

# ***High Energy Stellar Astrophysics***

Prialnik 11

Glatzmaier and Krumholz 18

# The Algol Mystery

- Algol is a double-lined eclipsing **binary** system with a period of about 3 days (very short). The two stars are:

Star A: B8,  $3.4M_{\odot}$  main-sequence star

Star B: G5,  $0.8M_{\odot}$  'subgiant' star

What is wrong with this picture?

# Algol

- The more massive star (A) should have left the main sequence and started up the RGB before the less massive star (B).
- What is going on here?
- The key is the short-period orbit and the evolved state of star B.

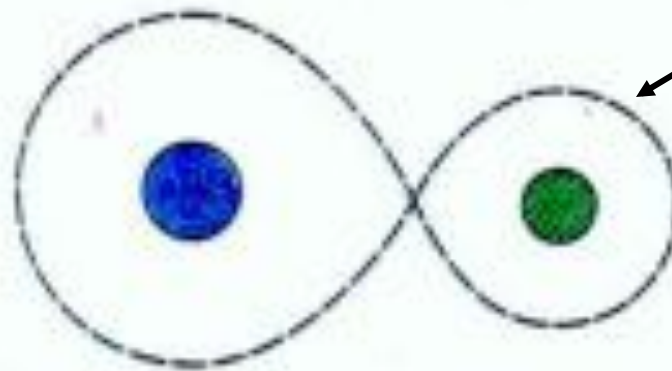
# Mass Transfer in Binaries

- In the case of Algol, Star B transferred  $2.2M_{\odot}$  of material to Star A.

Star A:  $1.2M_{\odot} \rightarrow 3.4M_{\odot}$

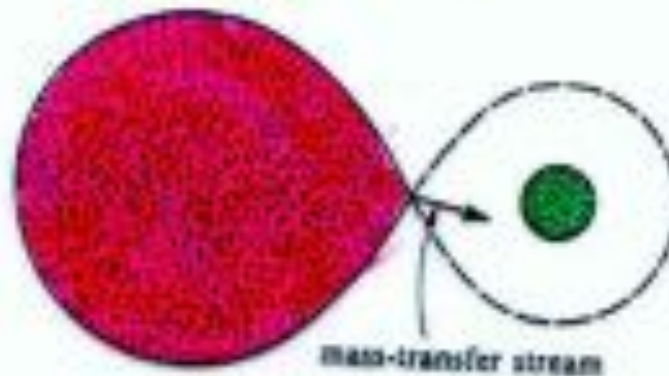
Star B:  $3.0M_{\odot} \rightarrow 0.8M_{\odot}$

# Binary Star Evolution



(a) detached binary

surface of equal total  
potential energy –  
*including rotation*



(b) semidetached binary

“Roche Lobe”

*Mass exchange can greatly alter stellar evolution.* It can change the composition we see on the surface of a star and can alter the lifetime and luminosity of both stars. Also ...

- When a massive star becomes a red giant, it may spill its H-envelope onto its companion changing the evolution of both. E.g.

### Type Ib supernova

- After the (initially) more massive star has died, interesting systems can be created in which one “star” is a white dwarf, neutron star, or black hole, with another more ordinary star spilling matter onto it.

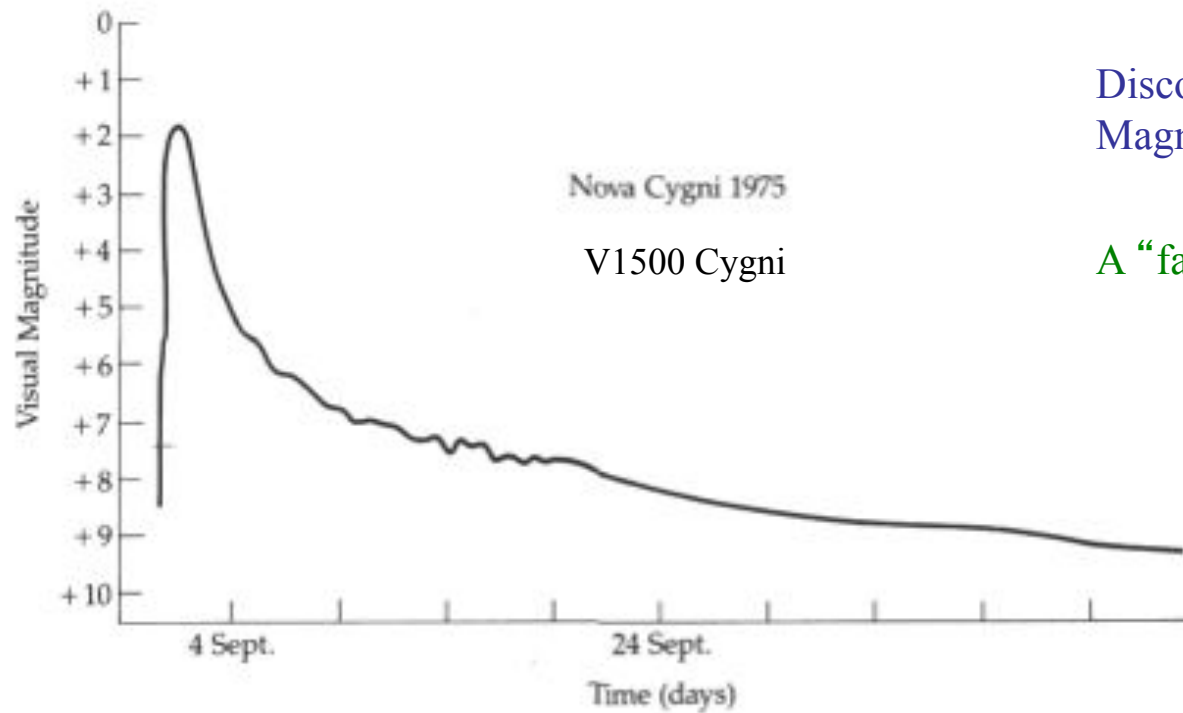
Classical novae

Type Ia supernovae

X-ray binaries

# CLASSICAL NOVAE

- Classical novae are thought to occur about 30 to 60 times a year in the Milky Way, but only about 10 are discovered each year.
- $L \sim 10^{38} \text{ erg s}^{-1}$  for several days to months. About  $10^5$  times the luminosity of the sun, but  $\sim 10^5$  times less luminous than the brightest supernova
- Recur – in theory - but the recurrence time scale may be very long - typically tens of thousands of years
- Some mass is ejected, but the amount is small  $10^{-6} - 10^{-4}$  solar masses. The velocities are slower than supernovae – 100's to perhaps  $1000 \text{ km s}^{-1}$
- Show emission lines of H, He, C, N, O, Ne, and Mg



Nova Cygni 1975

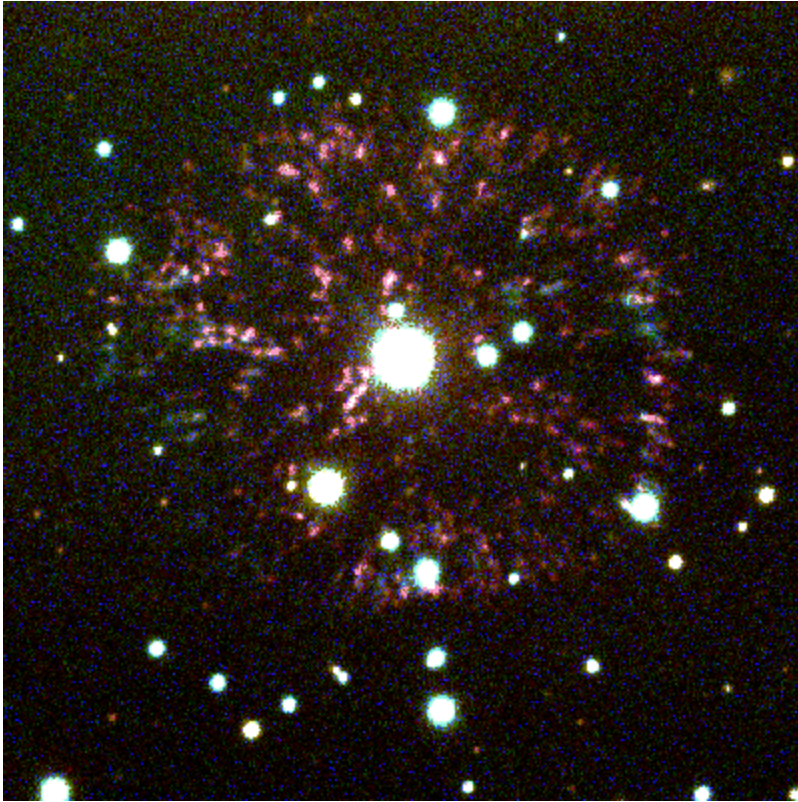
V1500 Cygni

Discovery Aug 29, 1975  
Magnitude 3.0

A “fast” nova

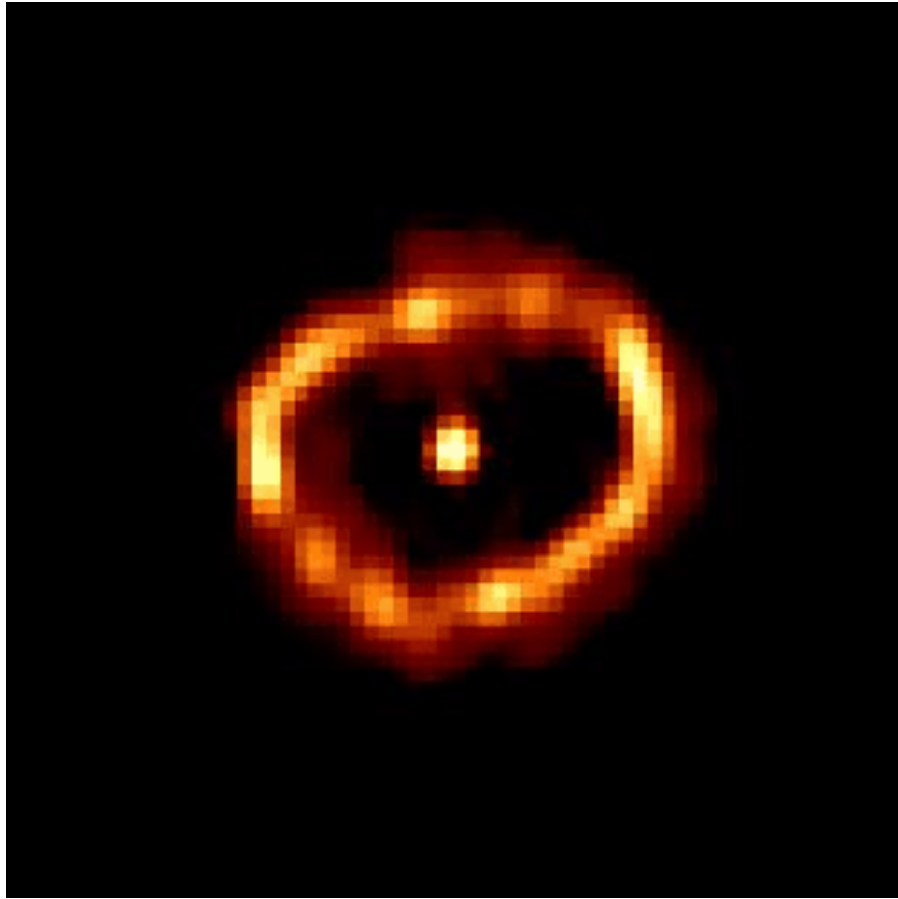


# Novae



- Nova Persei became one of the brightest stars in the sky in 1901. Look there now and see the expanding shell from the explosion. The velocity of the material is  $\sim 2000 \text{ km s}^{-1}$

# Nova Cygni 1992

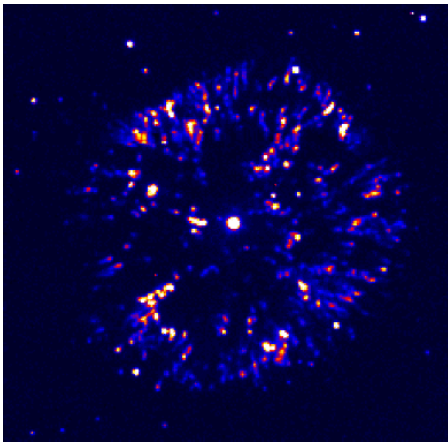


Visible magnitude at peak was 4.3. Photo at left is from HST in 1994. Discovered Feb. 19, 1992. Spectrum showed evidence for ejection of large amounts of neon, oxygen, and magnesium.

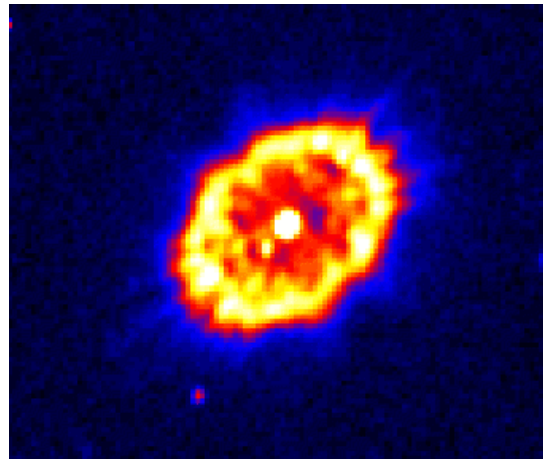
“Naked eye” novae occur roughly once per decade.

2.5 light days across  
ejected mass  $\sim 2 \times 10^{-4}$  solar masses

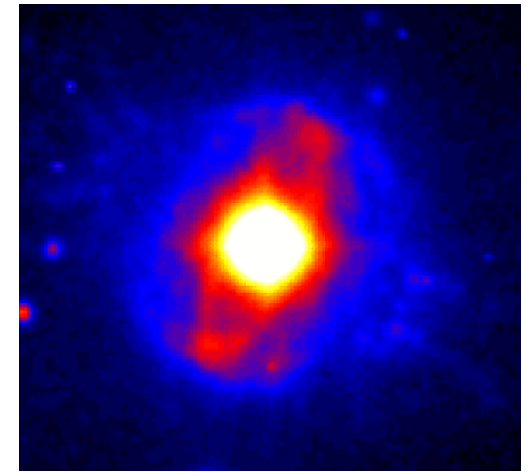
An earth mass or so is ejected at speeds of 100s to 1000s of  $\text{km s}^{-1}$ . Years later the ejected shells are still visible. The next page shows images from a ground-based optical survey between 1993 and 1995 at the William Herschel Telescope and the Anglo-Australian Telescope.



