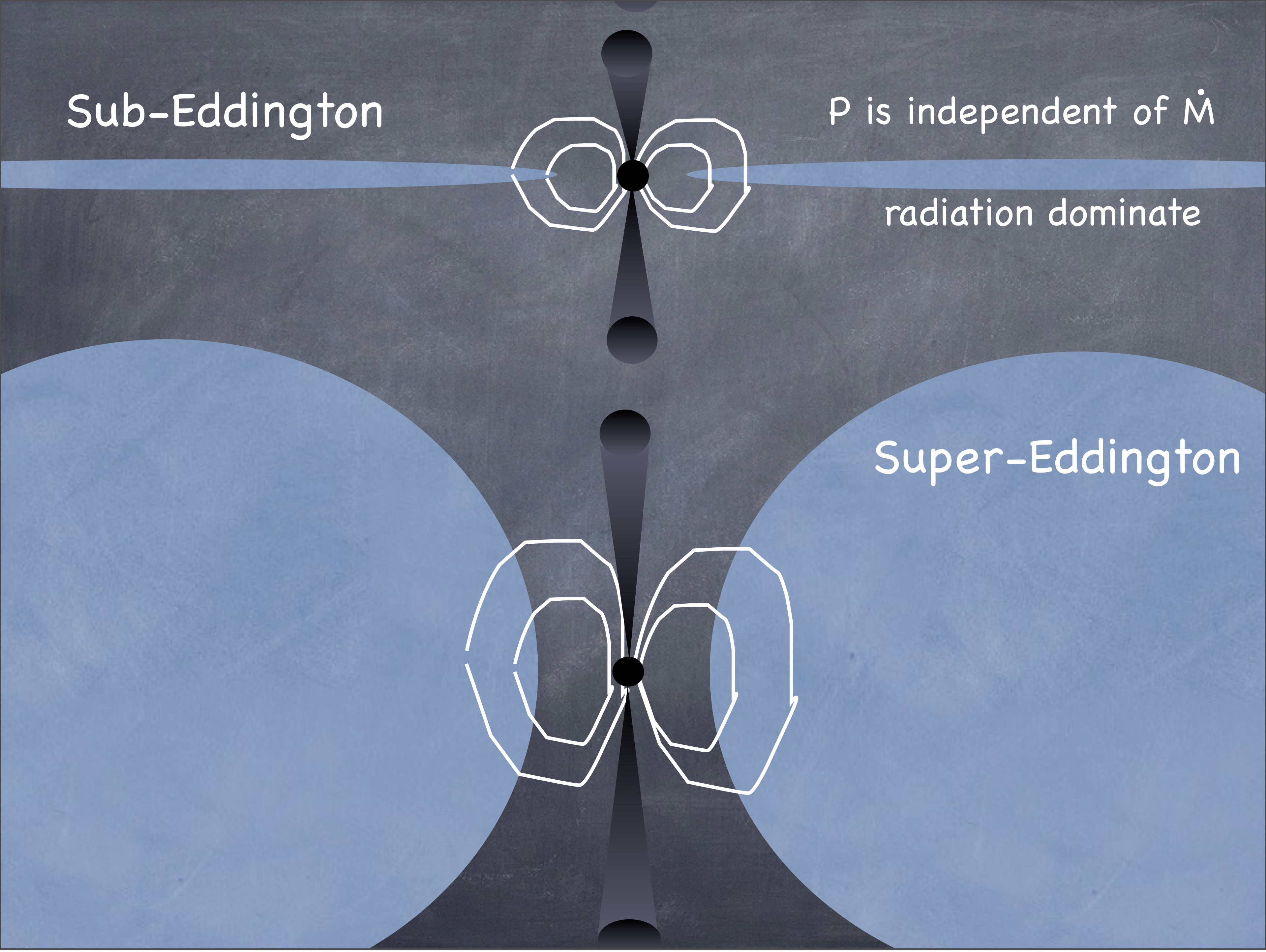


2x10^5 sec - onset of $t^{-5/3}$ decay



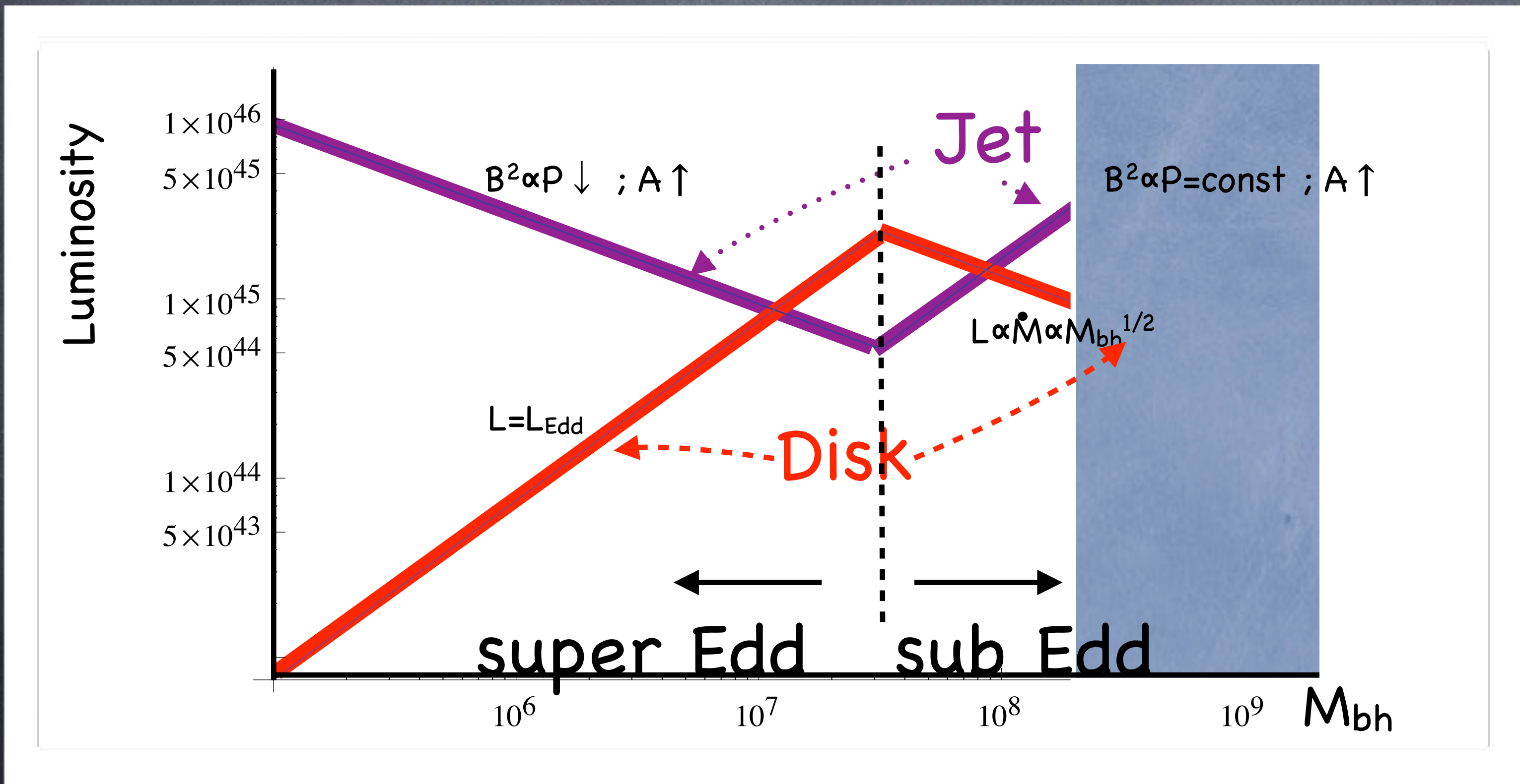
Why Jet?

- 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 $M \propto (M_*/M_{BH})^{1/2}$
- Thermal (UV) emission also depends on accretion mode.



