The EM Signals of ns Mergers -
The Lightening that follows the Thunder

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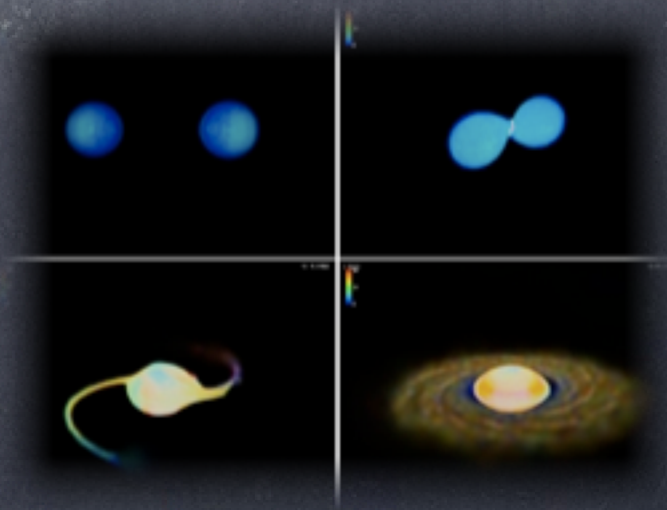
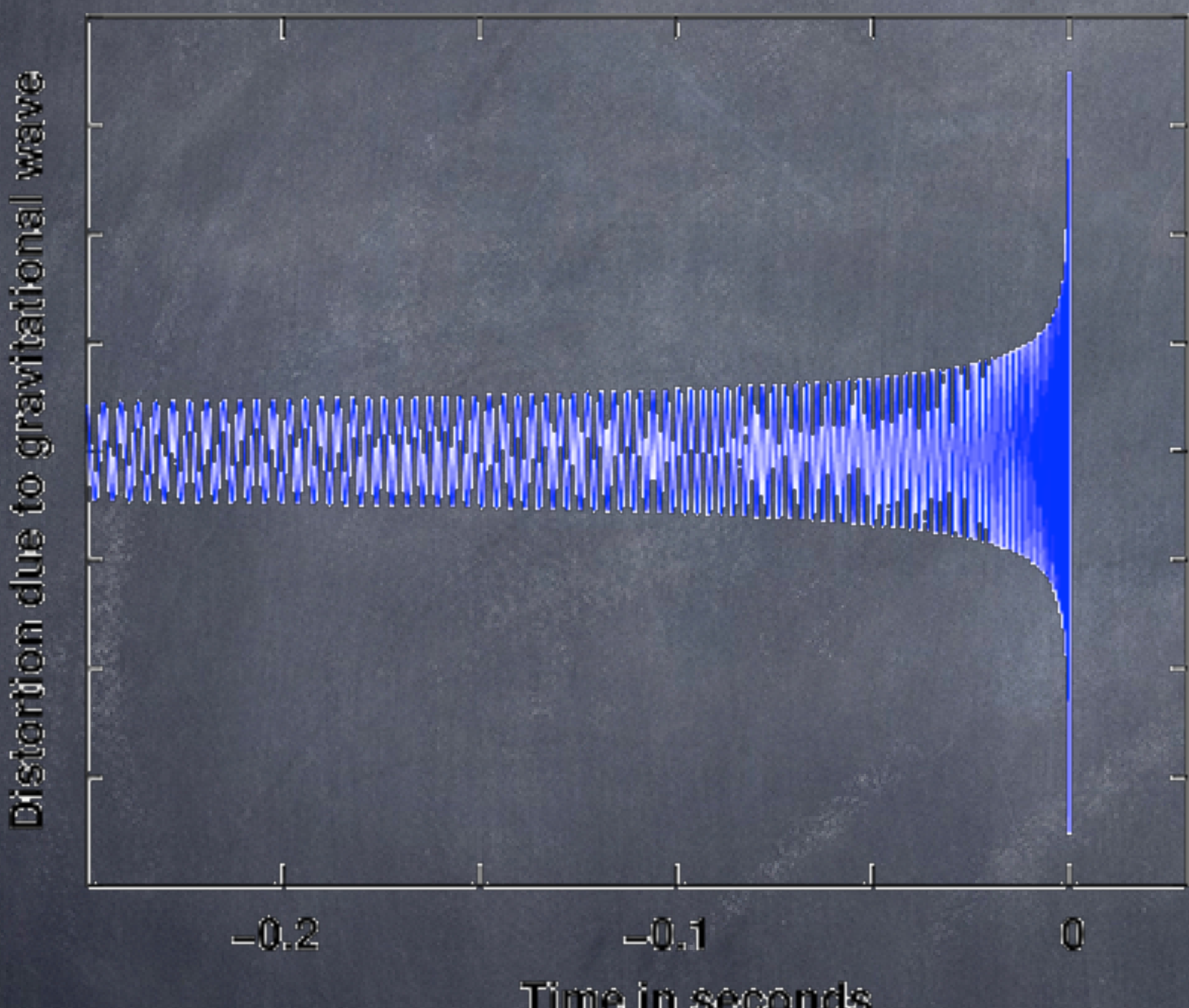
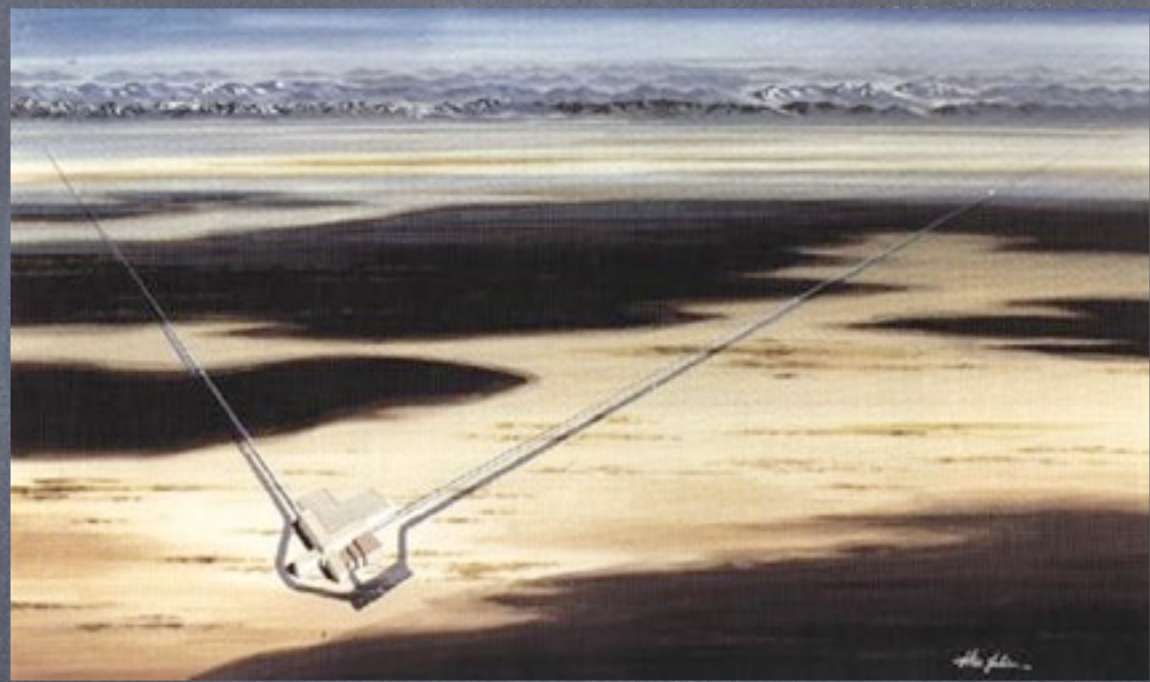


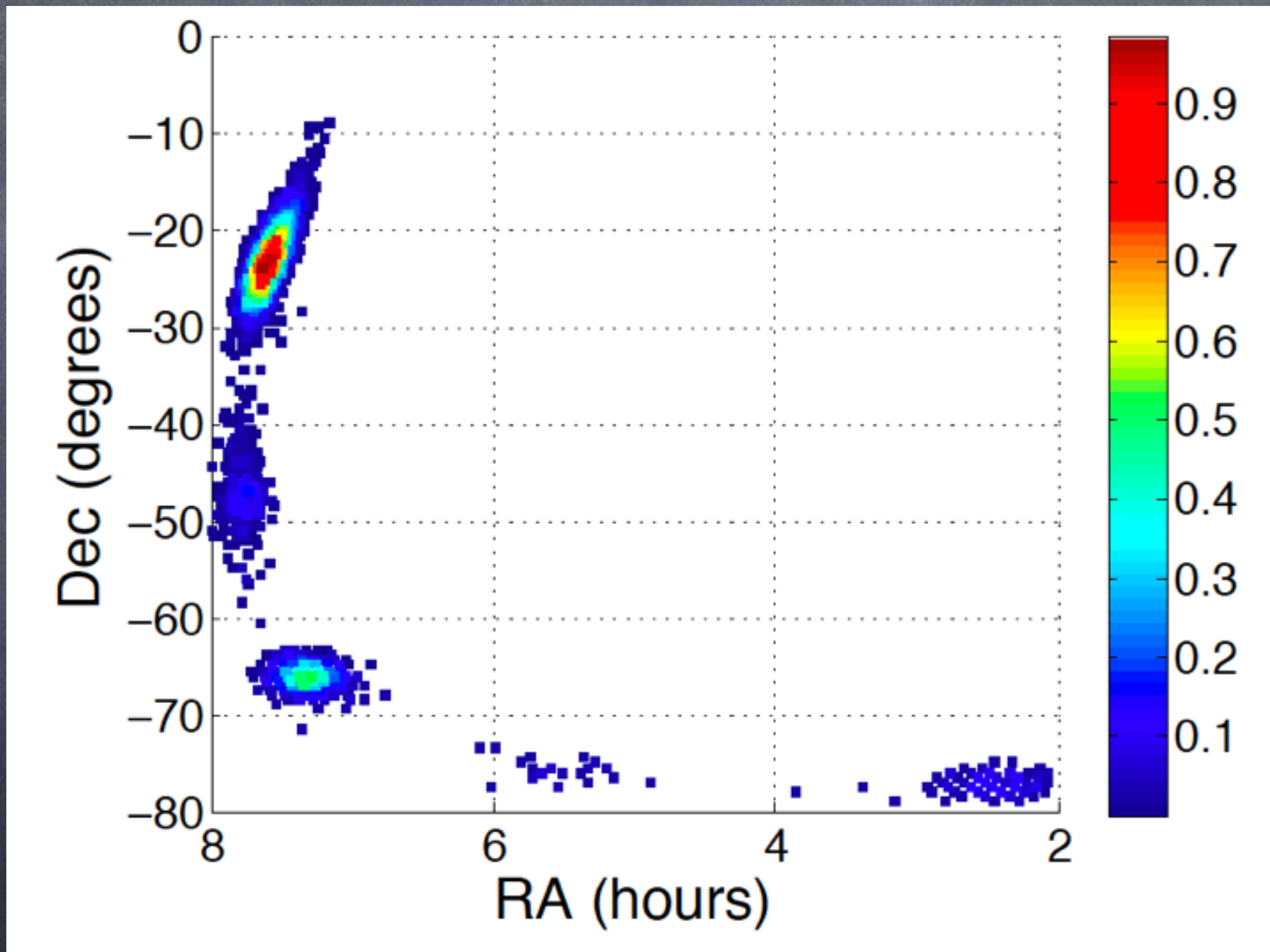
ns (or nsbh or bhbh) mergers => Gravitational waves





ALIGO Virgo and Kagra will become operatioan in 2016, 2018 and 2020.

Big Dog probability sky map

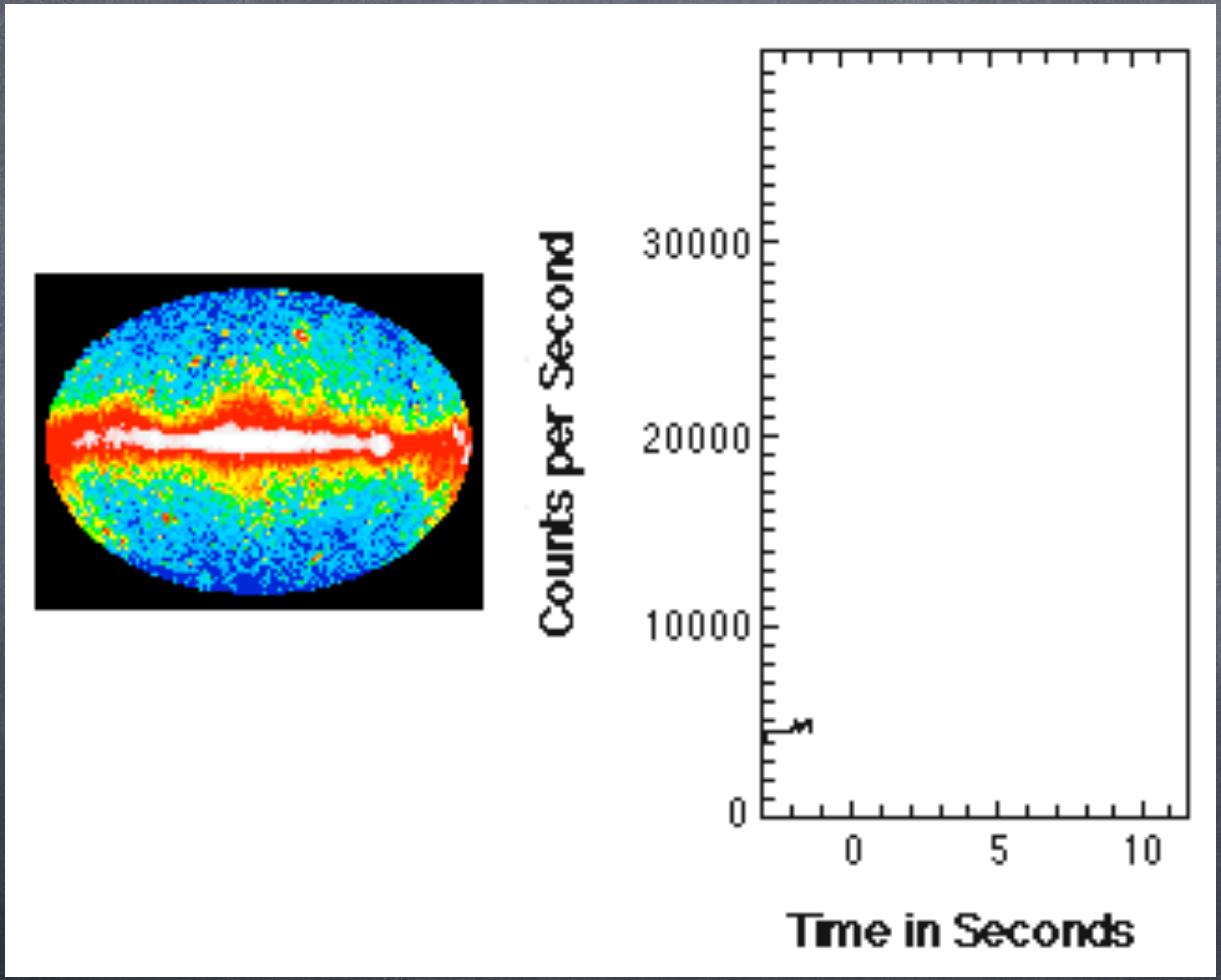


Why EM signal?

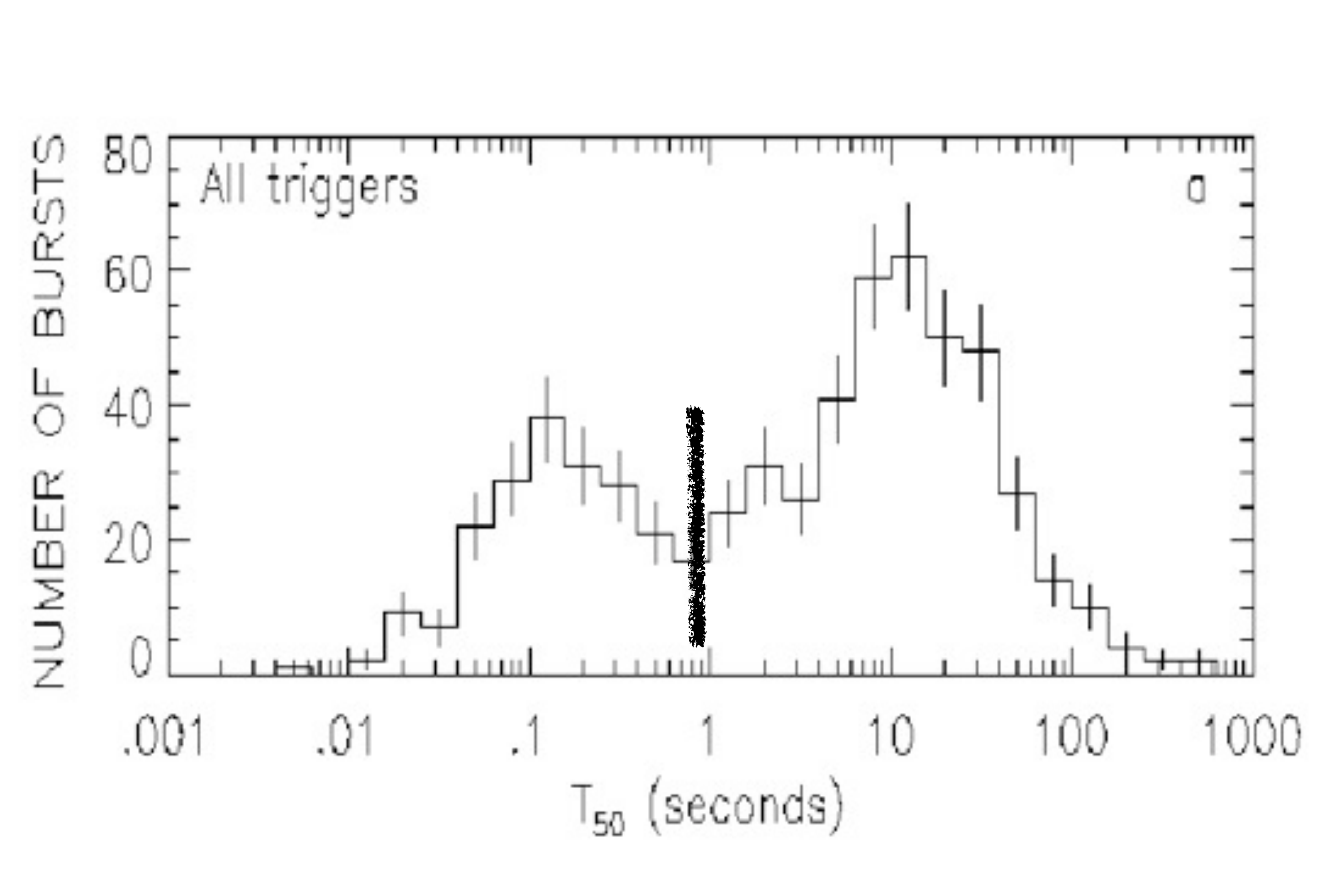
(Kochaneck & Piran 1993)

- Improve detectability (and confidence)
- Essential for localization
- Much more physics

Gamma Ray Bursts

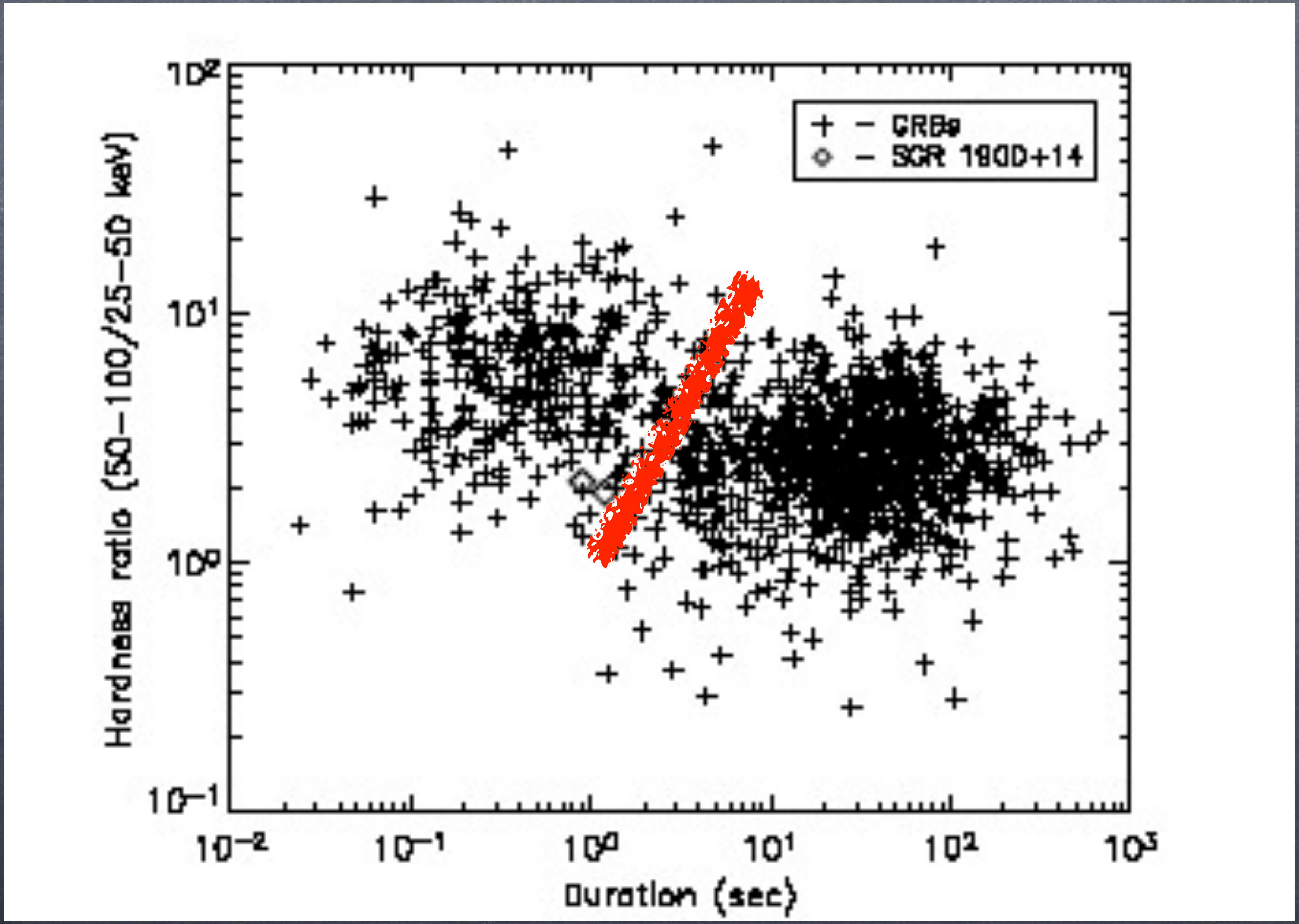


Long (and soft) and short (and hard)



- Traditional division at 2 seconds (based on BATSE data)

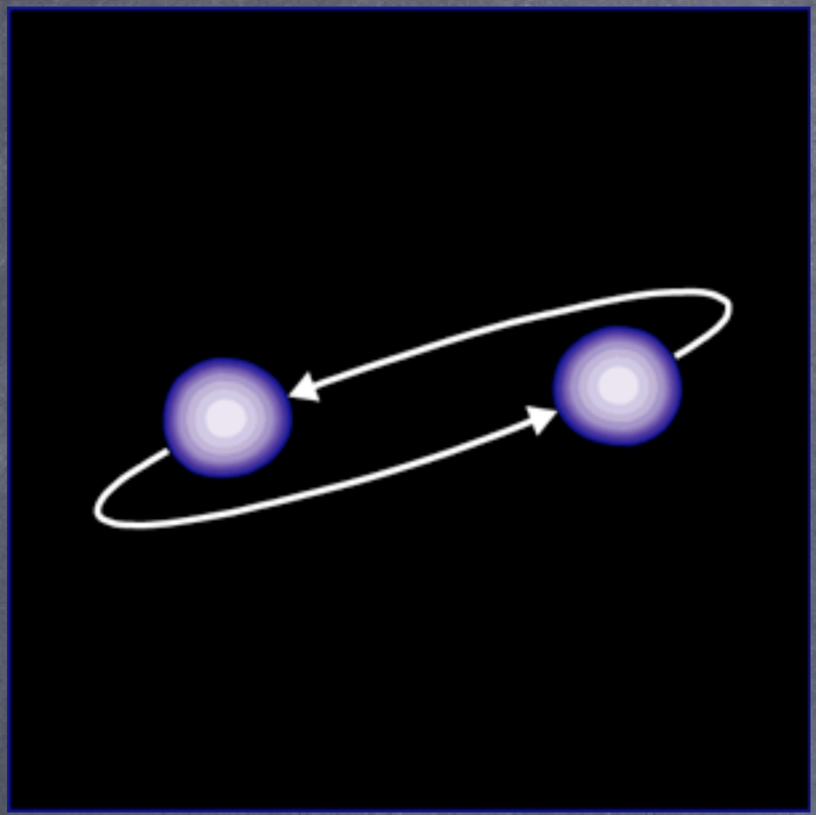
The photons of short GRBs have higher energies