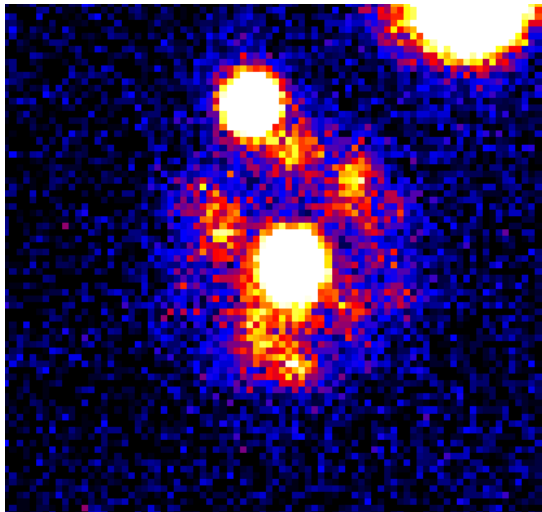
Nova Persei (1901)  
GK Per



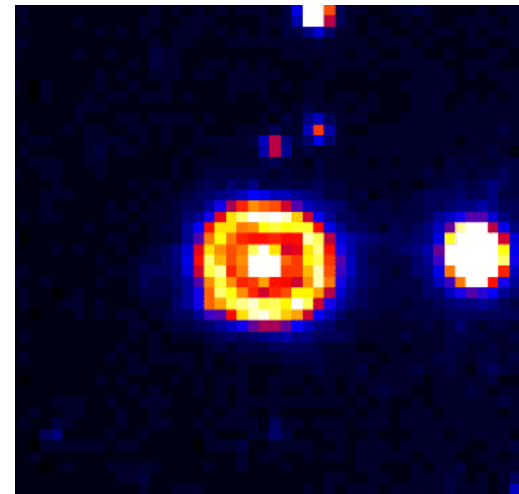
Nova Hercules (1934)  
DQ - Her



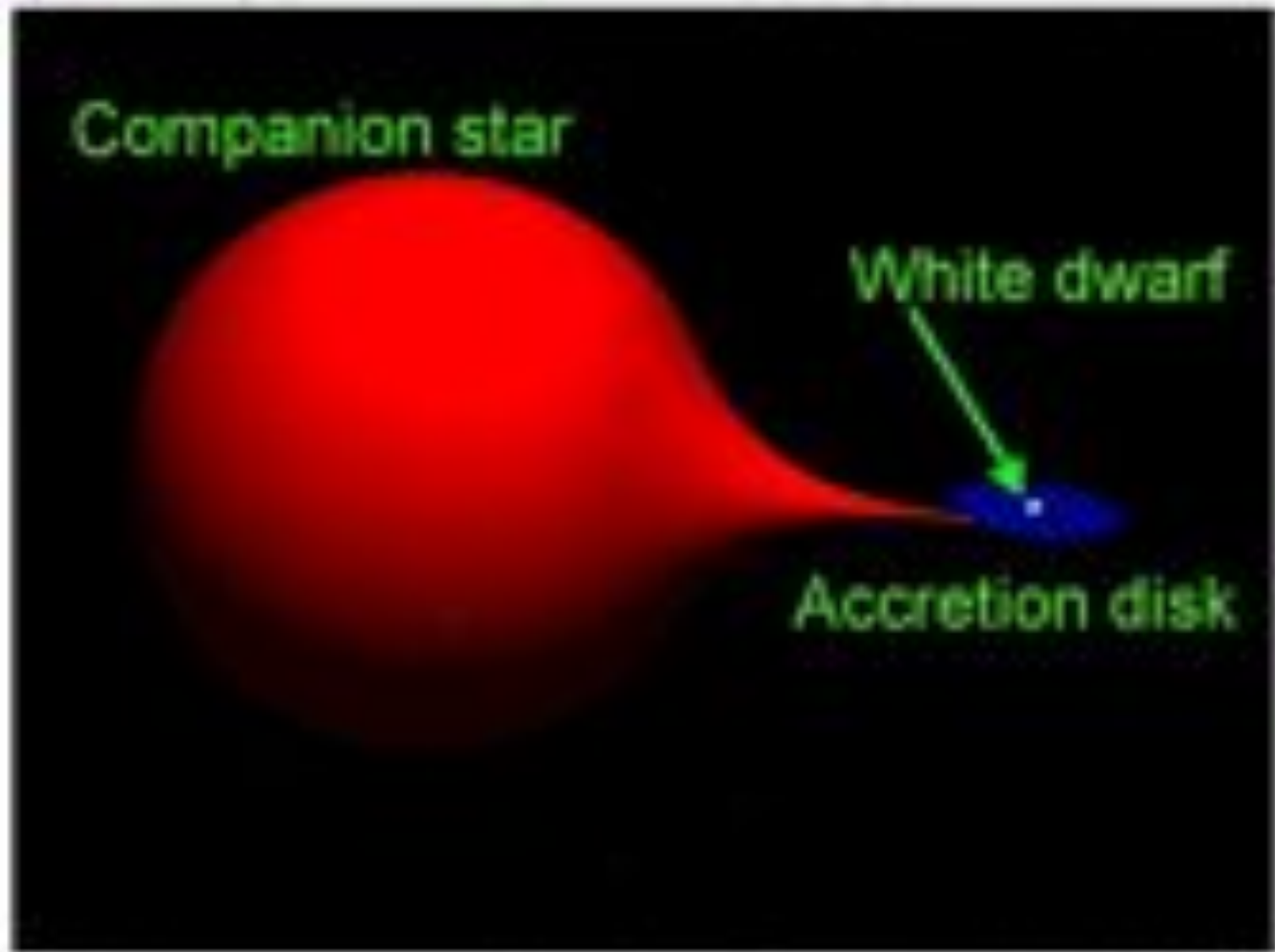
Nova Pictoris (1927)  
RR Pic



Nova Cygni (1975)  
V1500 Cygni



Nova Serpentis (1970)  
FH Ser



The companion star is typically a low mass (K or M) main sequence star. The orbital period is short  $< 1$  day.

# MODEL FOR CLASSICAL NOVAE

- A carbon-oxygen white dwarf accretes at a slow rate of about  $10^{-10}$  -  $10^{-8}$  solar masses per year from a binary companion. Hydrogen and helium accumulate on the surface (at higher accretion rates can get SN Ia).
- This material is initially too cool for nuclear reactions, but as accretion continues, it is compressed and heated. At about  $10^4$  g cm<sup>-3</sup>, hydrogen burning ignites (“hot” CNO cycle; temperature over 100 Million K)
- Initially the material is degenerate. Burning is also unstable because it happens in a thin shell on the WD surface. Hydrogen burns explosively. Not all of the hydrogen burns because the material is not very tightly bound to the white dwarf

Binding energy per gm for a  $1 M_{\odot}$  white dwarf

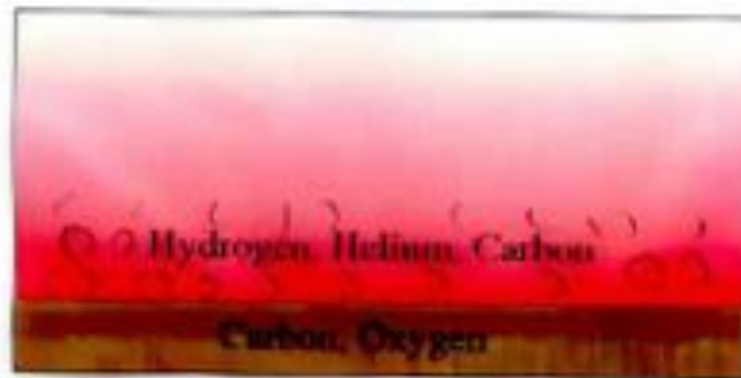
$$\frac{GM}{R} = \left( \frac{(6.67 \times 10^{-8})(2 \times 10^{33})}{5 \times 10^8} \right)$$
$$\approx 3 \times 10^{17} \text{ erg g}^{-1} \ll 6.8 \times 10^{18} \text{ erg g}^{-1} = q_H$$

- The hydrogen continues to burn for several months as the entire accreted layer is driven off the star in a powerful wind. None of the accreted material is left behind.
- Accretion then resumes and the cycle repeats

## Nova Model



## Explosion



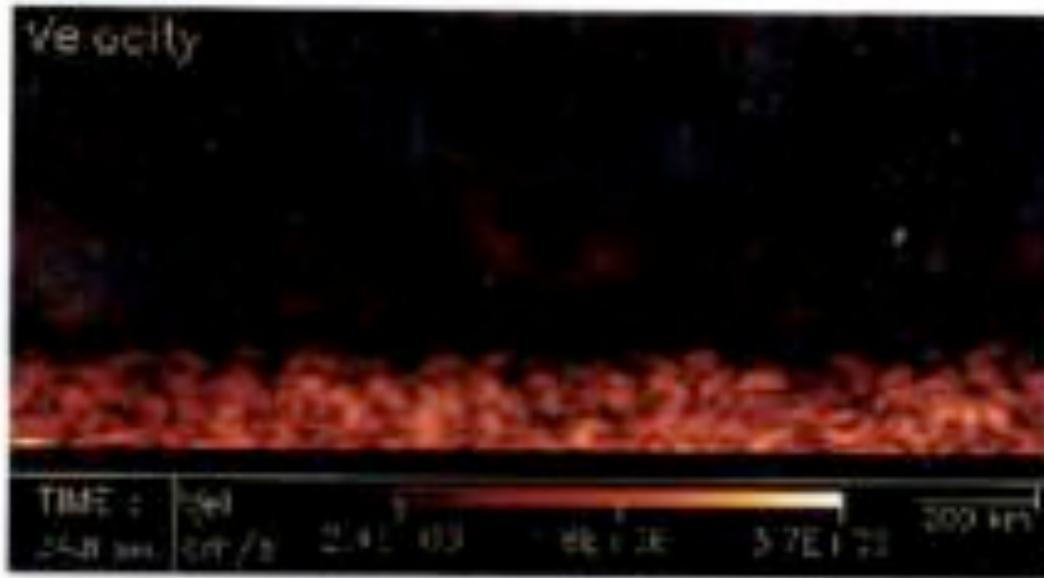
Typical peak hydrogen explosion temperatures are 200 million K at densities of  $10,000 \text{ g/cm}^3$

nb. Novae can *repeat*!

accrete  
explode  
accrete  
explode

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. .  
.





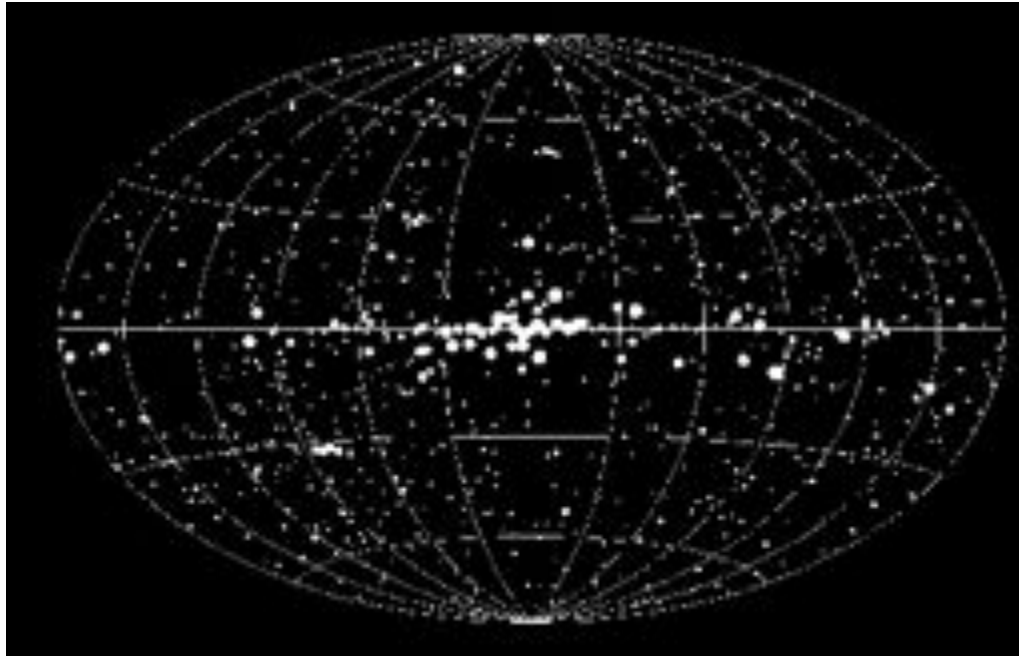
Kercek et al (1999)

About  
5000 trillion  
megatons/sec



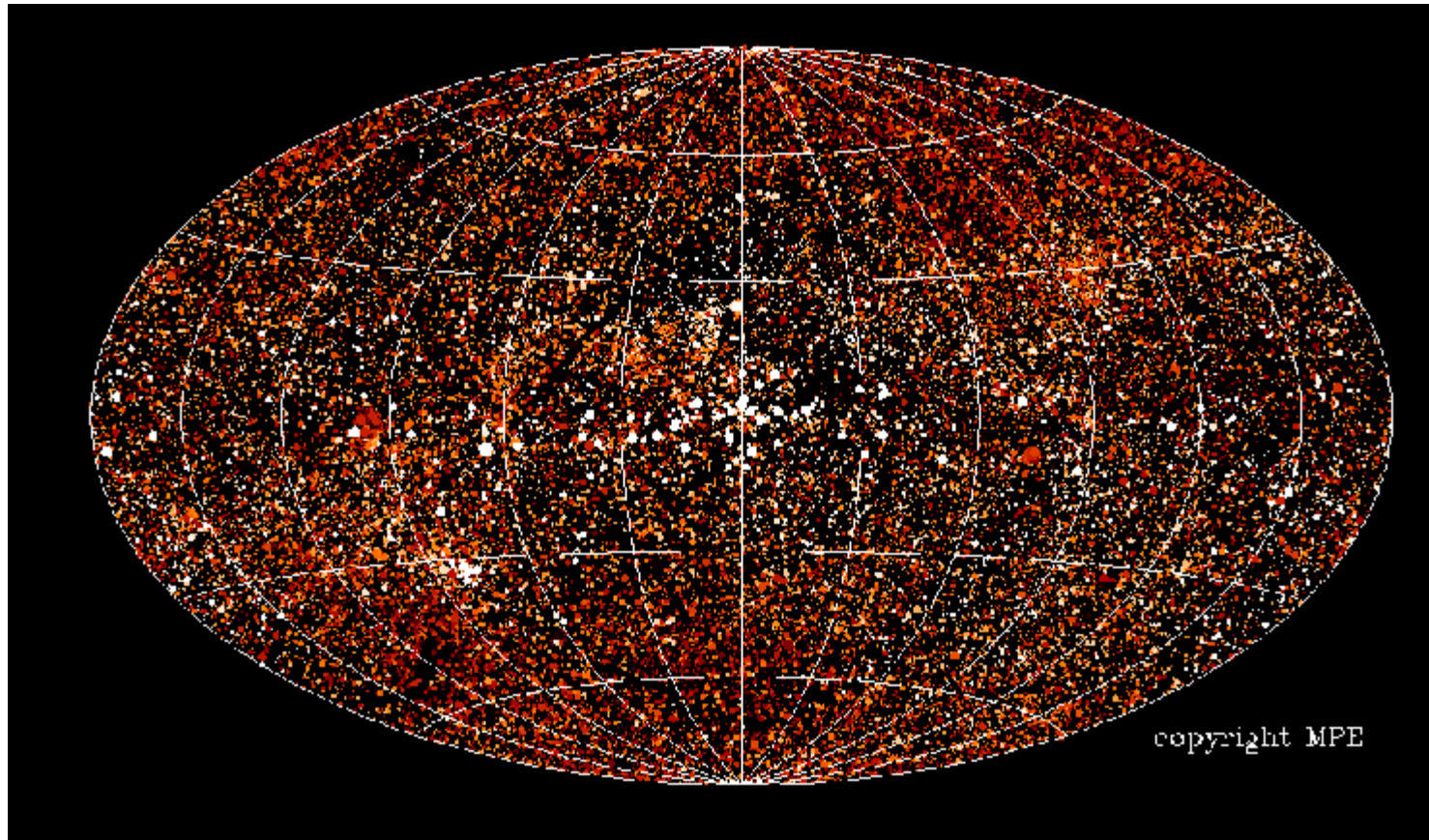
# *Binary X-Ray Sources*

# The bright x-ray sky – mostly point sources (AGN, SNR, black holes and neutron stars)



HEAO survey completed 1978  
841 sources mostly binary systems  
containing a neutron star or a black hole.