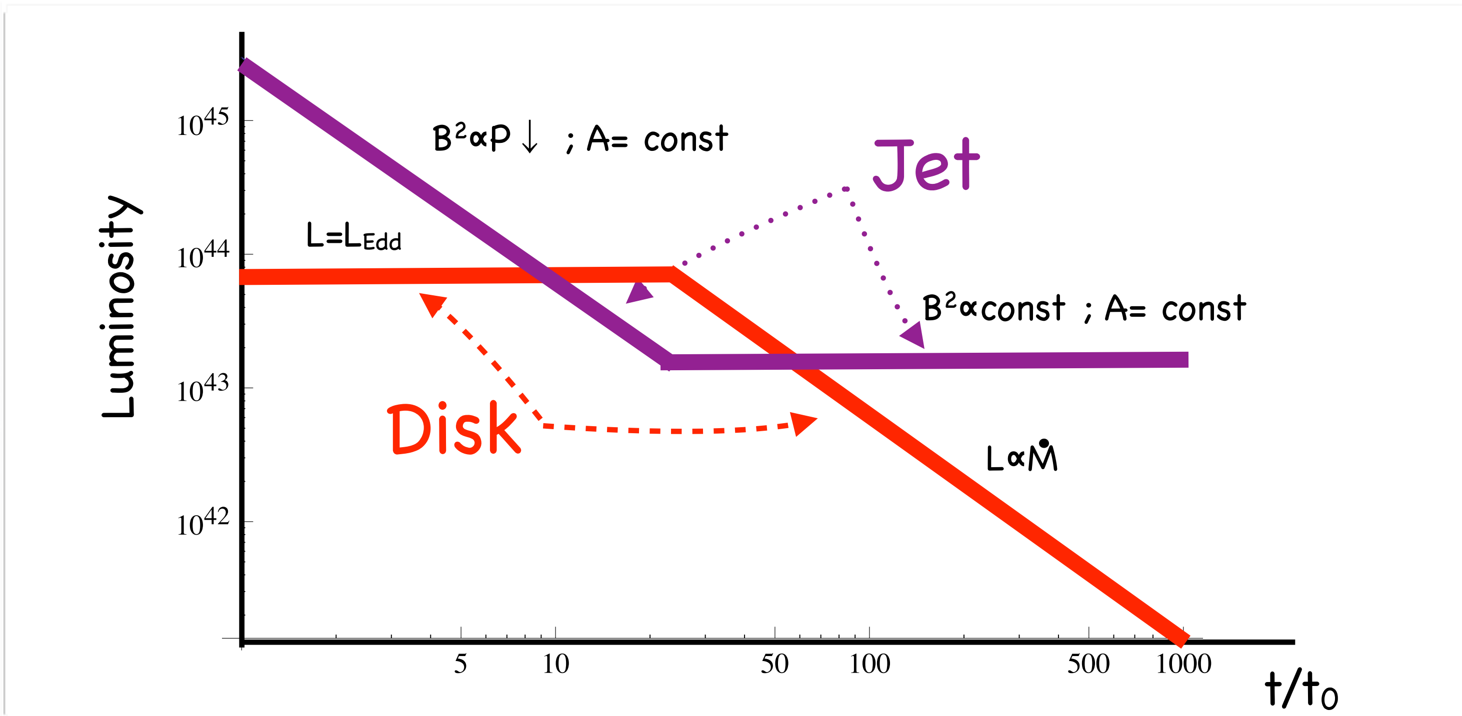
Sub-Eddington
P is independent of $\dot{M}$
radiation dominate
Super-Eddington

