Black Holes and Gamma-Ray Bursts

Some Properties of Black Holes

- Entirely defined by their mass, rotation rate, and charge.

- Believed that all the mass is concentrated at the center in a small quantum-mechanical "singularity"

- Effective density of stellar mass black holes is very high, but there are supermassive black holes in active galactic nuclei with "densities" no greater than water. they are just very big

- The gravitational field of a black hole close to the event horizon is complicated, but by the time you are several Schwarzschild radii away, it is indistinguishable from that of an ordinary star.

Kinds of black holes:

Class	Mass (solar masses)	Size
Supermassive	$\sim 10^5 - 10^9$	0.001 - 10 AU
Intermediate	~1000	$\sim R_{earth}$
Stellar	~10	~30 km
Primordial	Up to ~Moon	Up to ~0.1 mm

$$R_S = \left(\frac{2GM}{c^2} \right) = 2.96 \text{ km} \left(\frac{\mathrm{M}}{\mathrm{M}_\odot} \right)$$

Event Horizon

$$R_S = \left(\frac{2GM}{c^2}\right) = 2.96 \;\text{ km}\left(\frac{\text{M}}{\text{M}_\odot}\right)$$

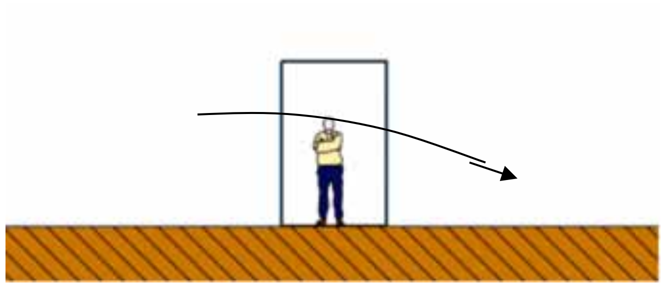
Note that this is proportional to M.
Very massive black holes – some over 10^9 solar masses have been inferred to exist in some Galactic centers. These black holes would be 20 AU in size.

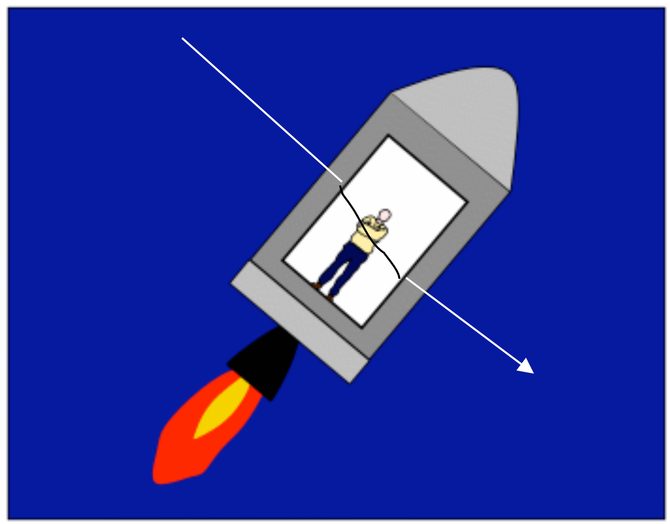
Note that the "density" of a black hole scales as M^{-2}.

$$\rho = \frac{M}{(4/3)\pi R^3} \propto \frac{M}{M^3} \propto \frac{1}{M^2}$$

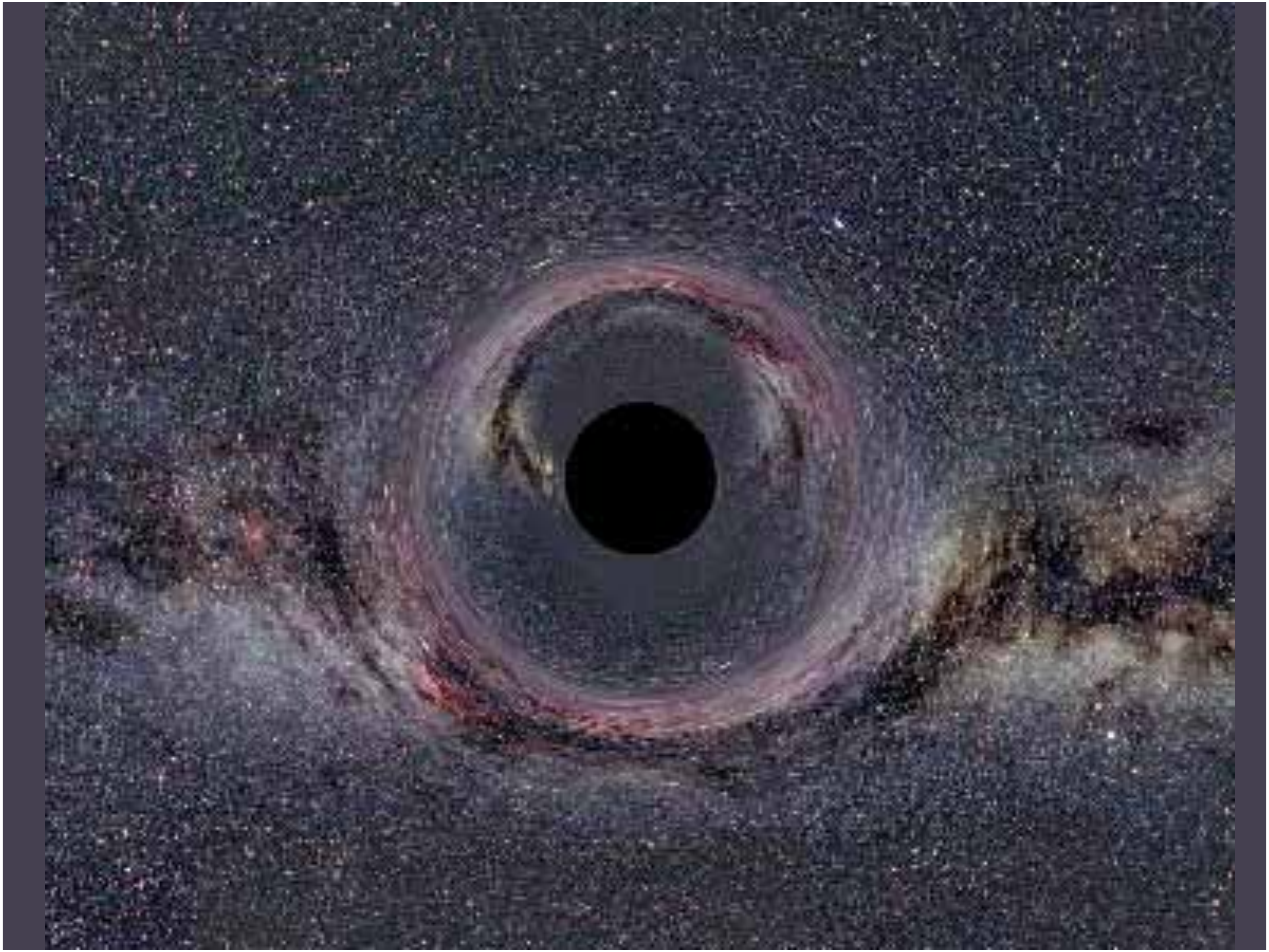
$$= 1.8 \times 10^{16} \left(\frac{M_\odot}{M}\right)^2 \text{ g cm}^{-3}$$