Also Giacconi - rockets in 60's  
UHURU = SAS 1 1970 - 1973



ROSAT – first pass in 1990 – 1991  
50,000 sources. By 1999  
over 150,000 sources had  
been catalogued. Many are  
“normal stars”.

red  $> 100,000$  K  
white  $\sim 20$  million K

luminosities  $\sim 10^{36} - 10^{38}$   
erg s $^{-1}$

## X Ray Binaries

- Two classes based upon mass of companion star that is feeding the x-ray emitting compact object
- High mass donors (over about 5 solar masses) are found in the disk of the galaxy and are Population I. The donor star is typically a B-type main sequence star or a blue supergiant. Roughly 300 are estimated to exist in our galaxy. Lifetime  $< 10^8$  years. Long period. High accretion rate.
- Low mass x-ray binaries contain a donor star of  $< \text{about } 1$  solar mass which may be a main sequence star. Population II. Found in Galactic center, globular clusters, in and above disk. Roughly 300 estimated to exist.
- Luminosities in X-rays for both are  $\sim 10^{36} - 10^{38}$  erg s $^{-1}$ . Spectra are approximately black bodies.

- The persistent emission of all x-ray binaries is due to the gravitational potential energy released by the accreted matter as it impacts the surface of the neutron star (or spirals into the black hole).
- For black holes it is a similar potential energy released by friction in a differentially rotating disk well outside the event horizon.
- Typical accretion rates are  $\sim \text{few} \times 10^{-9} M_{\odot} \text{ yr}^{-1}$   
( $2 \times 10^{17} \text{ gm s}^{-1}$ )

$$\begin{aligned}
 L &= \frac{GM}{R} \frac{dM}{dt} \\
 &= \frac{(6.67 \times 10^{-8})(3 \times 10^{33})}{10^6} (2 \times 10^{17}) \\
 &= 3 \times 10^{38} \text{ erg s}^{-1} \\
 &\quad \text{(i.e., about the Eddington luminosity)}
 \end{aligned}$$

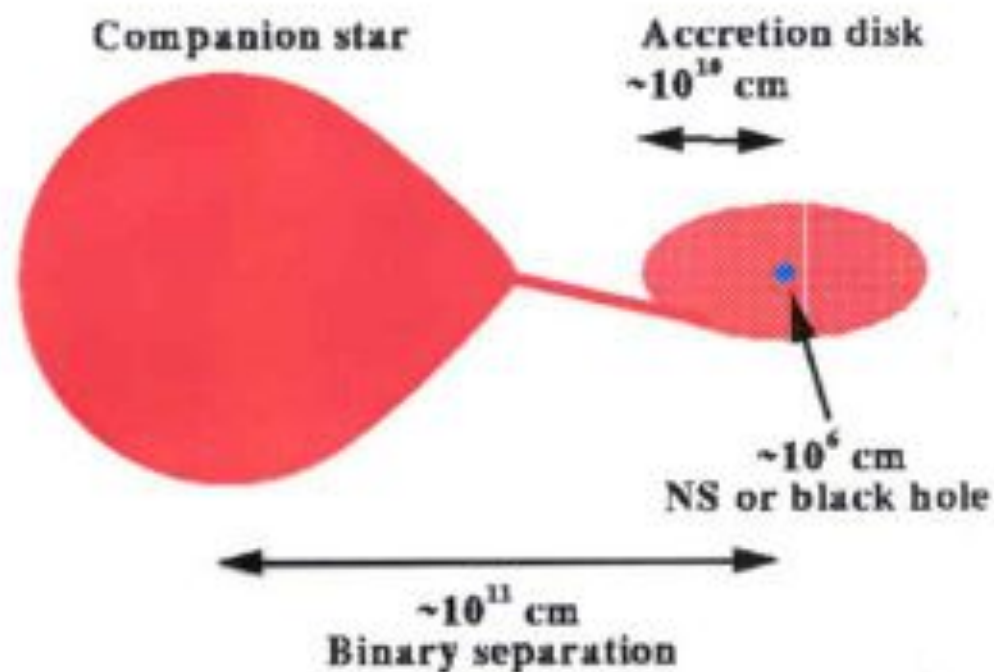
This is still approximately blackbody radiation so

$$T_{eff} = \left( \frac{L}{4\pi R^2 \sigma} \right)^{1/4} \approx 2.5 \times 10^7 \text{ K}$$

which corresponds to x-rays. The peak wavelength is

$$\begin{aligned} \lambda_{\max} &= \frac{0.289 \text{ cm}}{T_{eff}} = \frac{2.89 \times 10^7 \text{ Angstroms}}{T_{eff}} \\ &\approx 3 \text{ Angstroms (X-rays)} \end{aligned}$$

## Accreting neutron star or black hole

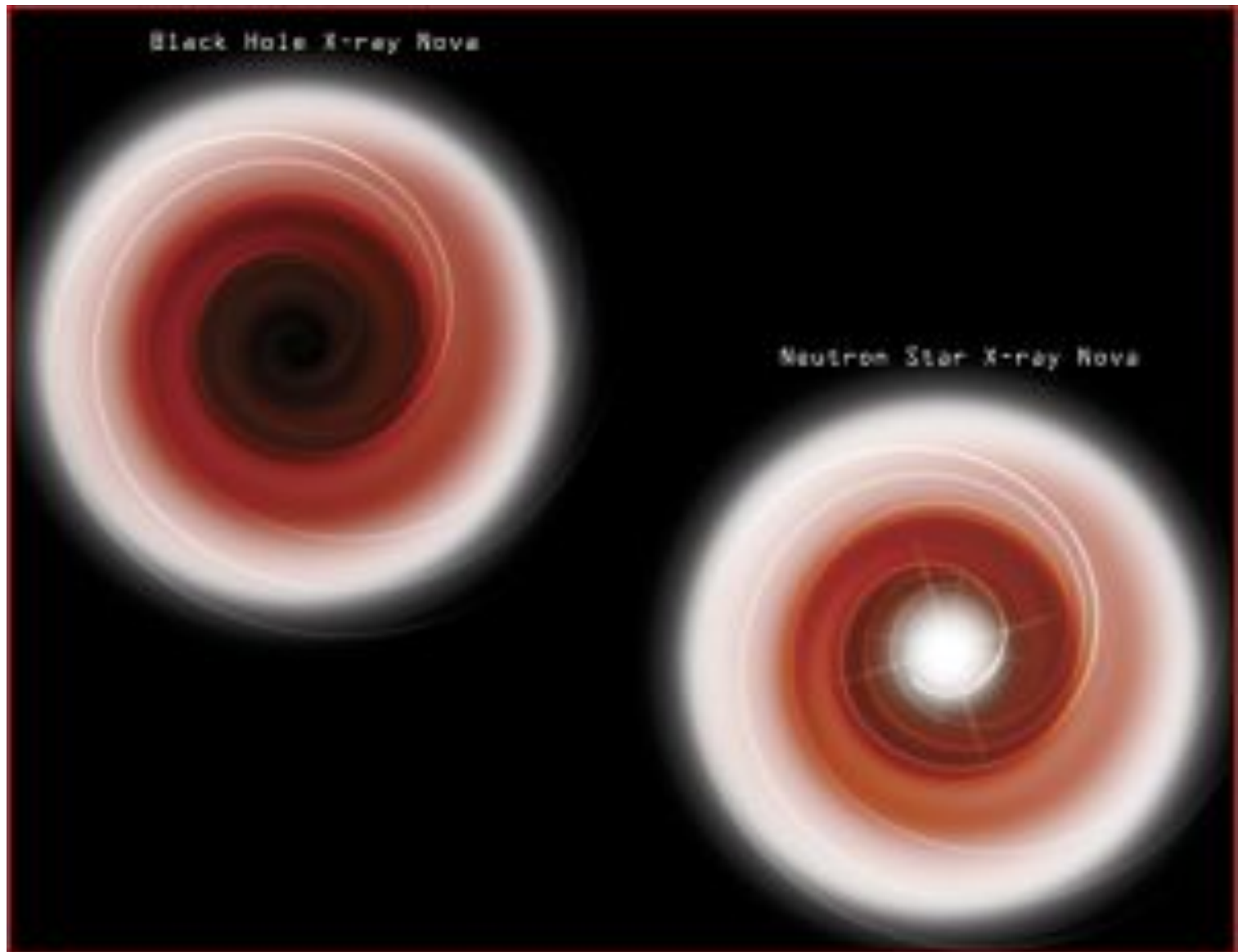


Luminosity  $\sim 10^{36} - 10^{38} \text{ erg s}^{-1} = 200 - 50,000 L_{\odot}$

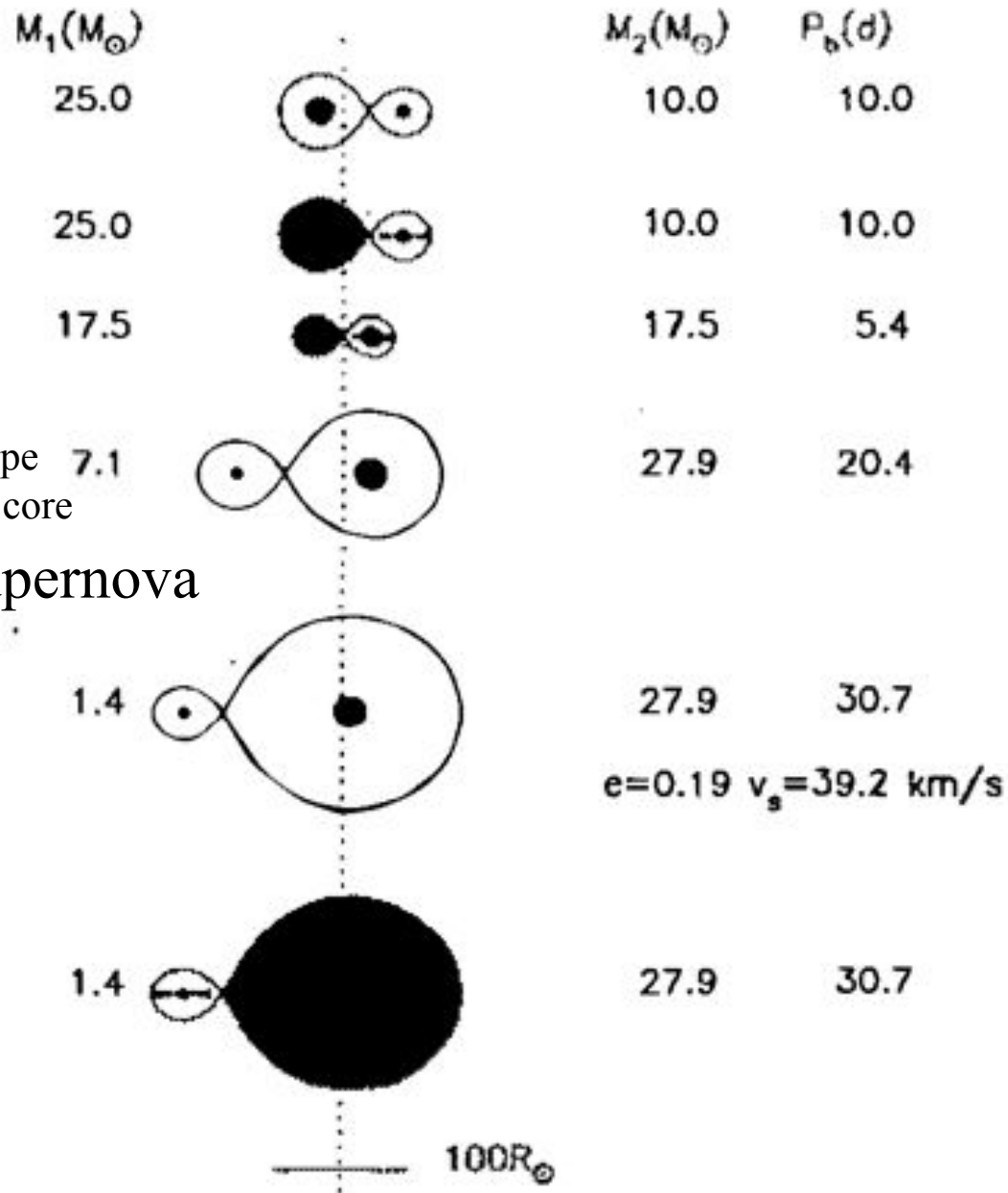
Temperature of disk  $\sim 10^7 \text{ K} \Rightarrow$  primarily X-rays



# Black Hole Illustration



# High Mass X-Ray Binary Formation



## Artist's Rendition of Cyg X-1



## Black hole candidates

<u>Source</u>	<u>Companion</u>	<u>P (days)</u>	<u>Mass</u>
Cygnus X-1	B supergiant	5.6	6-15
LMC X-3B	main sequence	1.7	4-11
A0620-00 (V616 Mon)	K main sequence	7.8	4-9
GS2023+338 (V404 Cyg)	K main sequence	6.5	> 6
GS2000+25 (QZ Vul)	K main sequence	0.35	5-14
GS1124-683 (Nova Mus 1991)	K main sequence	0.43	4-6
GRO J1655-40 (Nova Sco 1994)	F main sequence	2.4	4-5
H1705-250 (Nova Oph 1977)	K main sequence	0.52	> 4
+ 2 more			

# Gamma-Ray Bursts

*A Cosmic Gamma-Ray Burst*, GRB for short, is a brief, bright flash of gamma-rays lasting typically about 20 seconds that comes from an unpredictable location in the sky.

Some, in gamma-rays, are as bright as the planet Venus. Most are as bright as the visible stars. It is only because of the Earth's atmosphere and the fact that our eyes are not sensitive to gamma-rays that keep us from seeing them frequently.

They were discovered in the late 1960's by satellites orbiting the earth watching for atmospheric tests of nuclear weapons – the discovery was serendipitous

With appropriate instrumentation, we see about one of these per day at the Earth. They seem never to repeat from the same source.

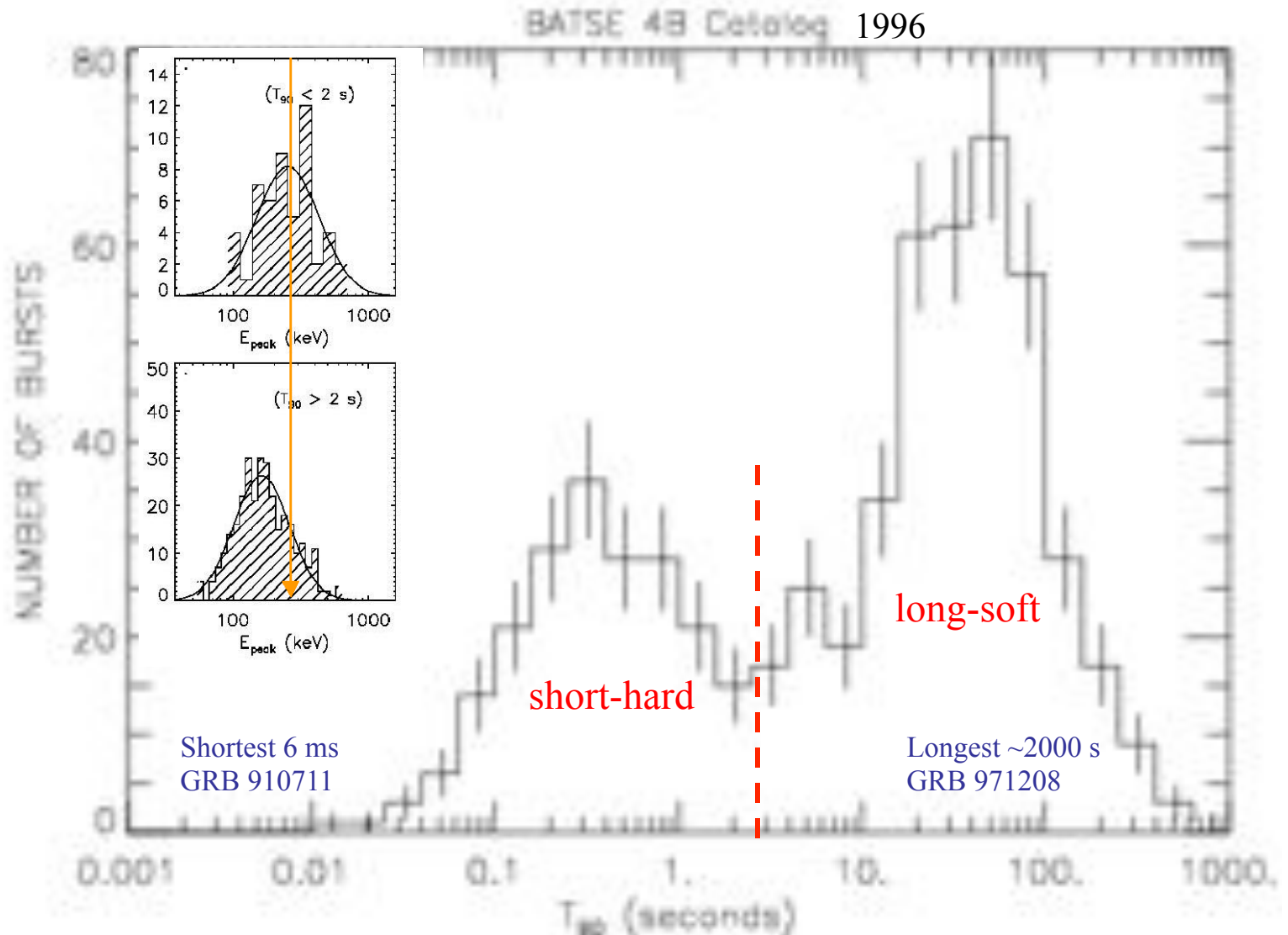


Ian Strong – left Ray Klebesadel – right  
September 16, 2003

Gamma-ray bursts (GRBs) discovered 1969 - 72 by Vela satellites. Published by Klebesadel, Strong and Olson (1973)