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

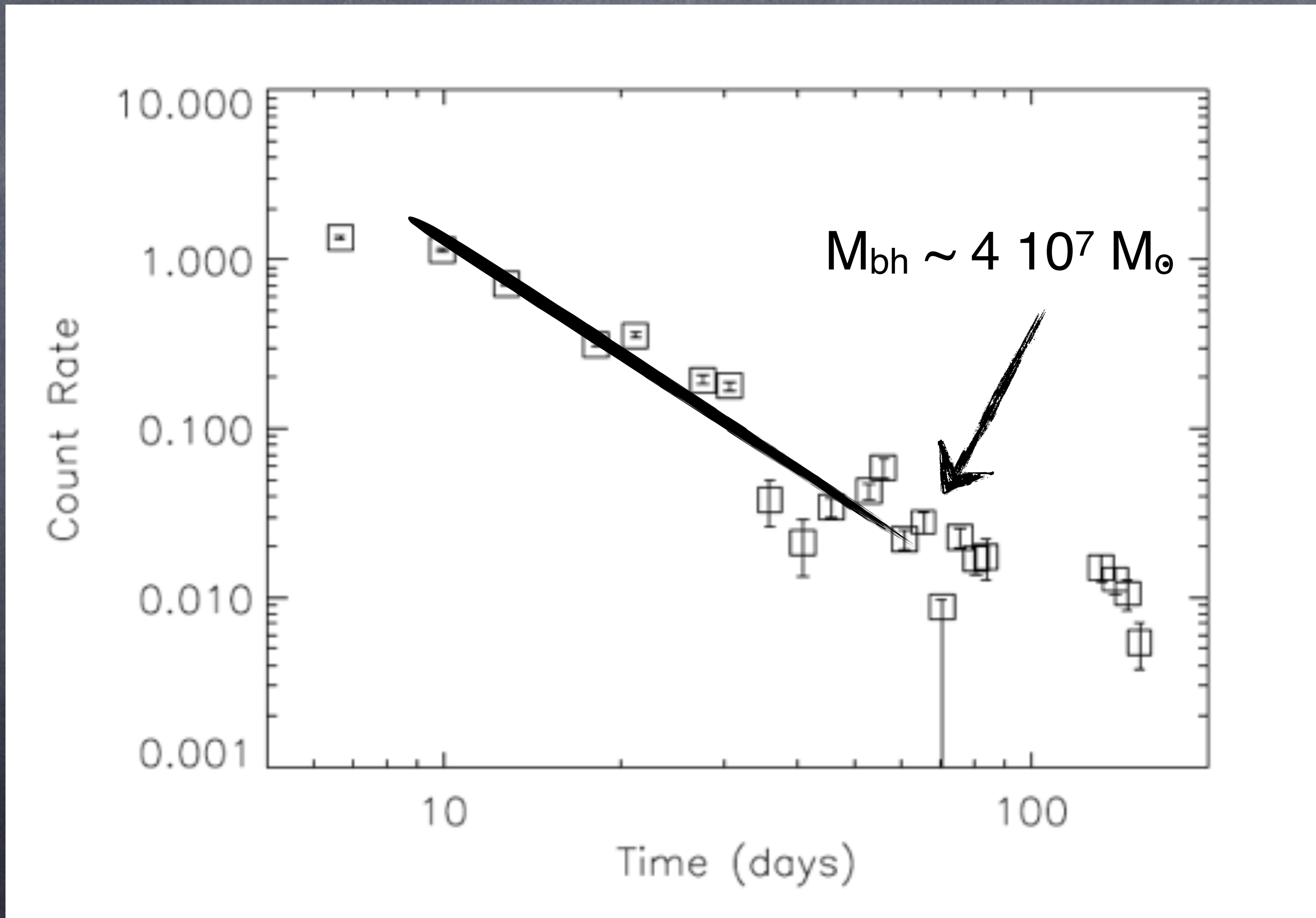


Light curves

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