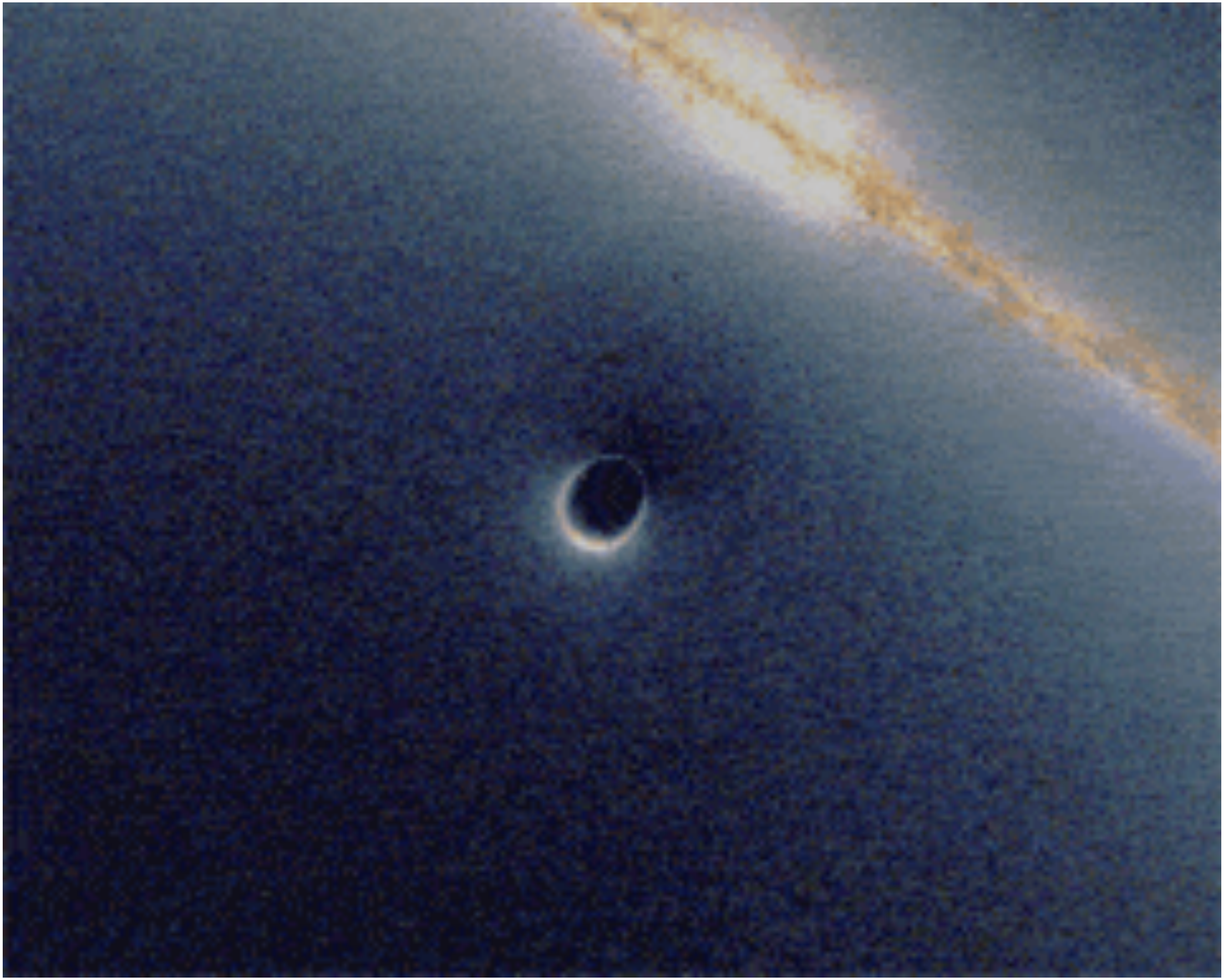
EQUIVALENCE PRINCIPLE





Gravity “bends” light





Circumference of orbit	Time experienced by outside observer per orbiter day
20,000 km	1.41 days
15,000 km	1.73 days
12,000 km	2.44 days
11,000	3.32
10,500	4.50
10,250	6.4
10,050	14.18
10,025	20.02
10,005	44.73
10,000.75	115.47
10,000.50	141.42
10,000.25	200.00
10,000.125	282.84
10,000.005	447.21
10,000.001	3162.28 days

For a black hole with circumference 10,000 km

About 500 solar masses

http://www.upscale.utoronto.ca/PVB/Harrison/GenRel/TimeDilation.html

Planck mass $\left(\frac{c\hbar}{G}\right)^{1/2}$ = 2.2 x 10^{-5} gm

Hawking Penrose radiation

$$\tau \sim 8.4 \times 10^{-17} \left(\frac{M}{kg}\right)^3 \text{ sec}$$

2×10^{67} *years for a* 1 *solar mass BH*

Planck time $\left(\frac{G\hbar}{c^5}\right)^{1/2}$ = 5.4 x 10^{-44} sec

$$\hbar = \frac{h}{2\pi}$$

Planck length $\left(\frac{G\hbar}{c^3}\right)^{1/2}$ = 1.6 x 10^{-33} cm = $\frac{G \text{ (Planck mass)}}{c^2}$

$\approx R_S$ for the Planck mass

$$\text{Planck density} = \left(\frac{\text{Planck mass}}{(\text{Planck length})^3}\right) = 5 \times 10^{93} \text{ gm/cm}^3$$

Scale of things: http://apod.nasa.gov/apod/ap120312.html

$$c = 2.99.. \times 10^{10} \text{ cm s}^{-1}$$

$$G = 6.67.. \times 10^{-8} \text{ dyne cm}^2 \text{ gm}^{-2}$$

$$\hbar = 1.05.. \times 10^{-27} \text{ erg s}$$

$$\frac{\hbar c}{G} = \frac{\left(2.99 \times 10^{10}\right)\left(1.05 \times 10^{-27}\right)}{\left(6.67 \times 10^{-8}\right)} \frac{\text{cm}}{\text{s}} \frac{\text{gm}^2}{\text{dyne cm}^2} \text{erg s}$$

$$= 4.70 \times 10^{-10} \frac{\text{gm}^2 \text{ erg}}{\text{dyne cm}} = 4.70 \times 10^{-10} \text{ gm}^2$$