# GRBs come in two flavors

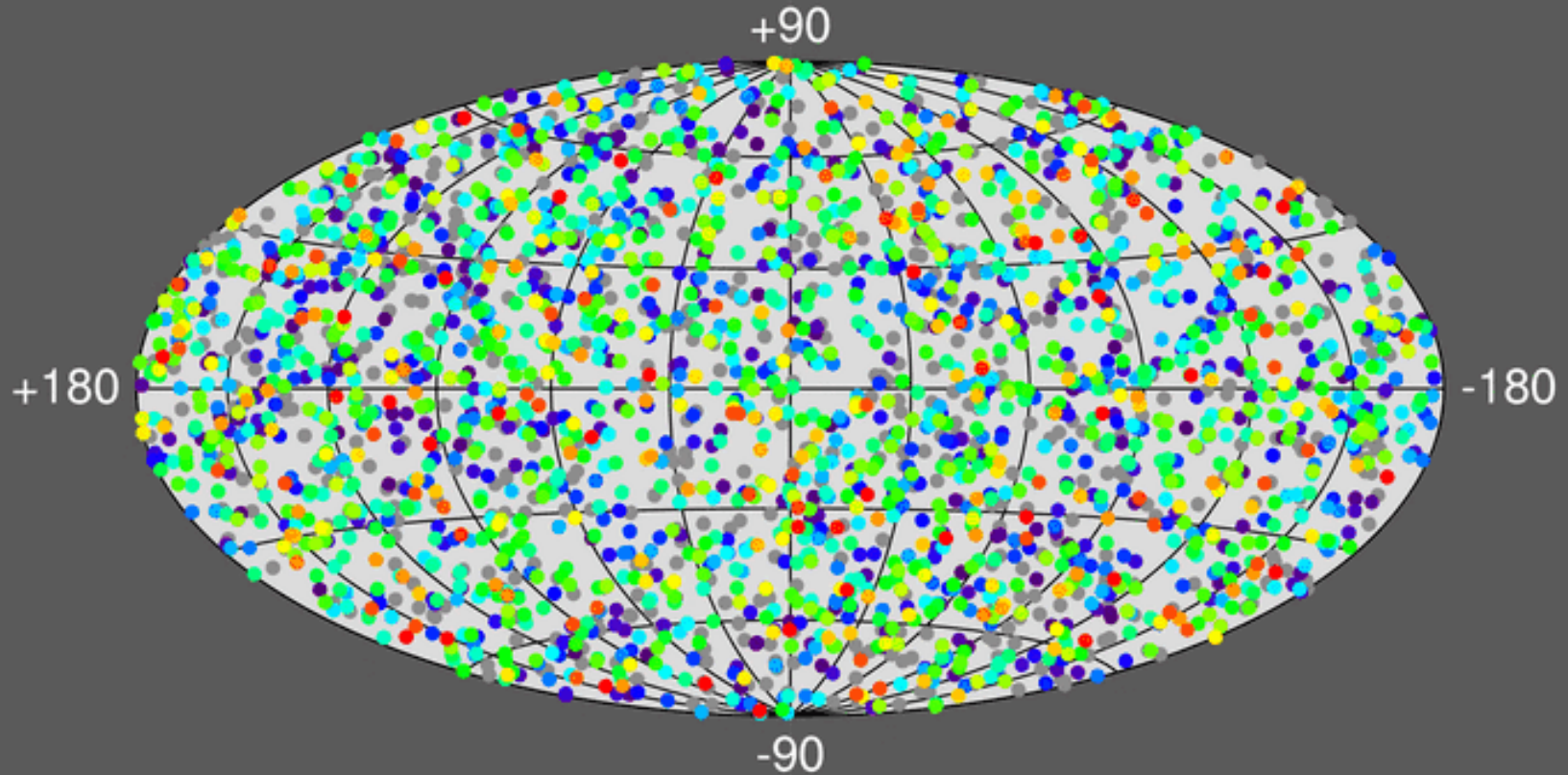
- short and long





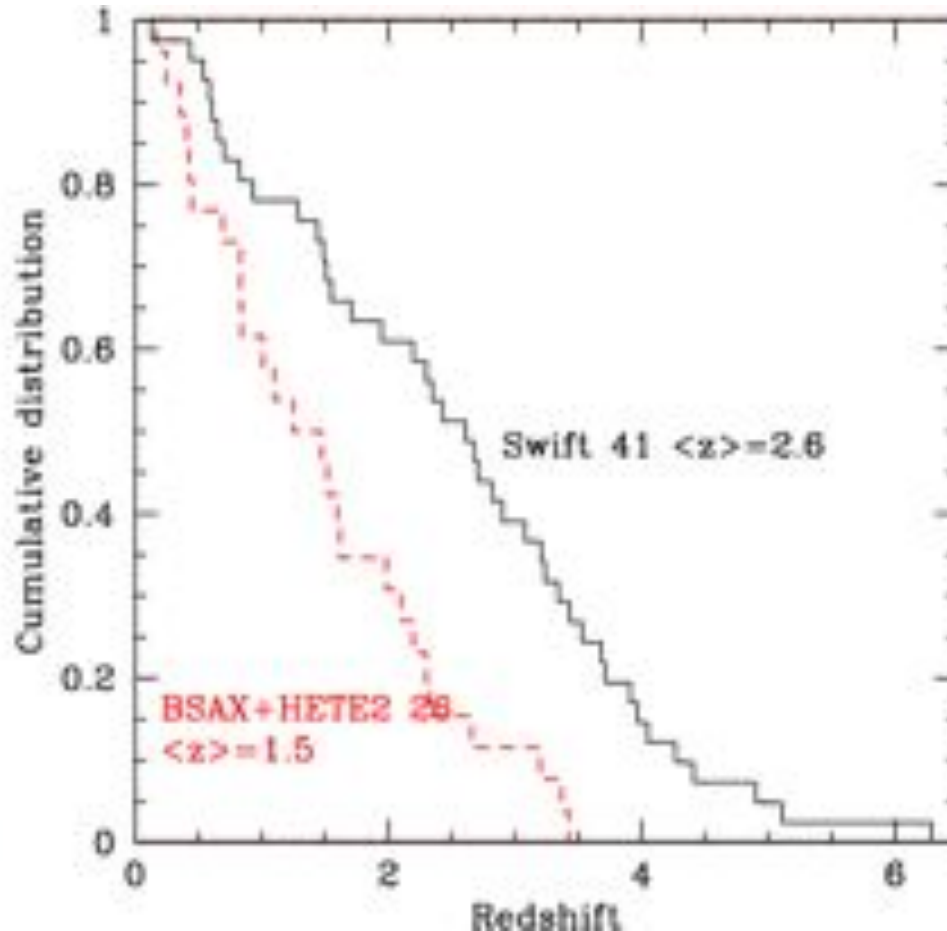
They are isotropic on the sky

## 2704 BATSE Gamma-Ray Bursts



Bright long bursts are red; short fainter bursts are purple. The rest are intermediate. Note – no correlation with Galactic disk. Each burst was localized to about 1 degree.

- They are at cosmological distances (this was controversial until the late 1990's)

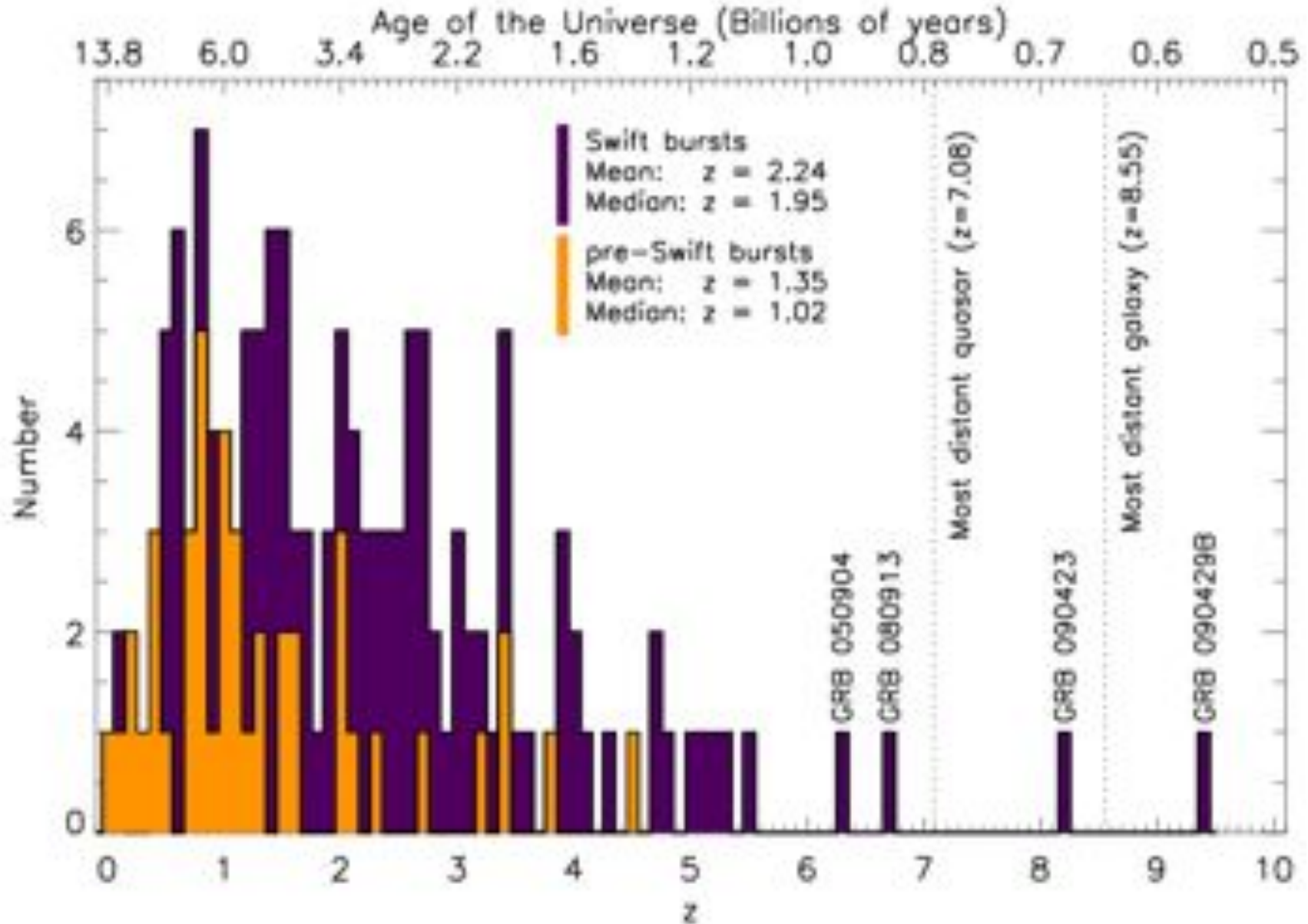


*SWIFT gives  
an average  $z$   
for 41 bursts  
with good distance  
determinations  
of 2.6*

*The farthest  
GRB, so far,  
is at  $z = 8.2$*

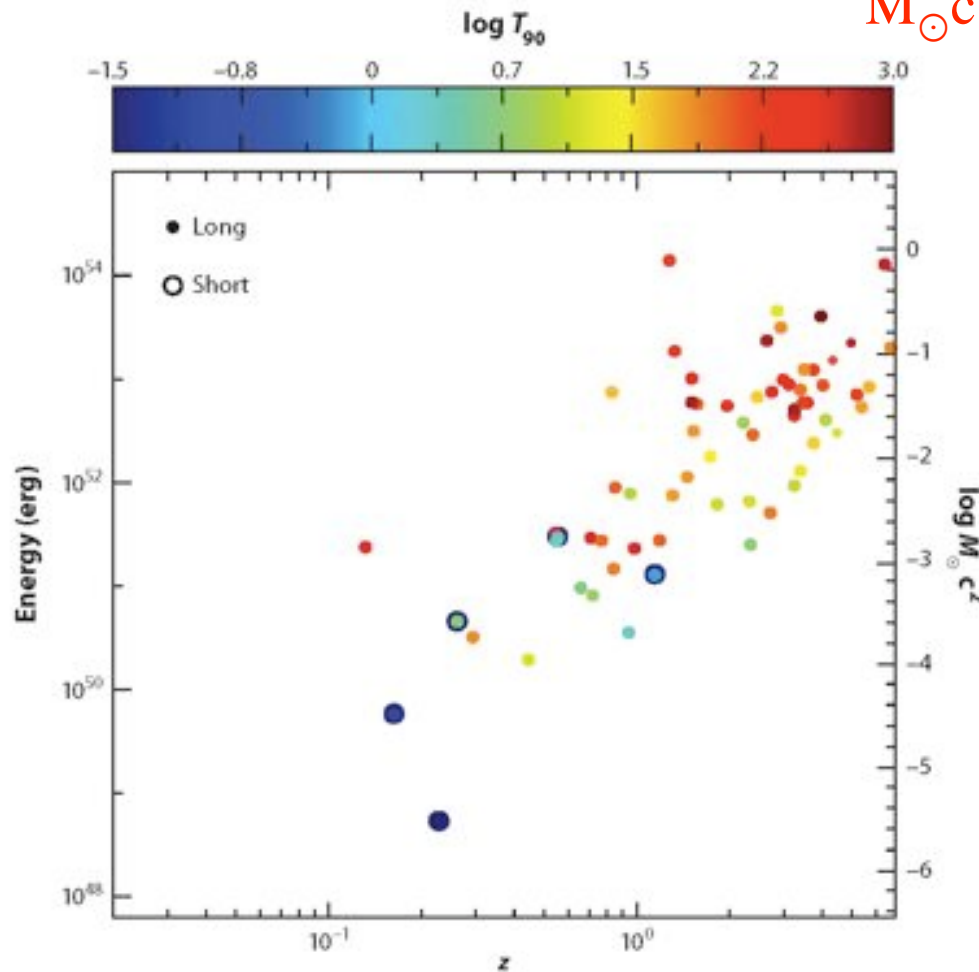
Fiore et al (2007)

They are among the most distant events in the universe



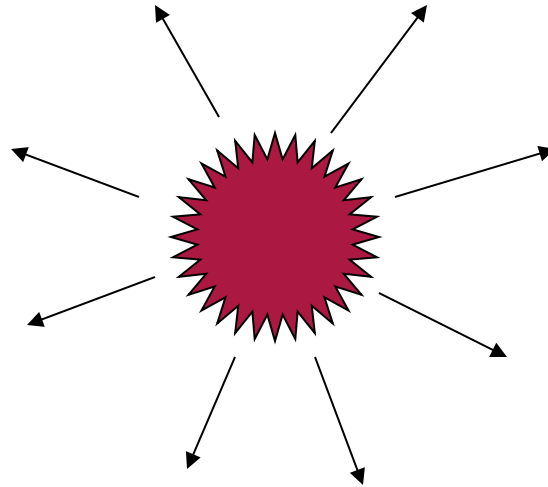
Inferred energy if bursts emit their radiation equally at all angles extends up to  $10^{54}$  erg!

$$M_{\odot} c^2 = 1.8 \times 10^{54} \text{ erg} !$$



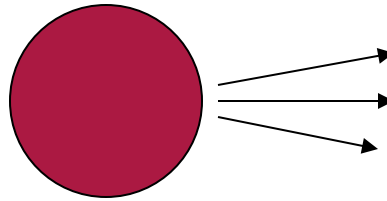
But the total energy is greatly reduced if they are beamed in our direction.