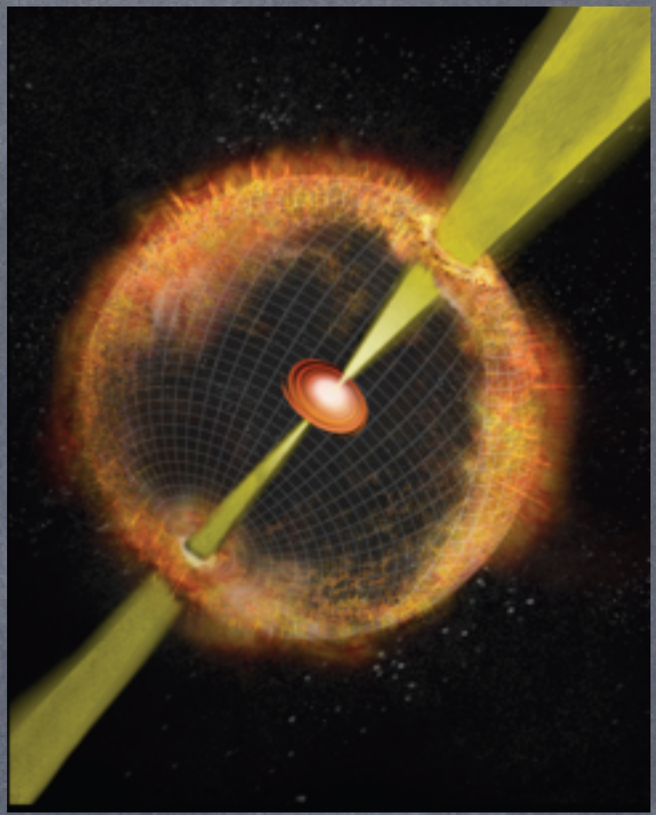


Wednesday, October 9, 13

Eichler, Livio, TP, Schramm, 88

MacFadyen & Woosley, 98

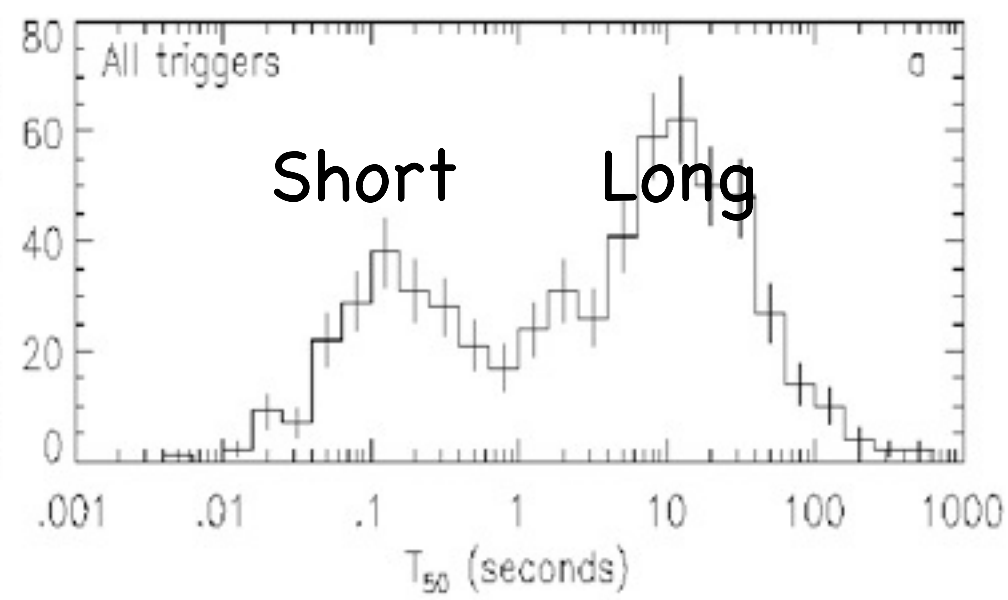




NS mergers

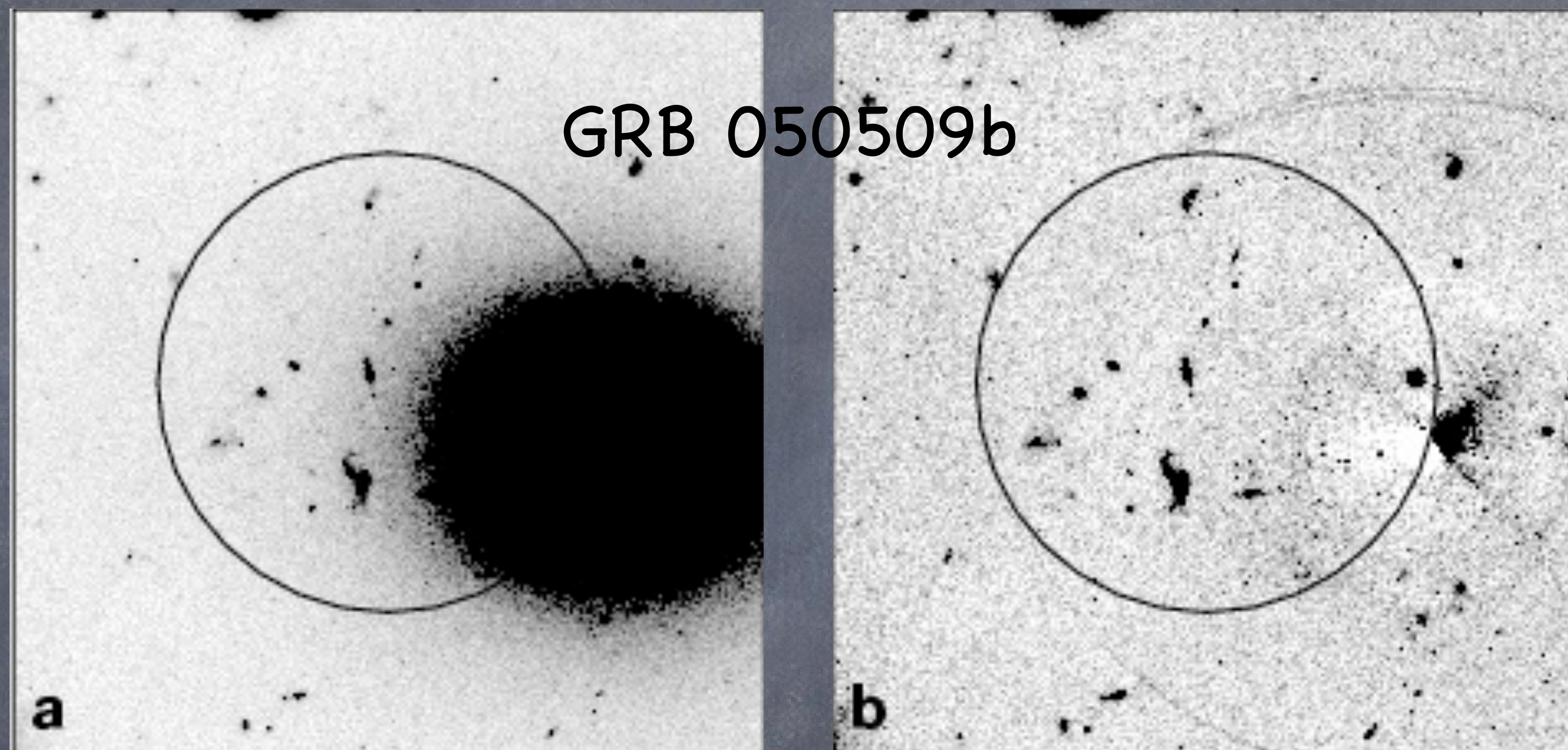
Collapsars

Indirect Observations



Direct Observations

Short GRBs Some Elliptical hosts -> Old stellar population



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

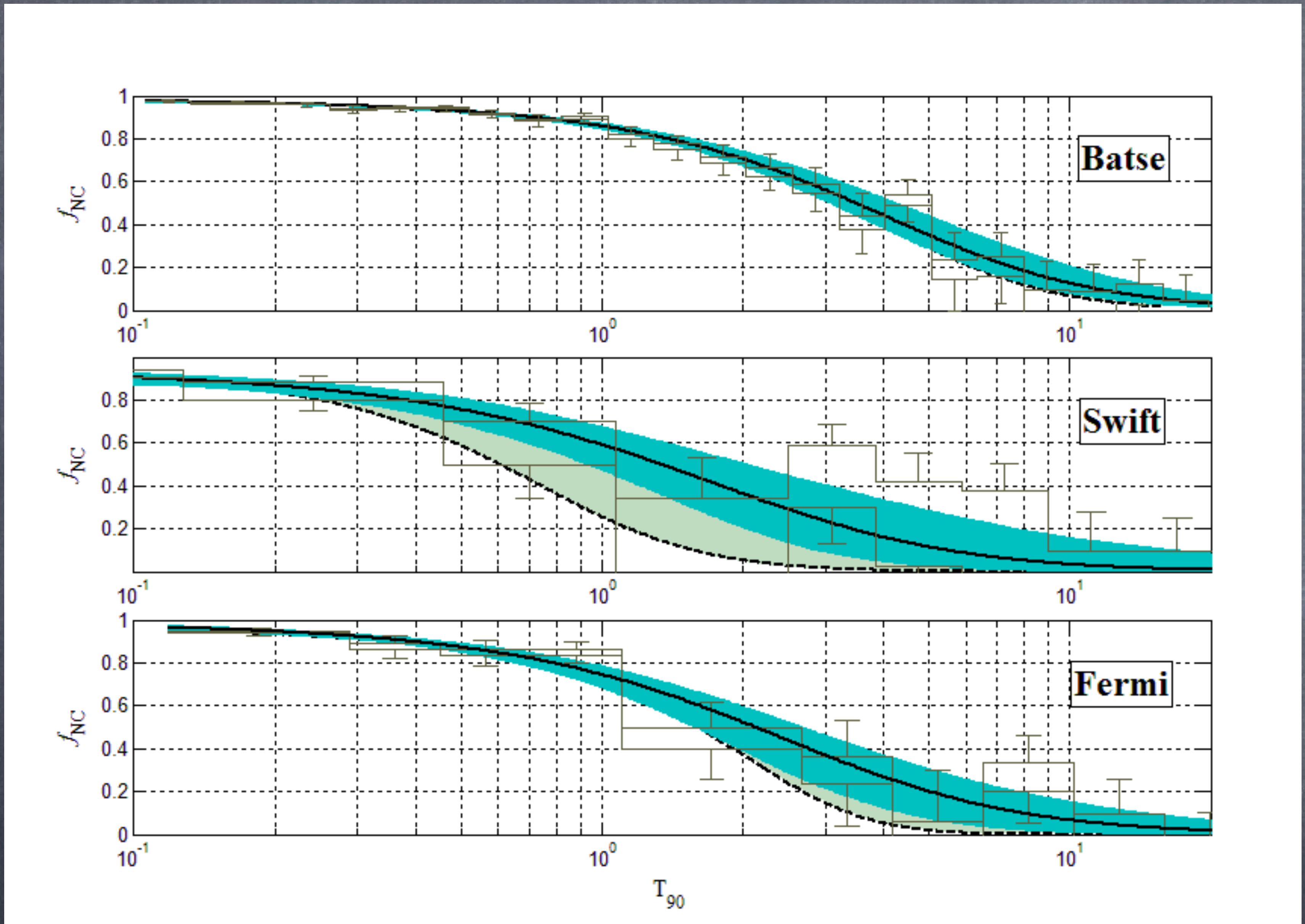
Bloom et al. 2005

Castro-Tirado et al. 2005

Gehrels et al. 2005

Hjorth et al. 2005

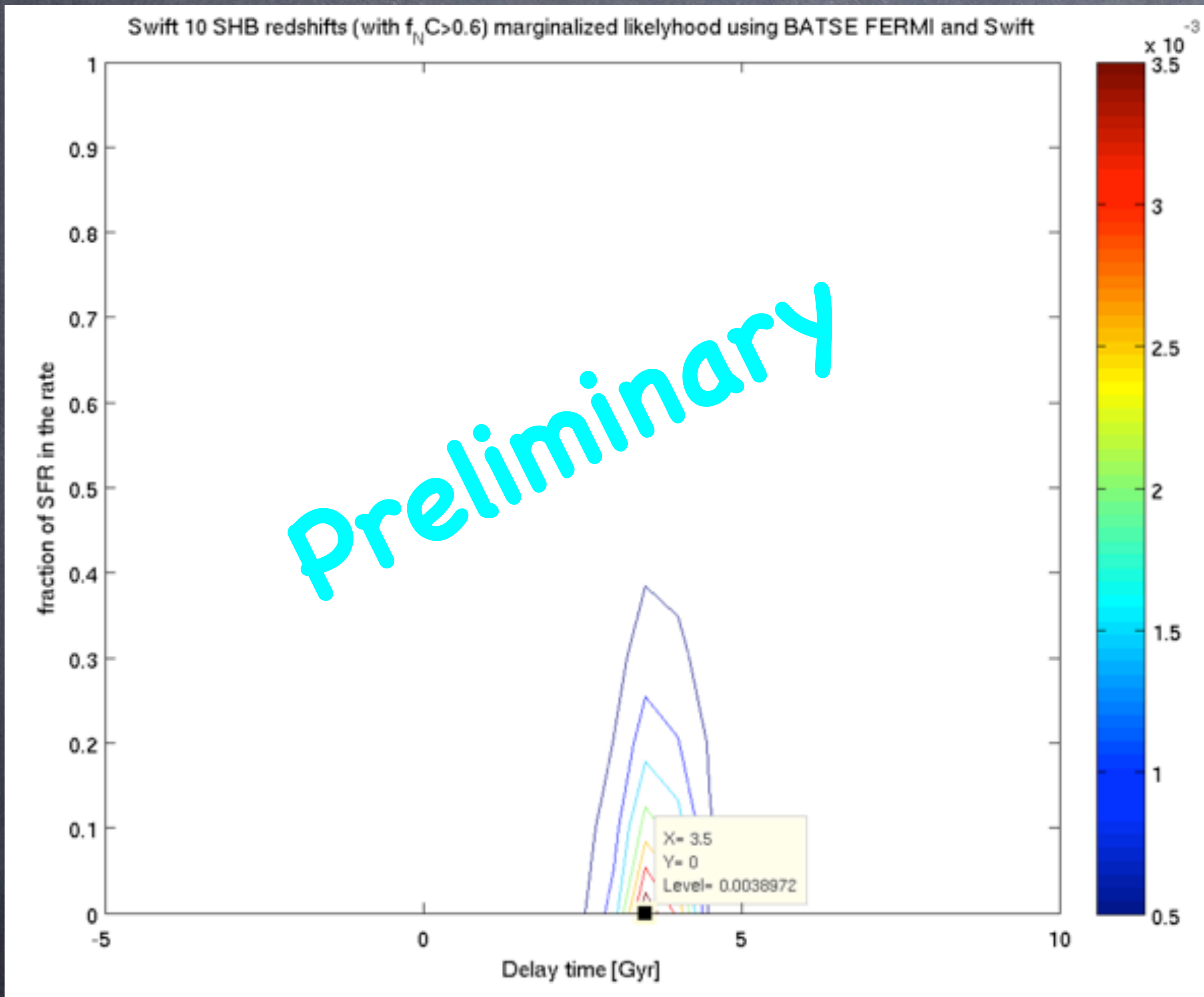
Not all short GRBs are "short" (Bromberg + 12)



And some long are "short"

The rate of Short GRBs

(Guetta TP, 05 Nakar + 05,..., Coward + 12, Wanderman & TP 13)



10 "genuine" Swift short GRBs

$R \approx 14^{(9-24)}$ $Gpc^{-3}\ yr^{-1}$

$\tau \approx 3.5^{(3-4)}$ Gyr

Preliminary

- Short GRBs don't follow the SFR!

Rate estimates

(Wanderman & TP in preparation)

$R \approx 14^{(9-24)}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

$\tau \approx 3.5^{(3-4)}\ \mathrm{Gyr}$

Preliminary

- This rate depends critically on the assumed lowest luminosity! (we use 2×10^{49} ergs/sec)
- The actual rate depends on a poorly constrained beaming factor (30?). NOT INCLUDED HERE!

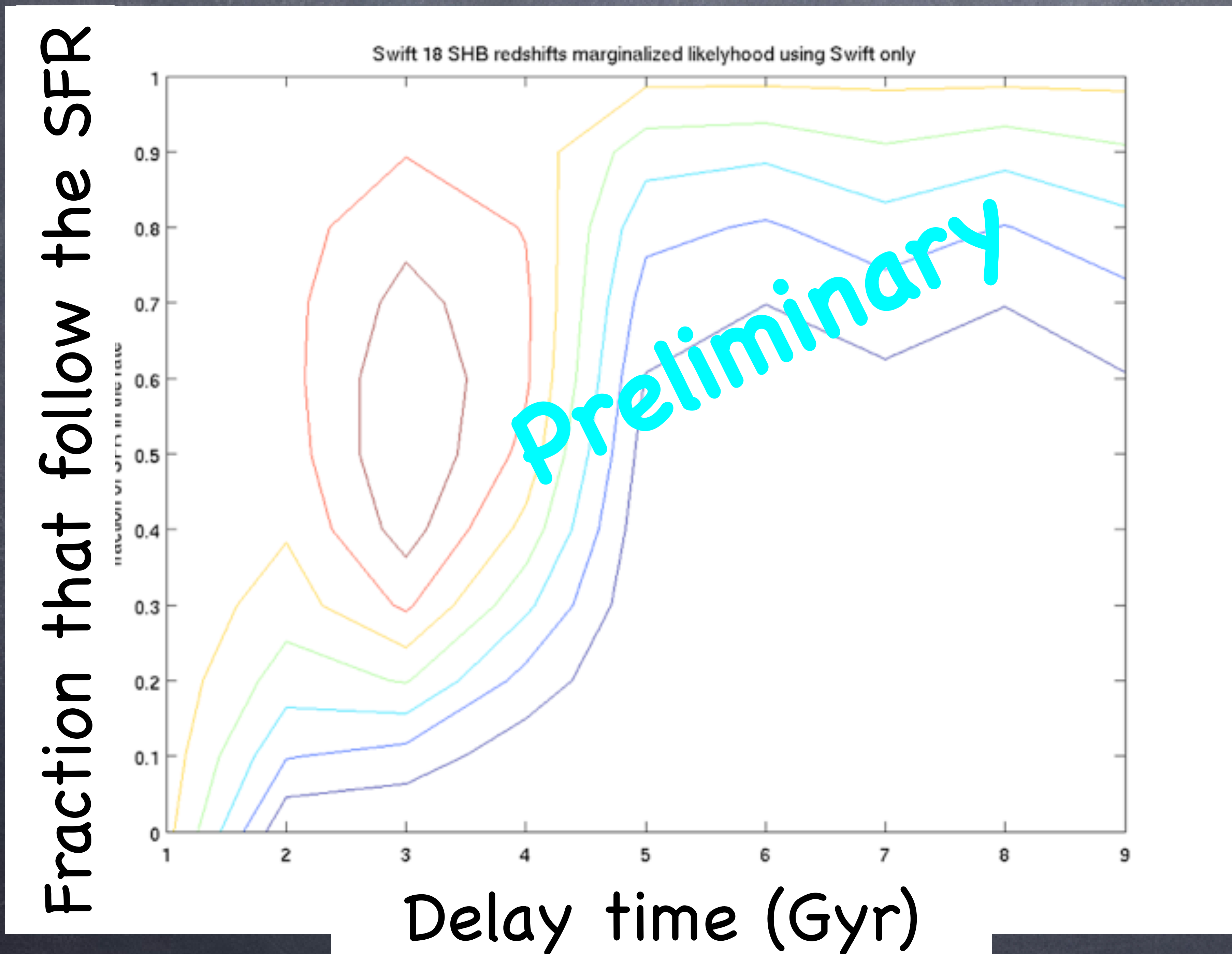
GRB130603B @ z=0.356

- GRB 130603B at z=0.356 fits perfectly the expectations based on the previous analysis (parameters don't change when this burst is added to the data and the margin narrows!)

Preliminary

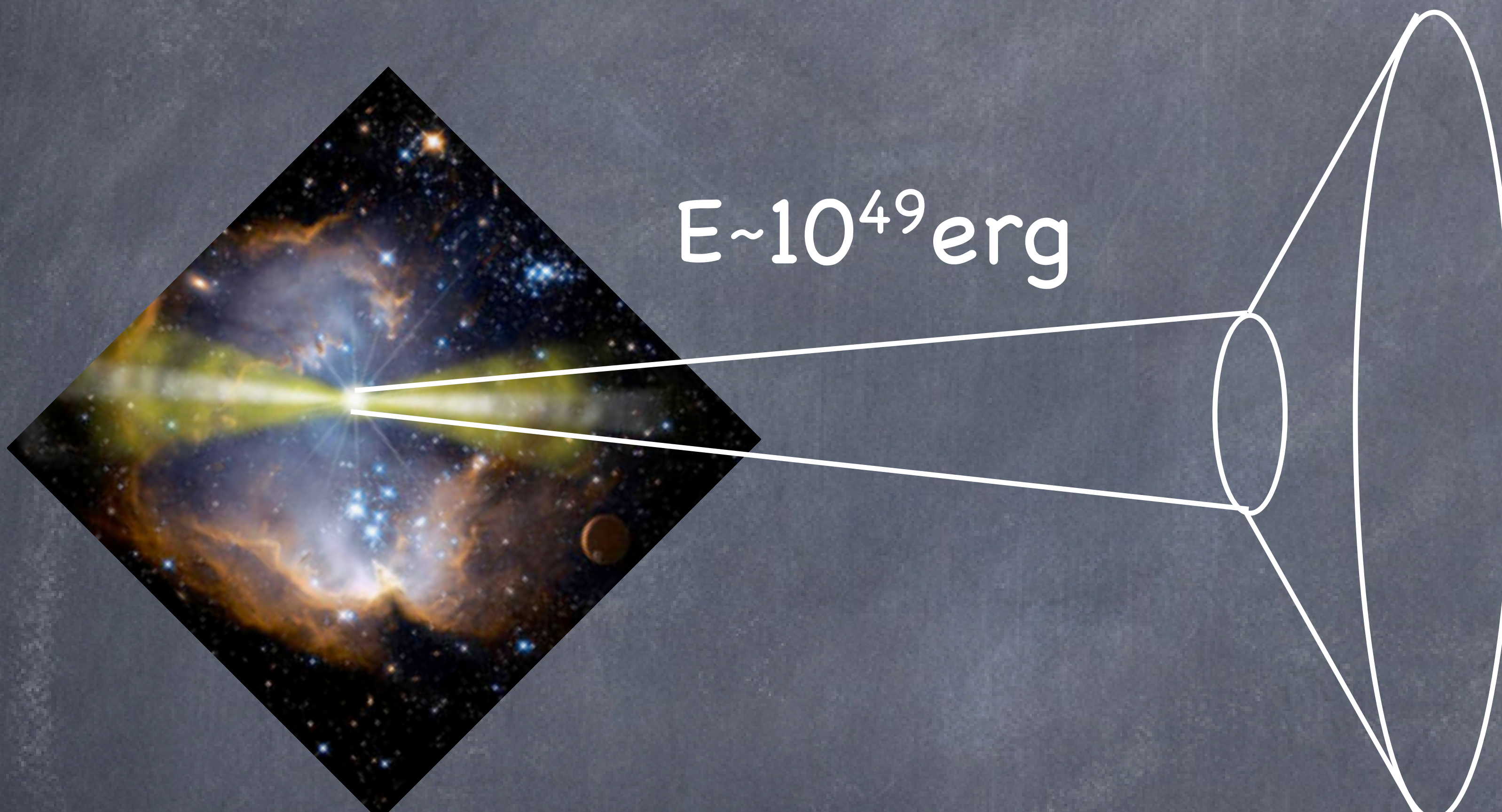
Short GRB Rate

(Guetta TP, 05 Nakar + 05,..., Coward + 12, Wanderman & TP 13)



All Swift short GRBs

EM Counterparts
GRBs are beamed (1/30?)



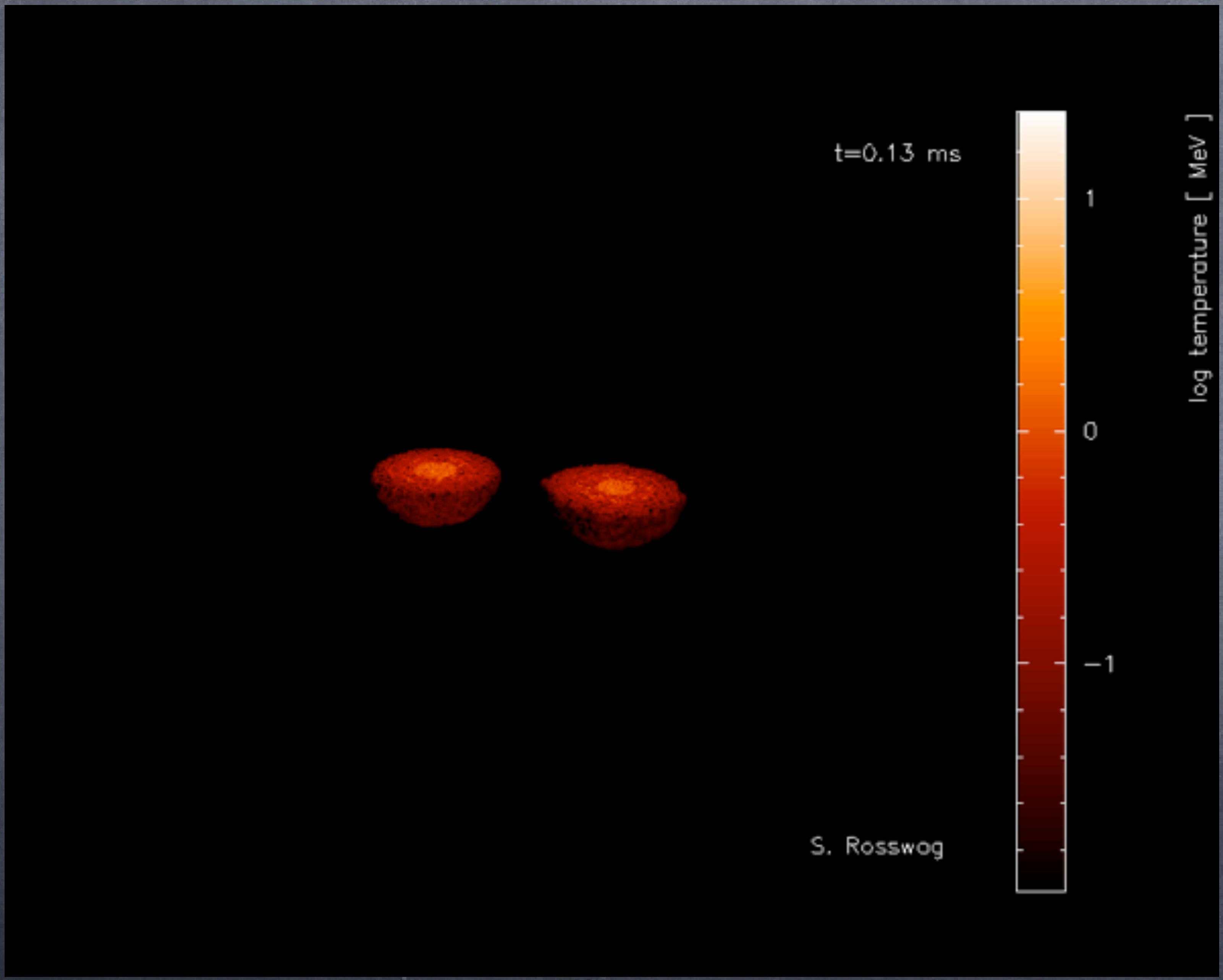
E~10^{49}erg

Prompt GRB +
Afterglow

Orphan afterglow -
late off axis emission

Orpha afterglow will be too weak

ns mergers eject 0.01–0.1 M_{sun}
$E_k \sim 10^{50}$–10^{51} ergs



Stephan Rosswog

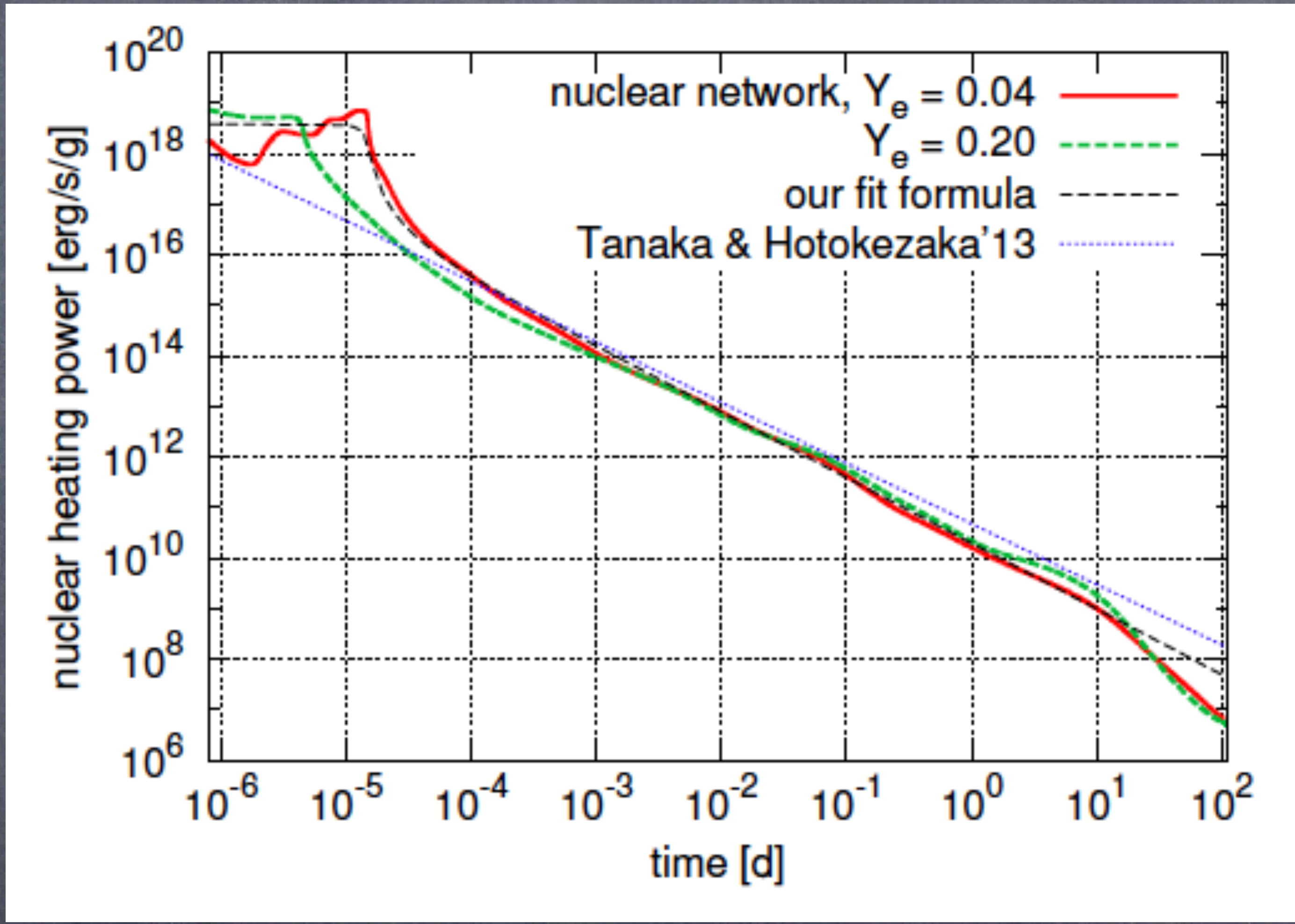
Macronova

Paczynski & Li 1997; Kulkarni 05; Metzger + 10, ...