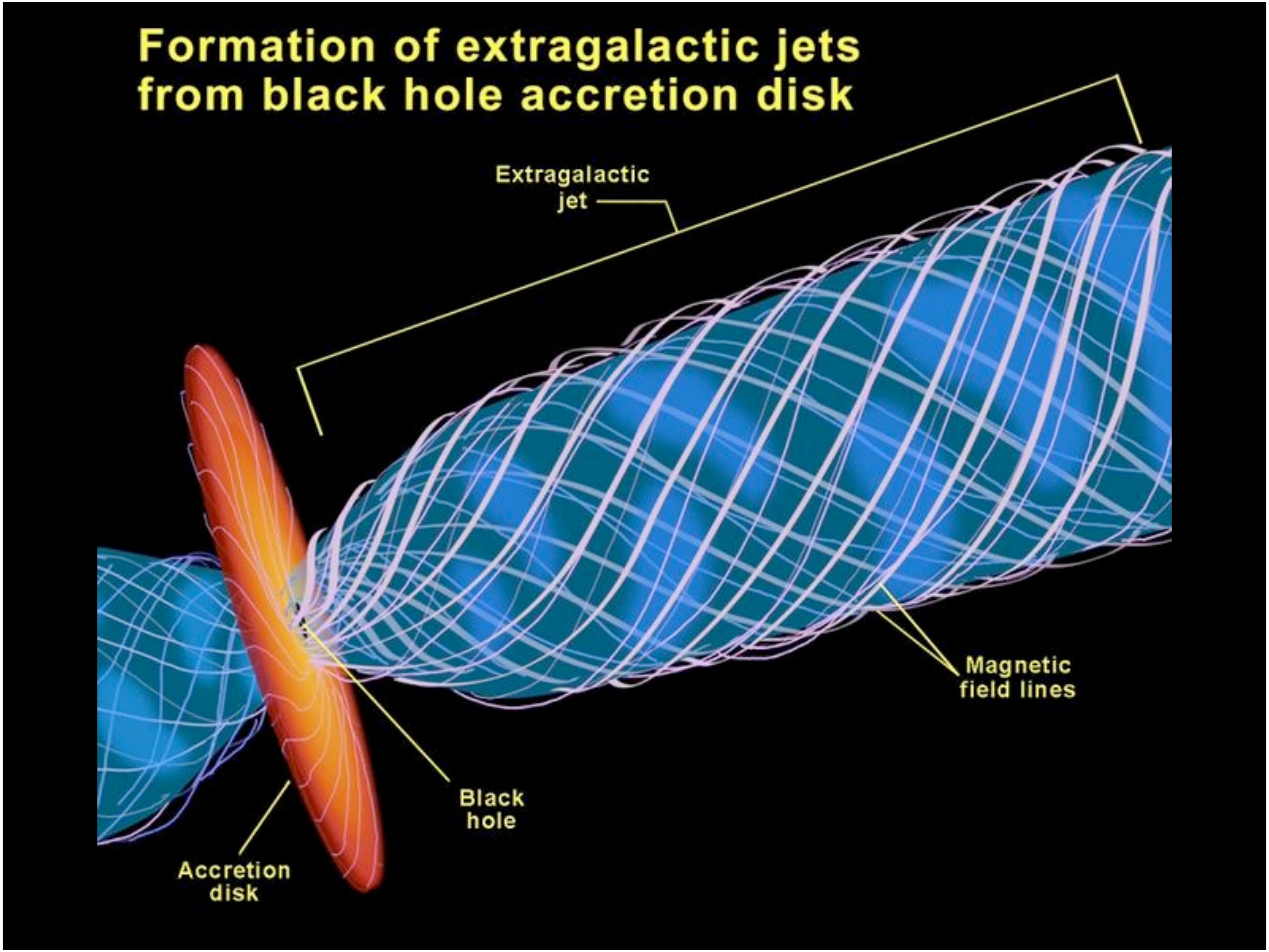
$$\left(\frac{\hbar c}{G}\right)^{1/2} = 2.17 \times 10^{-5} \text{ gm}$$