The x-ray light curve of Swift J2508



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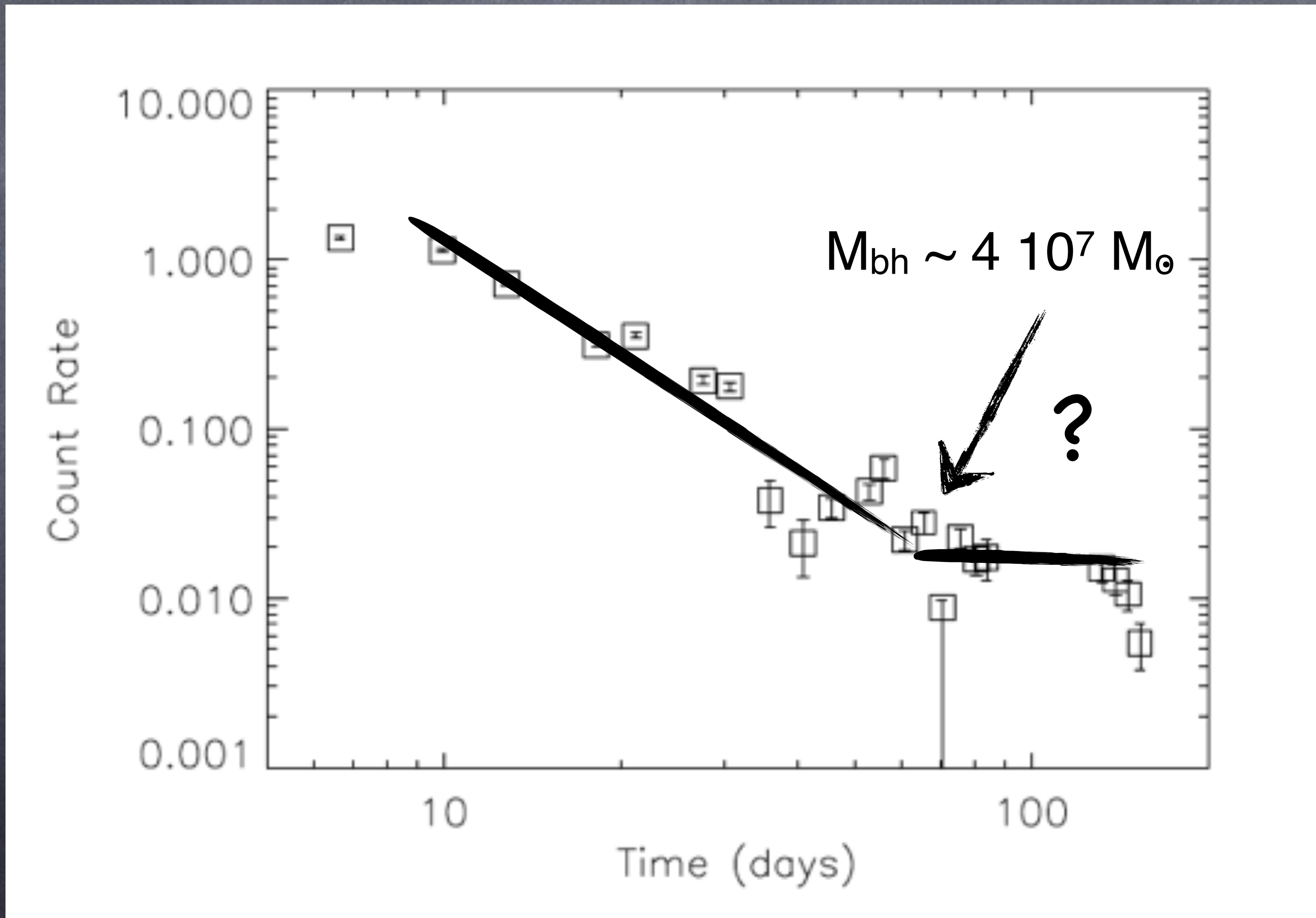
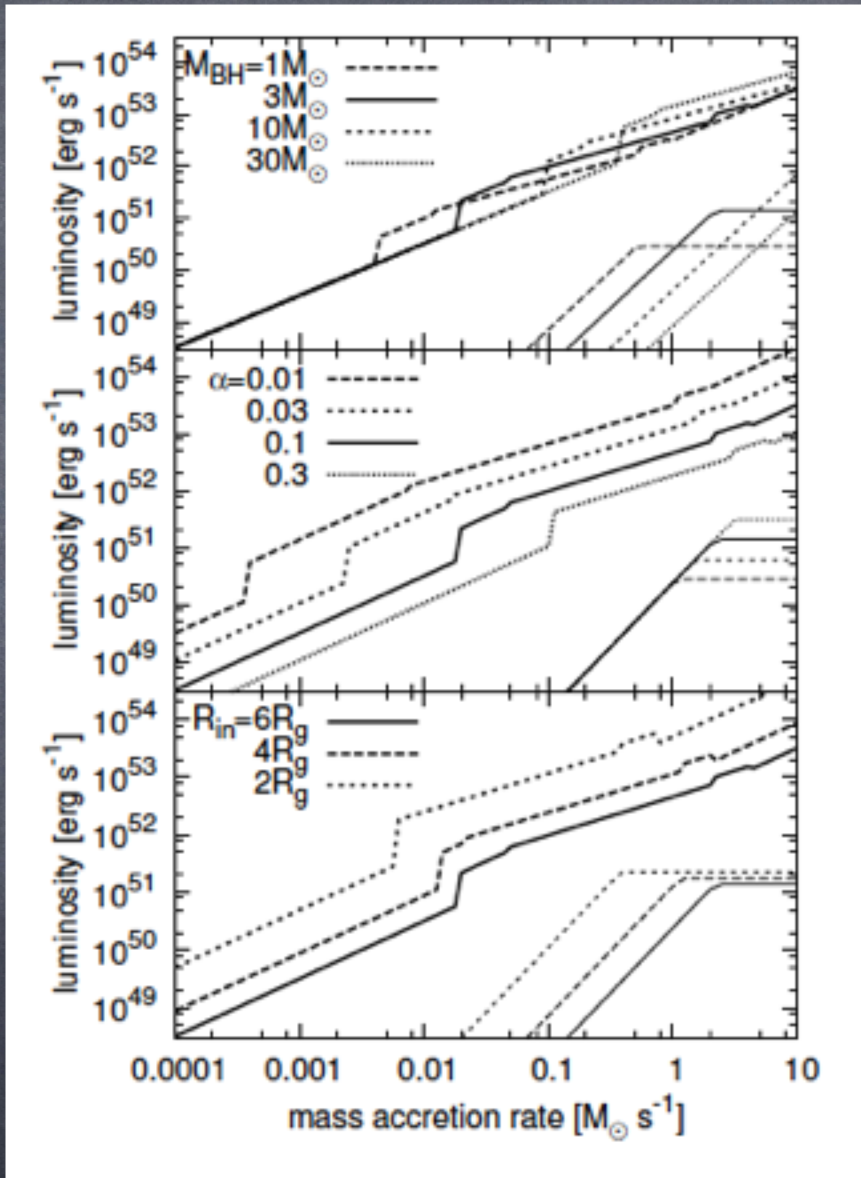