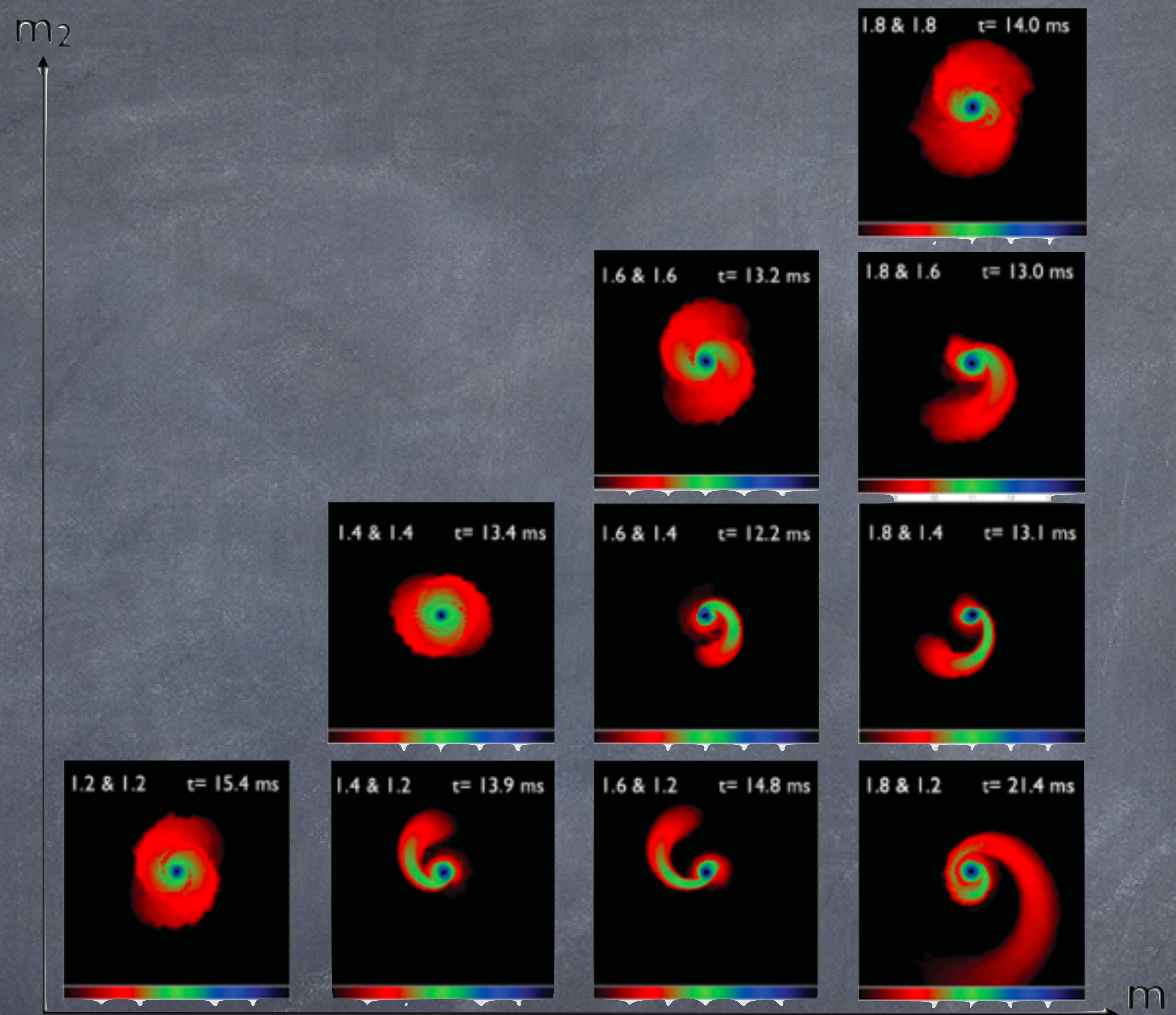
- Radioactive decay of the neutron rich matter (source of r process nucleosynthesis).
- $E_{radioactive} \approx 0.001\ Mc^2 \approx 10^{50}$ erg (mostly goes to acceleration of the ejecta to 0.05c)

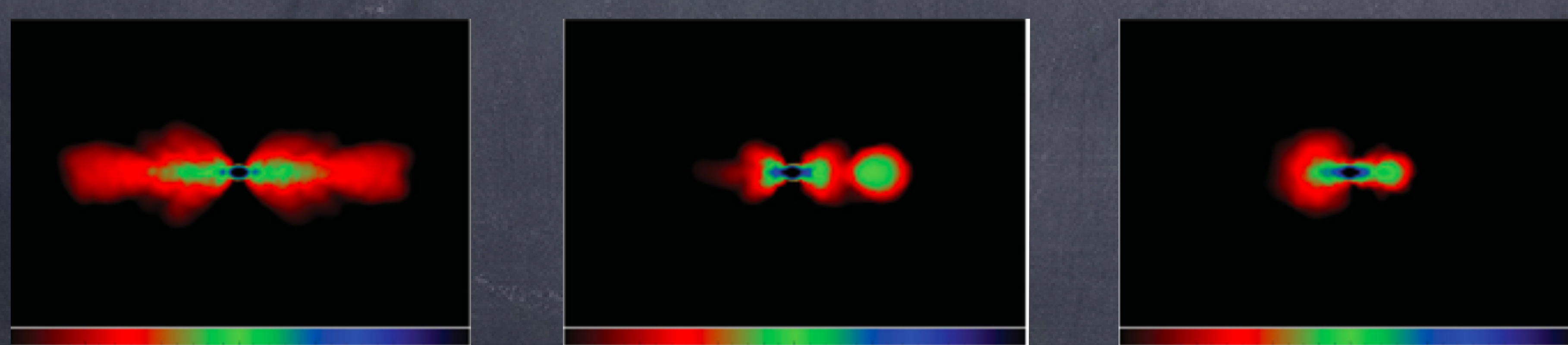
Radioactive Decay

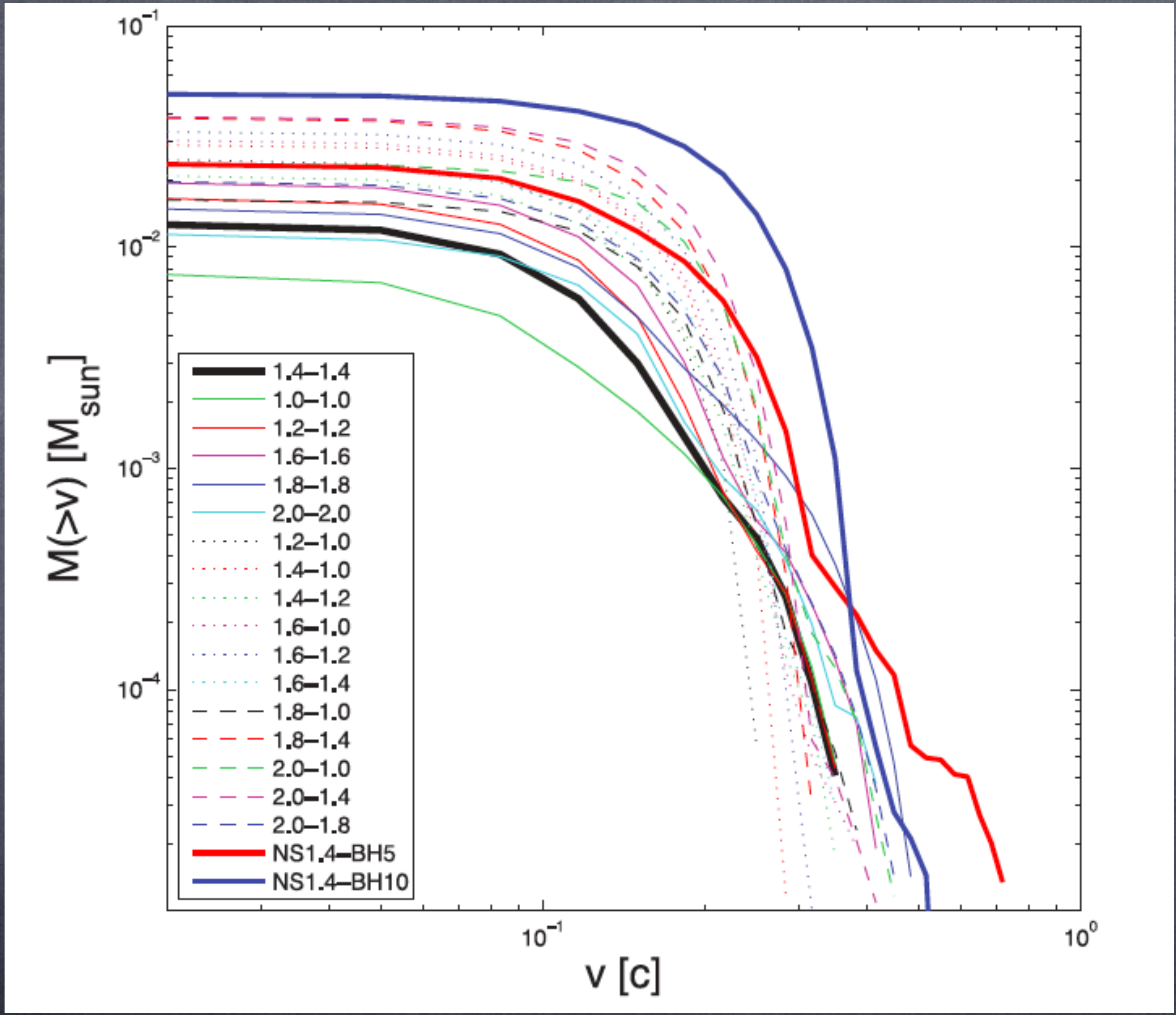
Korobkin + 13; Rosswog, Korobkin + 13



- After a second $dE/dt \propto t^{-1.3}$ (Freiburghaus+ 1999; Korobkin + 2013)

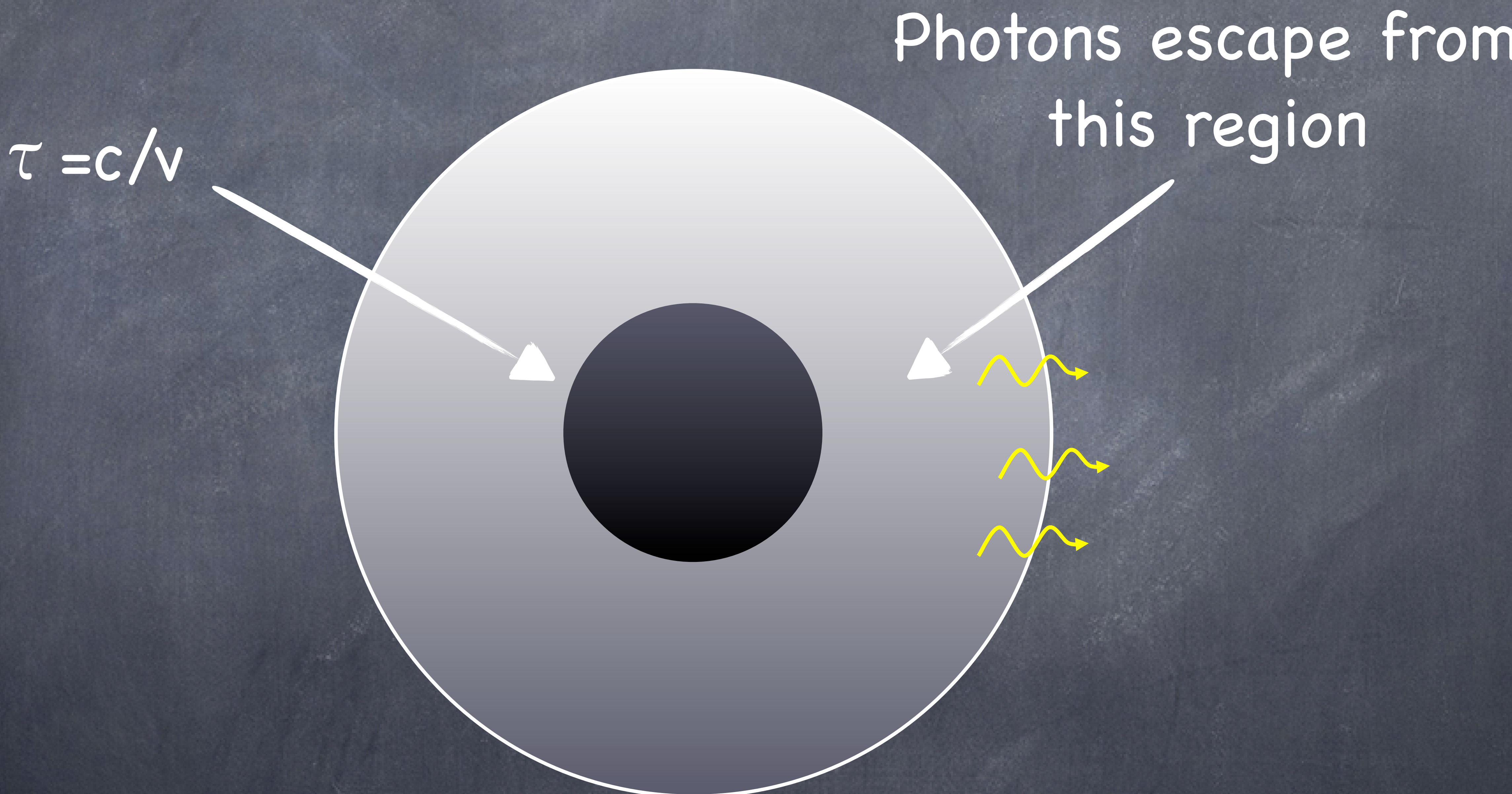

m2
1.8 & 1.8 t= 14.0 ms
1.6 & 1.6 t= 13.2 ms
1.8 & 1.6 t= 13.0 ms
1.4 & 1.4 t= 13.4 ms
1.6 & 1.4 t= 12.2 ms
1.8 & 1.4 t= 13.1 ms
1.2 & 1.2 t= 15.4 ms
1.4 & 1.2 t= 13.9 ms
1.6 & 1.2 t= 14.8 ms
1.8 & 1.2 t= 21.4 ms
m1



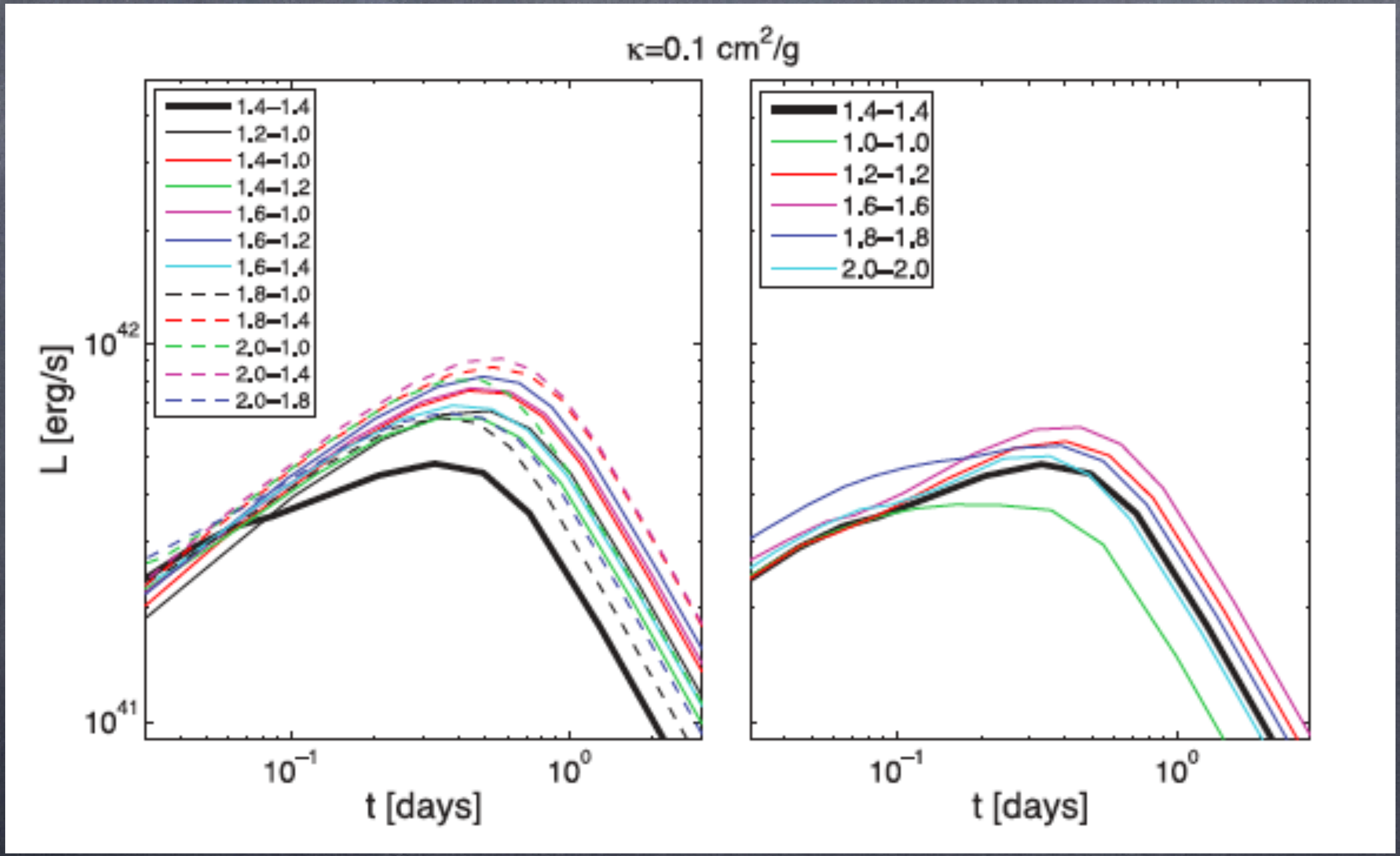


10^{-1}
10^{-2}
10^{-3}
10^{-4}
M(>v) [M$_{sun}$]
1.4–1.4
1.0–1.0
1.2–1.2
1.6–1.6
1.8–1.8
2.0–2.0
1.2–1.0
1.4–1.0
1.4–1.2
1.6–1.0
1.6–1.2
1.6–1.4
1.8–1.0
1.8–1.4
2.0–1.0
2.0–1.4
2.0–1.8
NS1.4–BH5
NS1.4–BH10
10^{-1}
10^{0}
v [c]

Macronova emission



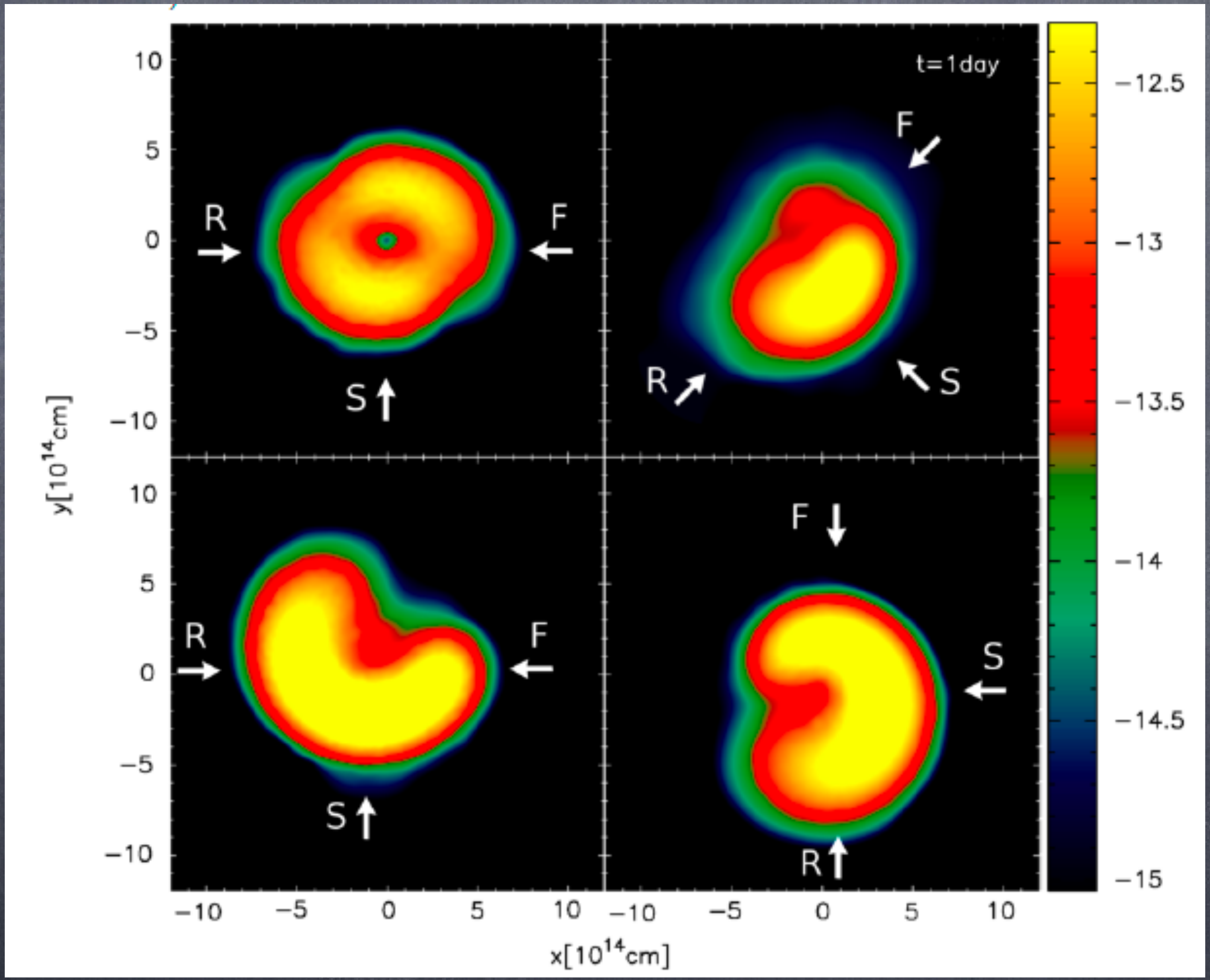
Early ns^2 macronova light curves



TP, Nakar, Rosswog, 13

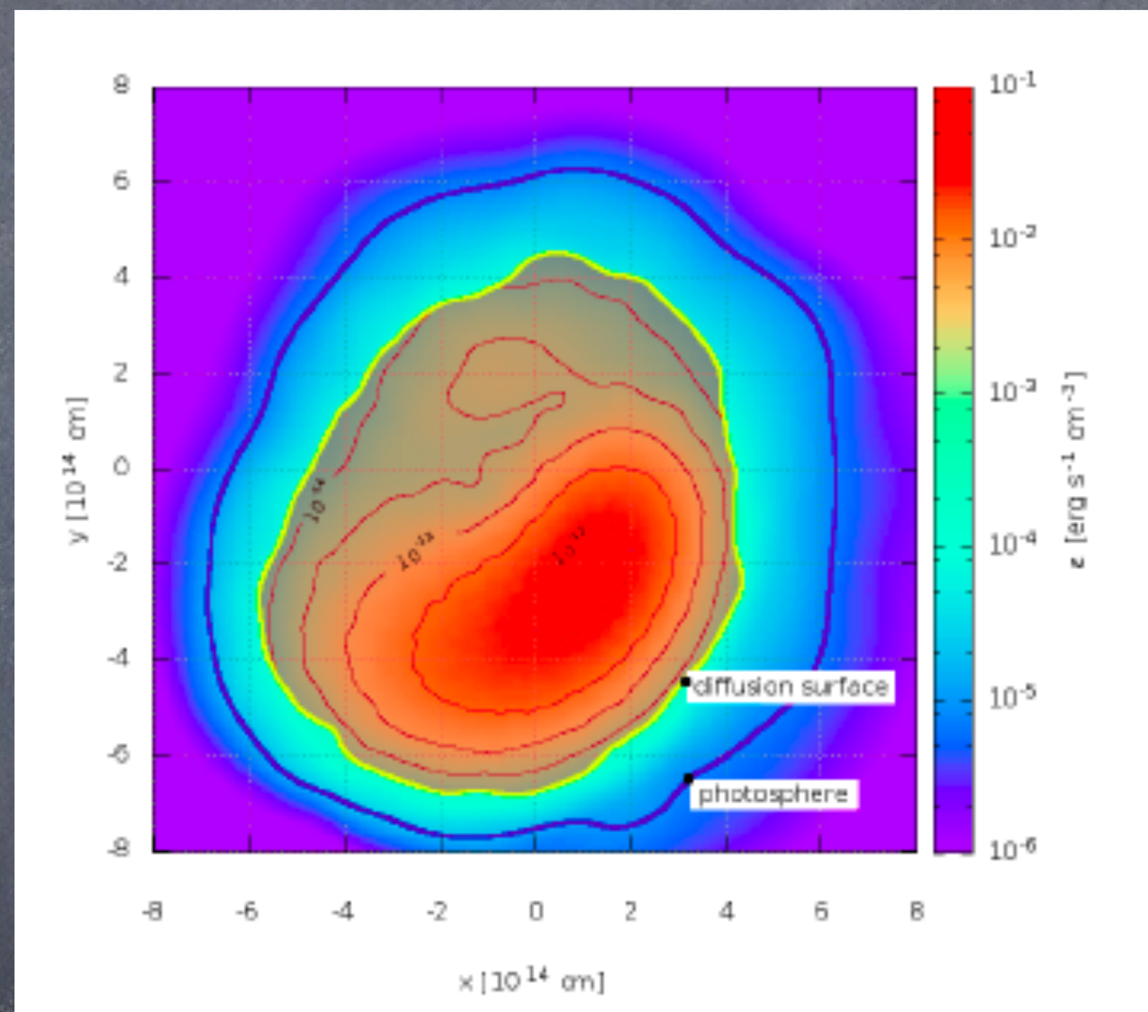
More detailed estimates

Grossman Korobkin TP Rosswog, 13



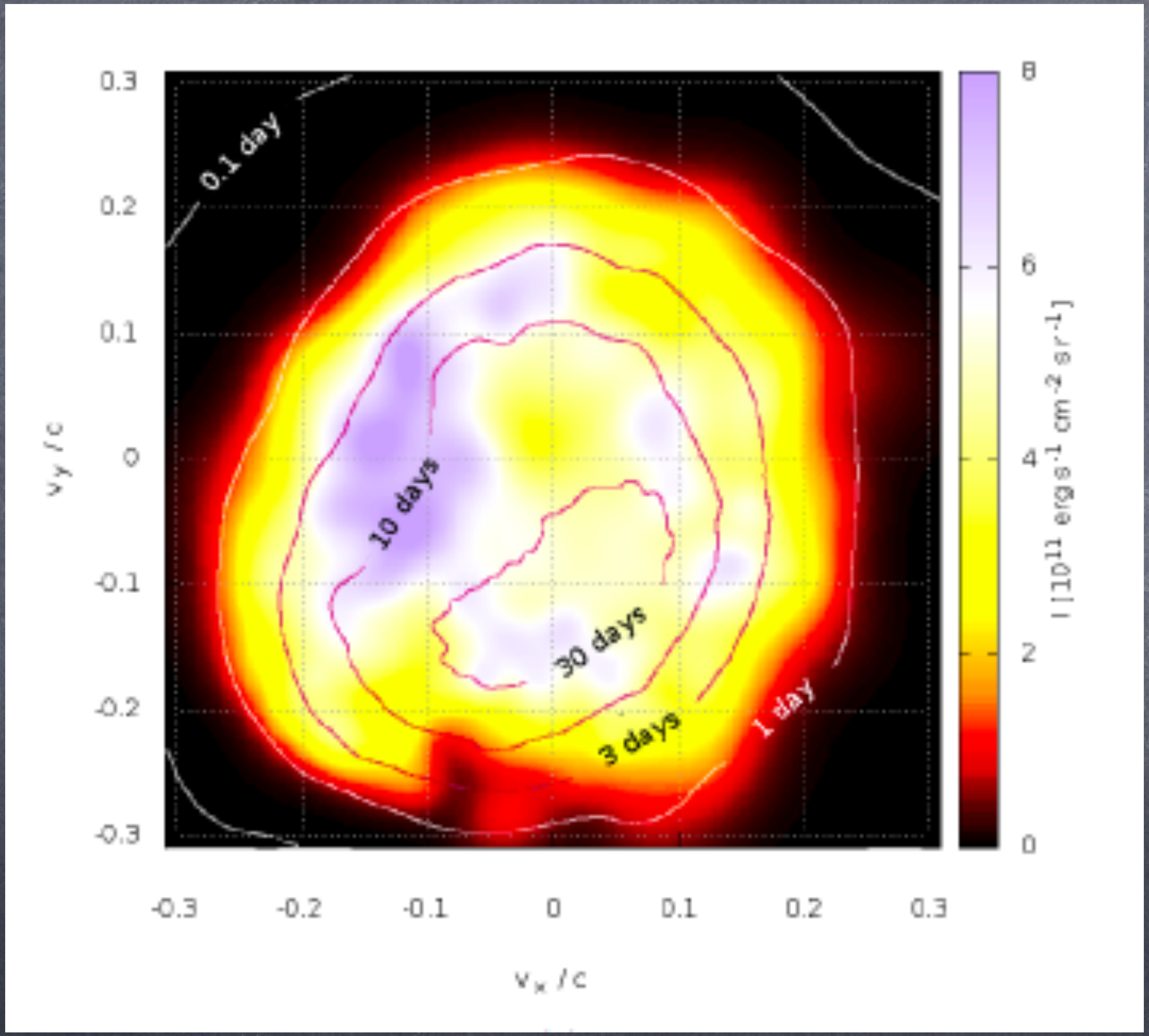
Radiation diffused from τ=c/v surfaces and escapes from τ=2/3 surfaces