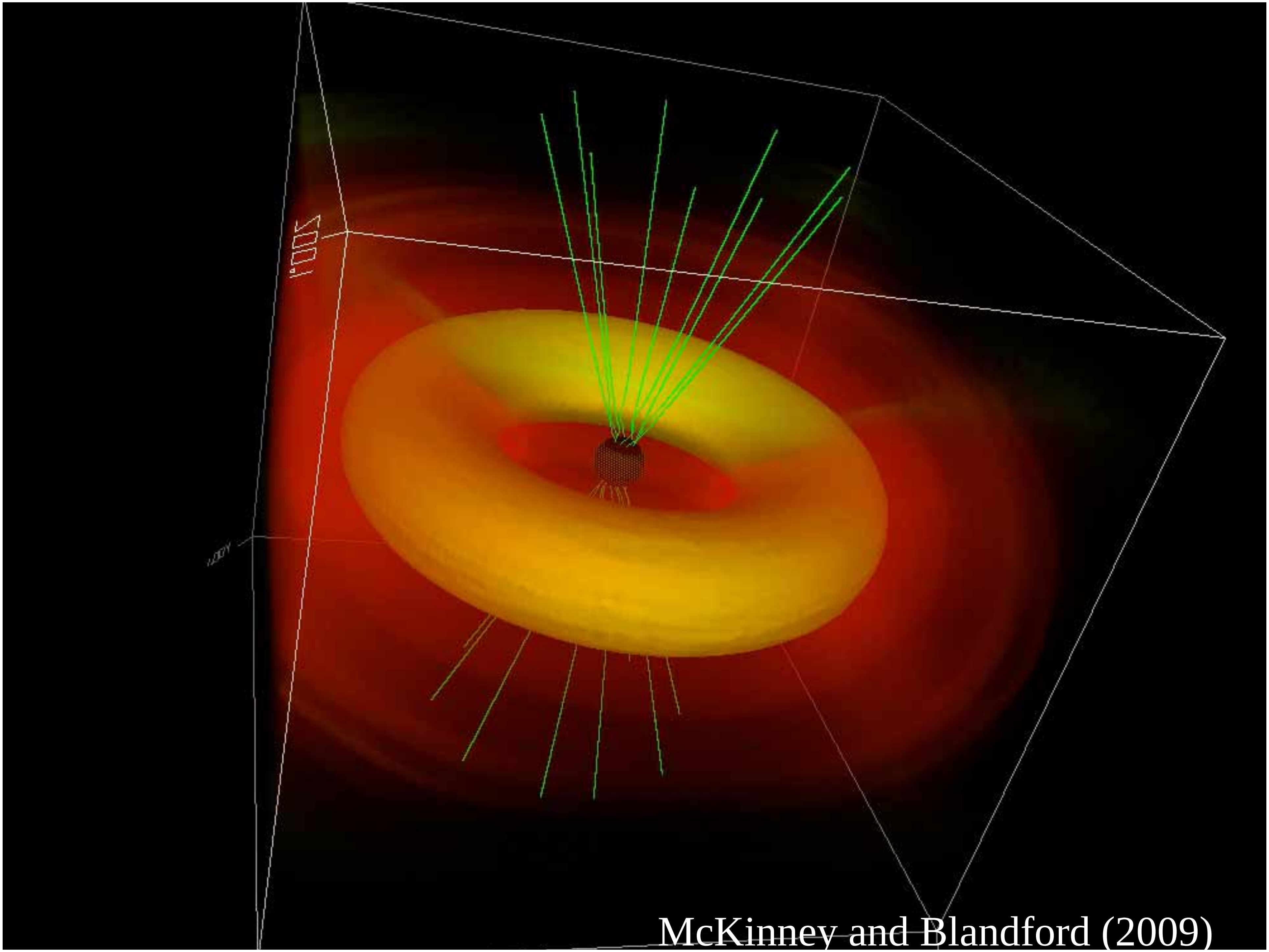
Uncertainty Principle

(Uncertainty in energy)(Uncertainty in time)$\sim\hbar$

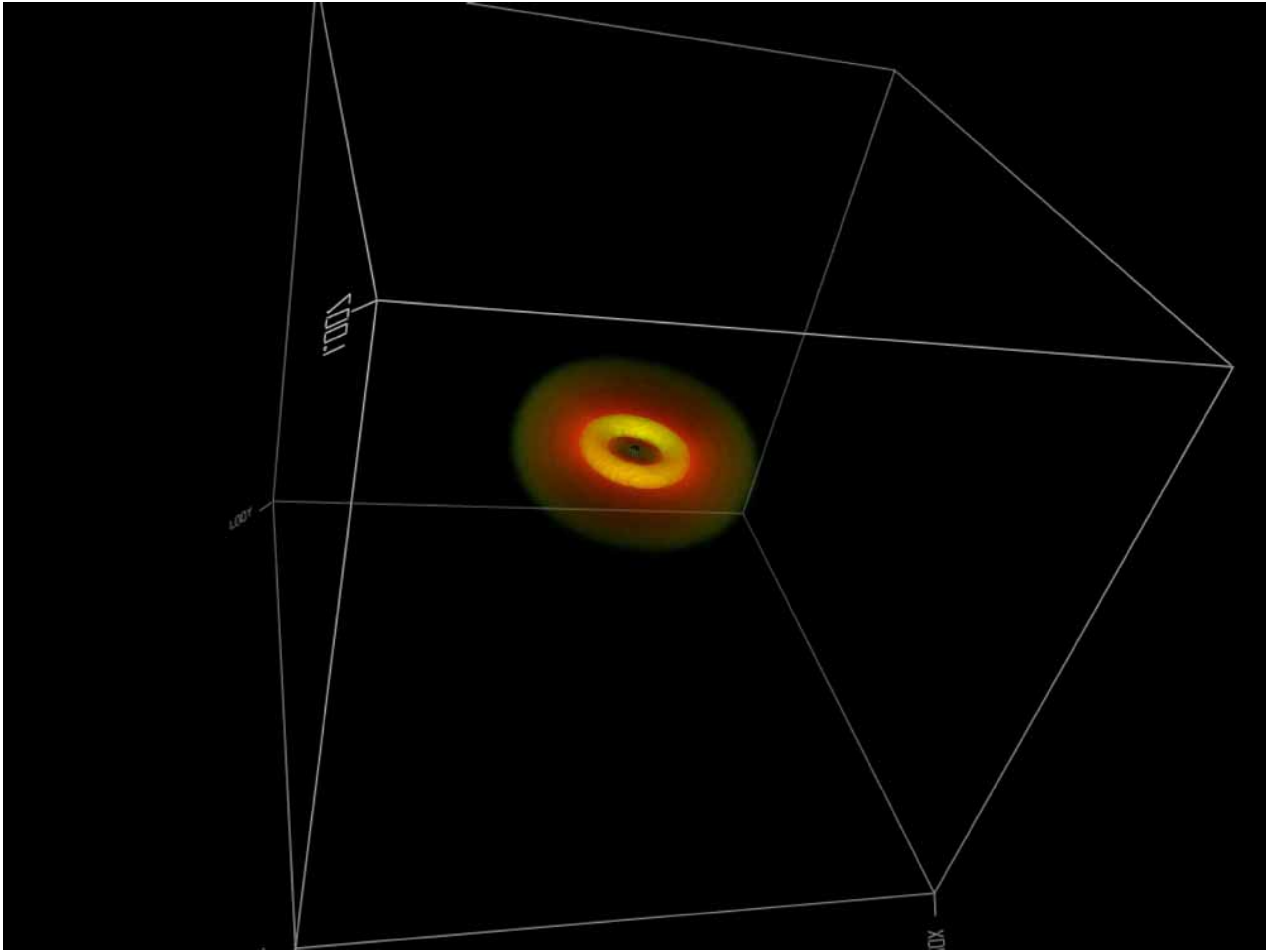
$$\left(Planck\ Mass \times c^2\right)\left(Planck\ time\right) \sim \hbar$$

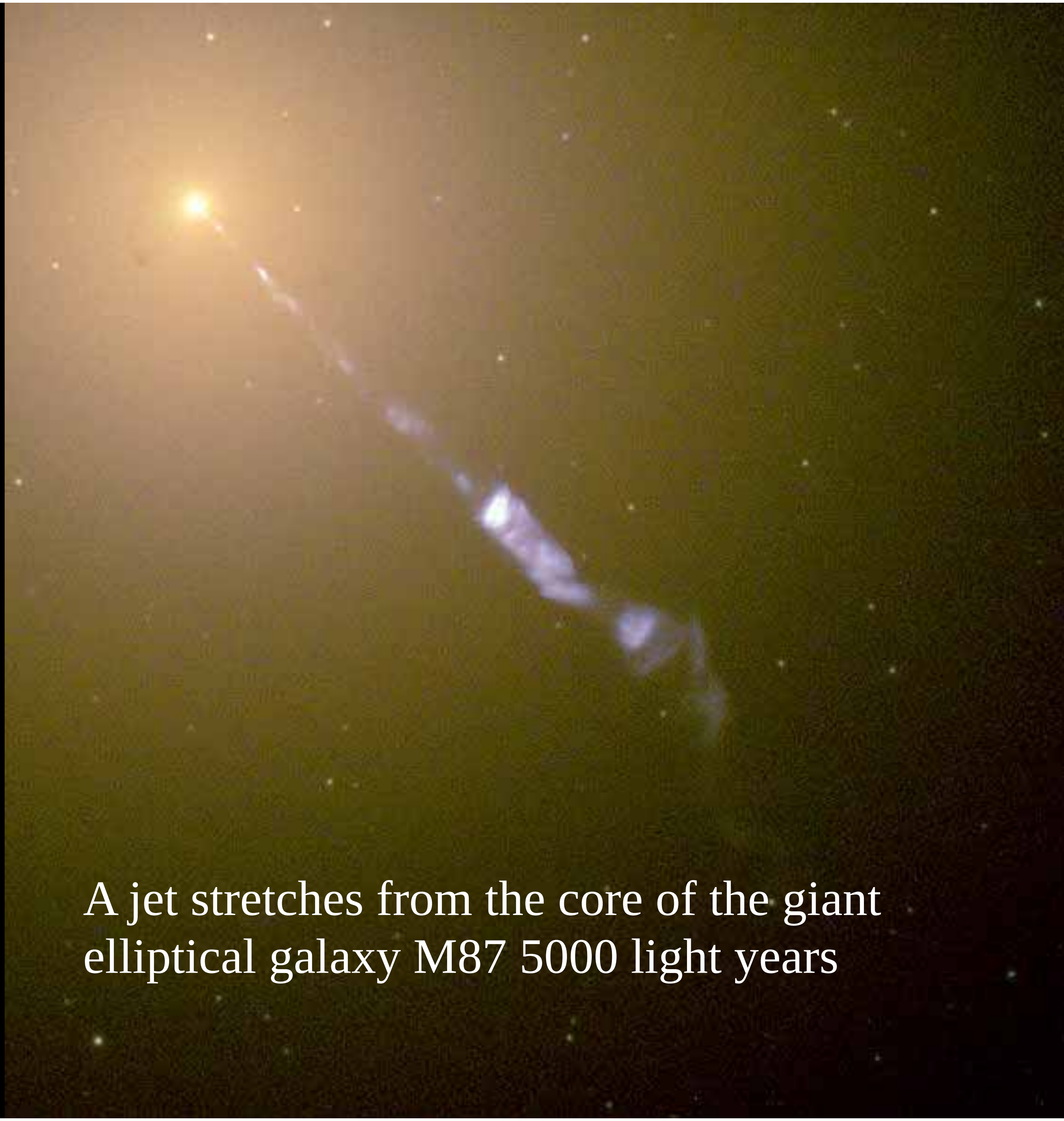
$$\left(\frac{c\hbar}{G}\right)^{1/2} c^2 \left(\frac{G\hbar}{c^5}\right)^{1/2} = \hbar$$


Formation of extragalactic jets
from black hole accretion disk
Extragalactic
jet
Magnetic
field lines
Black
hole
Accretion
disk