But are the energies required really  
as great as  $10^{54}$  erg?



○  
*Earth*

*If the energy were  
beamed to 0.1% of the  
sky, then the total  
energy could be  
1000 times less*

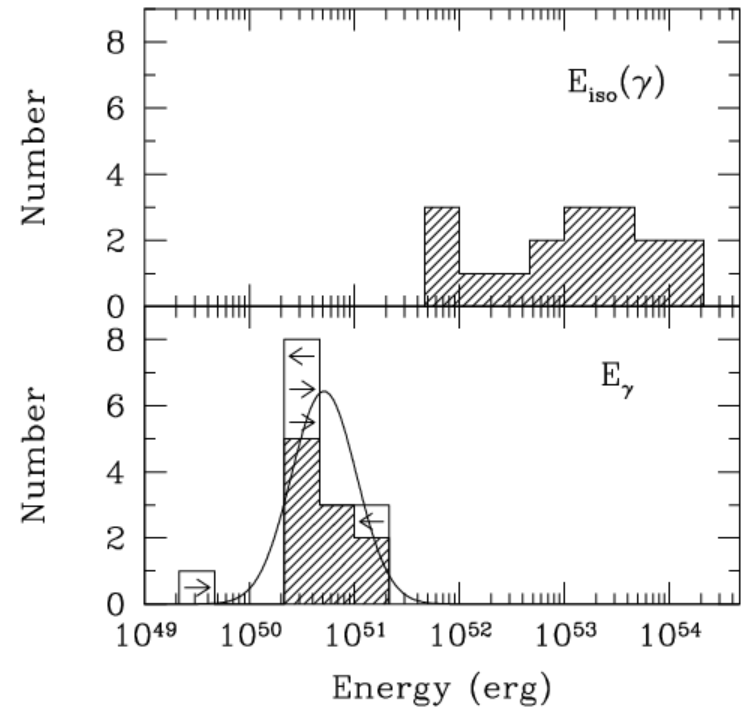
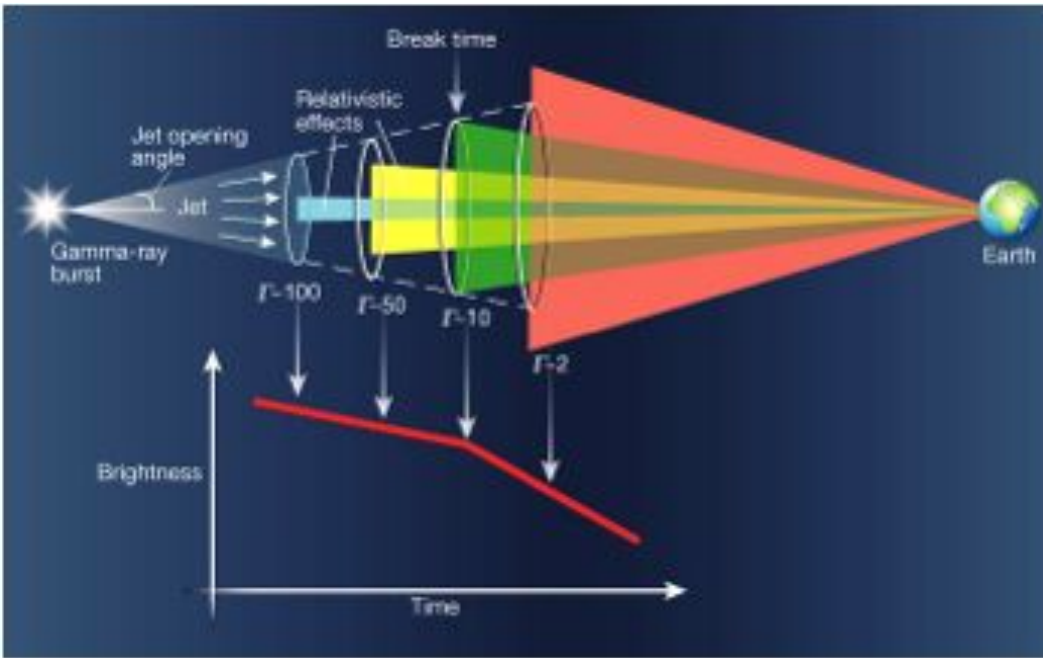


○  
*Earth*

*Nothing seen down here*

GRBs are beamed and their total energy in relativistic ejecta is  $\sim 10^{51}$  erg.

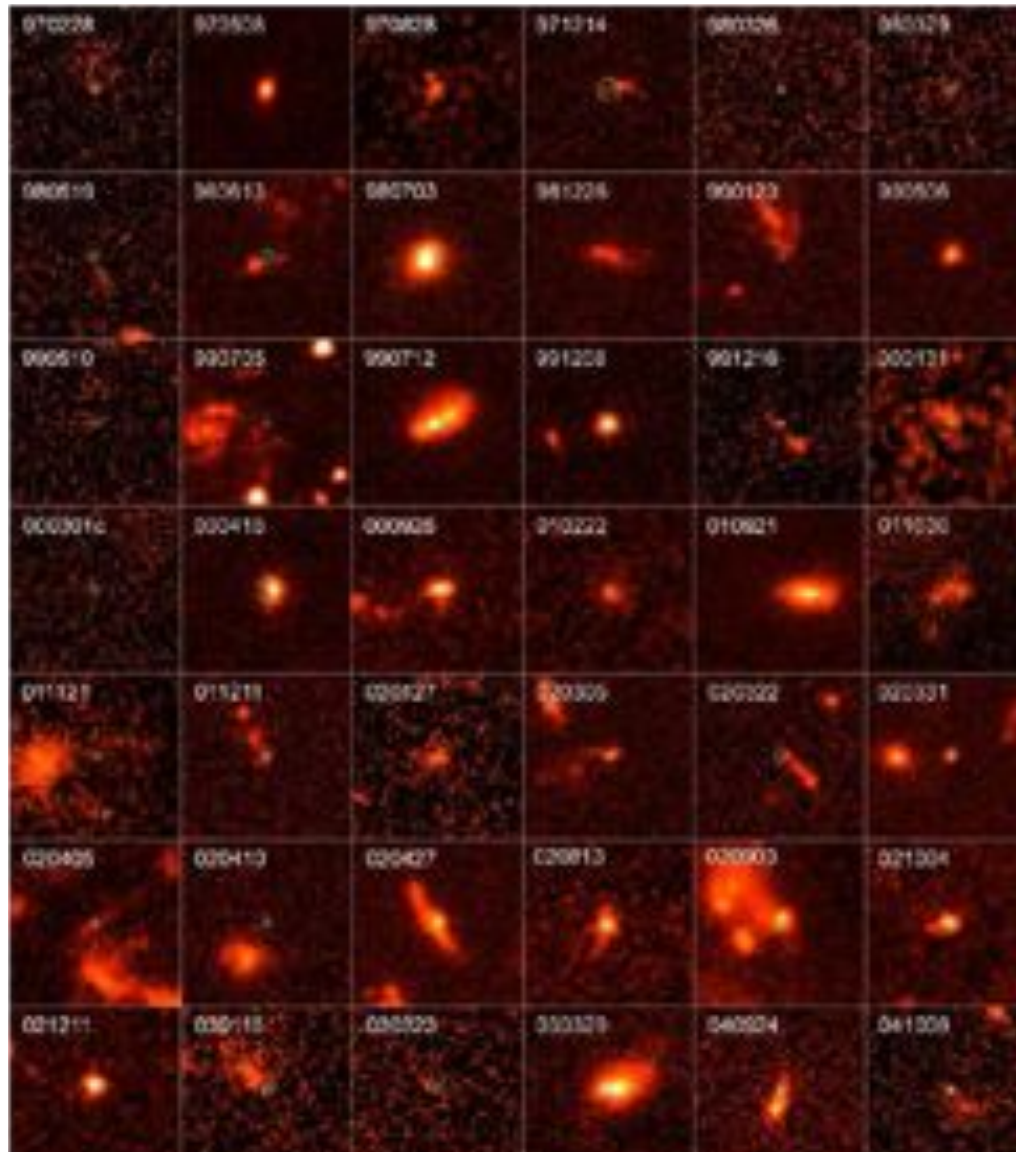
Frail et al. (2001)



*As a relativistic jet decelerates we see a larger fraction of the emitting surface until we see the edges of the jet. These leads to a panchromatic break slope of the the afterglow light curve.*



# LS-GRBs occur in star-forming regions

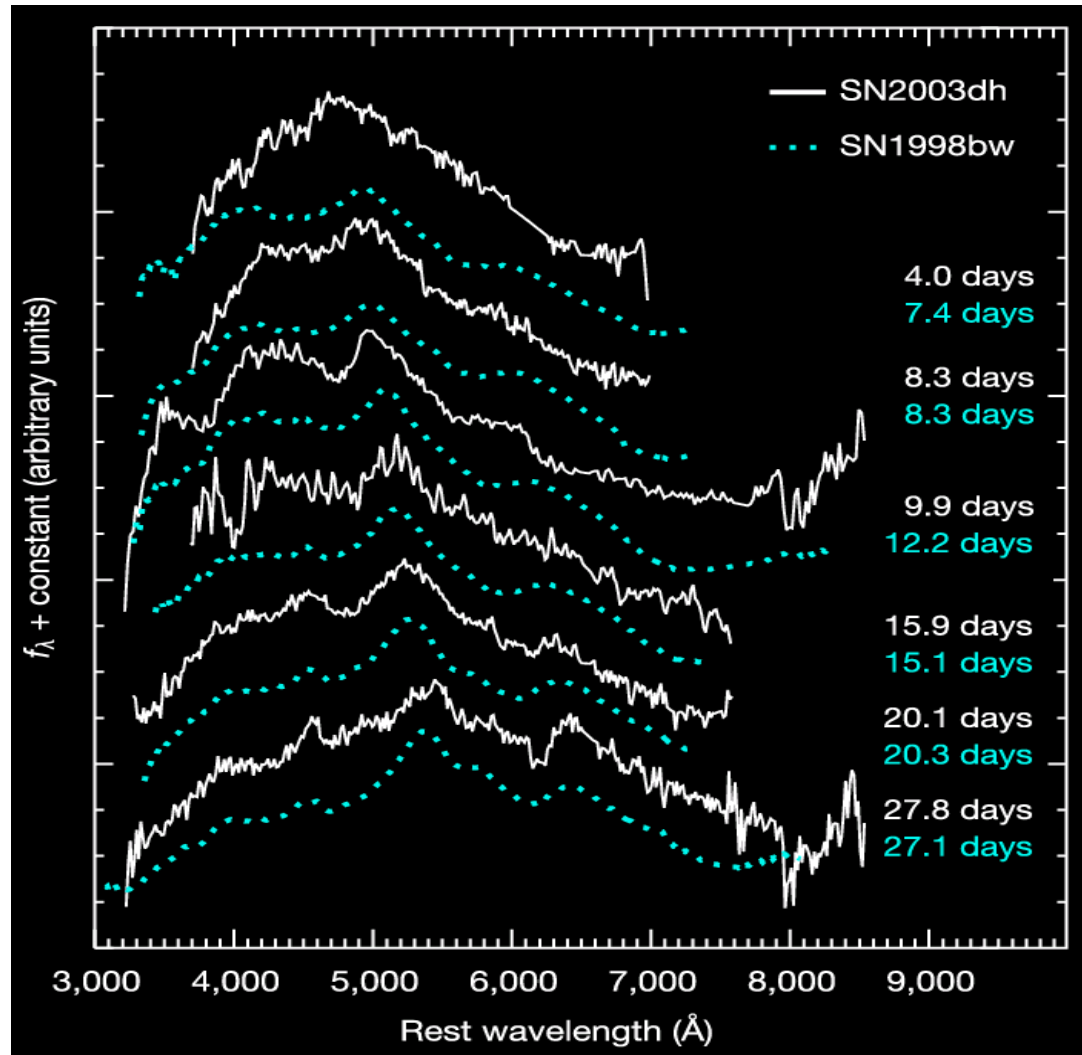


Fruchter et al (2005).

*The green circles show long soft GRB locations to an accuracy of 0.15 arc sec.*

Conclusion: *GRBs trace star formation even more than the average core-collapse supernova. They are thus to be associated with the most massive stars. They also occur in young, small, star forming galaxies that might be metal poor.*

LS-GRBs, at least frequently, occur in simultaneous conjunction with supernovae of Type Ic