Homologous evolution -> $\tau \propto t^{-2}$



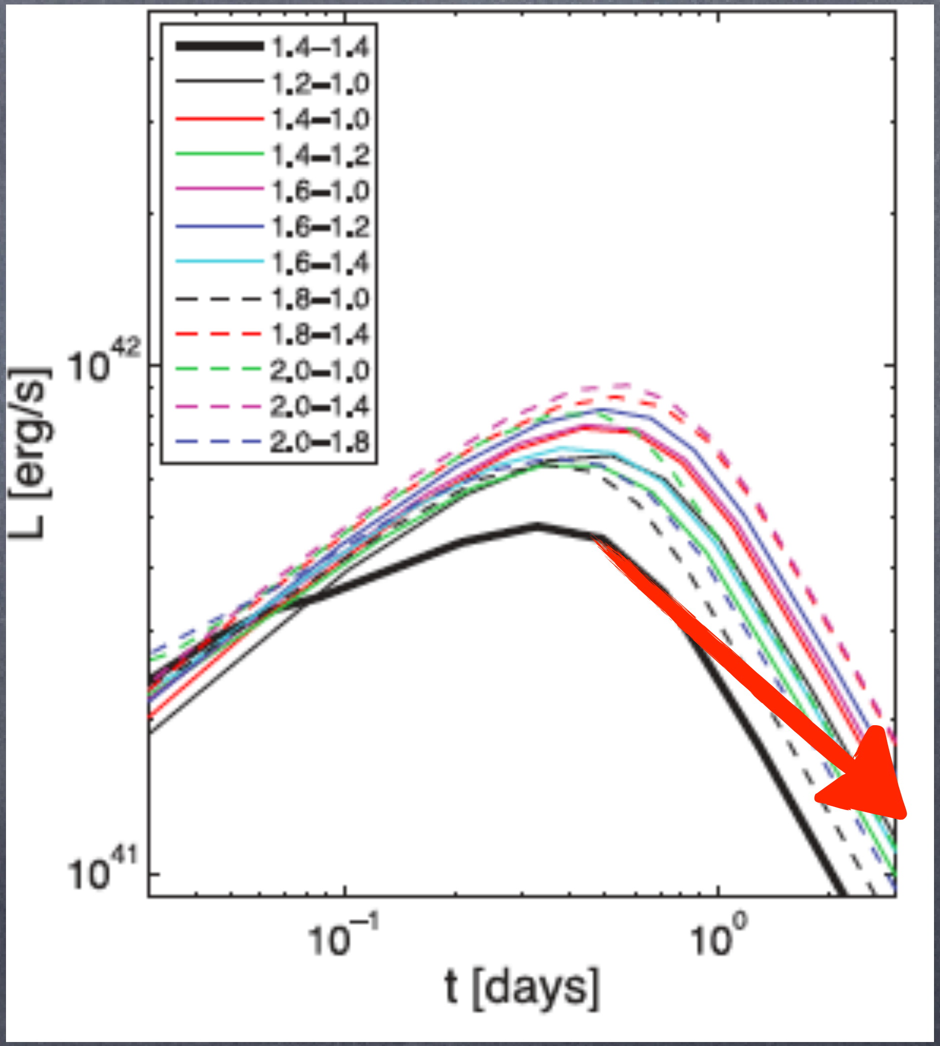
- $t_{max} \approx \sqrt{[M\kappa/(vc)]} \approx$ day
- $L_{max} \approx E_{rad}\,(t_{max}/1\ sec)^{-1.3} \approx 10^{40-42}$ erg/sec

Effective temperatures of the photosphere

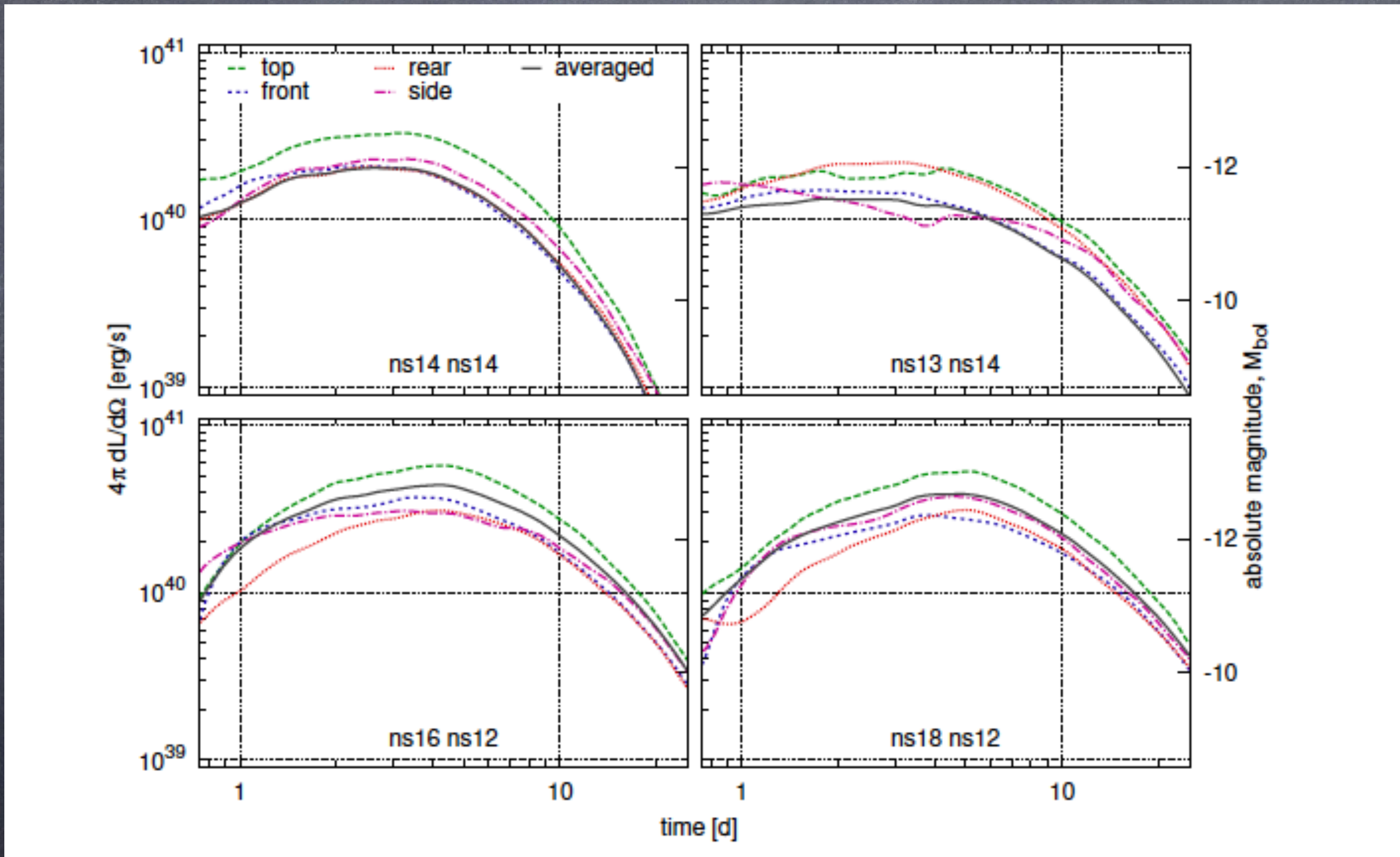


Opacity dominated by Lanthanides (Kasen + 13)

- $\kappa = 10 cm^2/gm$
- $t_{max} \propto \kappa^{1/2}$ (longer)
- $L_{max} \propto \kappa^{-0.65}$ (weaker)
- $T \propto \kappa^{-0.4}$ (redder)



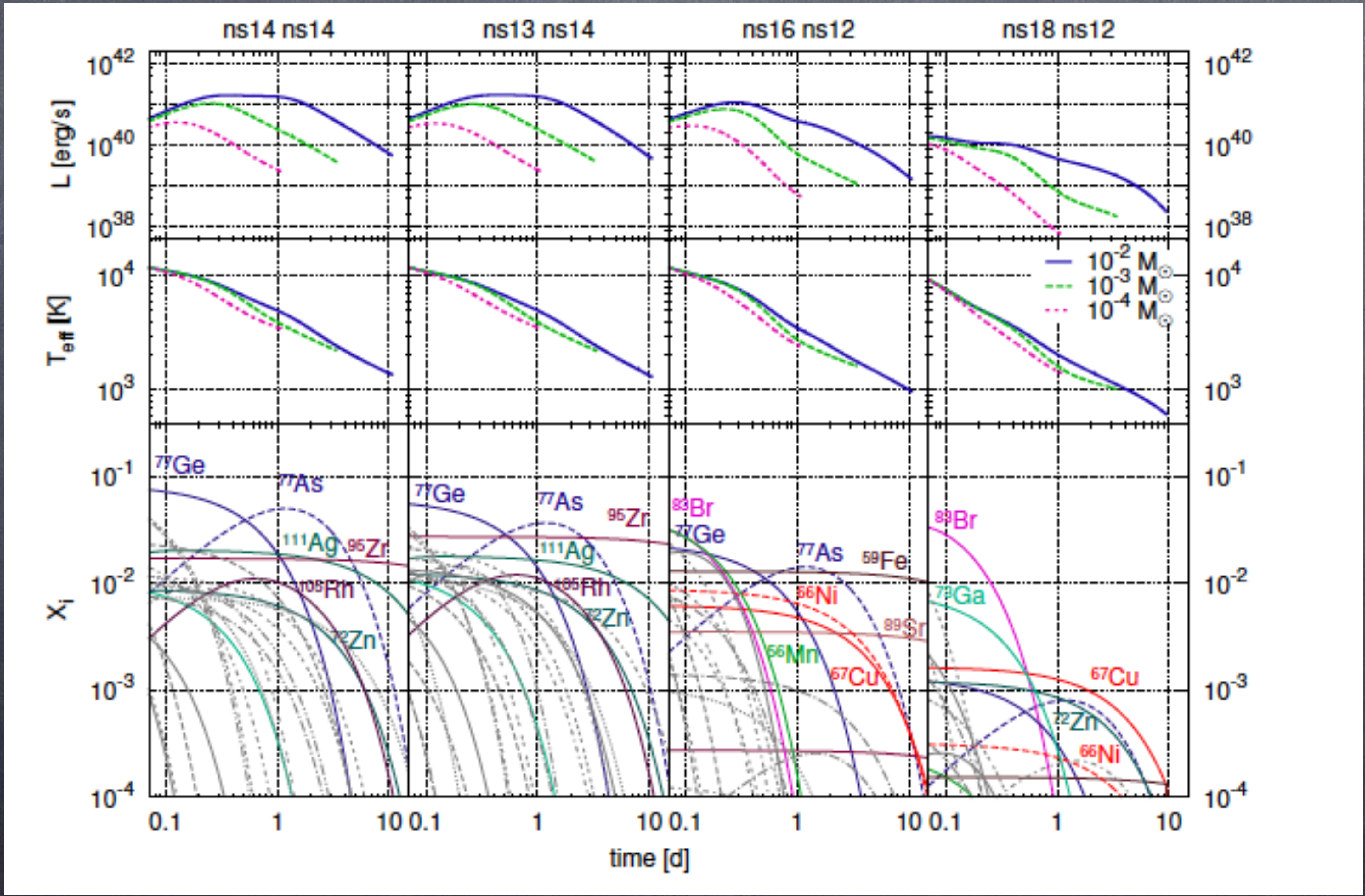
Bolometric light curves



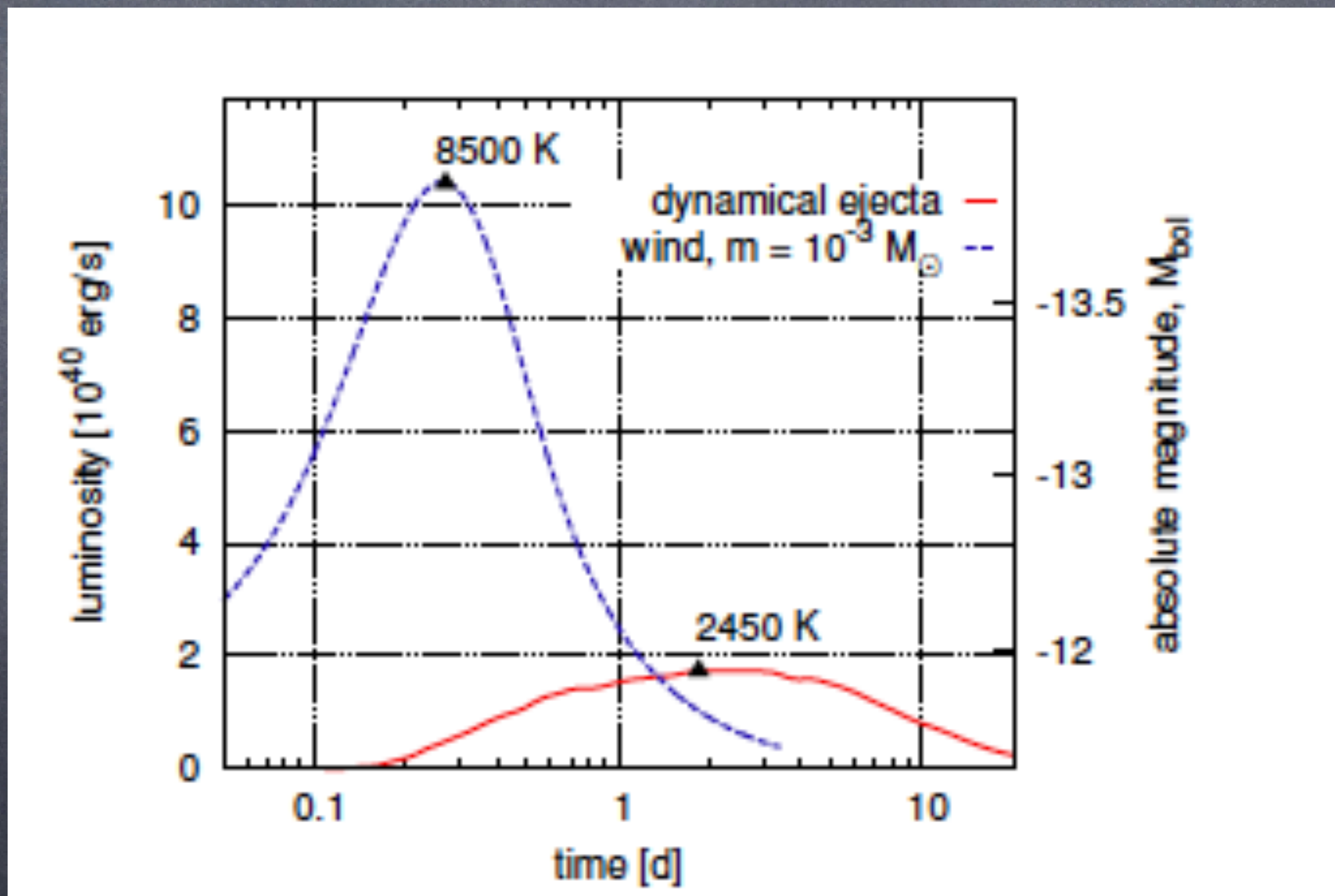
neutrino driven winds

Different Y_e, different nucleosynthsis, different opacity: $\kappa = 1 cm^2/gm$

neutrino driven winds - lightcurves



Combined macronova signal



Detectability

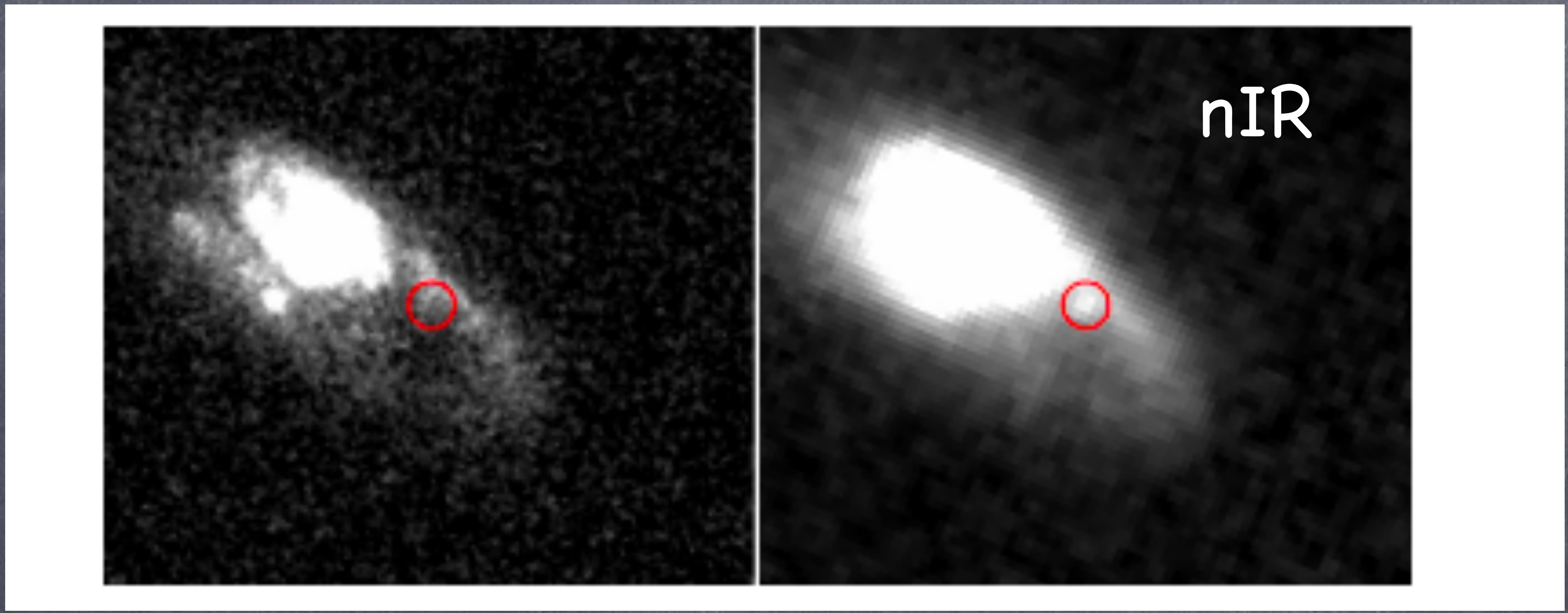
aLIGO will provide a 100 deg^2 error box

- The Dynamical ejecta IR signal
  - @ 300 Mpc -> $M_H \approx 23.5-24.5$ (-1 at optimal viewing angle) on a time scale of a few days
  - Rapid follow up is impossible in the IR.
- neutrino driven wind UV/Blue signal
  - @ 300 Mpc -> $M_H \approx 23.7-24.2$ on a time scale of a < day
  - Possible with SHC on subaru or continous cover with ZTF or equivalent.

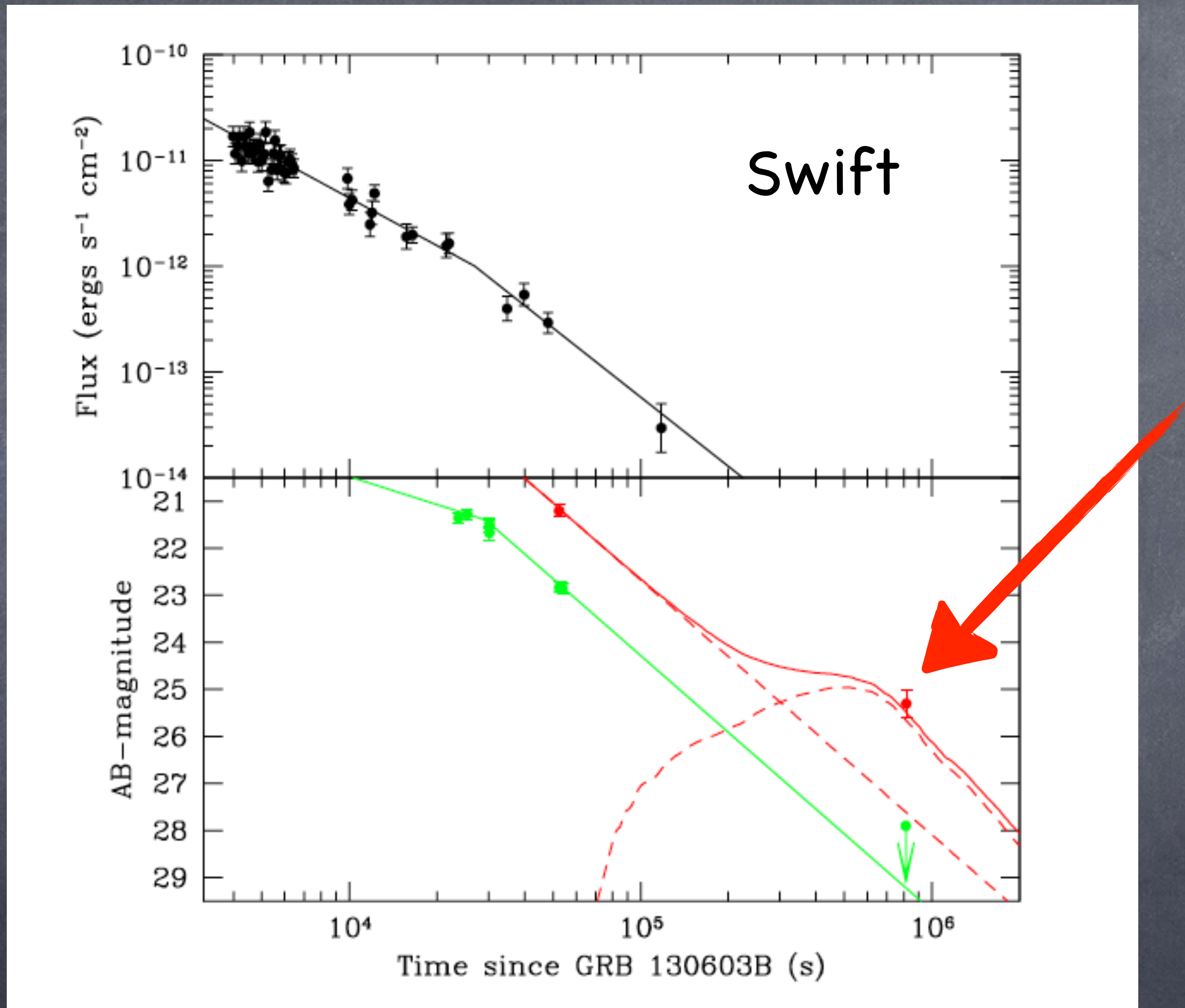
Detection strategy

- Deep search in the optical using HSC or multiple exposures on a very wide field telescope (ZTF).
- With detection deep localized search in the near IR
- Blind searches in Optical and clearly in IR are hopeless (a few single event detections per year with the LSST).

GRB130603B @ z=0.356



HST image (Tanvir + 13)



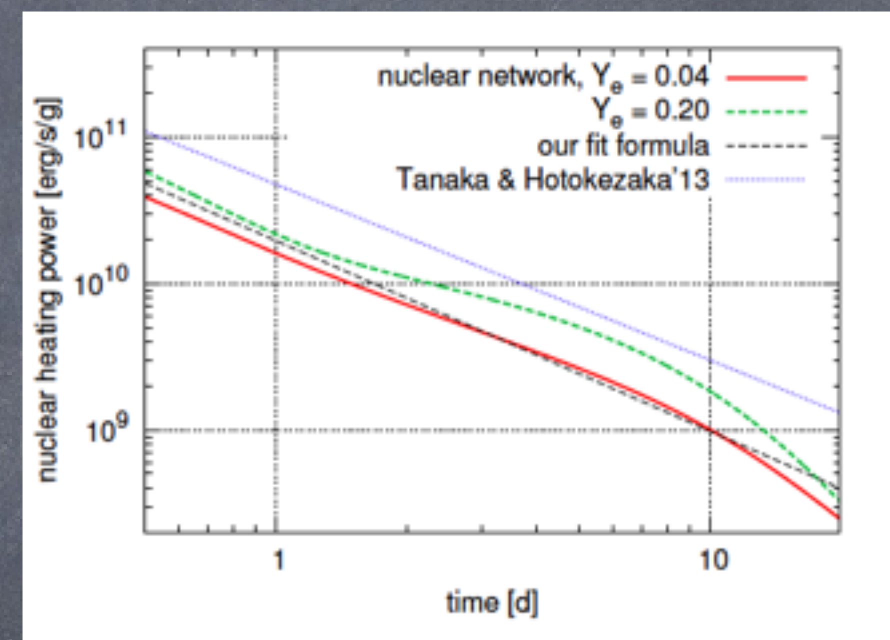
?

From Tanvir + 13

GRB130603B @ z=0.356 nIR transient

- Consistent with Barnes & Kasen (13) and Tanaka & Hotozoka (13)

- But Both groups overestimate radioactive heating rate by a factor of 3-5



- The expected signal is slightly too large

If correct

- Confirmaiton of the neutron star merger model for short GRBs (Eichler, Livio, Piran & Schramm 1989)

R process nucleosynthesis

- The ejected mass is about 0.1 M_{sun}
- Neutron star mergers are the source of r-process nucleo synthesis (Gold, Silver, Platinum, Plotonium, Uranium etc...)
- $M_{r\text{-}proc}=10^{-4}\ M_{sun} = 0.1\ M_{sun}\ T\ R_{merger}$
  => $R_{merger} = 10^{-5}$/yr/MWgalaxy = 100 /yr/Gpc^3
- Consistent with merger rate estimates

Early nucleosynthesis - a challenge

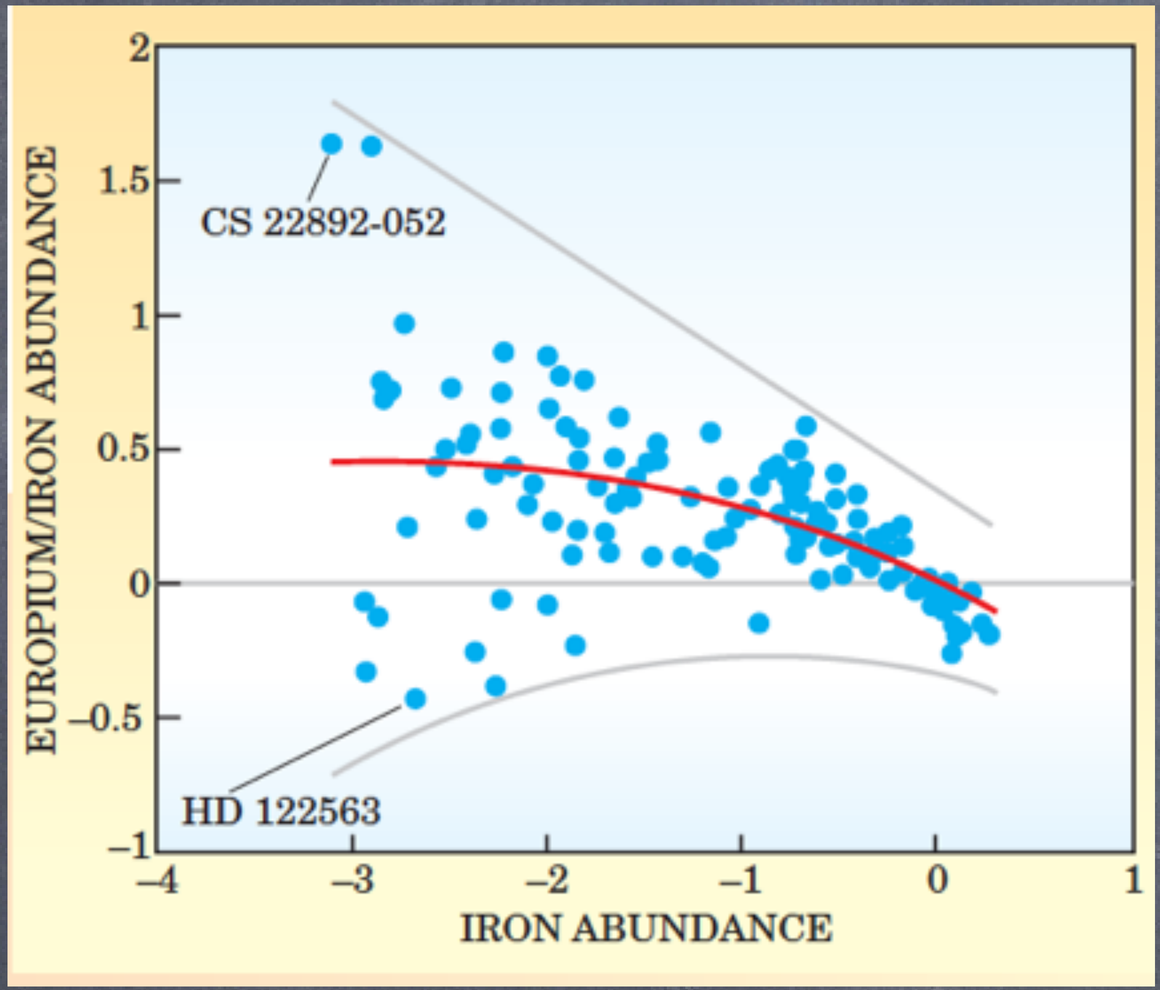
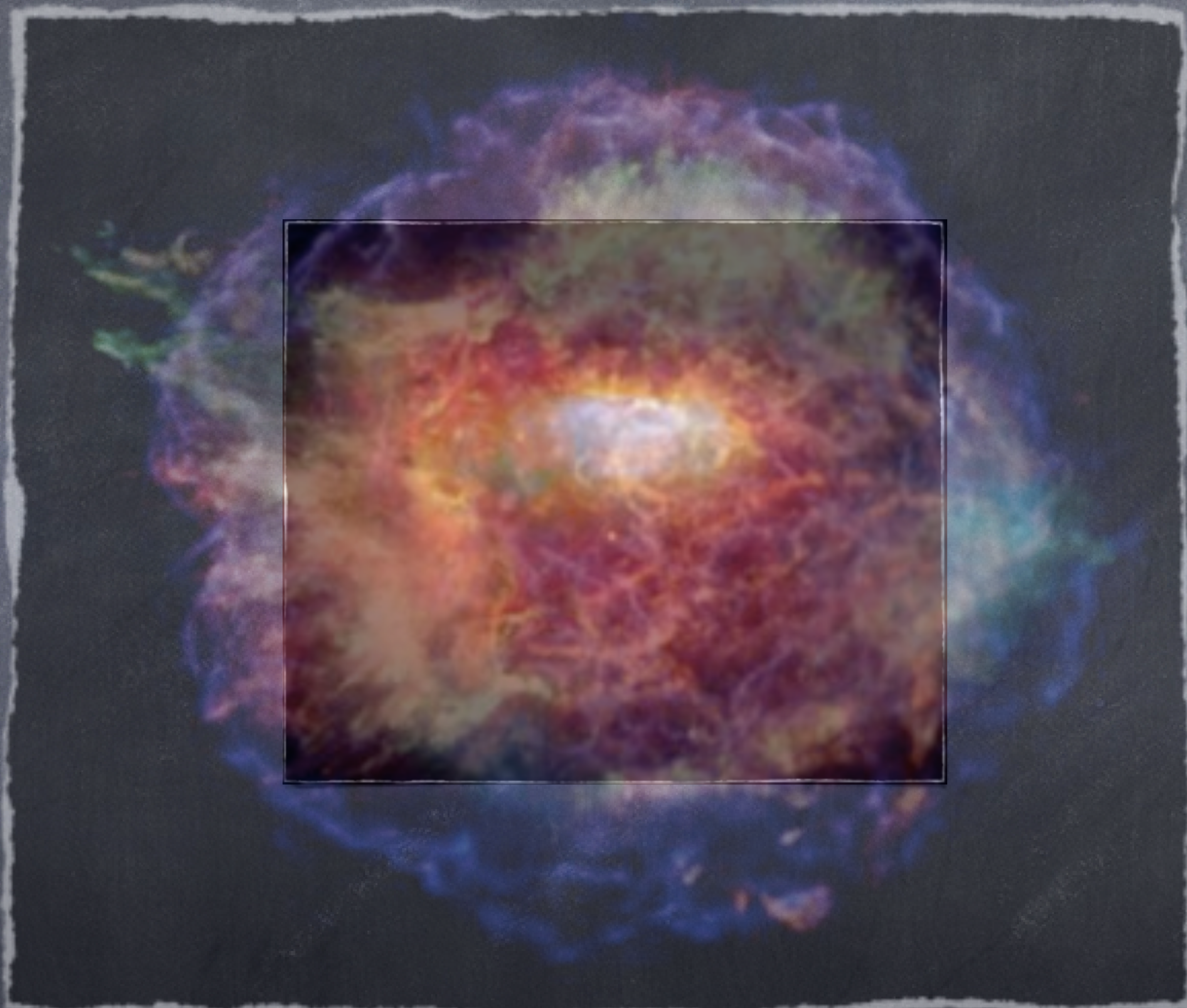


Figure 6. Europium abundance in a large sample of old and young stars, age being inferred from Fe abundance. The halo star HD 122563 is almost as Fe-poor as CS 22892-052, and therefore presumably just about as old, but it has much less Eu, an element made only in the r-process. The red line is a least-square-fit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

A population of fast mergers?