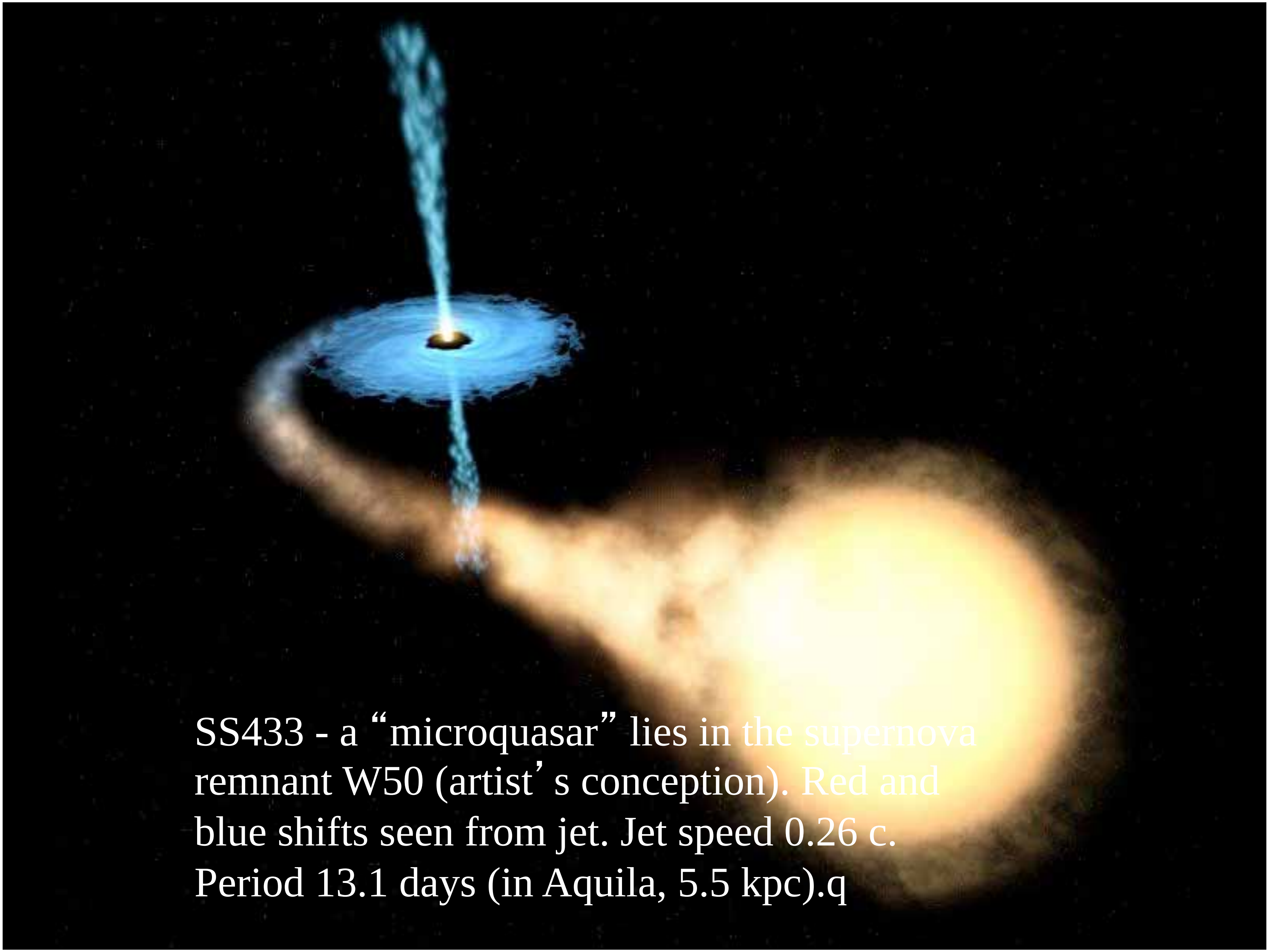


McKinney and Blandford (2009)





A jet stretches from the core of the giant elliptical galaxy M87 5000 light years



SS433 - a "microquasar" lies in the supernova remnant W50 (artist's conception). Red and blue shifts seen from jet. Jet speed 0.26 c. Period 13.1 days (in Aquila, 5.5 kpc).q

Gamma-Ray Bursts

http://apod.nasa.gov/apod/ap120312.html

http://apod.nasa.gov/apod/ap120310.html

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 keeps us from seeing them frequently.

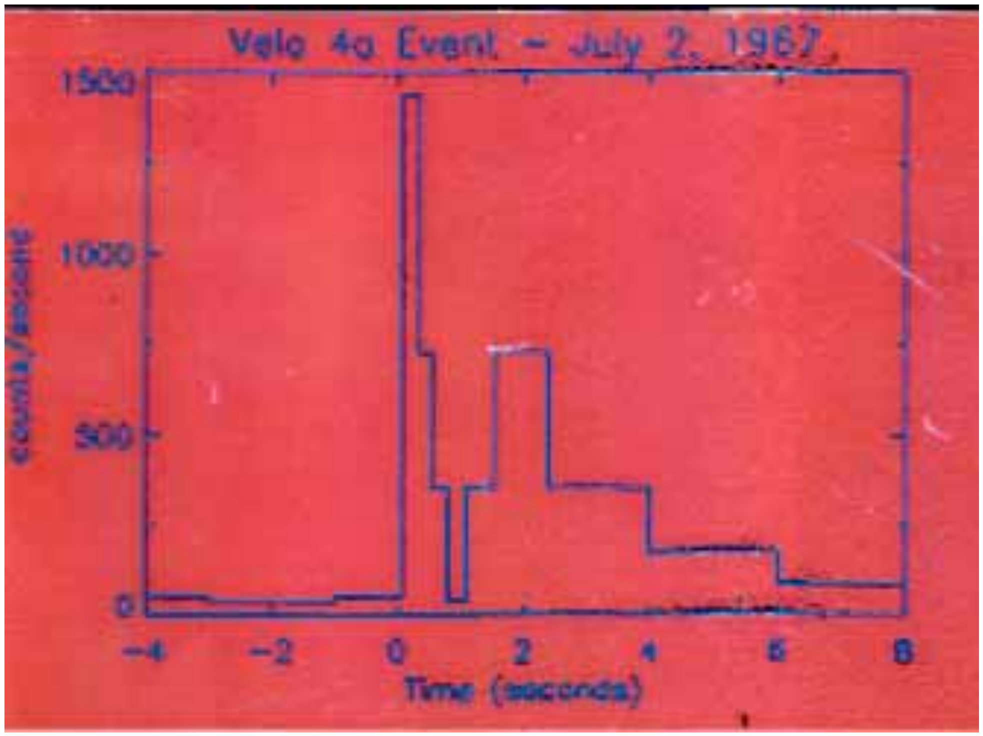
With appropriate instrumentation, we see about one of these per day at the Earth. They seem never to repeat from the same source.