GRB980425/  
SN1998bw

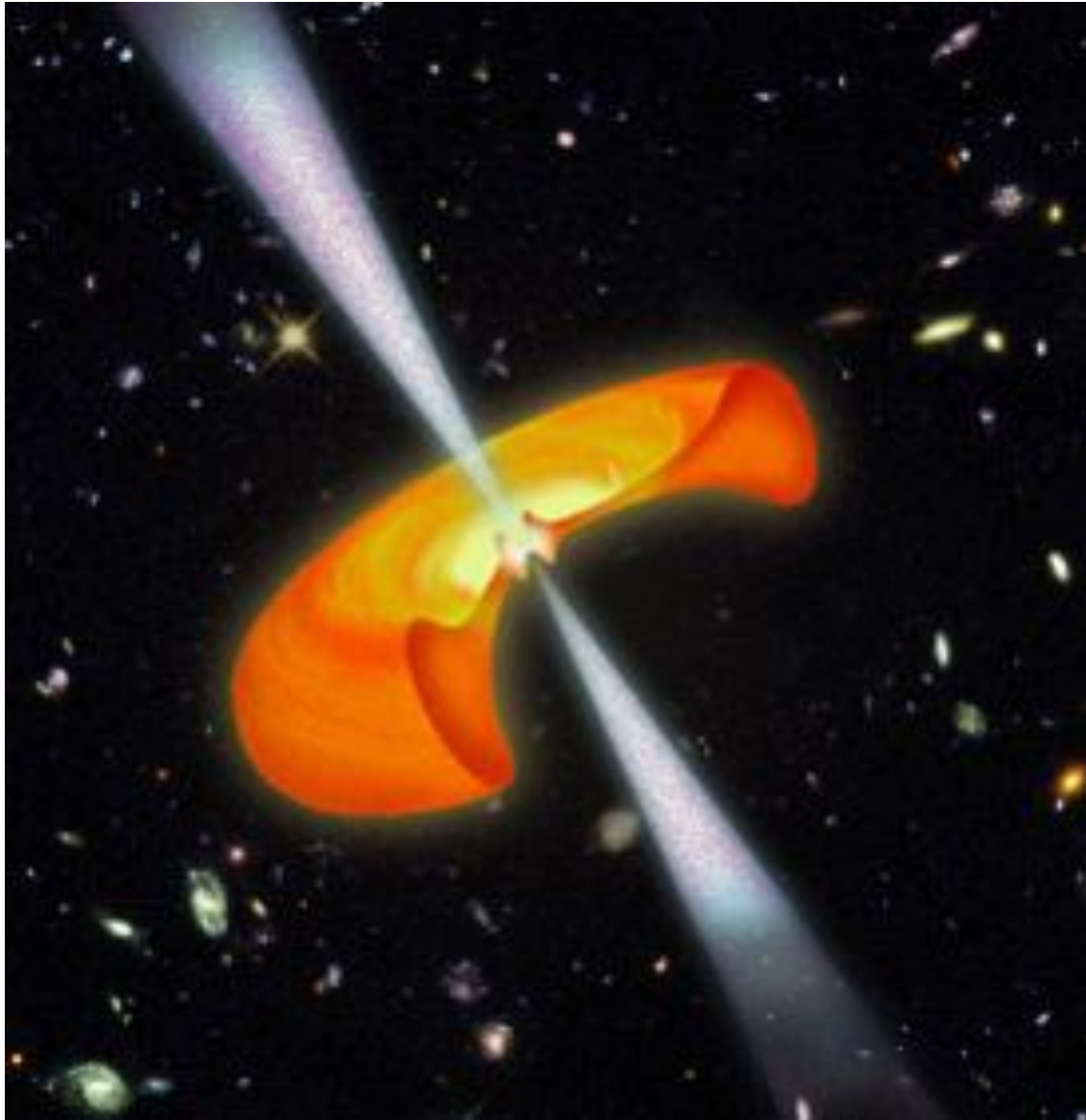
GRB030329/  
SN2003dh

GRB031203/  
SN2003lw

GRB060218/  
SN2006aj



# The Collapsar Model (Woosley 1993)



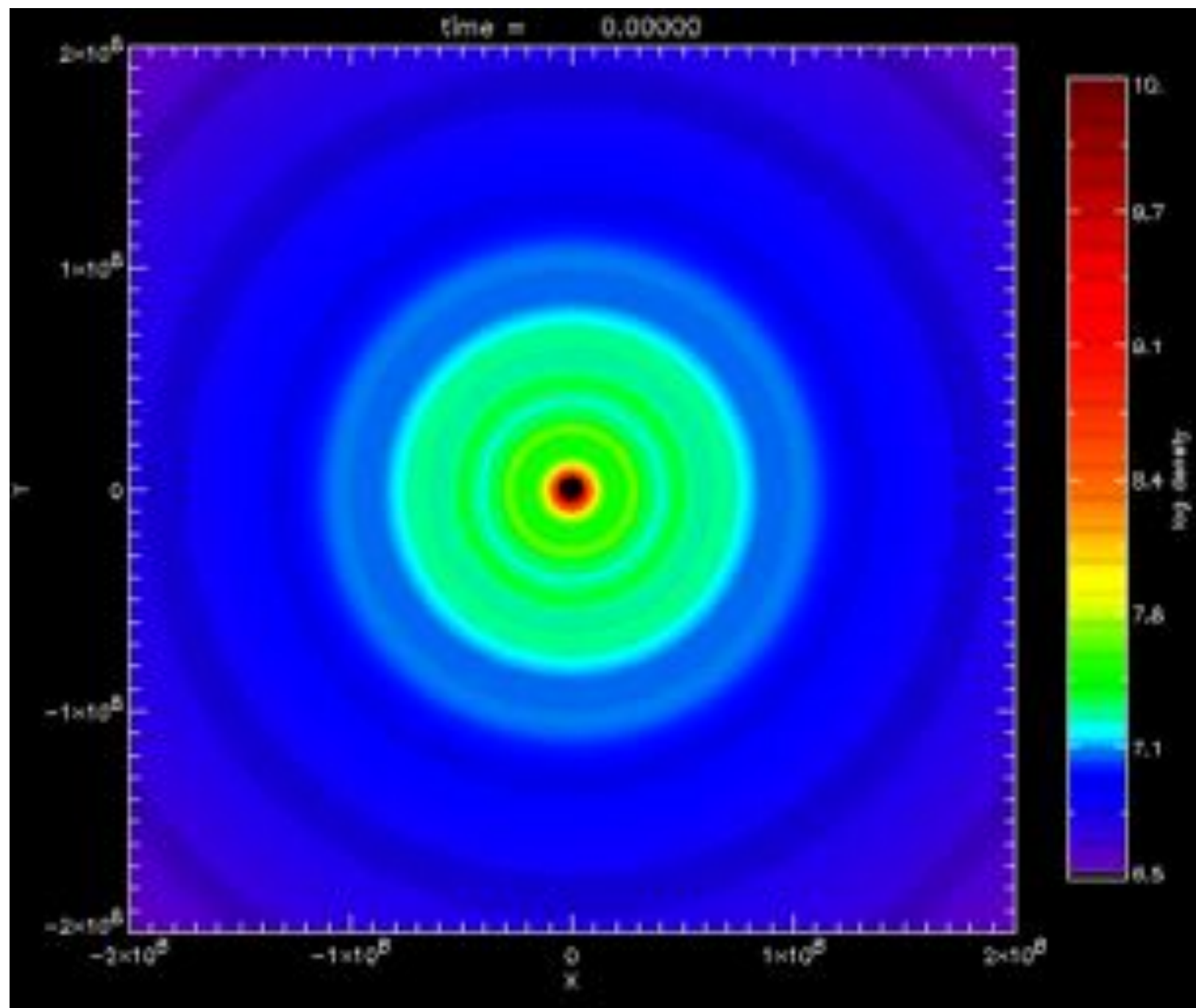
Usually massive stars make supernovae. Their iron core collapses to a neutron star and the energy released explodes the rest of the star.

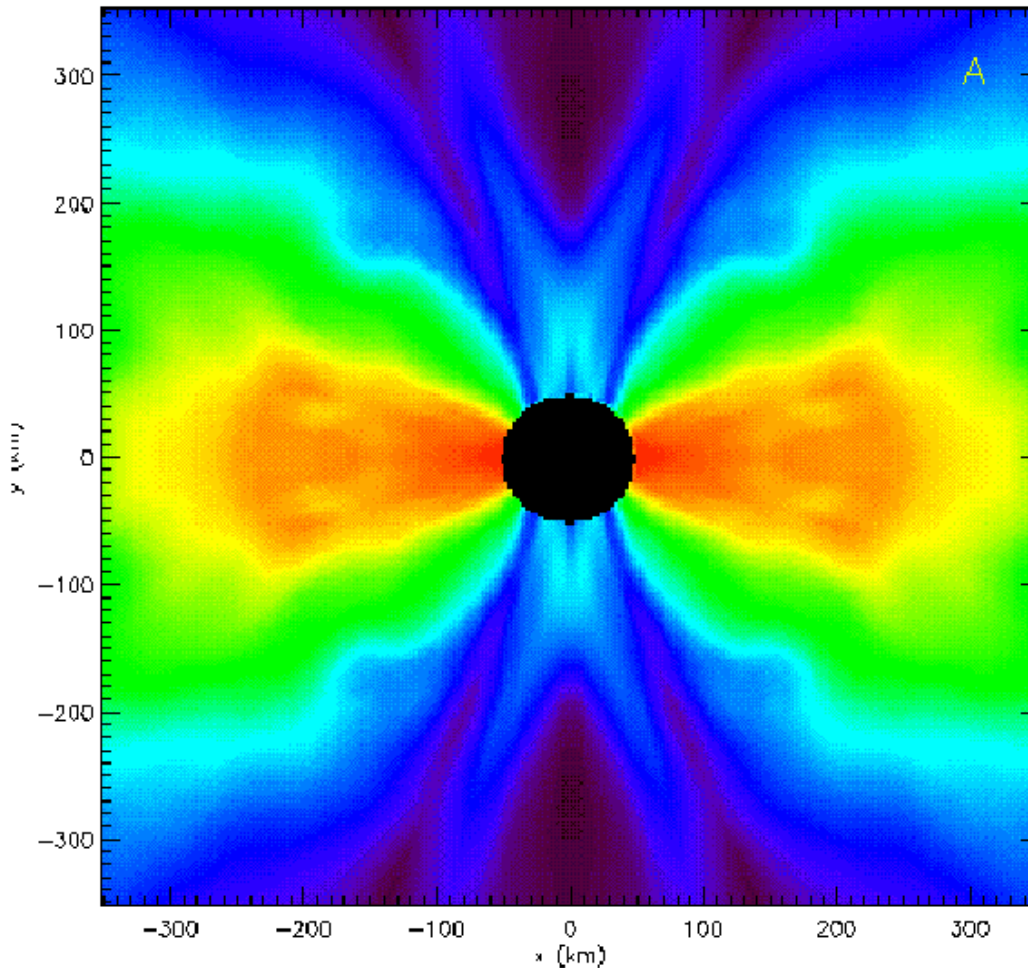
But what if the explosion fizzled? What if the iron core collapsed to an object too massive to be a neutron star – a black hole.

A star without rotation would then simply disappear....

But what if the star had too much rotation to all go down the (tiny) black hole?

If supernovae are the observational signal that a neutron star has been born, what is the event that signals the birth of a black hole?





MacFadyen & Woosley (1998)

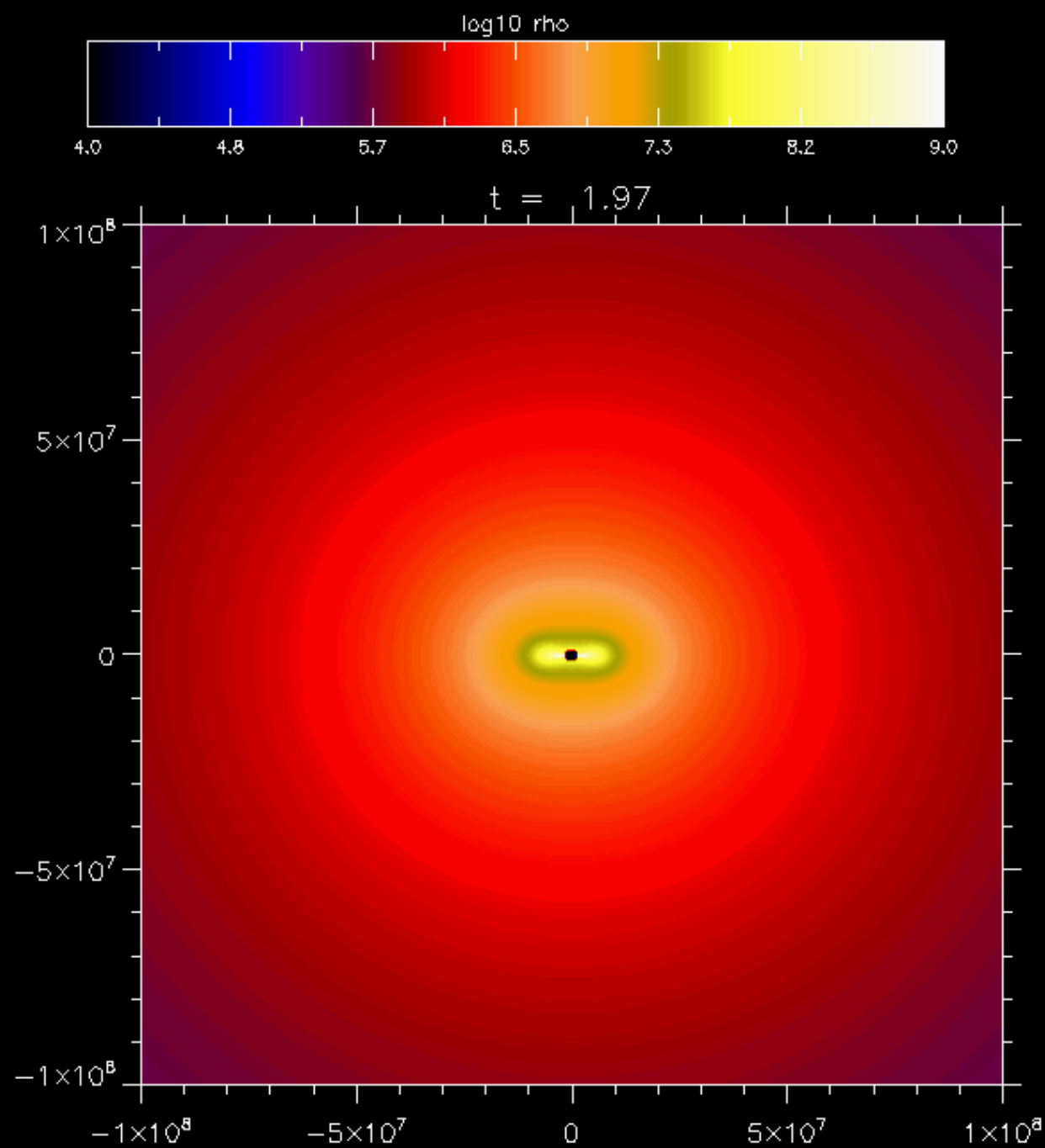
log density ( $\text{g cm}^{-3}$ )



In the vicinity of the rotational axis of the black hole, by a variety of possible processes, energy is deposited.

The exact mechanism for extracting this energy either from the disk or the rotation of the black hole is fascinating physics, but is not crucial to the outcome, **so long as the energy is not contaminated by too much matter.**

7.6 s after core collapse; high viscosity case.