From Cowan and Thielemann



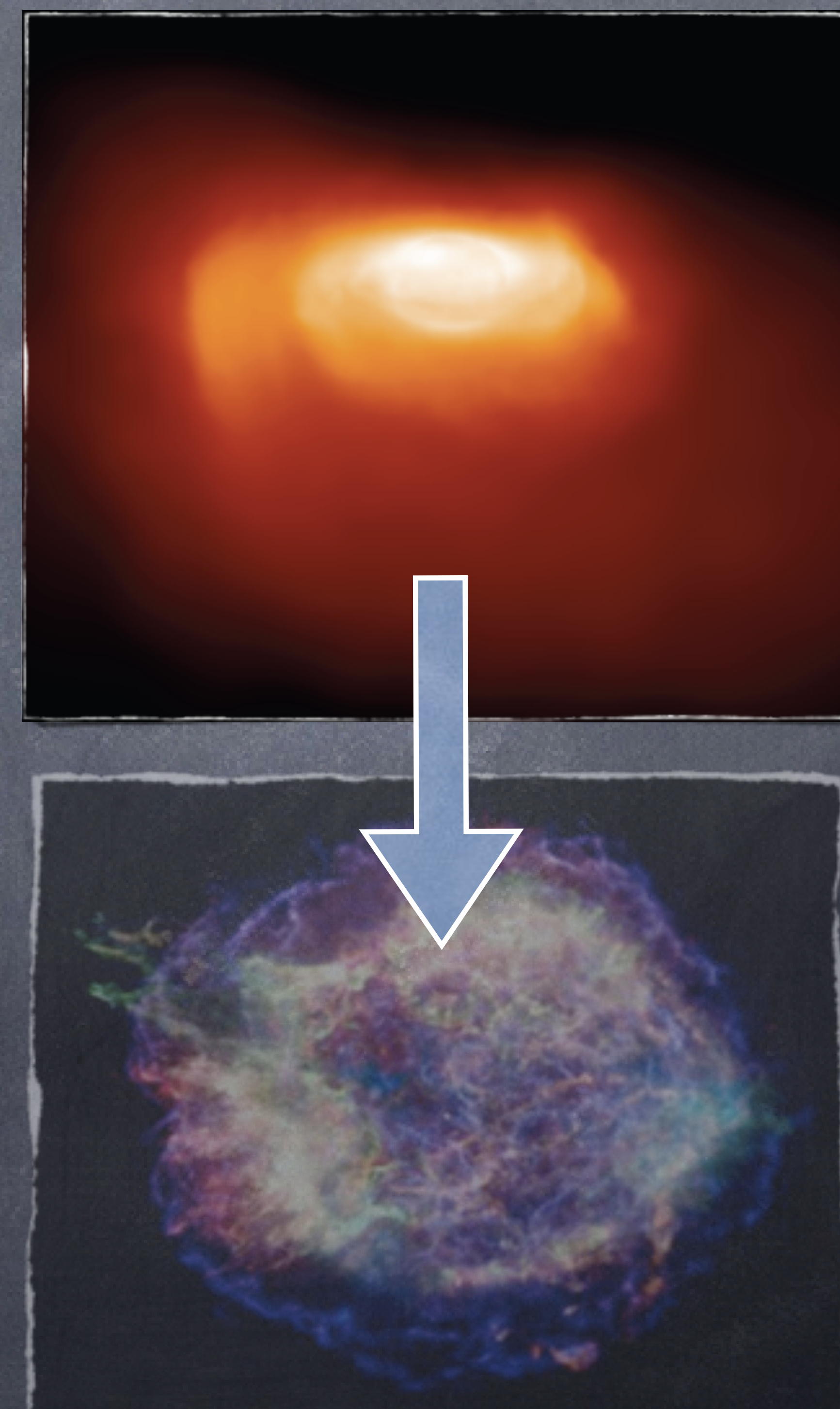
Radio Flares

Nakar & TP 2011; TP, Nakar Rosswog 2013

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

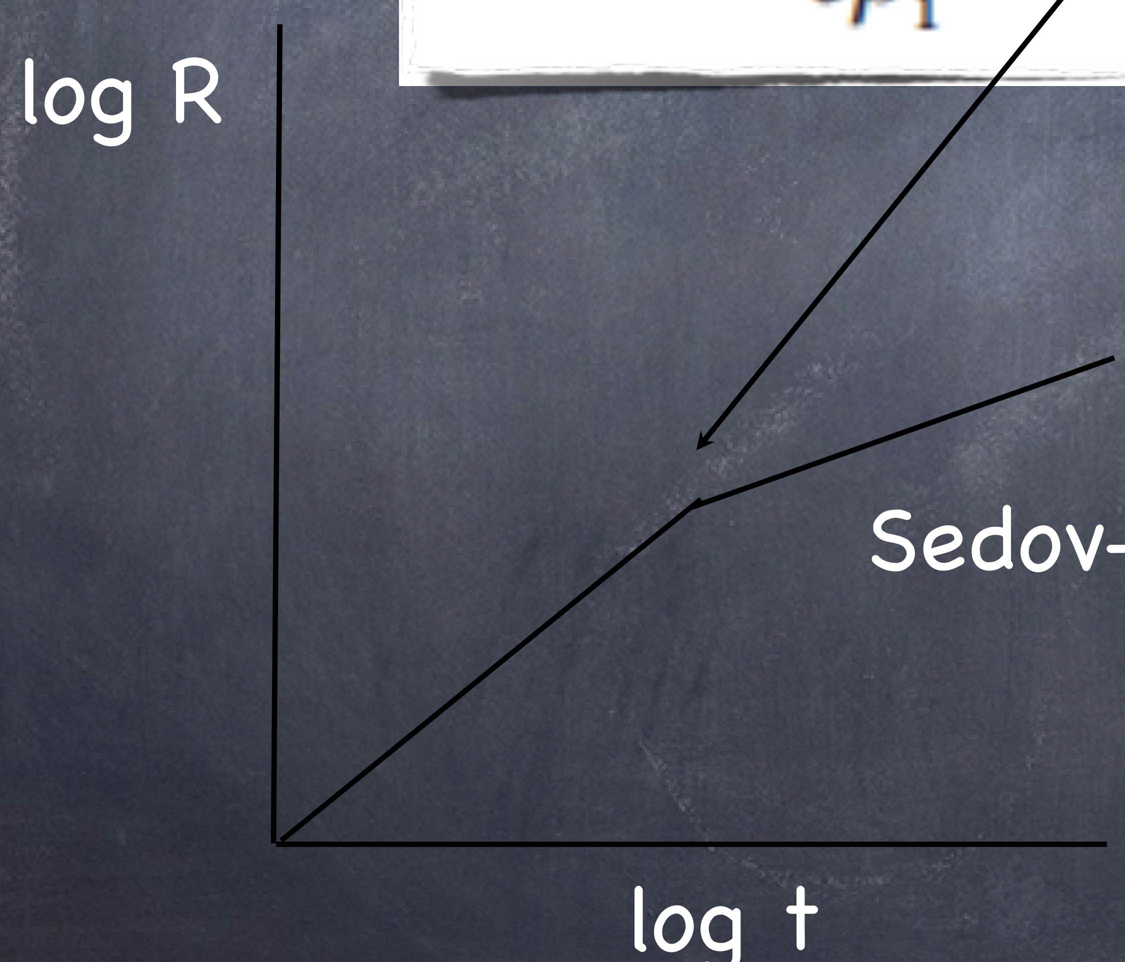
Supernova -> SNR

macronova -> Radio Flare

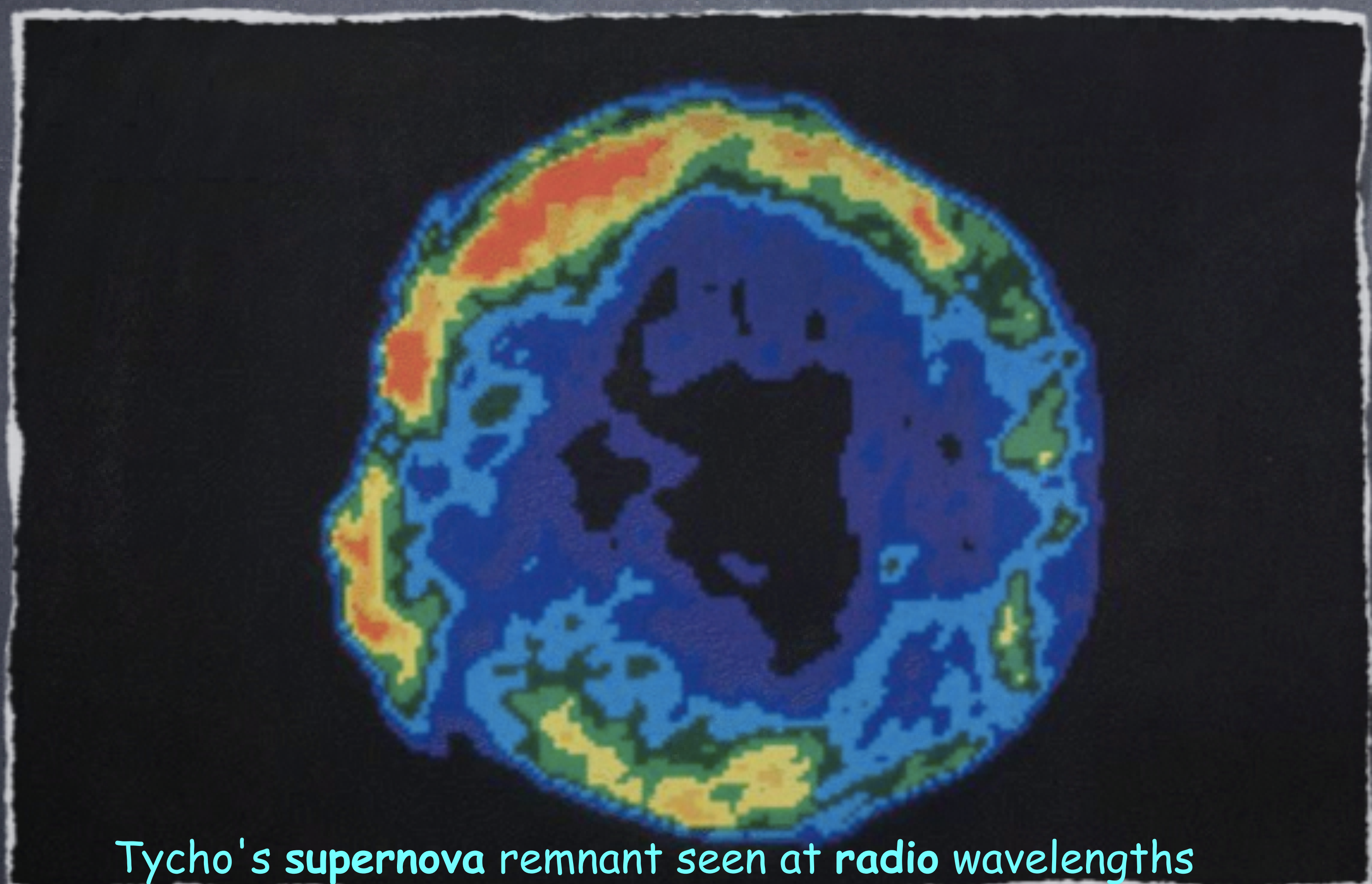


Dynamics

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



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



$e_e = \varepsilon_e e$

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

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

$p = 2.5 - 3$

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

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

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

Time Frequency and Intensity

(Nakar & TP Nature, 2011)

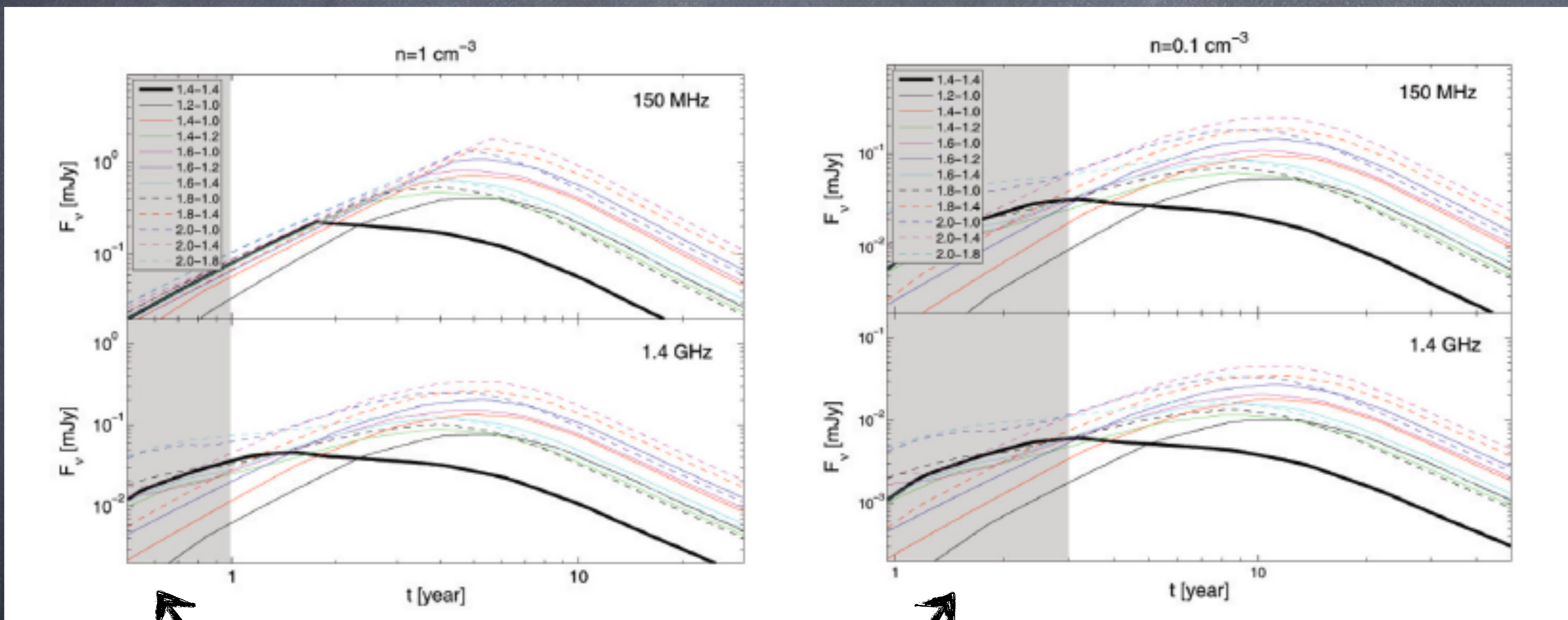
$$t_{\rm dec} = \frac{R_{\rm dec}}{c\beta_0} \approx 30\,{\rm d}\,E_{49}^{1/3} n^{-1/3} \beta_0^{-5/3}$$

$$\nu_{\rm m,dec} \equiv \nu_{\rm m}(t_{\rm dec}) \approx 1\,{\rm GHz}\,n^{1/2} \epsilon_{B,-1}^{1/2} \epsilon_{\rm e,-1}^{2} \beta_0^{5}$$

$$F_{\nu_{\rm obs},{\rm peak}}(\nu_{\rm a,dec}, \nu_{\rm m,dec} < \nu_{\rm obs})$$

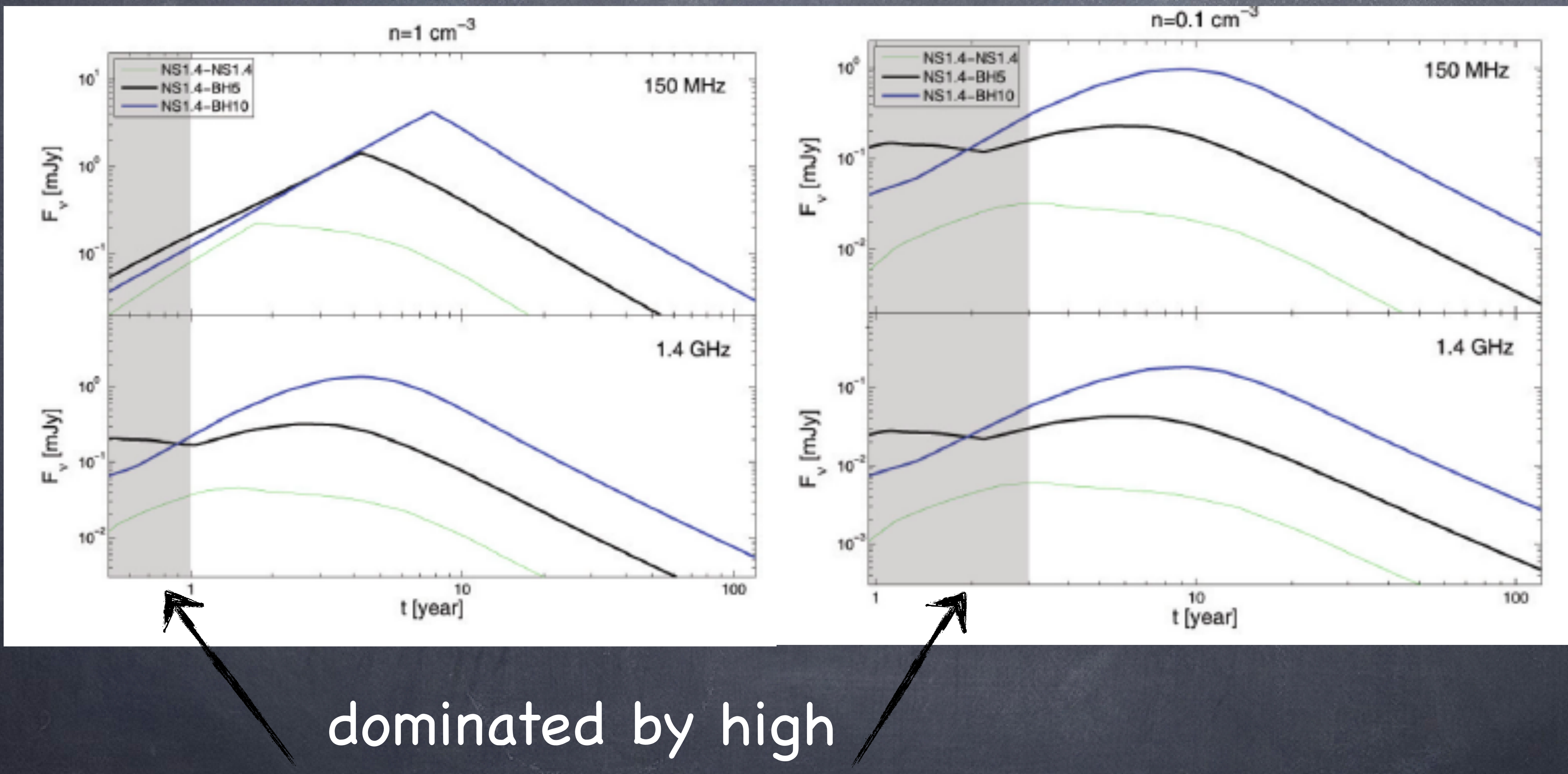
$$\approx 0.3\,{\rm mJy}\,E_{49} n^{\frac{p+1}{4}} \epsilon_{B,-1}^{\frac{p+1}{4}} \epsilon_{\rm e,-1}^{p-1} \beta_0^{\frac{5p-7}{2}} d_{27}^{-2} \left(\frac{\nu_{\rm obs}}{1.4\,{\rm GHz}}\right)^{-\frac{p-1}{2}}$$

ns^2 radio flares



dominated by high velocity ejecta

nsbh radio flares



dominated by high
velocity ejecta

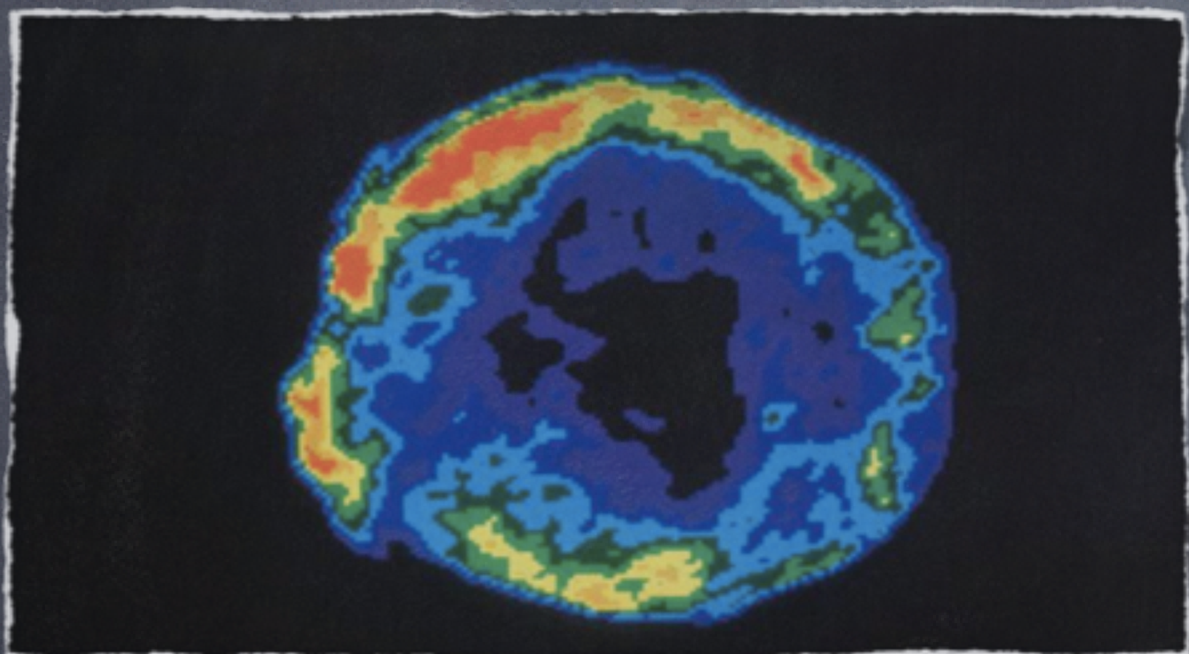
typical values

Masses	$n = 1\ cm^{-3}$				$n = 0.1\ cm^{-3}$			
	1.4 GHz		150 MHz		1.4 GHz		150 MHz	
	F_ν (peak)[a]	t (peak)[a]	F_ν (peak)[a]	t (peak)[a]	F_ν (peak)[a]	t (peak)[a]	F_ν (peak)[a]	t (peak)[a]
($M_\odot$)	(mJy)	(yr)	(mJy)	(yr)	(μJy)	(yr)	(μJy)	(yr)
1.4–1.2	0.09	4	0.5	4	10	9	50	9
1.4–1.4	0.04	1.5	0.2	2	5	3	30	3
1.4–2.0	0.3	5	2	6	50	10	200	10
1.4–10	1.5	4	4	8	200	10	1000	10

radio flare uncertainty

- External density 1 cm^{-3} :) or 10^{-3} cm^{-3} :(?
- High velocity ejecta: neutrino winds, GRB jet, shock between the two ns (Shibata + 12)
  $F_p \propto \beta^{(5p-7)/2} \propto \beta^4$!
  $t \propto \beta^{-5/3}$
- High velocity ejecta could produce other signatures like a regular afterglow (x-ray, etc..)

Contamination: Radio Supernova

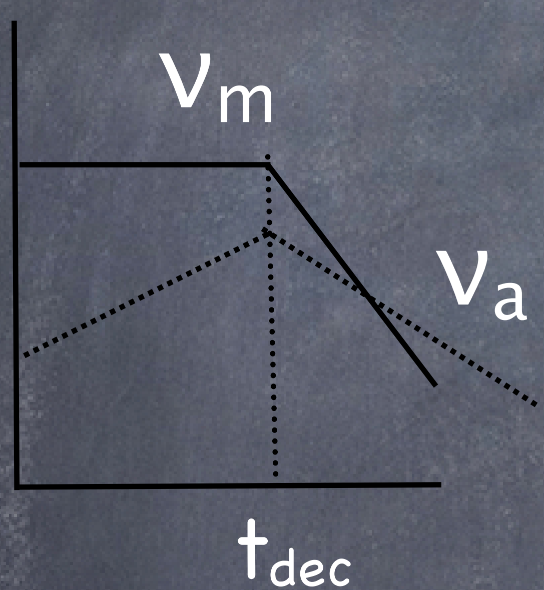


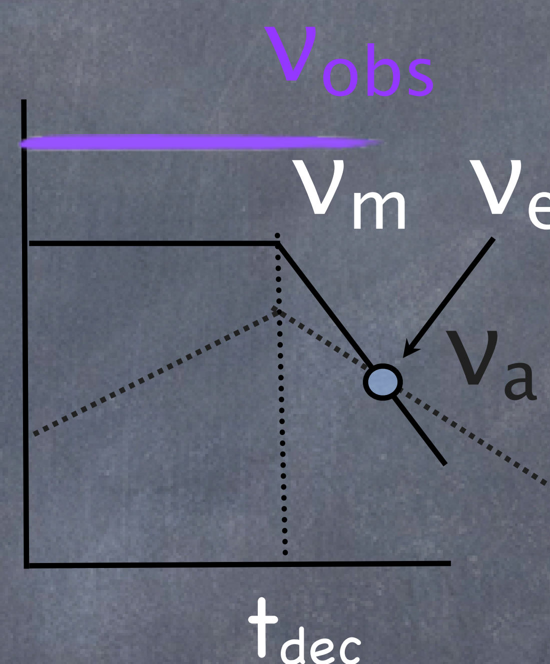
Tycho's **supernova** remnant seen at **radio** wavelengths

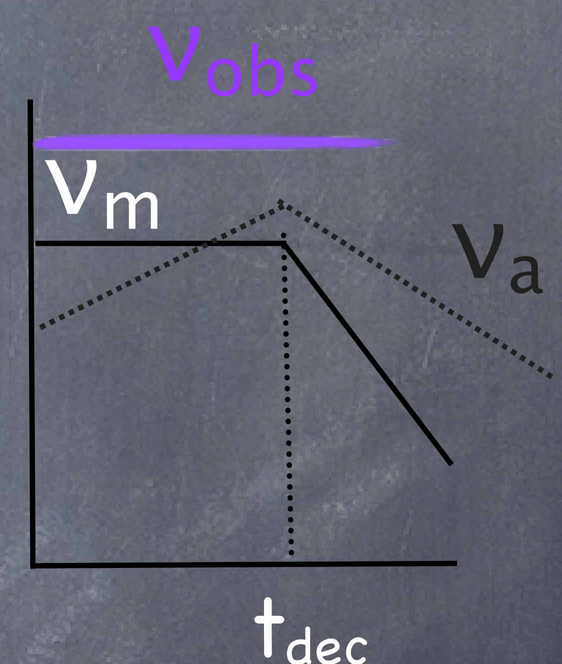
- Different spectrum
- Identification of an optical counterpart

Tidal disruption events (?)