Can we apply a similar reasoning to Neutrino Dominated Accretion Disks in GRBs?

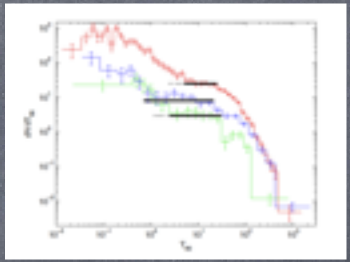
Kawanaka, TP & Krilok 2012



luminosity [erg s^{-1}]
M_{BH}=1$M_\odot$
3$M_\odot$
10$M_\odot$
30$M_\odot$
α=0.01
0.03
0.1
0.3
R_{in}=6R_g
4R_g
2R_g
10^{49} 10^{50} 10^{51} 10^{52} 10^{53} 10^{54}
0.0001 0.001 0.01 0.1 1 10
mass accretion rate [$M_\odot$ s^{-1}]

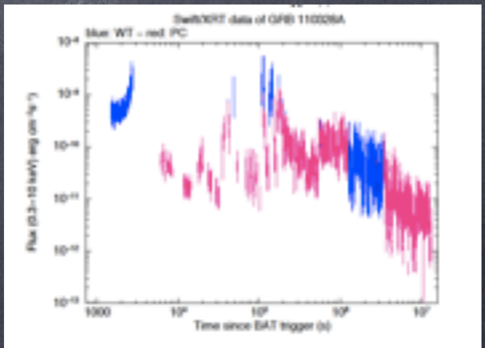
Summary

- There is a third population of GRBs - low luminosity GRBs - llGRBs - that arise from a different physica mechanism



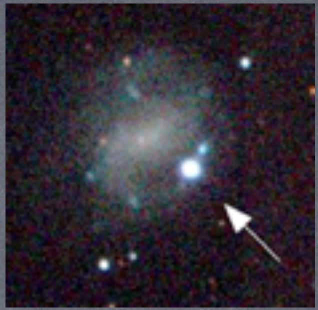
- The observed plateau in the duration distribution of LGRBs show that LGRBs arise from Collapsars!

- 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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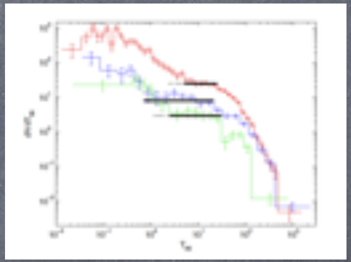

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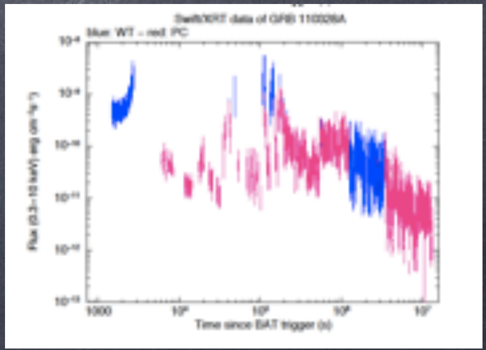

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