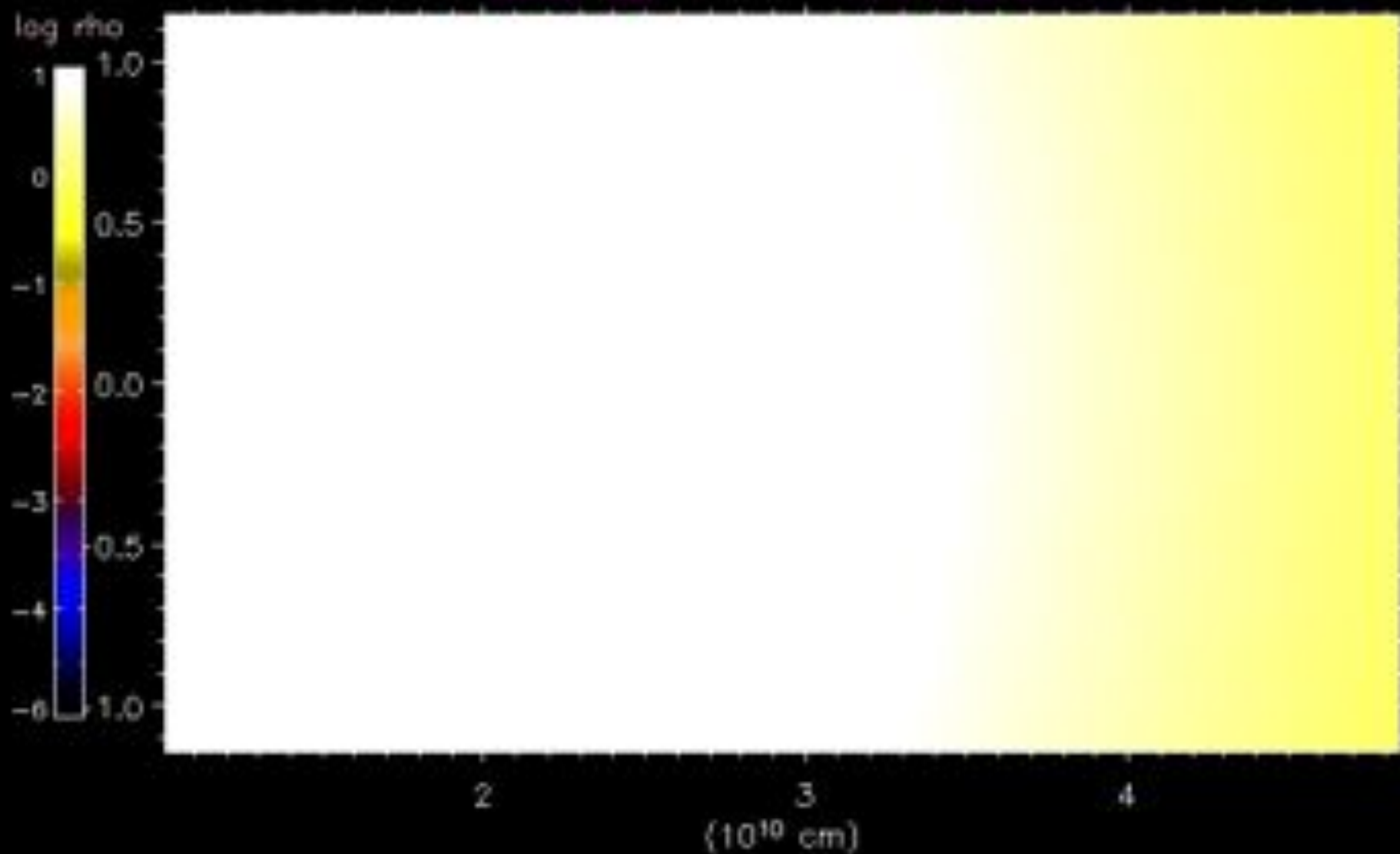


# 3-D Special Relativistic Hydro Simulation of Collapsar Jet

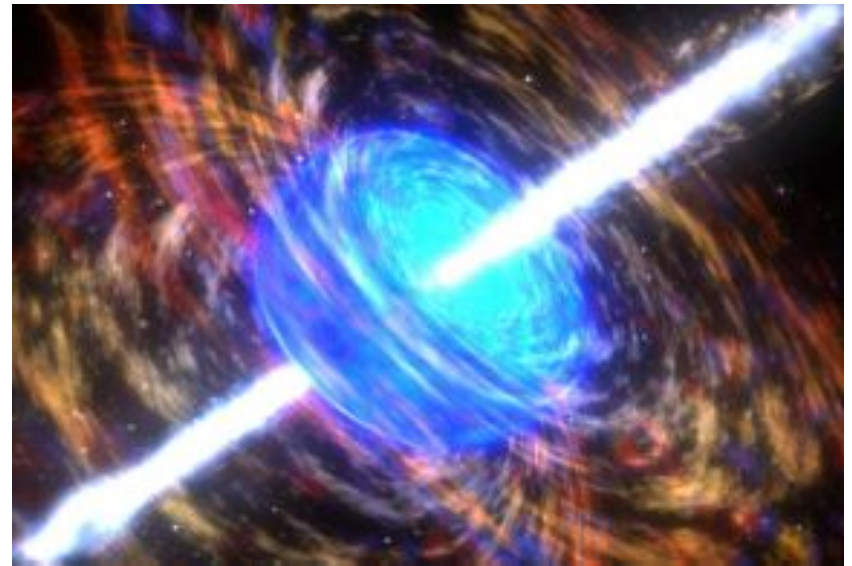
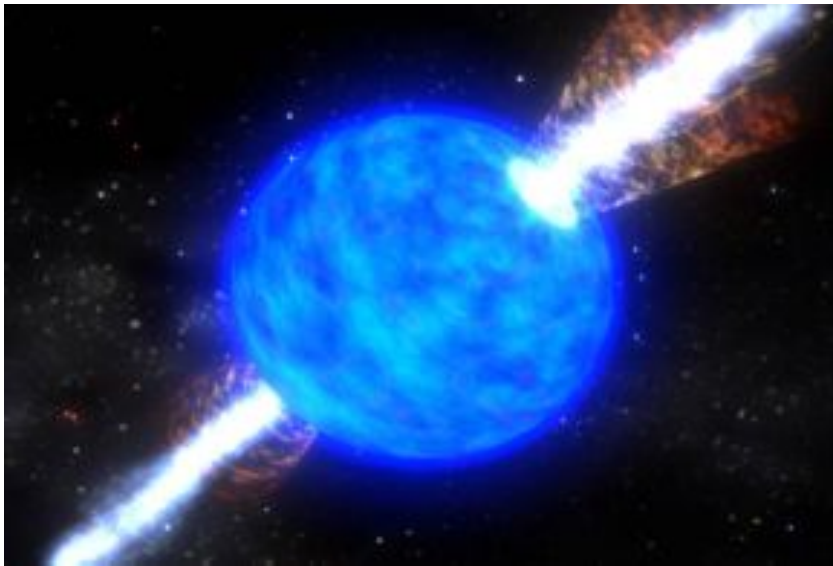
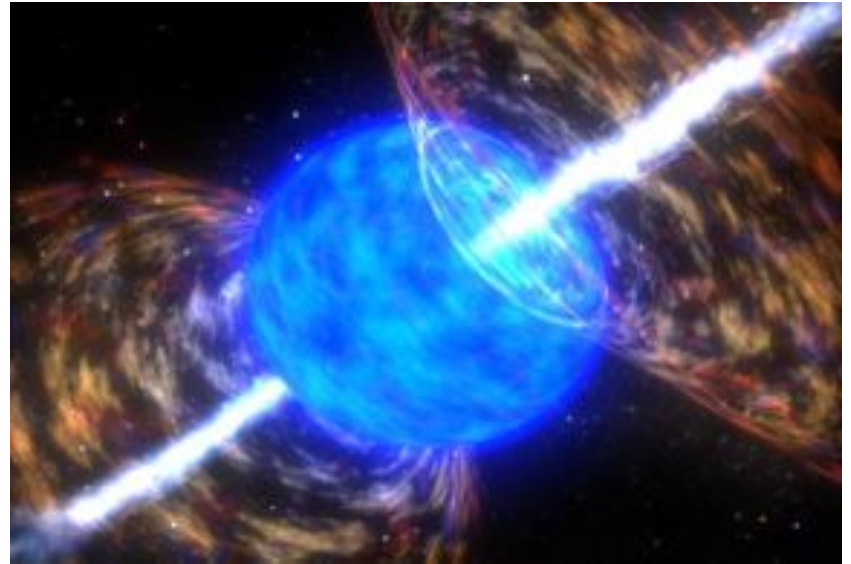
Wei-qun Zhang, S.E. Woosley & A. Heger

Model 3BL

$t = 0.00$  s







Dana Berry (Skyworks) and SEW





# Predictions of the Collapsar Model

- ✓ Gamma-ray bursts should occur in star regions
- ✓ GRBs should be accompanied by Type I b or c supernovae (the jet doesn't get out of a giant star in time, need to lose envelope)
- ✓ GRBs should be favored by low metallicity and high redshift

# Proto-magnetars

Magnetars have fields  $\sim 10^{14-15}$  G  
They might be born as fast rotators  
Efficient dynamo implies  $P \sim t_{\text{core}} \sim \text{ms}$

Millisecond magnetar have the correct energy

$$E_{\text{rot}} \approx 2 \times 10^{52} \left( \frac{P}{1 \text{ ms}} \right)^{-2} \text{ ergs}$$

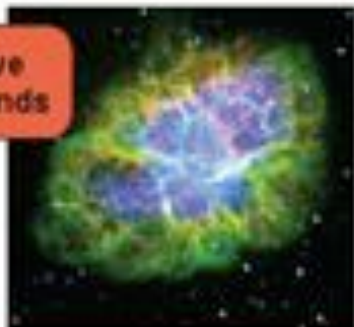
*Pro*

NS are naturally associated to core collapse SN  
Less angular momentum required than BH-AD  
NS population can explain transition from asymmetric SNe to XRFs to GRBs

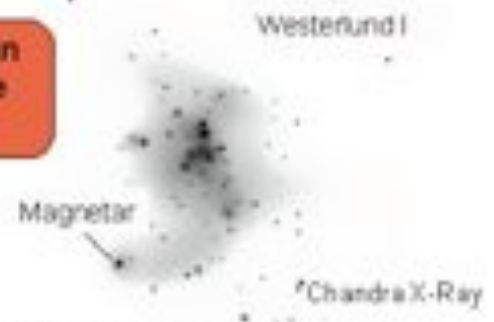
Typical spin-down times are  $\sim 100-1000$  sec

$$E \approx 10^{49} \left( \frac{P}{1 \text{ ms}} \right)^{-4} \left( \frac{B_{\text{eq}}}{10^{15} \text{ G}} \right)^2 \text{ ergs s}^{-1}$$

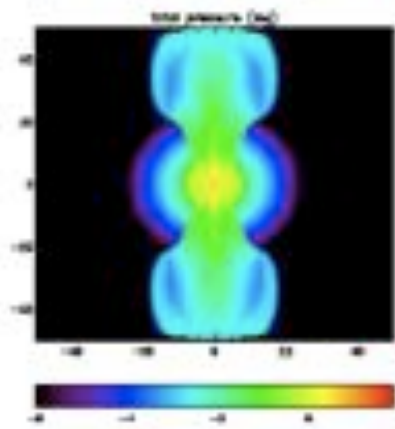
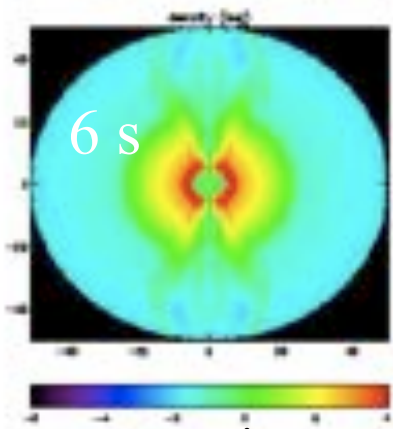
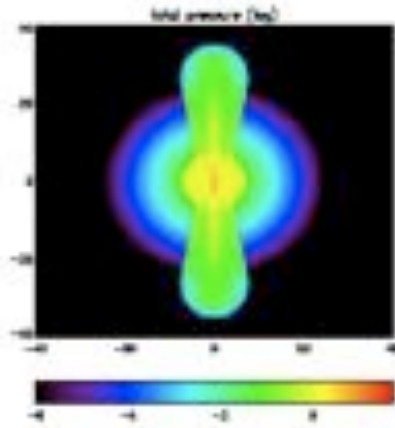
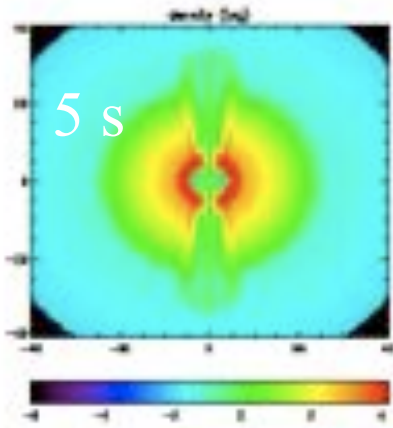
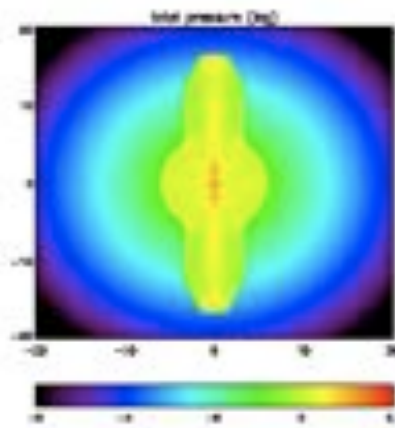
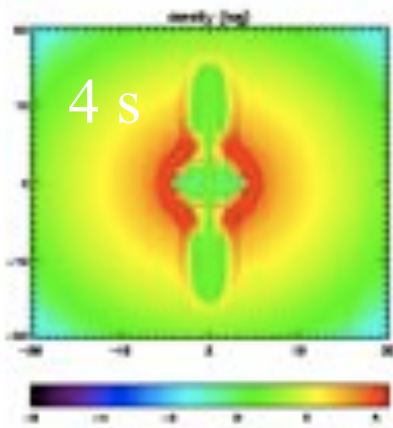
Pulsars have relativistic winds



Magnetars can have massive progenitors



Faintest Cluster Members are O7 (Muno 2006)



Density

Pressure

Assume a pre-existing supernova explosion in the stripped down core of a 35 solar mass star.

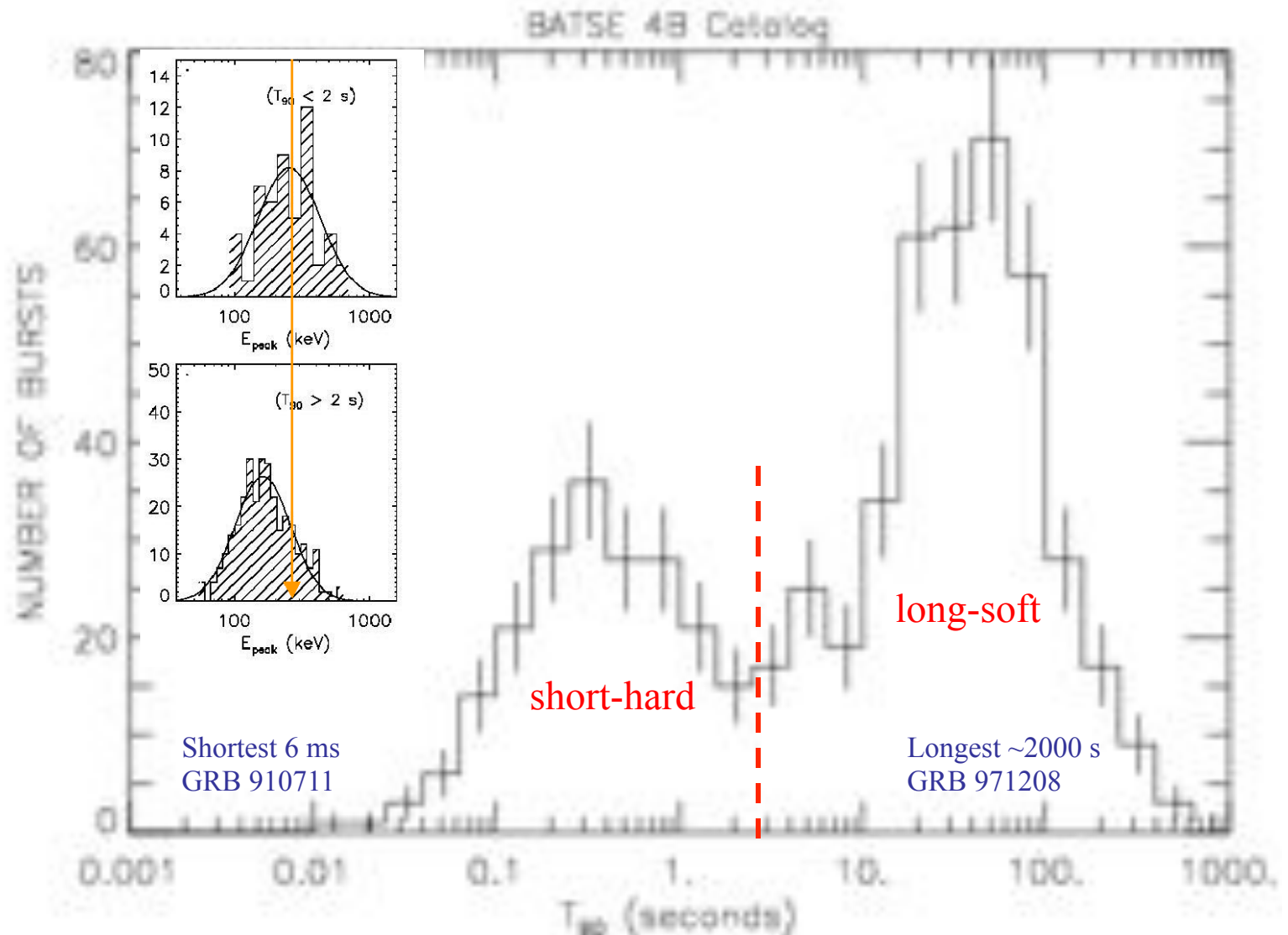
Insert a spinning down 1 ms magnetar with  $B \sim 10^{15}$  gauss.