The light curve



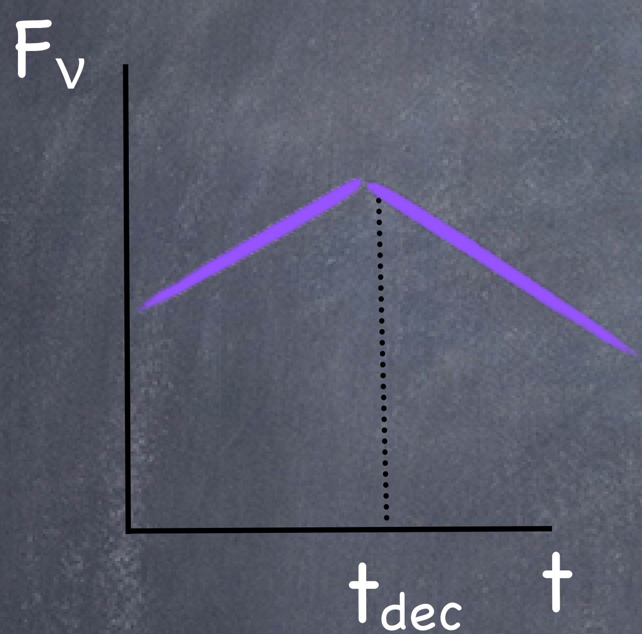


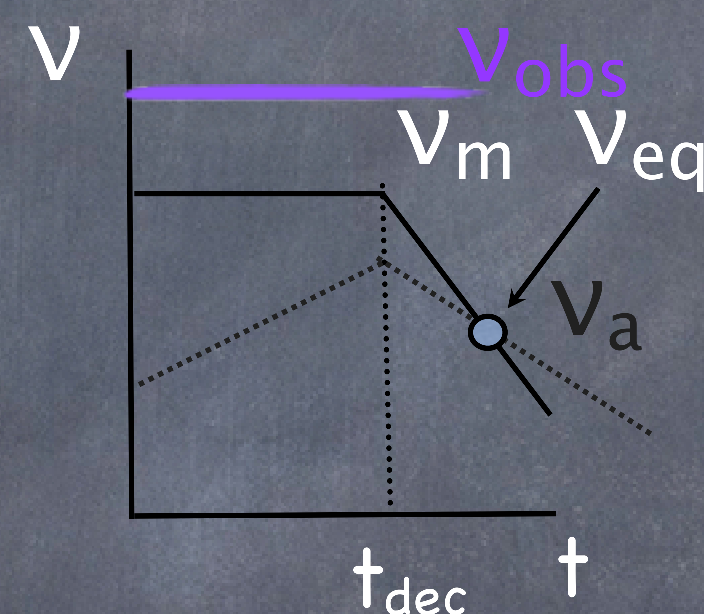


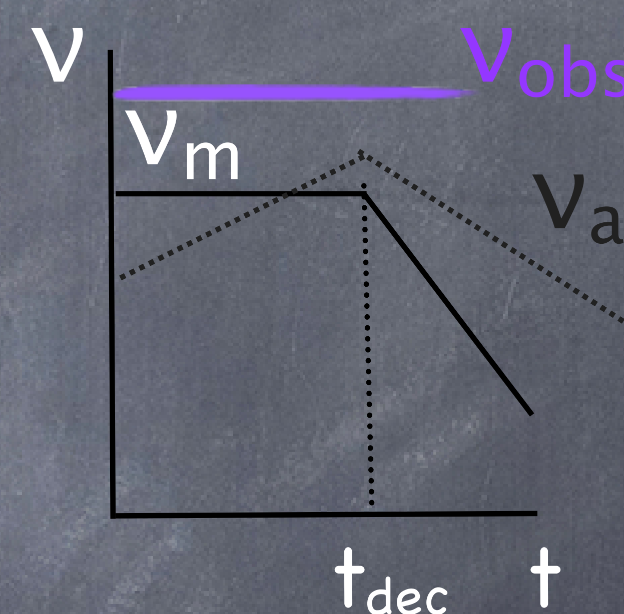
Text

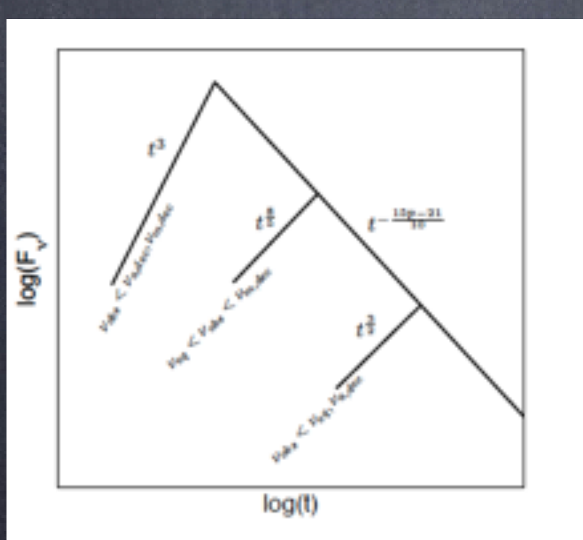
$$\nu_{eq} = 1 \text{ GHz } E_{49}^{1/7} n^{4/7} \epsilon_{B,-1}^{2/7} \epsilon_{e,-1}^{-1/7}$$

The light curve





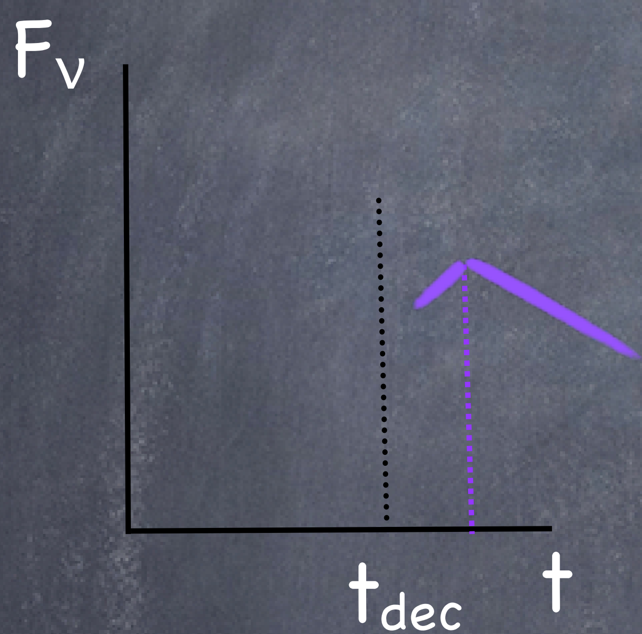


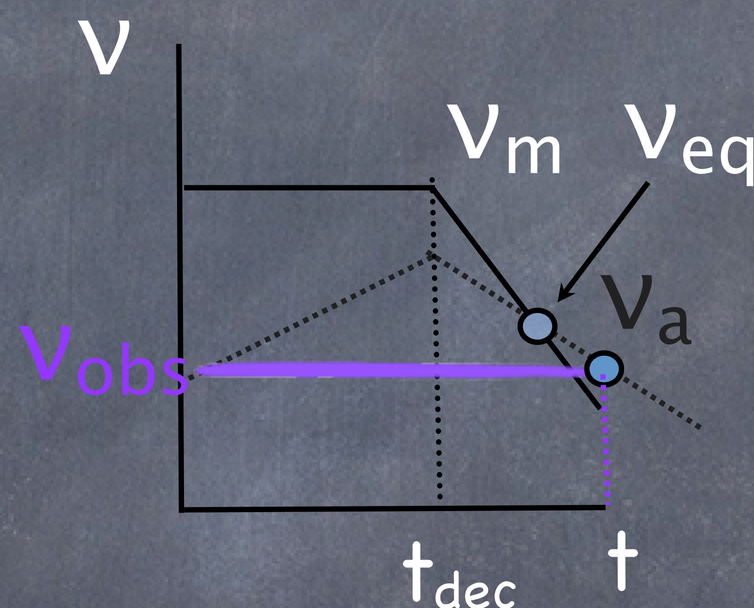


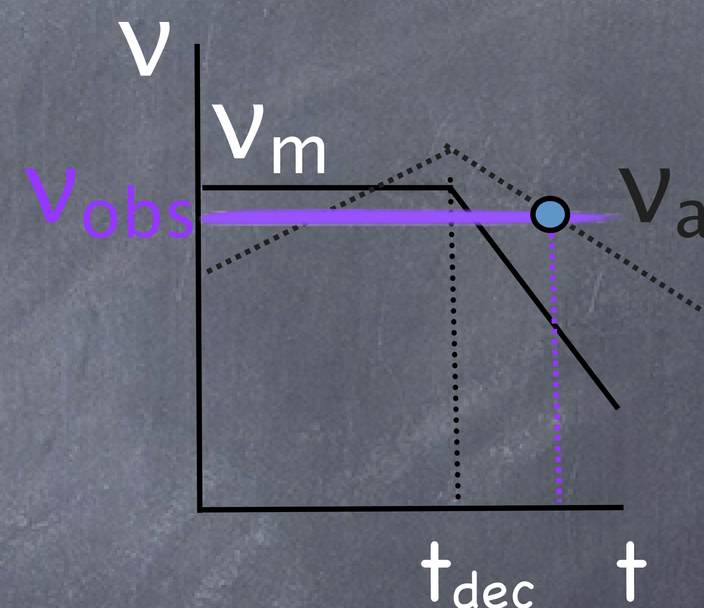
Text

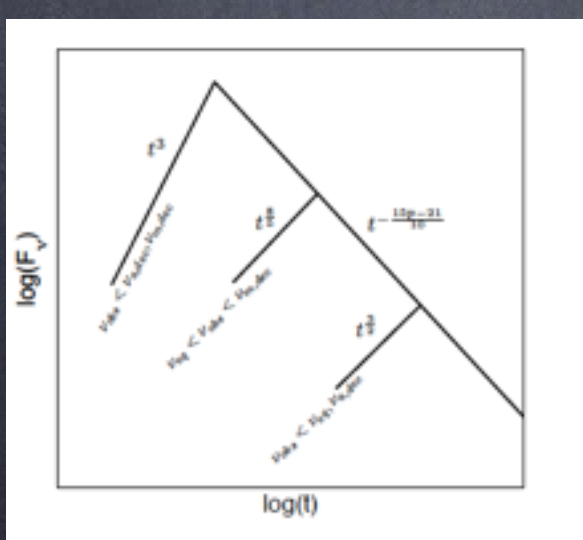
$$\nu_{eq} = 1 \text{ GHz } E_{49}^{1/7} n^{4/7} \epsilon_{B,-1}^{2/7} \epsilon_{e,-1}^{-1/7}$$

The light curve









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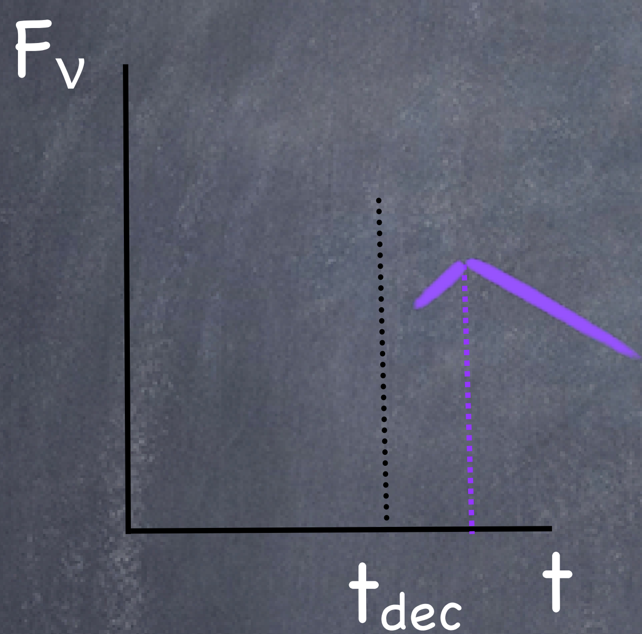
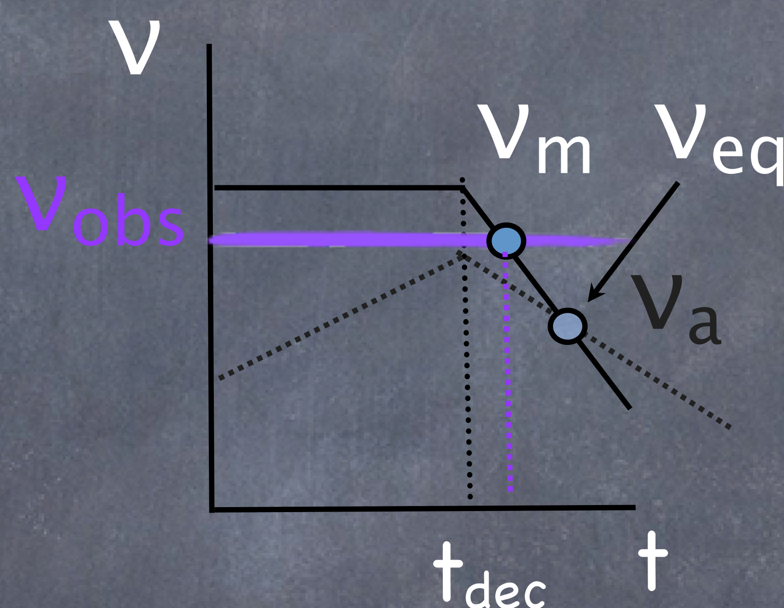
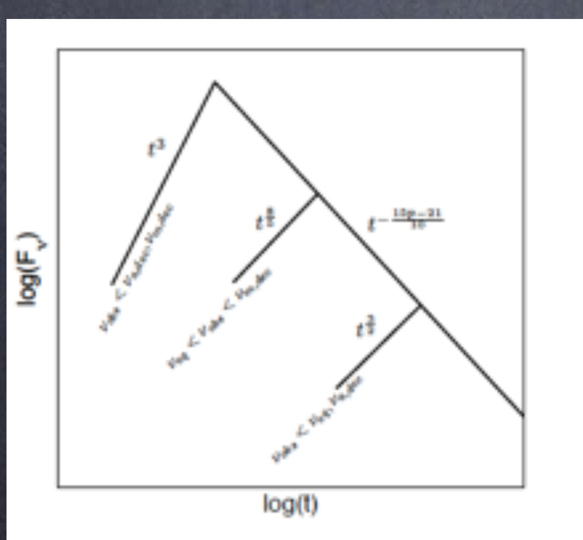


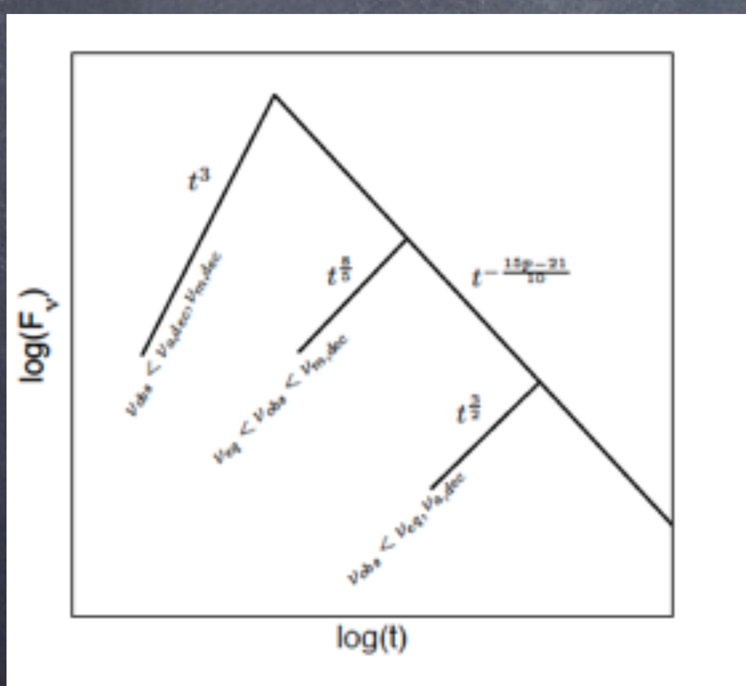




Text

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

Regime	$F_{\nu_{obs},peak}/F_{m,dec}$	t_{peak}/t_{dec}	$F_{\nu_{obs}}$ $t > t_{peak}$	$F^{\dagger}_{\nu_{obs}}$ $t < t_{peak}$
$\nu_{m,dec}, \nu_{a,dec} < \nu_{obs}$	$(\nu_{obs}/\nu_{m,dec})^{-\frac{p-1}{2}}$	1	$\propto t^{-\frac{15p-21}{10}}$	$\propto t^3$
$\nu_{eq} < \nu_{obs} < \nu_{m,dec}$	$(\nu_{obs}/\nu_{m,dec})^{-1/5}$	$(\nu_{obs}/\nu_{m,dec})^{-1/3}$	$\propto t^{-\frac{15p-21}{10}}$	$\propto t^{\frac{8}{5}}$
$\nu_{obs} < \nu_{eq}, \nu_{a,dec}$	$\nu_{m,dec}^{\frac{p-1}{2}} \nu_{a,dec}^{-\frac{3(p+4)(5p-7)}{10(3p-2)}} \nu_{obs}^{\frac{(32p-47)}{5(3p-2)}}$	$(\nu_{obs}/\nu_{a,dec})^{-\frac{4+p}{3p-2}}$	$\propto t^{-\frac{15p-21}{10}}$	$\propto t^{\frac{3}{2}}$



Radio Search

Radio facilities for GW-EM Counterpart Searches: EVLA

- The 500-lb gorilla of radio astronomy
- 27 25-m antennas
- Upgrade project almost finished. Will deliver order of magnitude increase in continuum sensitivity
- 1-50 GHz + 74 and 327 MHz
- 1-hrs, rms~7 uJy at 1.4 GHz
- Responds to external triggers
- Sub-arrays can be used to image a large (irregular) error box

NRAO

Dale Frail

Radio facilities for GW-EM Counterpart Searches

Radio Facility	Observing Freq.	Field of View	1 hr rms	Beam	Start Date
ASKAP	1.4 GHz	30 deg^2	30 uJy	20”	2013
Apertif	1.4 GHz	8 deg^2	50 uJy	15”	2013
MeerKAT	1.4 GHz	1.5 deg^2	35 uJy	15”	2013
EVLA	1.4 GHz	0.25 deg^2	7 uJy	1.3-45”	2010
EVLA	327 MHz	5 deg^2	2 mJy	5-18”	2011
LOFAR	110-240 MHz	50 deg^2	1 mJy	5”	2011
EVLA	74 MHz	100 deg^2	50 mJy	25-80”	2011
MWA	80-300 MHz	1000 deg^2	8 mJy	300”	2011+
LOFAR	15-80 MHz	500 deg^2	8 mJy	120”	2011

(Only Apertif, EVLA, LOFAR has demonstrated noise perfprmance)

Dale Frail

NRAO

Detection

1.4 GHz

$$F_{\nu_{obs},peak}(\nu_{a,dec}, \nu_{m,dec} < \nu_{obs}) \approx 0.3\ \mathrm{mJy}\ E_{49} n^{\frac{p+1}{4}} \epsilon_{B,-1}^{\frac{p+1}{4}} \epsilon_{e,-1}^{p-1} (\Gamma_0 - 1)^{\frac{5p-7}{4}} d_{27}^{-2} \left(\frac{\nu_{obs}}{1.4\ \mathrm{GHz}}\right)^{-\frac{p-1}{2}}$$

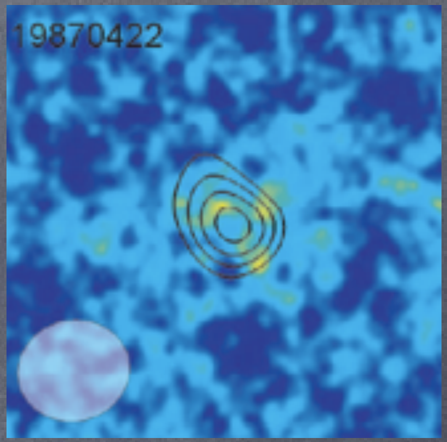
$$t_{dec} = \frac{R_{dec}}{c\beta_0} \approx 30\ \mathrm{day}\ E_{49}^{1/3} n^{-1/3} (\Gamma_0 - 1)^{-5/6}.$$

150 MHz

$$t_{peak}(\nu_{obs} < \nu_{eq}, \nu_{a,dec}) \approx 200\ \mathrm{day}\ E_{49}^{\frac{5}{11}} n^{\frac{7}{22}} \epsilon_{B,-1}^{\frac{9}{22}} \epsilon_{e,-1}^{\frac{6}{11}} \left(\frac{\nu_{obs}}{150\ \mathrm{MHz}}\right)^{\frac{13}{11}},$$

$$F_{\nu_{obs},peak}(\nu_{obs} < \nu_{eq}, \nu_{a,dec}) \approx 50\ \mu\mathrm{Jy}\ E_{49}^{\frac{4}{5}} n^{\frac{1}{5}} \epsilon_{B,-1}^{\frac{1}{5}} \epsilon_{e,-1}^{\frac{3}{5}} d_{27}^{-2} \left(\frac{\nu_{obs}}{150\ \mathrm{MHz}}\right)^{\frac{6}{5}}.$$

- 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



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

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

- A long lived (months-year) strong (sub-mJy) radio remnant of a compact binary merger is a robust prediction.
- With typical parameters 1.4GHz is the optimal observation band
- The signal depends on the energy of the outflow, its Lorentz factor and the surrounding circum-merger density.
- The outflow parameters can be determined from neutron star simulations.
- **It is relatively easy to test this hypothesis by radio searches (work in progress)**

Summary

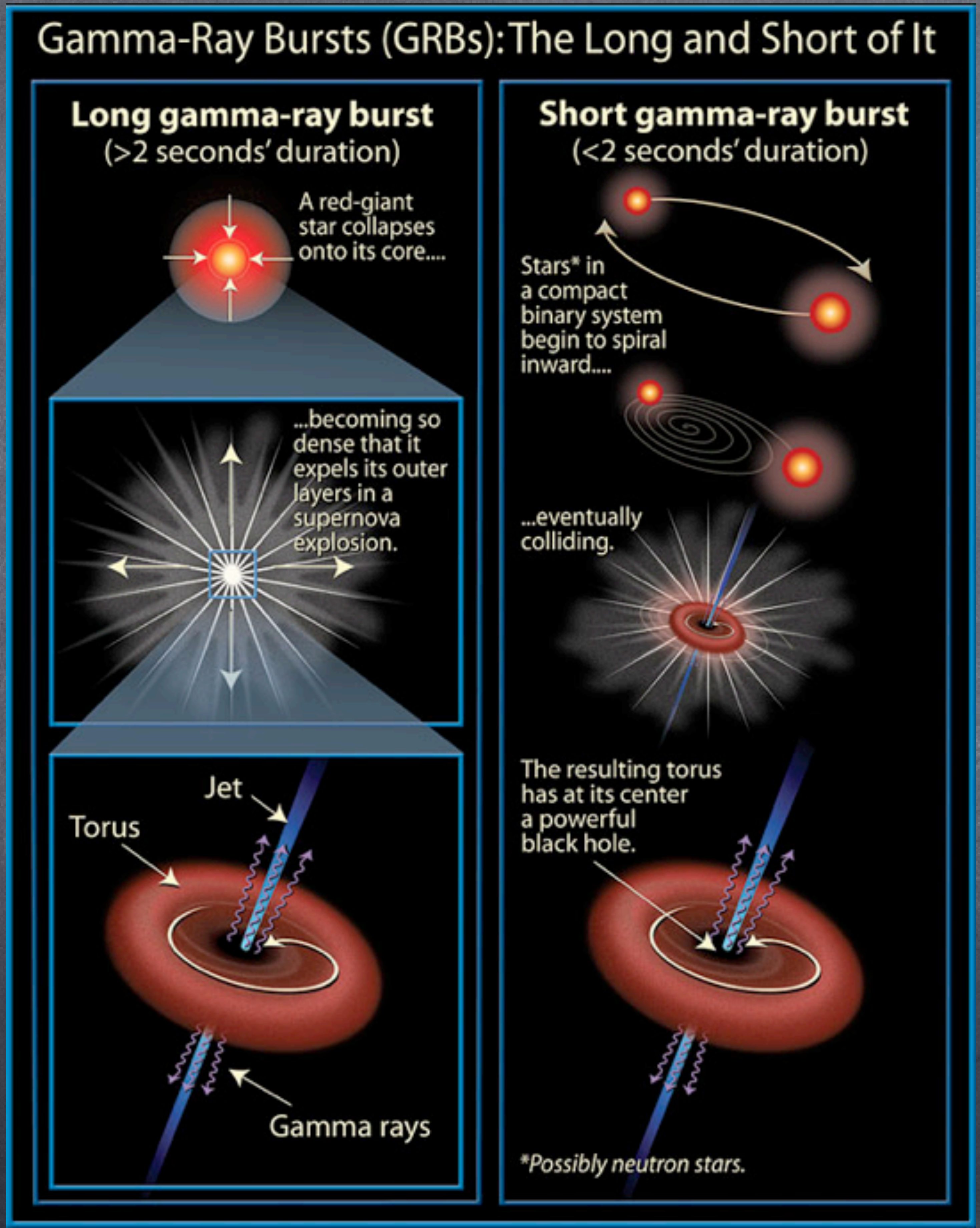
- Macronova - uv/optical <1 day 24 Mag @ 300 Mpc

  followed by nIR 4-10 days 25 Mag @ 300 Mpc

- Radio flare - sub mJy at 1.4 GHz (lower at 150Mhz - LOFAR) easily detectable in followup. Excellent candidates for blind search in the radio that can determine the rate of ns^2 merges. But warning about ambient density.