Velar – to watch

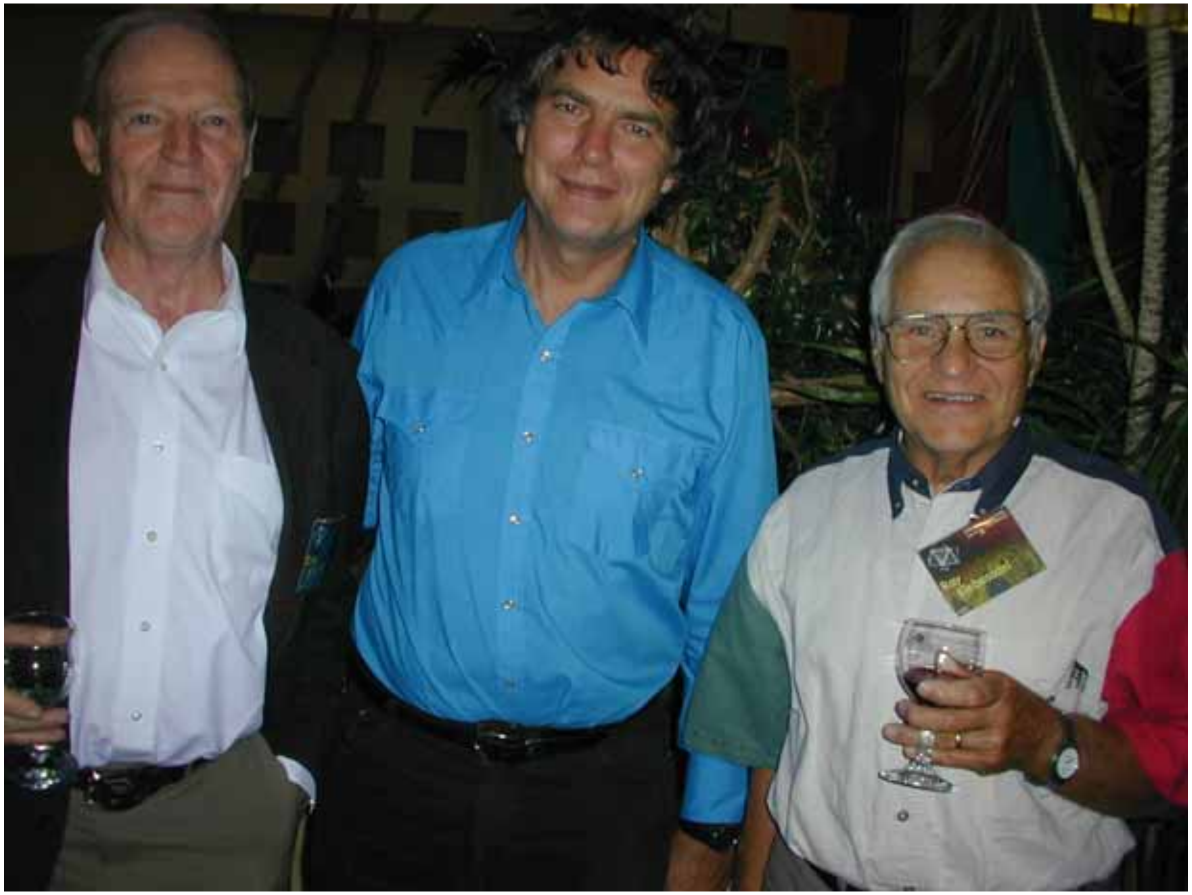
Nuclear Test Ban Treaty, 1963
First Vela satellite pair launched 1963

The Vela 5 satellites were placed in orbit by the Advanced Research Projects of the DoD and the AEC. Launched on May 23, 1969 into high earth orbit (118,000 km), this pair of satellites and their predecessors, Vela 4, discovered the first gamma-ray bursts. The discovery was announced in 1973.

First Gamma-Ray Burst



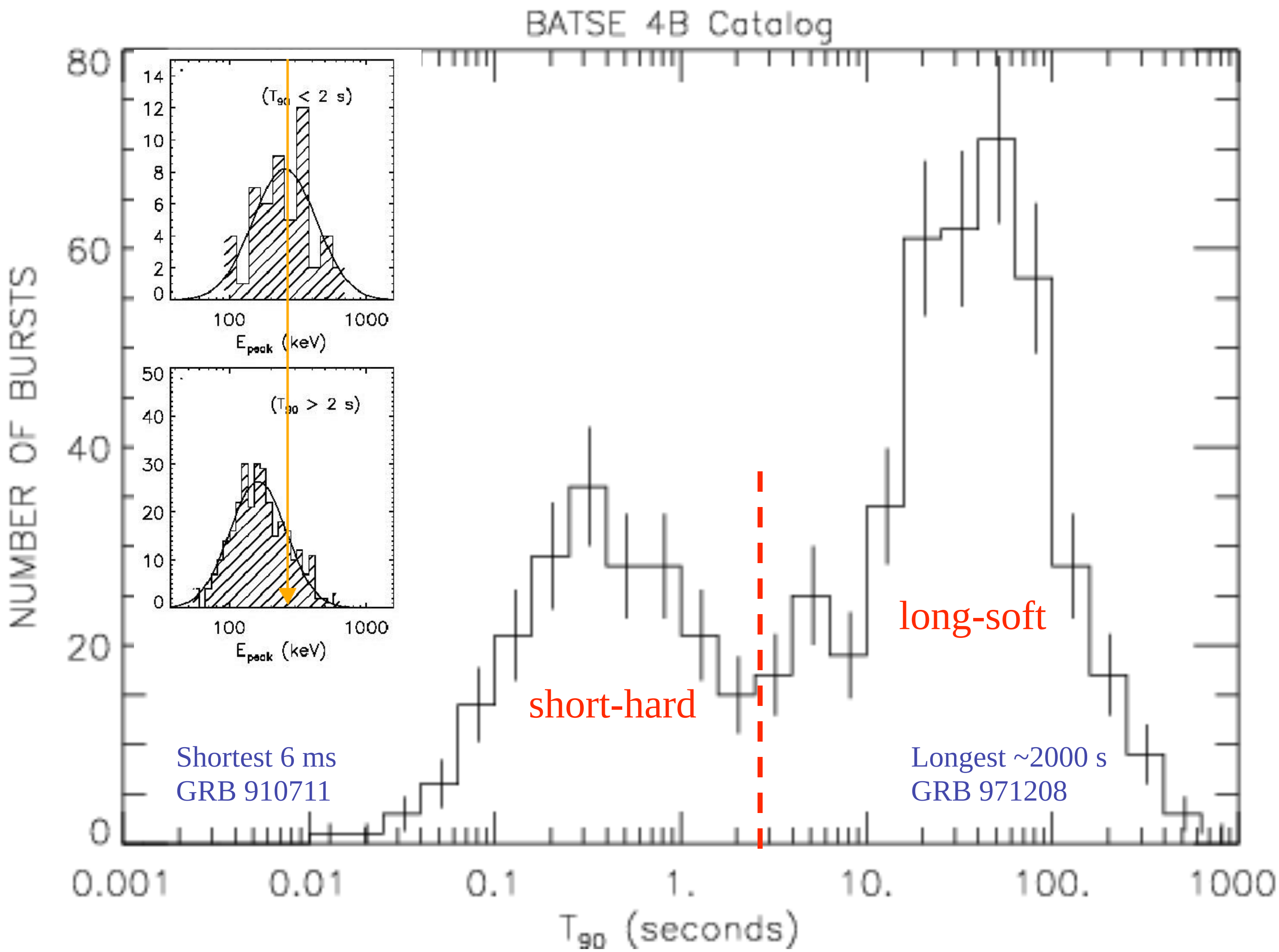
The Vela 5 satellites functioned from July, 1969 to April, 1979 and detected a total of 73 gamma-ray bursts in the energy range 150 – 750 keV (n.b,. Greater than 30 keV is gamma-rays). Discovery reported Klebesadel, Strong, and Olson (1973).



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 at least two flavors



An Observational Dilemma

The gamma-ray detectors could detect brightness and spectra but had only crude angular resolution (> several degrees).

After the burst was over, these huge error boxes showed nothing particularly unusual (or maybe too many unusual things).