Two phase wind:

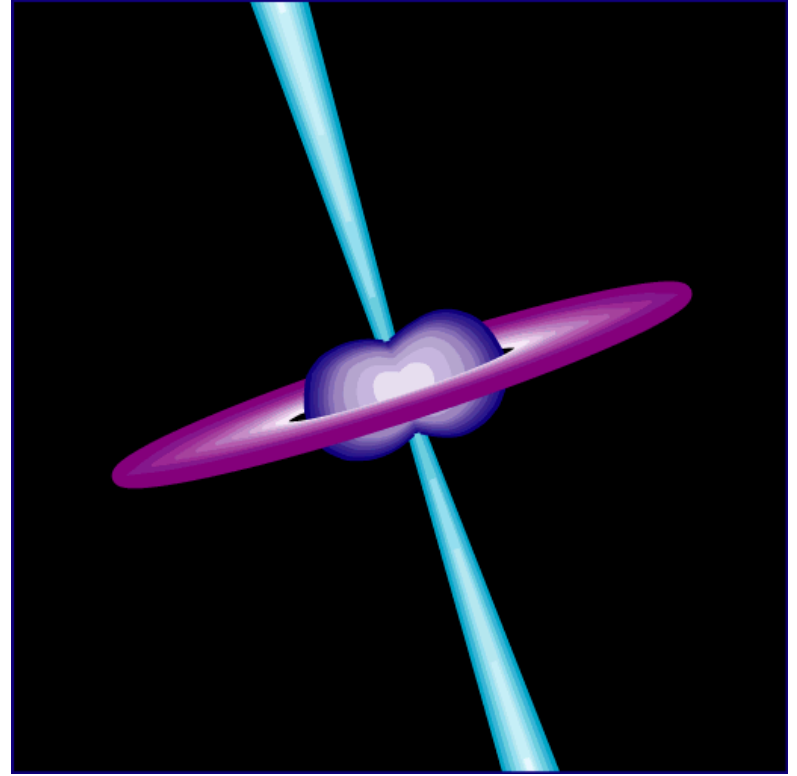
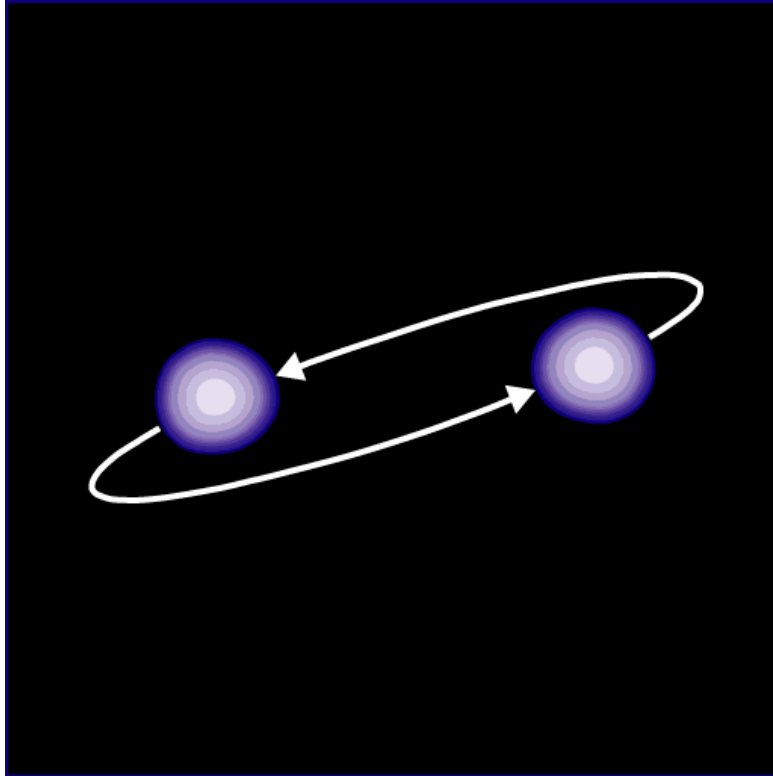
Initial magnetar-like wind contributes to explosion energy. Analog to pulsar wind. Sub-relativistic

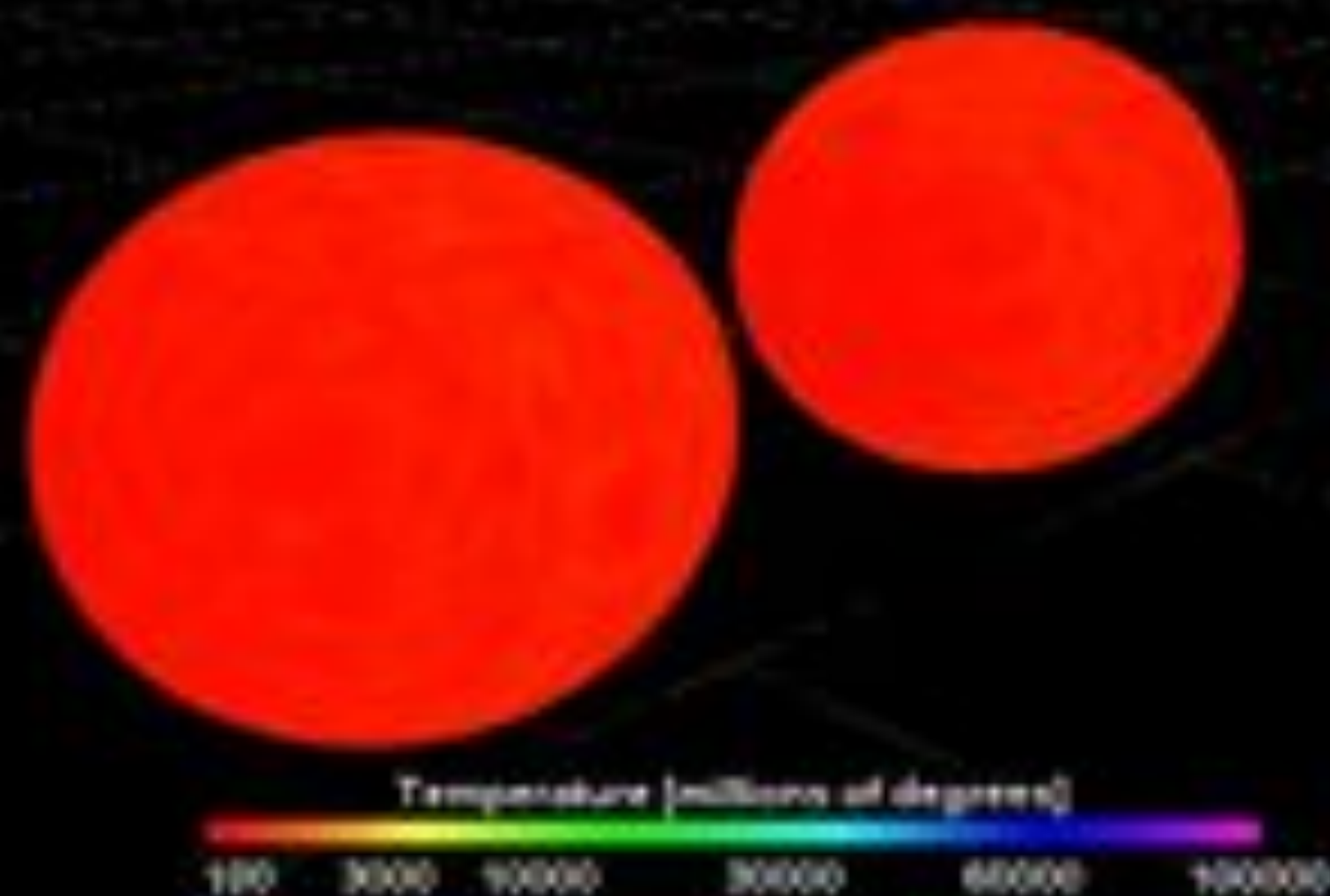
Later magnetically accelerated neutrino powered wind with wound up B field makes jet.

But what about the short hard bursts?



## One Model: Merging Neutron Stars



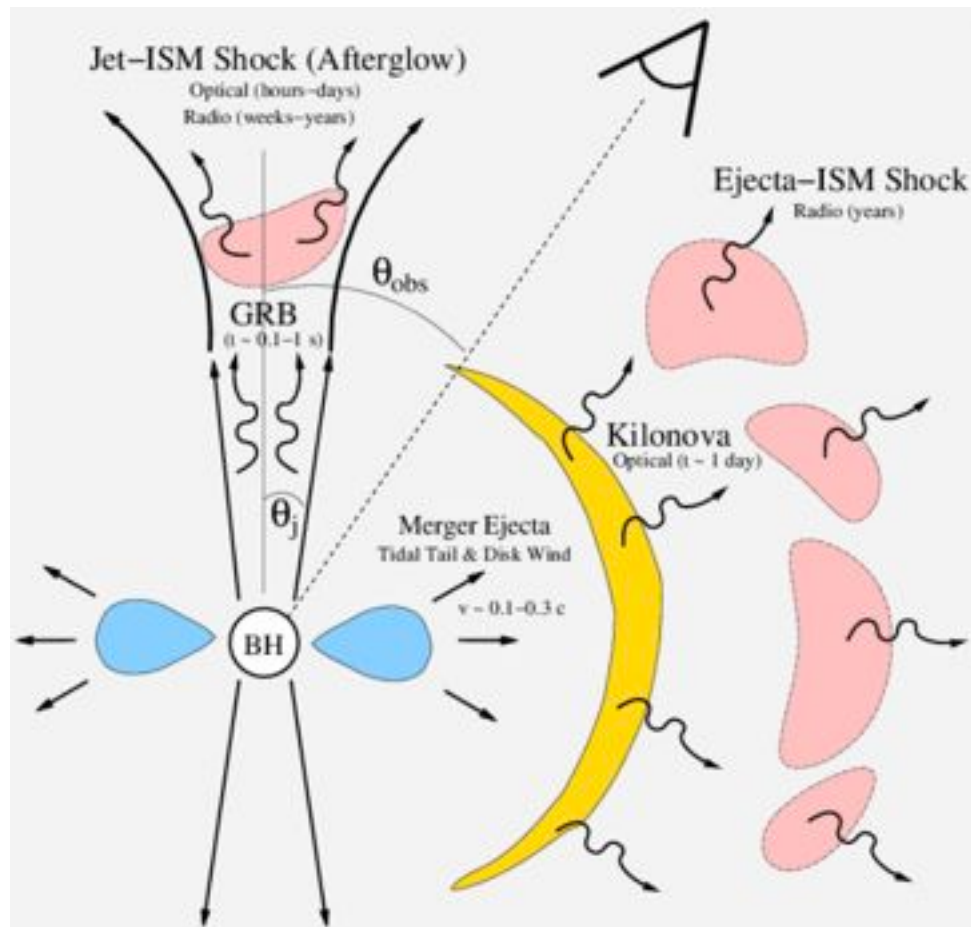


*Starting in May 2005, about a half dozen short hard bursts were localized by the HETE-2 and SWIFT satellites.*

*These bursts did not come from star forming regions, and in fact showed all the characteristics expected of merging neutron stars. It is widely believed that merging neutron stars (and neutron stars merging with black holes) have now been observed as short hard gamma-ray bursts. In the next 10 - 15 years, gravitational radiation detectors may detect these mergers.*

*These GRBs are much closer than the LS GRBs and have  $\sim 30$  times less energy.*



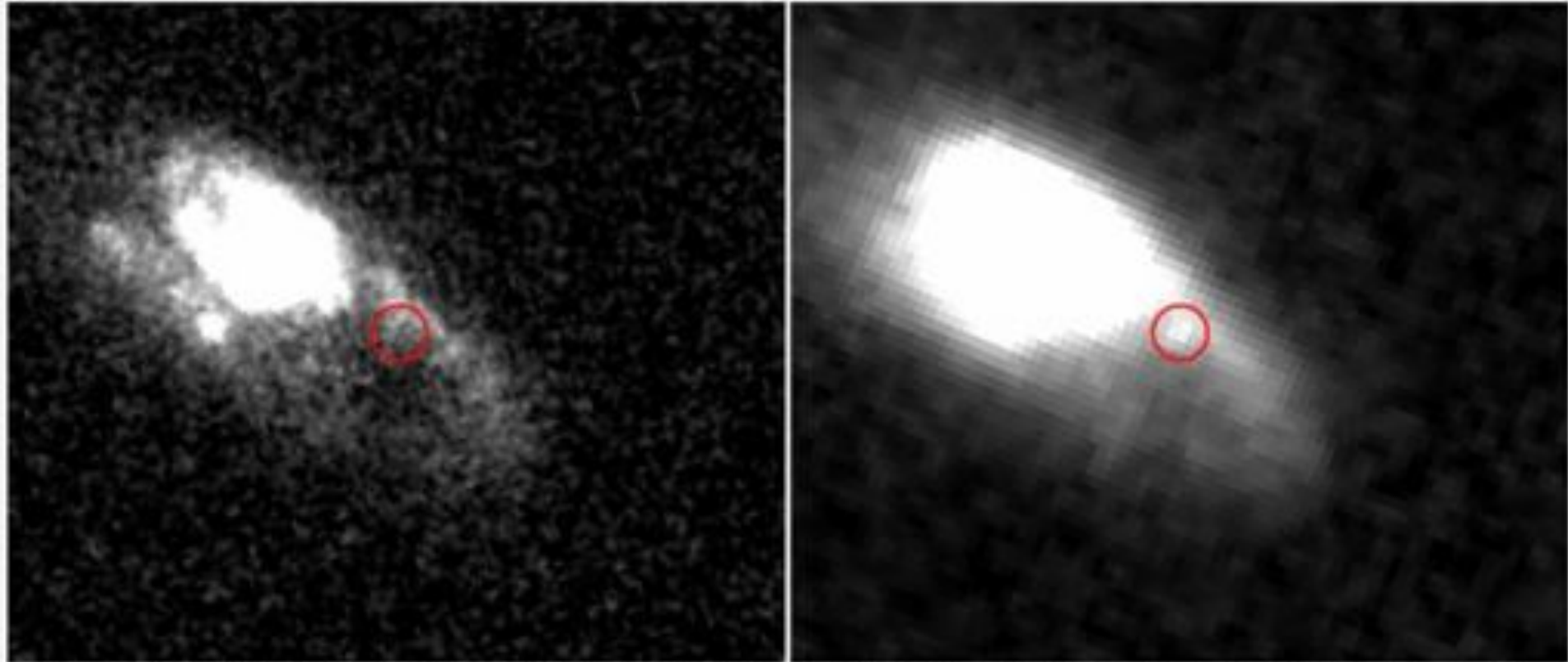


A cartoon of the electromagnetic radiation emitted by a black hole after the merger of two compact objects. The GRB is produced by the shock generated after the accretion of material into the black hole. The kilonova is produced by radioactive decay of the ejecta around the black hole. The pink blobs represent the circumburst medium. [These authors](#) showed that the kilonova emission would actually last longer and be redder than quoted in this figure. Figure 1 of [Metzger & Berger](#).



## GRB130603B

Point source identified in a galaxy 3 hours later  
10 days later a strong infrared source was identified



The position where the short GRB occurred in its host galaxy, obtained with the Hubble Space Telescope. The left and right panel show the same galaxy in the optical and the infrared, respectively. In the right panel, Tarvir et al. detect a source in coincidence with the position of the short GRB. Figure 1 of Tarvir et al.

Afterglow or kilonova??

*Things I am working on now:*

- Type Ia supernova models
- Presupernova evolution
- Magnetar powered supernovae
- Shock break out
- Pulsational pair instability supernovae
- Anything that blows up...