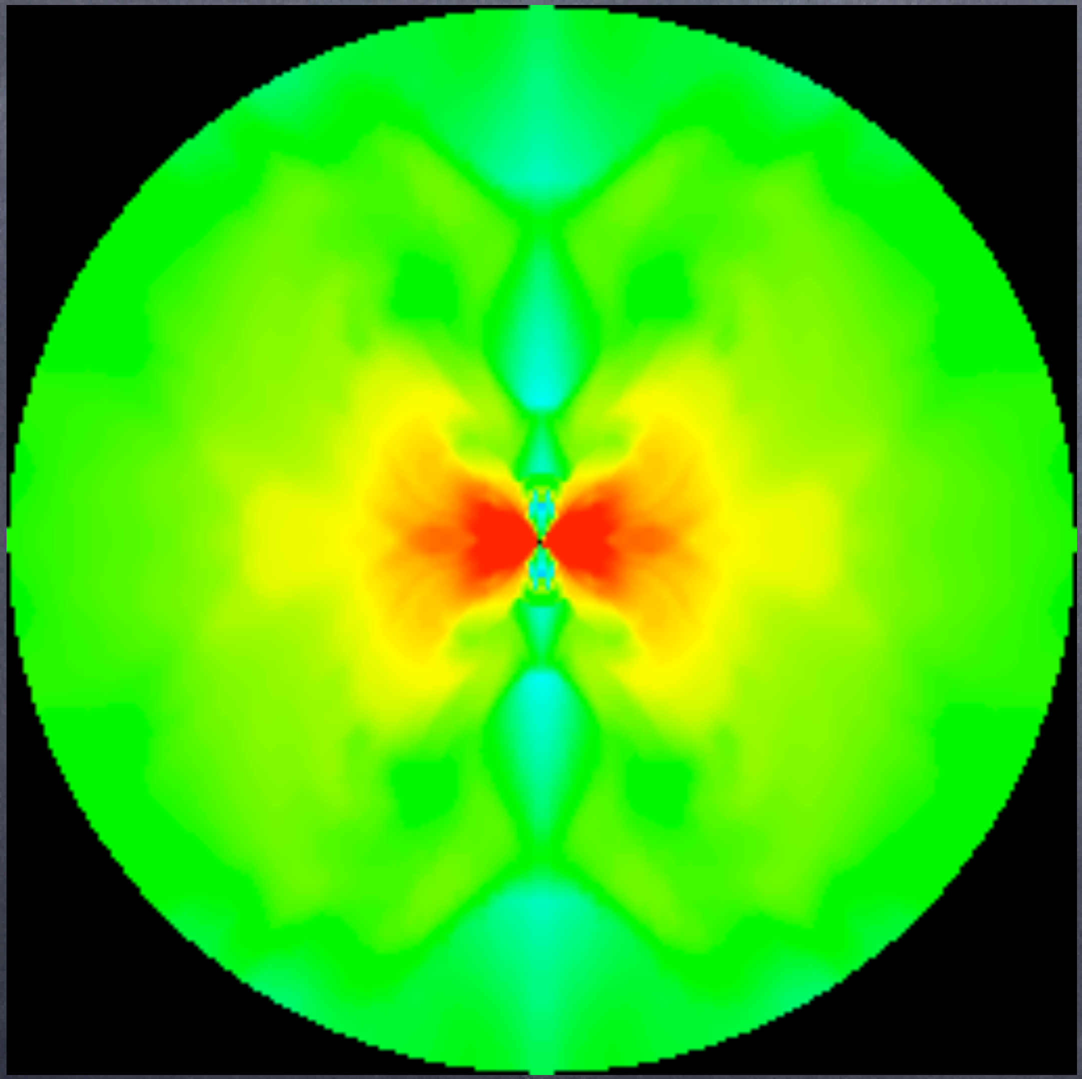
END

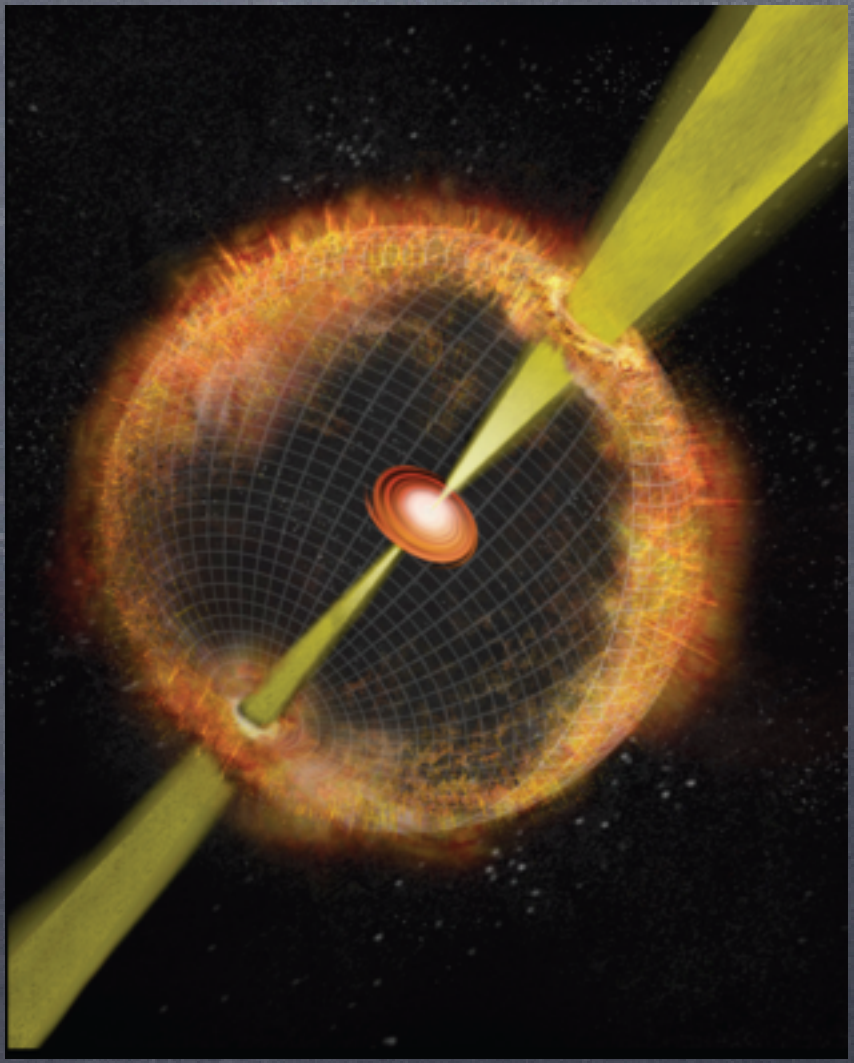
Route to GRBs



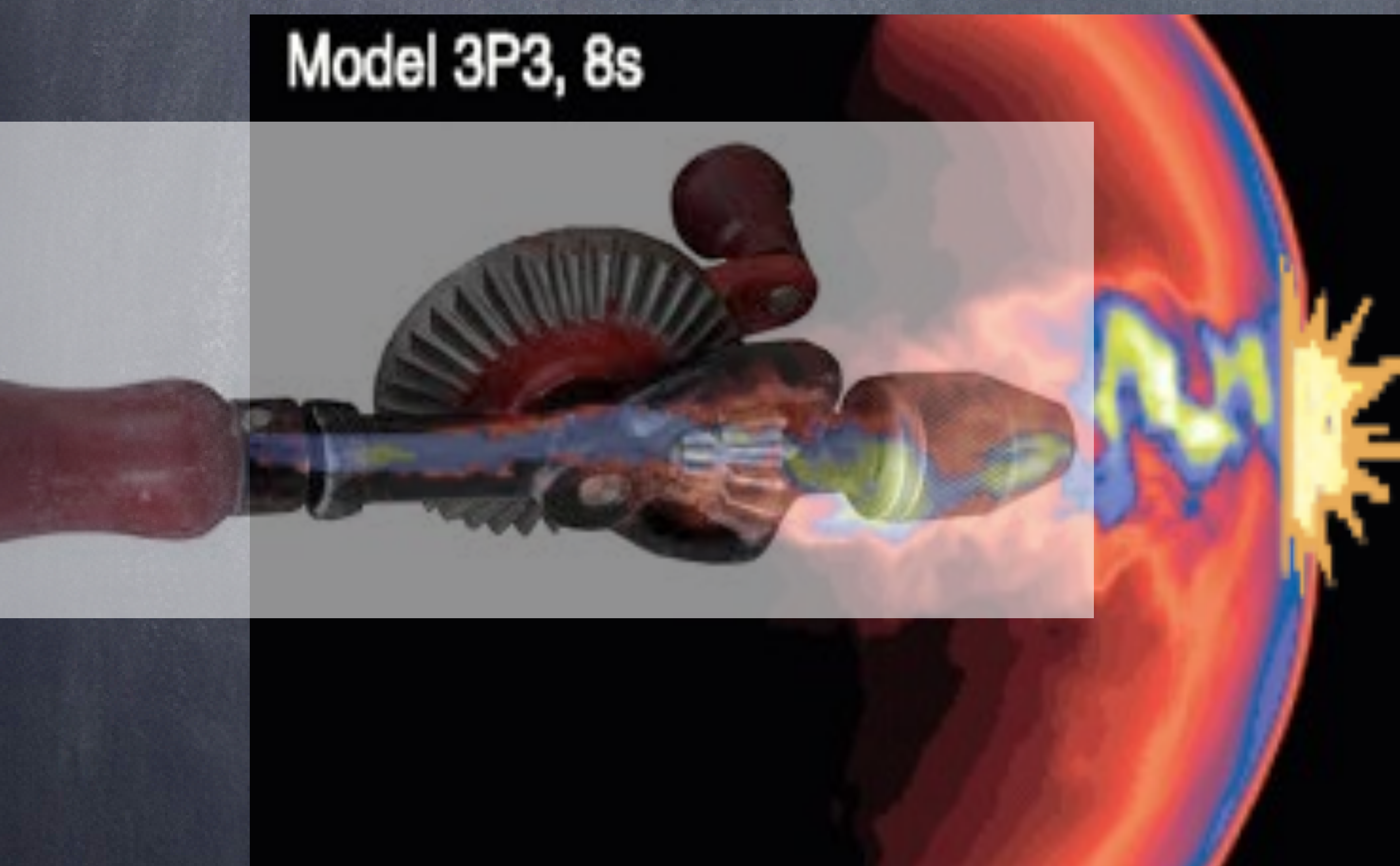
The Collapsar Model

(MacFadyen & Woosley 1998)



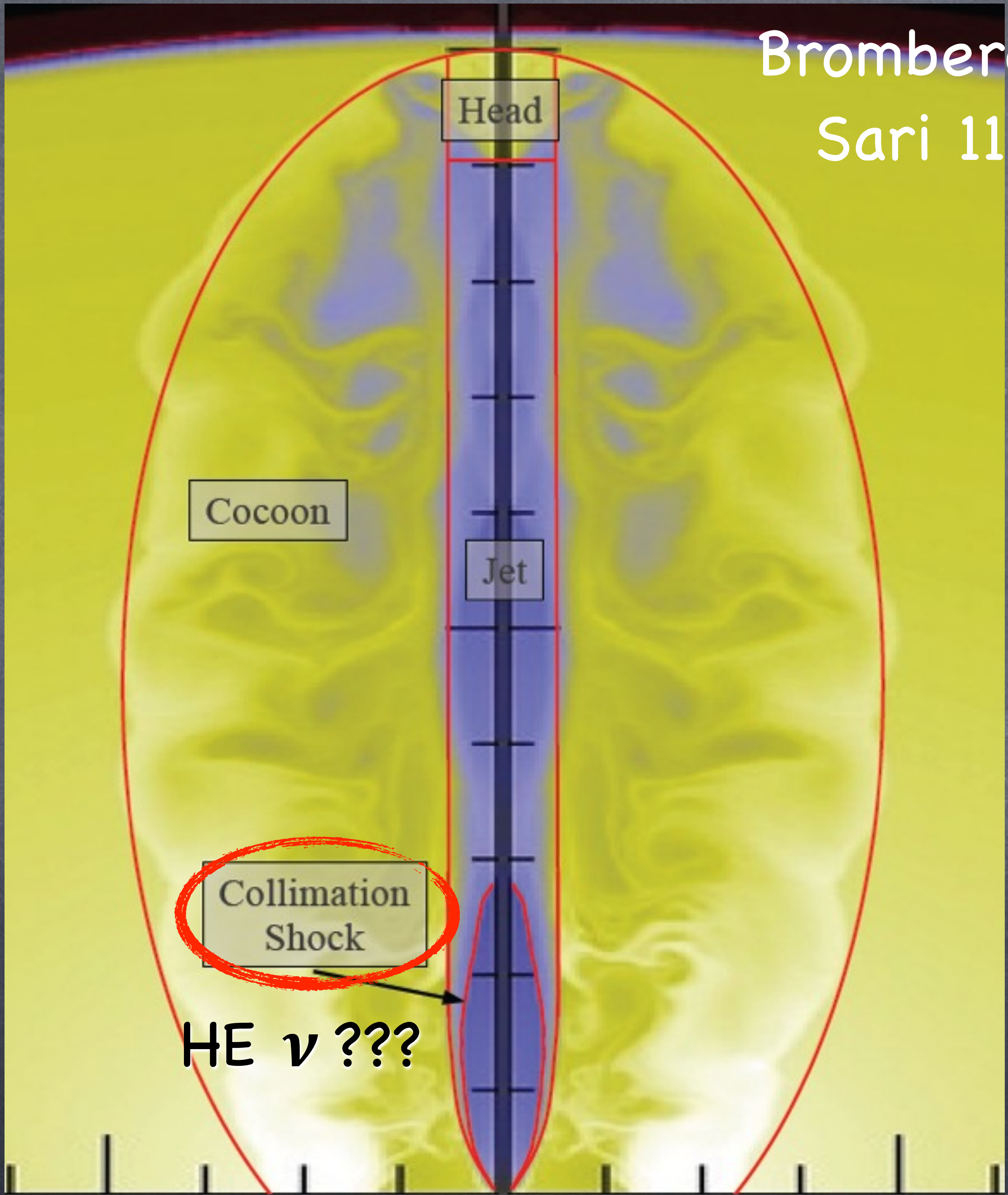


The Jet drills a hole in the star Model



Zhang, Woosley & MacFadyen 2004

Bromberg Nakar, TP,
Sari 11 ApJ 2011



Jet breakout time

(Bromberg Nakar, TP, Sari 11 ApJ 2011)

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

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

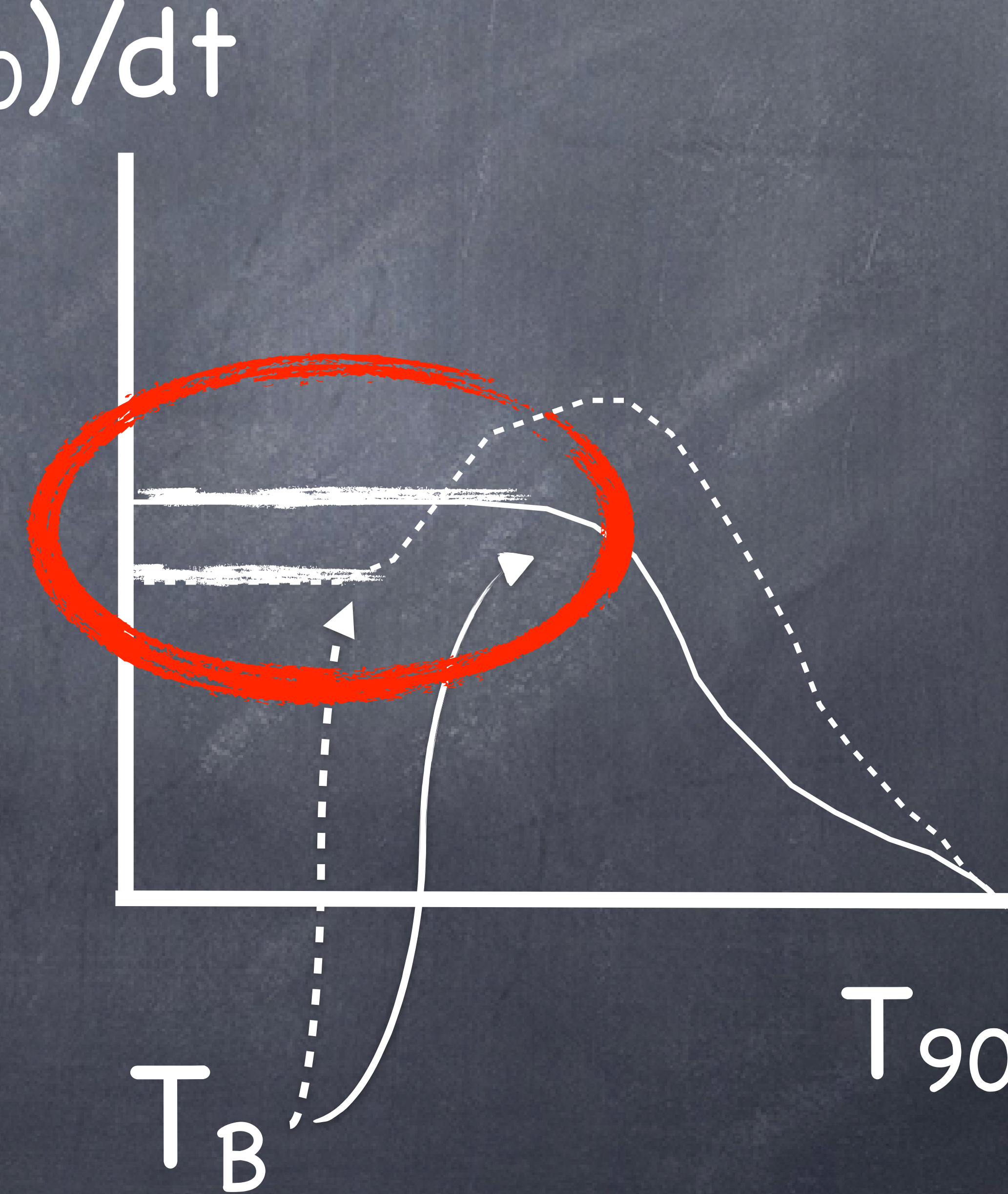
A prediction of the Collapsar model

Observed duration

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

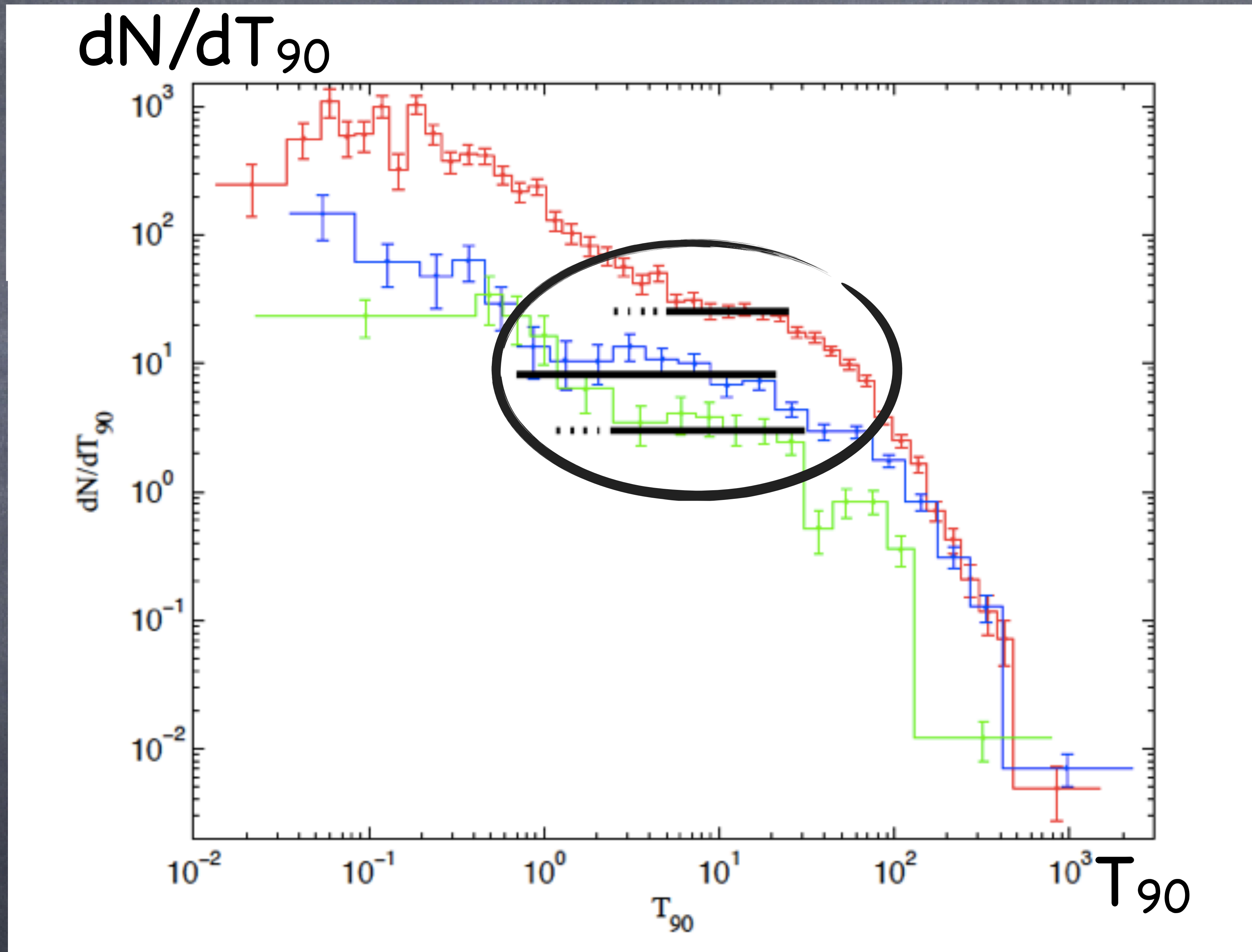
Engine time

Break out time



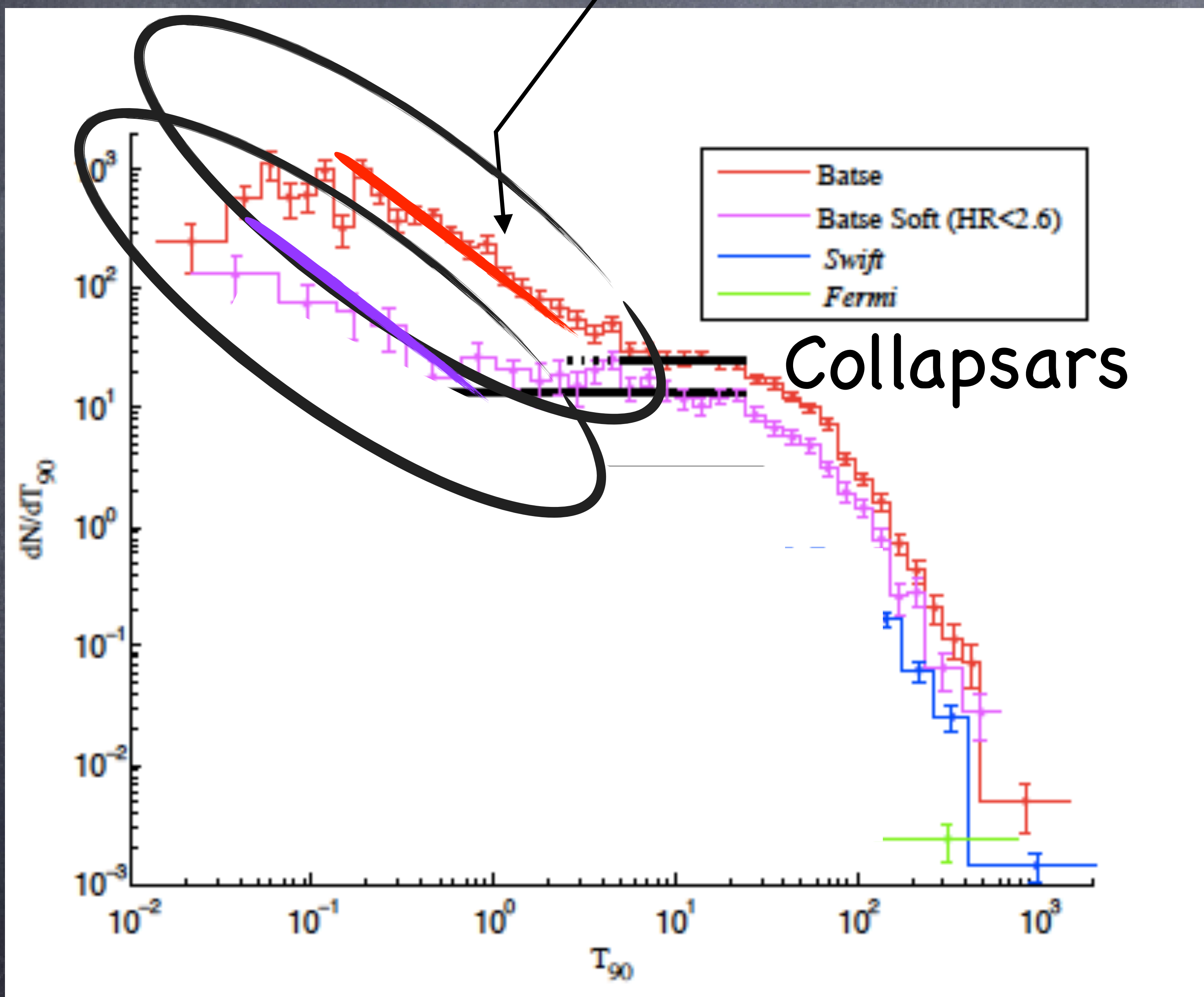
A second look at dN/dT

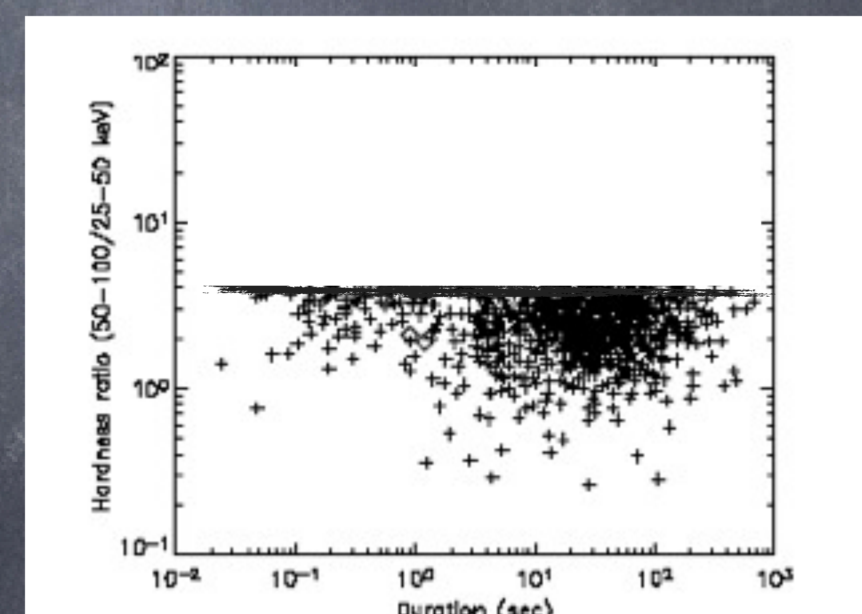
(Bromberg Nakar, TP & Sari, 2011)

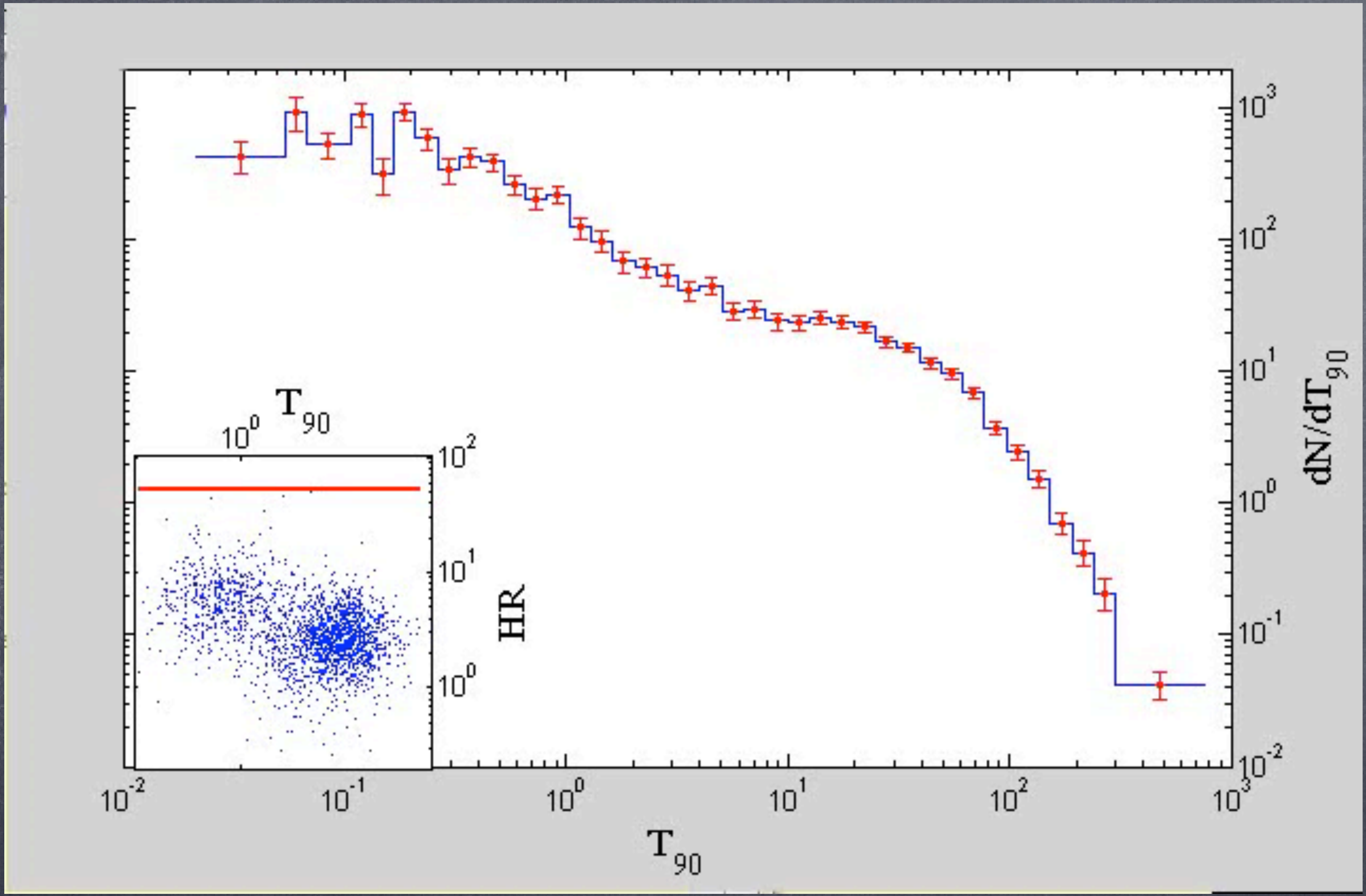


A direct observational proof of the Collapsar model.