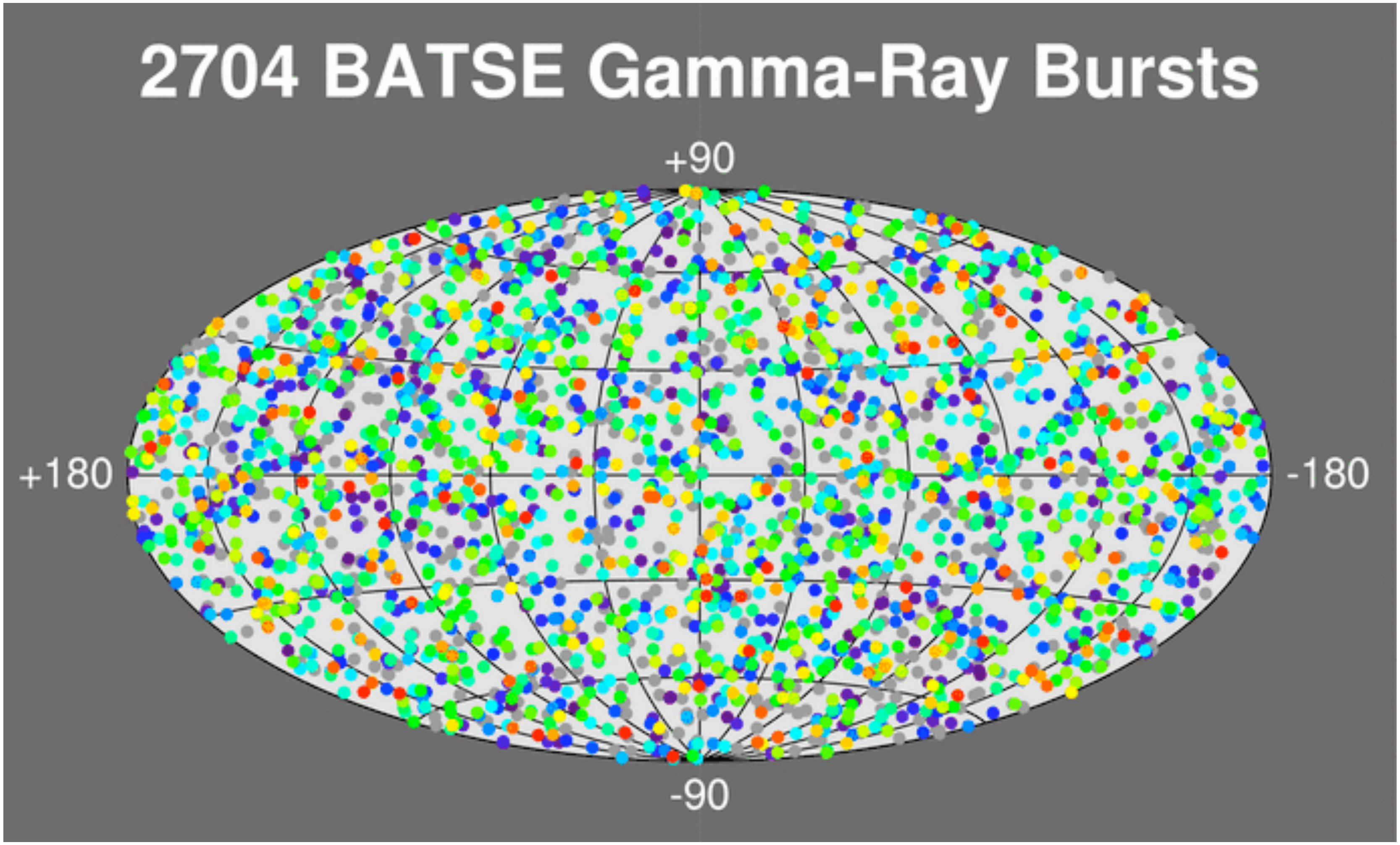
We thus had no idea of the nature of the objects emitting the bursts – and hence no knowledge of their burst or energy.

Early on some weak indication of association with the Galactic disk

- Interstellar warfare
- Primordial black hole evaporation
- Flares on nearby stars
- Distant supernovae
- Neutron star quakes
- Comets falling on neutron stars
- Comet anti-comet annihilation
- Thermonuclear explosions on neutron stars
- Name your own ....

During the 1970's until the early 90's.
uncertainty in distance –
a factor of one billion.

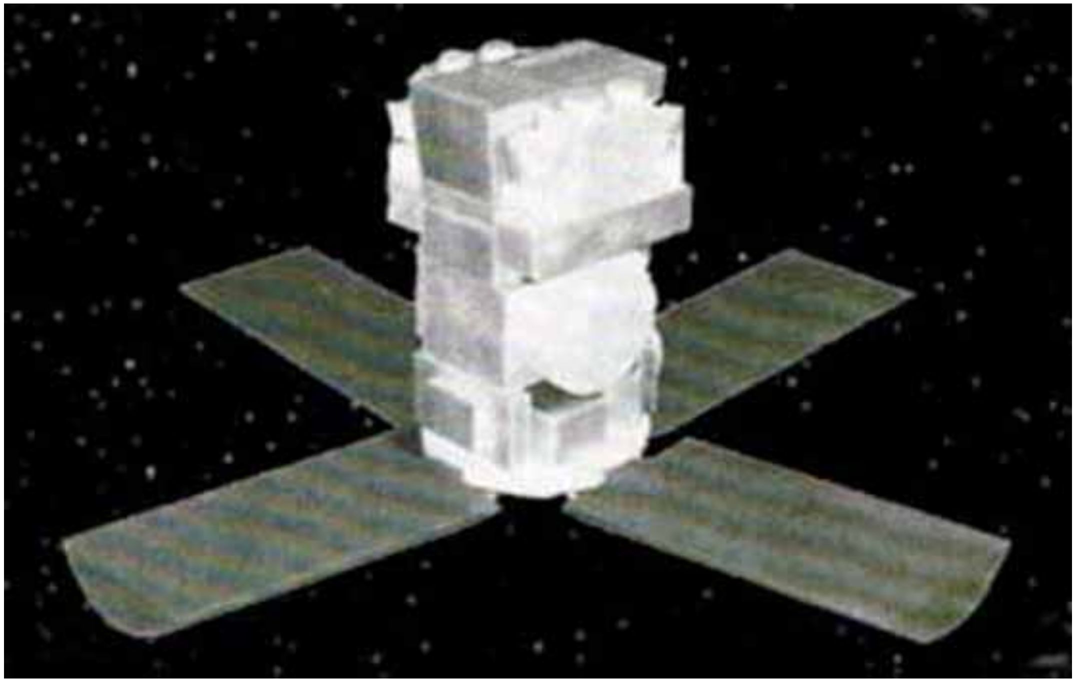
In the late 90's



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.