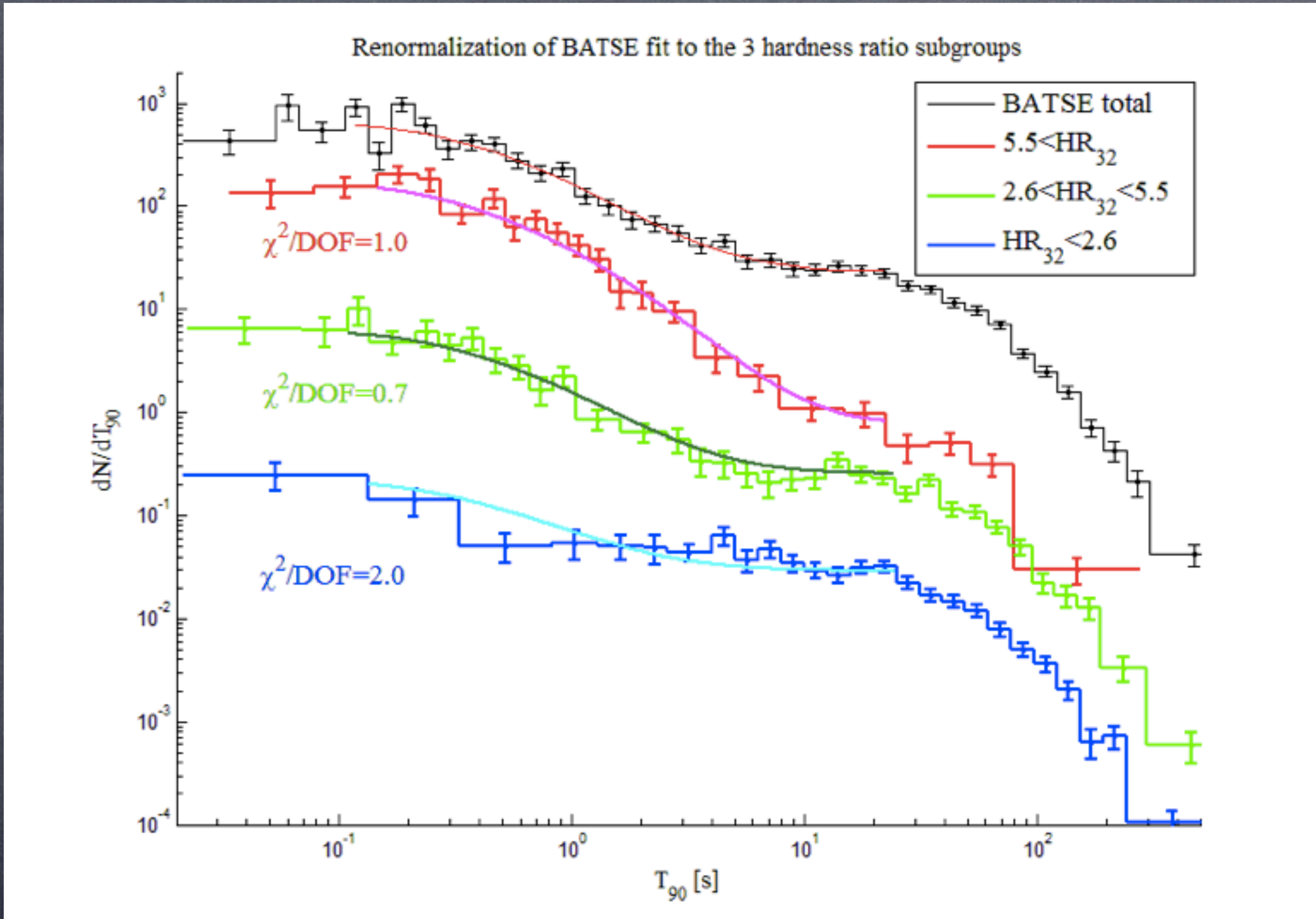
Short (Non-Collapsars) GRBs





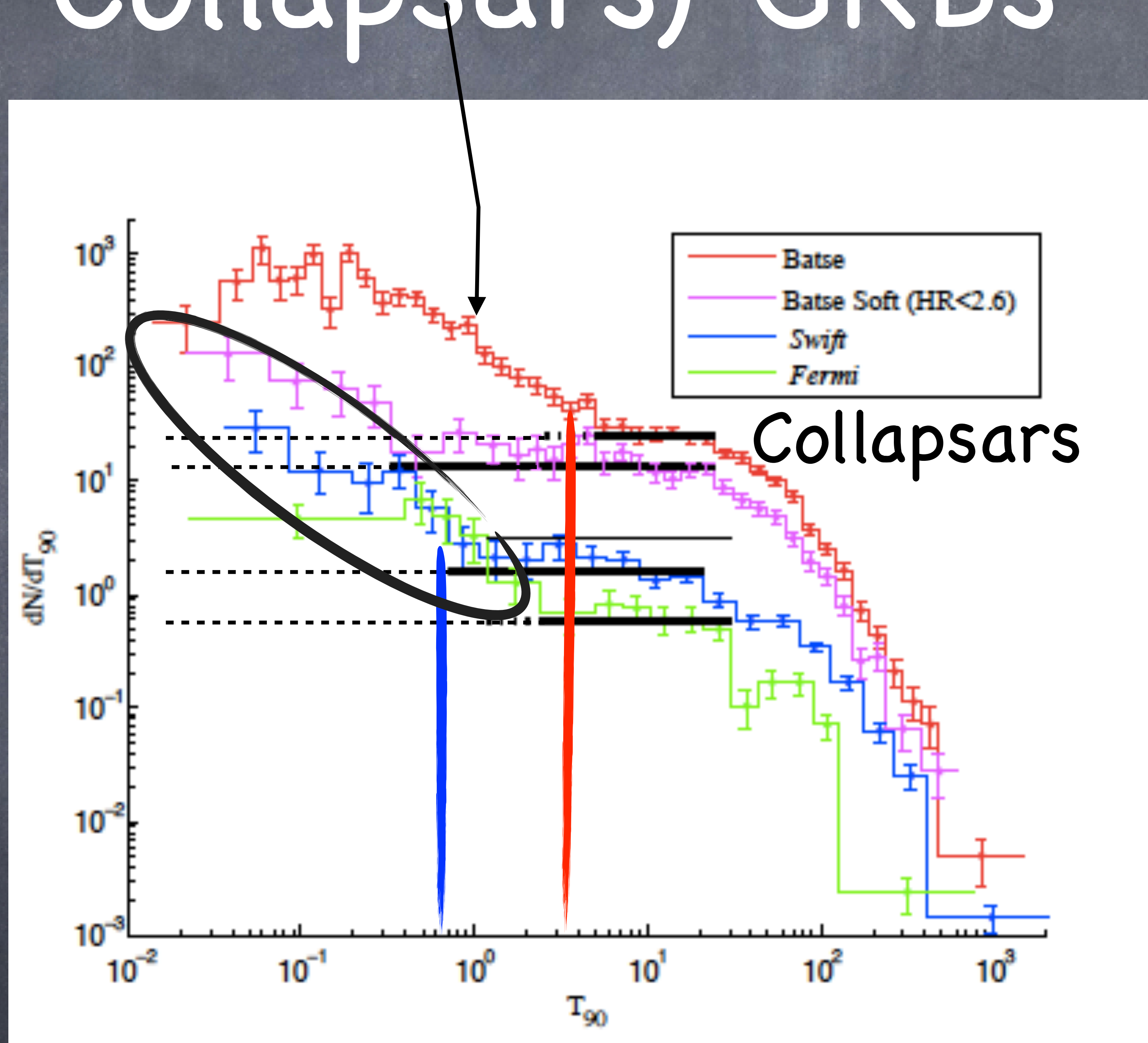


T90
HR
dN/dT90



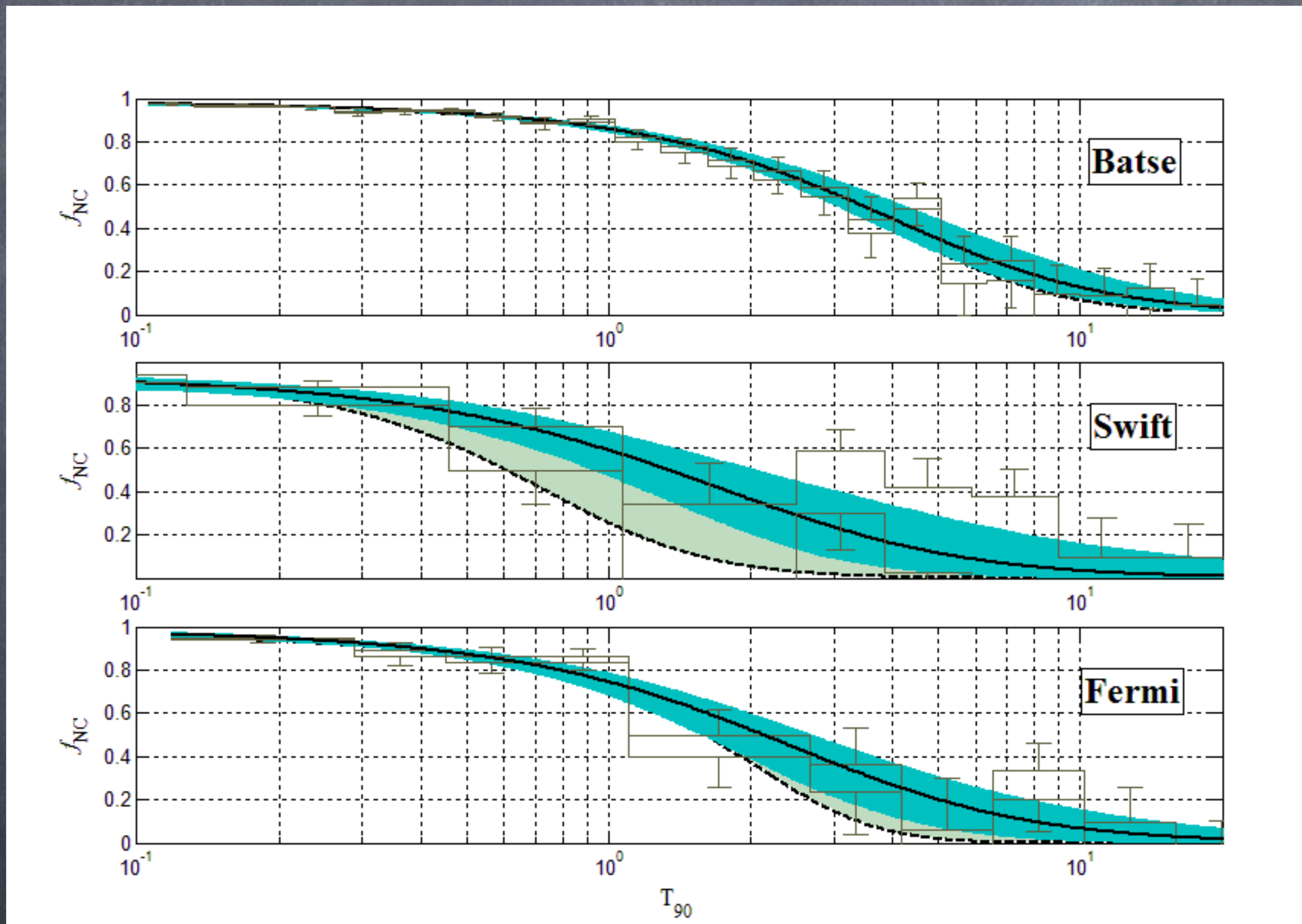
Renormalization of BATSE fit to the 3 hardness ratio subgroups
BATSE total
5.5<HR32
2.6<HR32<5.5
HR32<2.6
χ2/DOF=1.0
χ2/DOF=0.7
χ2/DOF=2.0
dN/dT90
T90 [s]

Swift Short (Non-Collapsars) GRBs



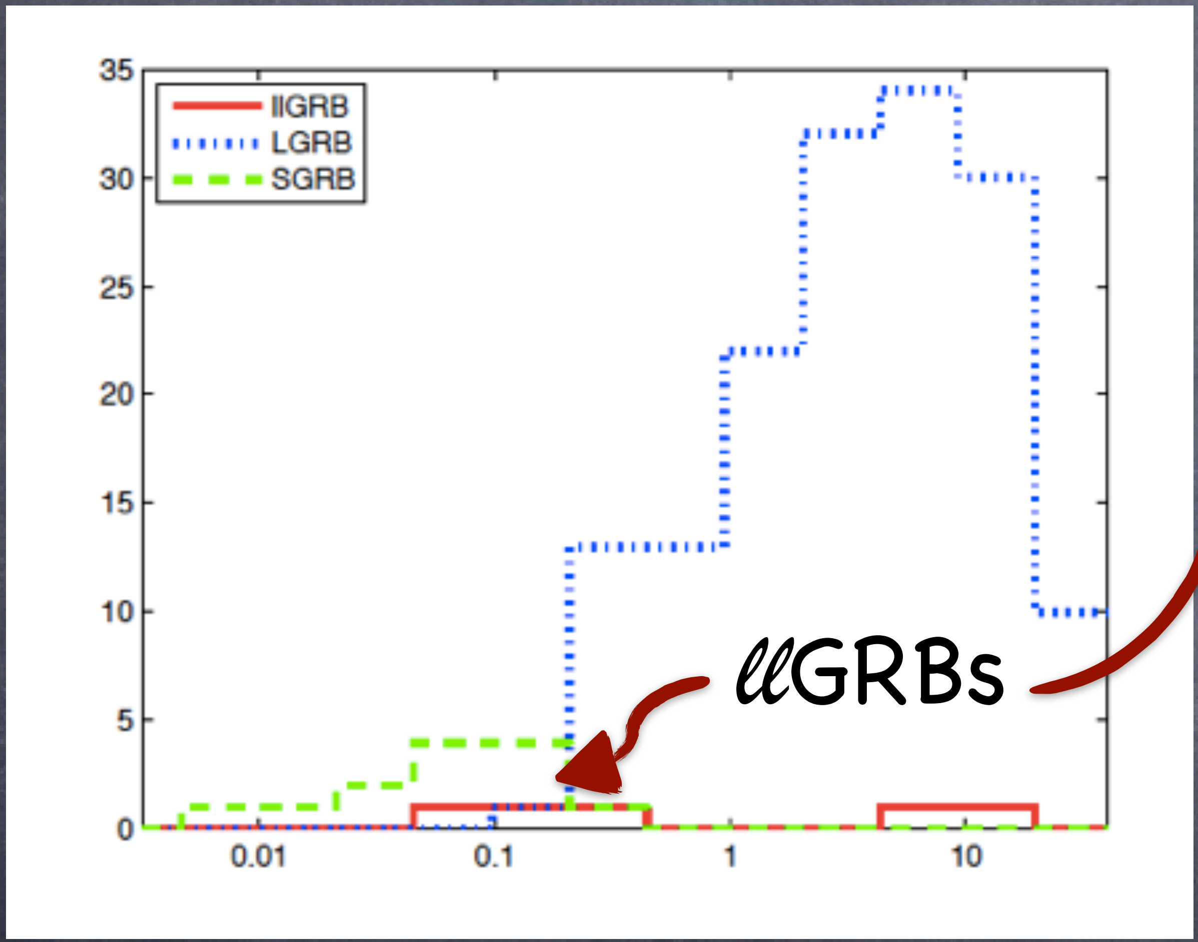
Short Swift GRBs with T_{90}>0.7sec are not "short"!

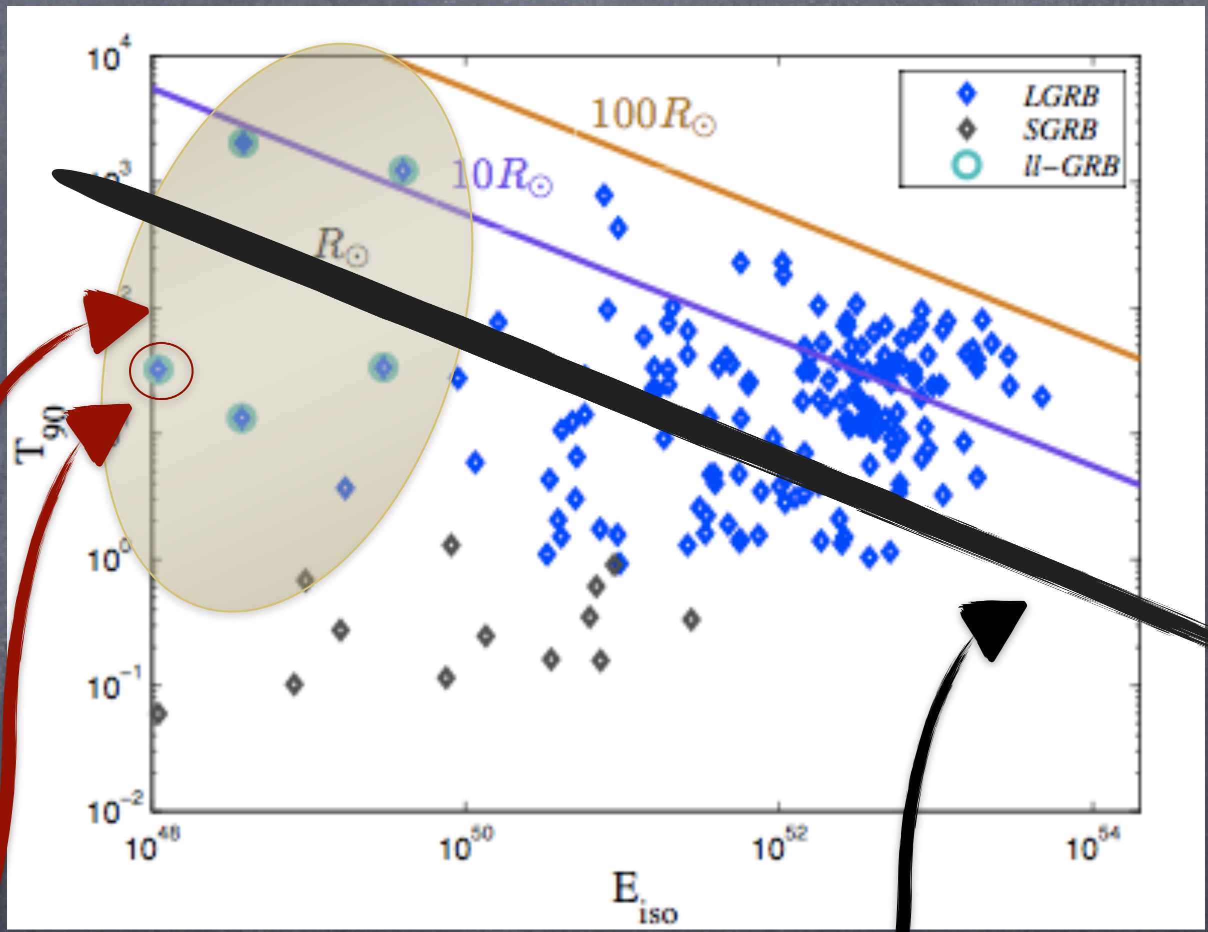
Not all short GRBs are "short" (Bromberg + 12)



And some long are "short"

Low luminosity GRBs - $\ell\ell$GRBs don't arise from Collapsars



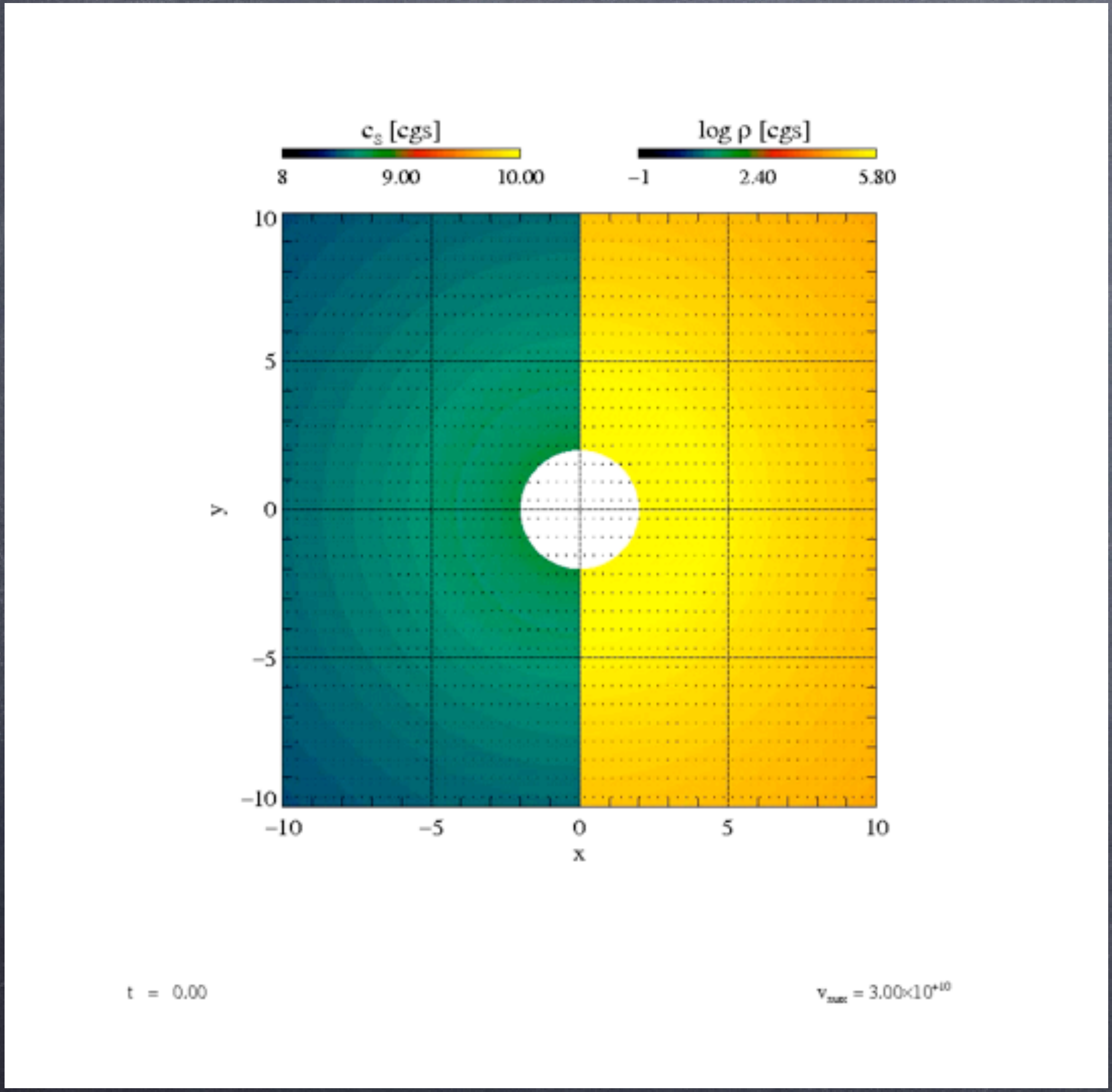


$\ell\ell$GRBs

98bw

T_B

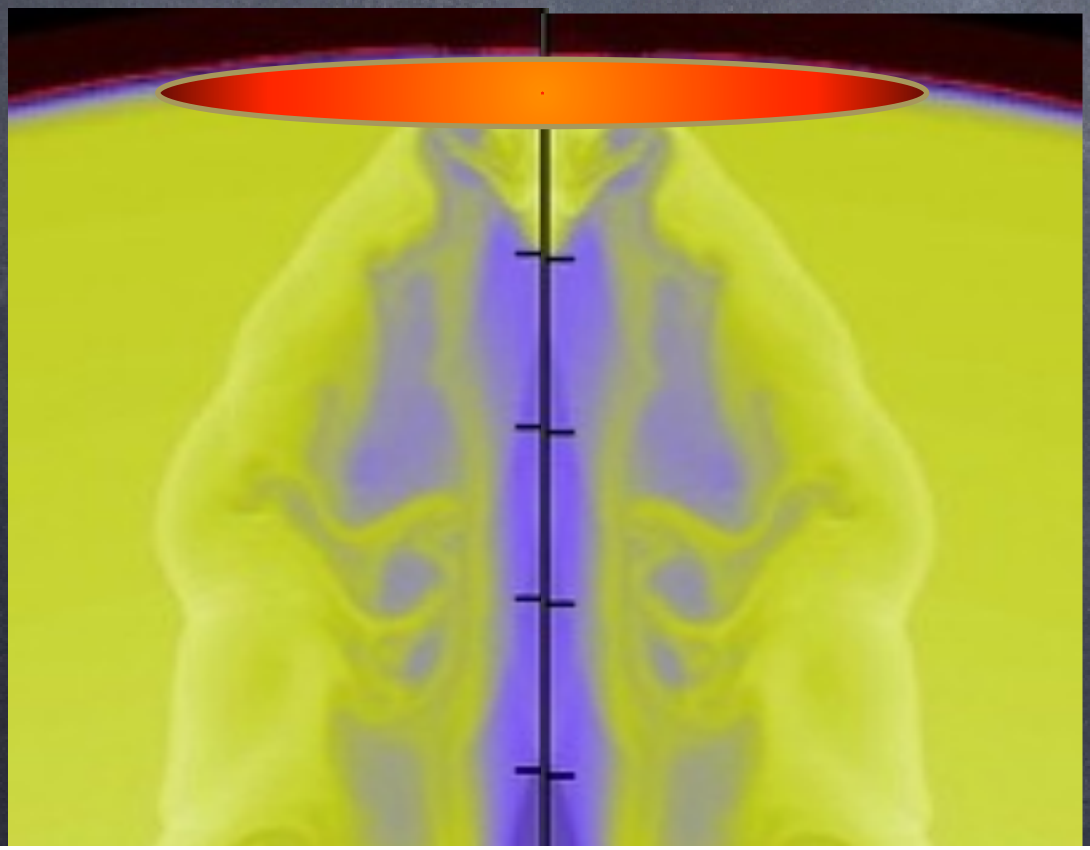
A Failed Jet
(Obergaulinger, Piran + 13)

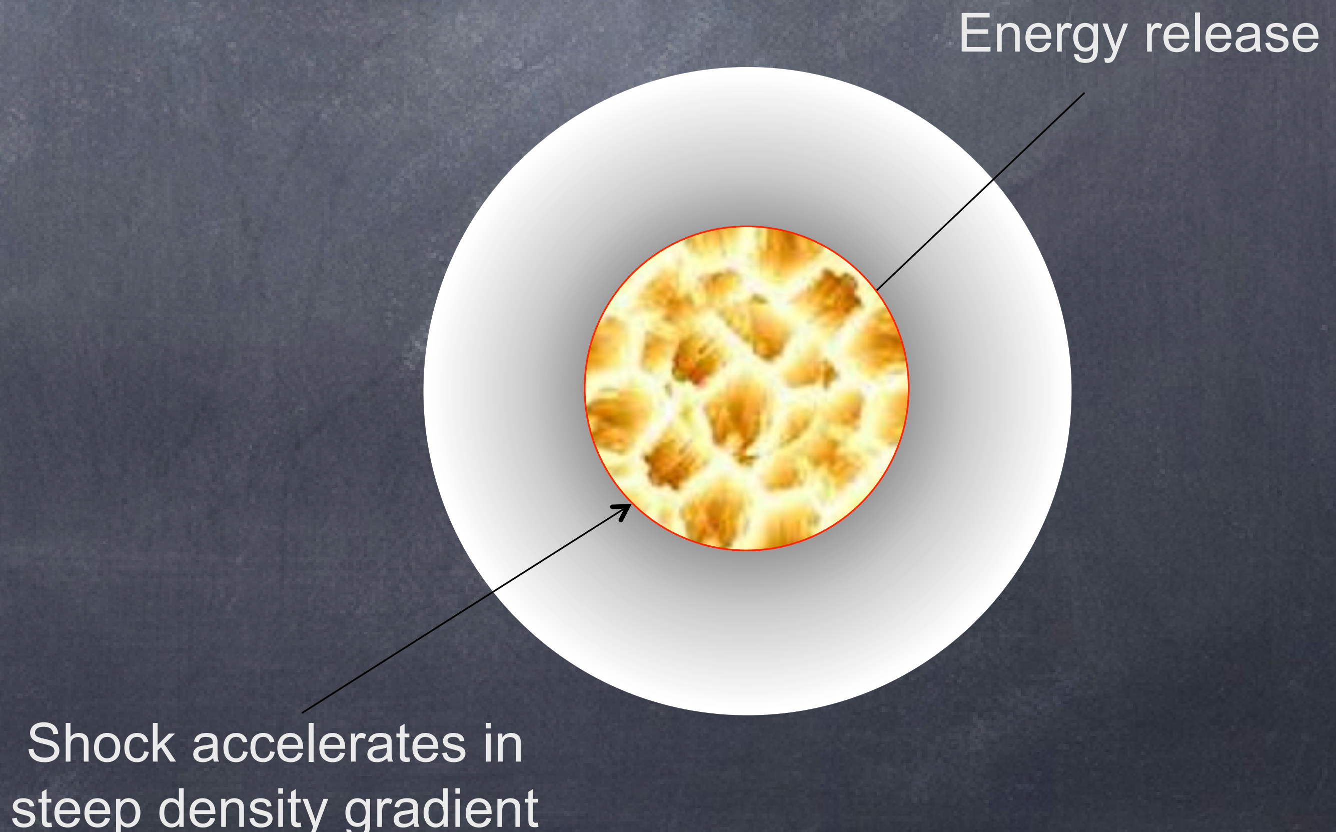


Opening angle of 15° degrees at 2000 km into a star of 15 solar masses and solar metallicity. Constant energy injection rate, $5{*}10^{50}$erg/s, for 2 seconds.

What makes a ℓℓGRBs?

- 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)





	Observations				Theory		
GRB	E_{bo} (erg)	T_{bo} (keV)	t_{bo} (s)		t_{bo} (s)	R_{bo} (cm)	$\gamma\beta_{bo}$
980425	10^{48}	150	30		10	$6 \cdot 10^{12}$	3
031203	$5 \cdot 10^{49}$	>200	30		<35	$2 \cdot 10^{13}$	>4
060218	$5 \cdot 10^{49}$	40	2100		1500	$5 \cdot 10^{13}$	1
100316D	$5 \cdot 10^{49}$	40	1300		1500	$5 \cdot 10^{13}$	1

$$\frac{t_{bo}}{20\ \mathrm{s}} \approx \left(\frac{E_{bo}}{10^{46}\ \mathrm{erg}}\right)^{1/2} \left(\frac{T_{bo}}{50\ \mathrm{keV}}\right)^{-2.7}$$

The Relativistic breakout relation