Intermezzo – HETE – 1 (High Energy Transient Explorer)

Launch April 11, 1996; died April 14, 1996



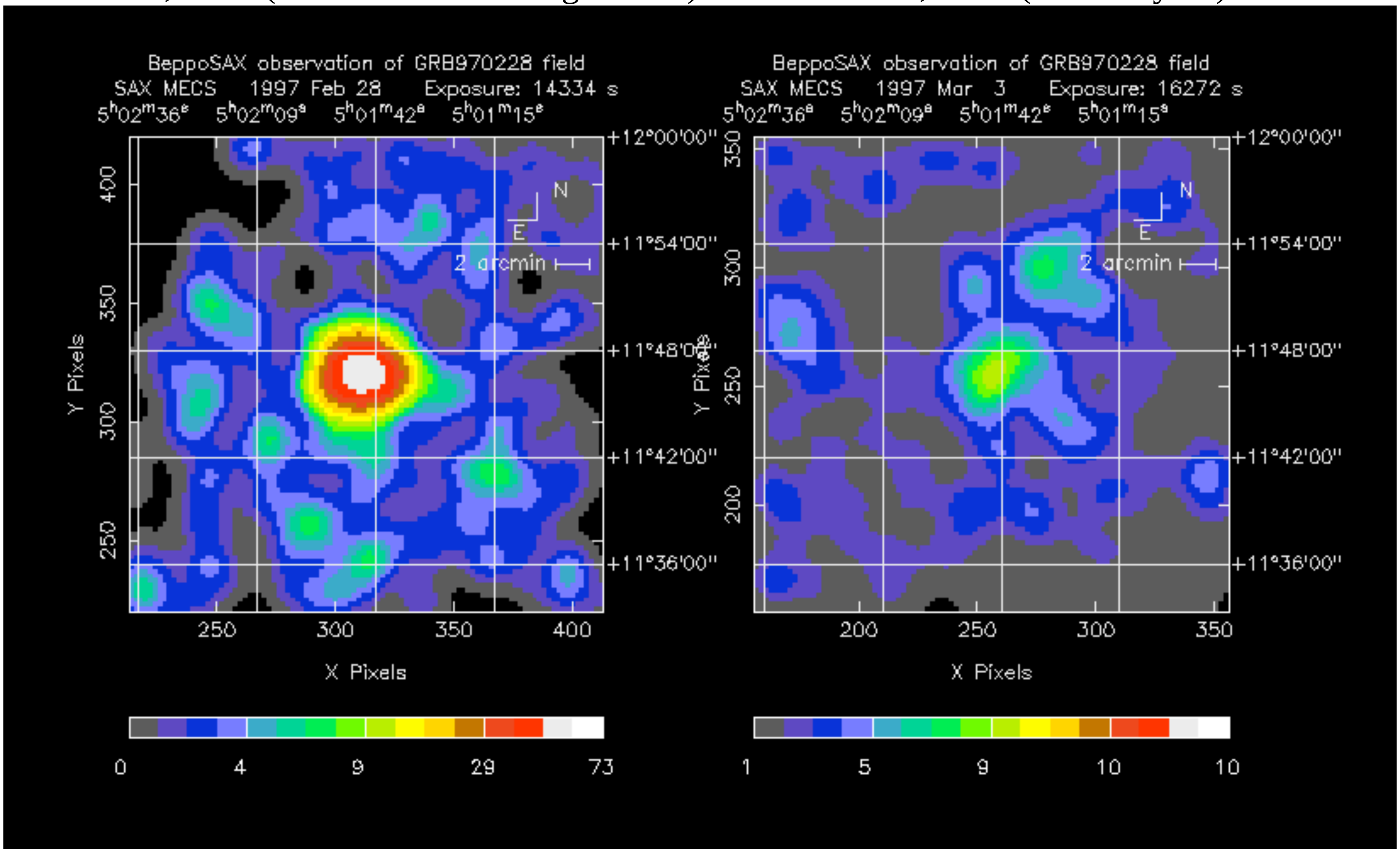
http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1996-061A

175 kg; Instruments – FREGATE, WXM, UVC, SXC

(HETE – 2 – launched September 9, 2000)

BeppoSax GRB 970228 (discovered with WFC)

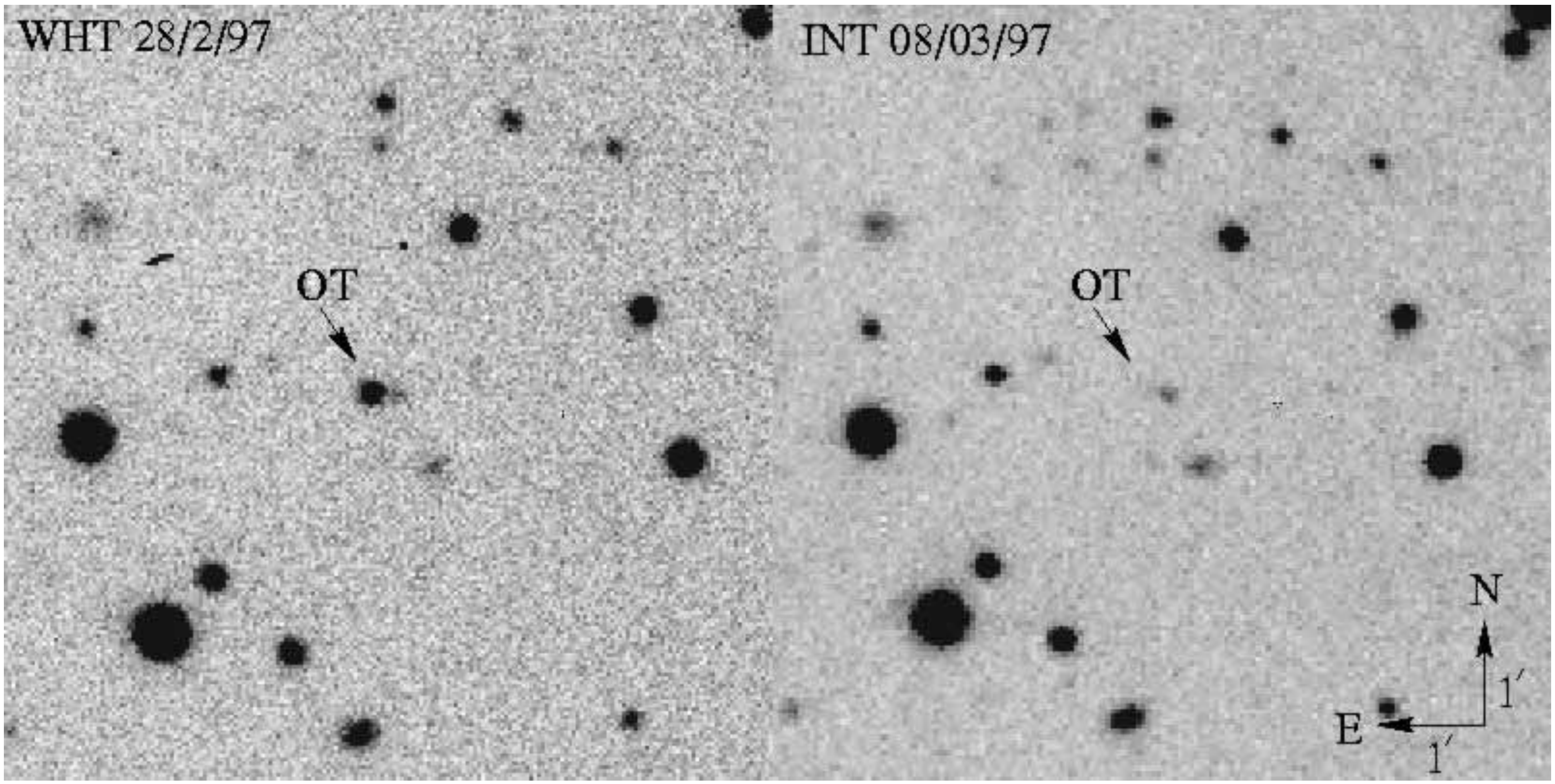
Feb 28, 1997 (8 hr after GRB using MECS) March 3, 1997 (fainter by 20)



Each square is about 6 arc min or 1/5 the moon's diameter

GRB 970228

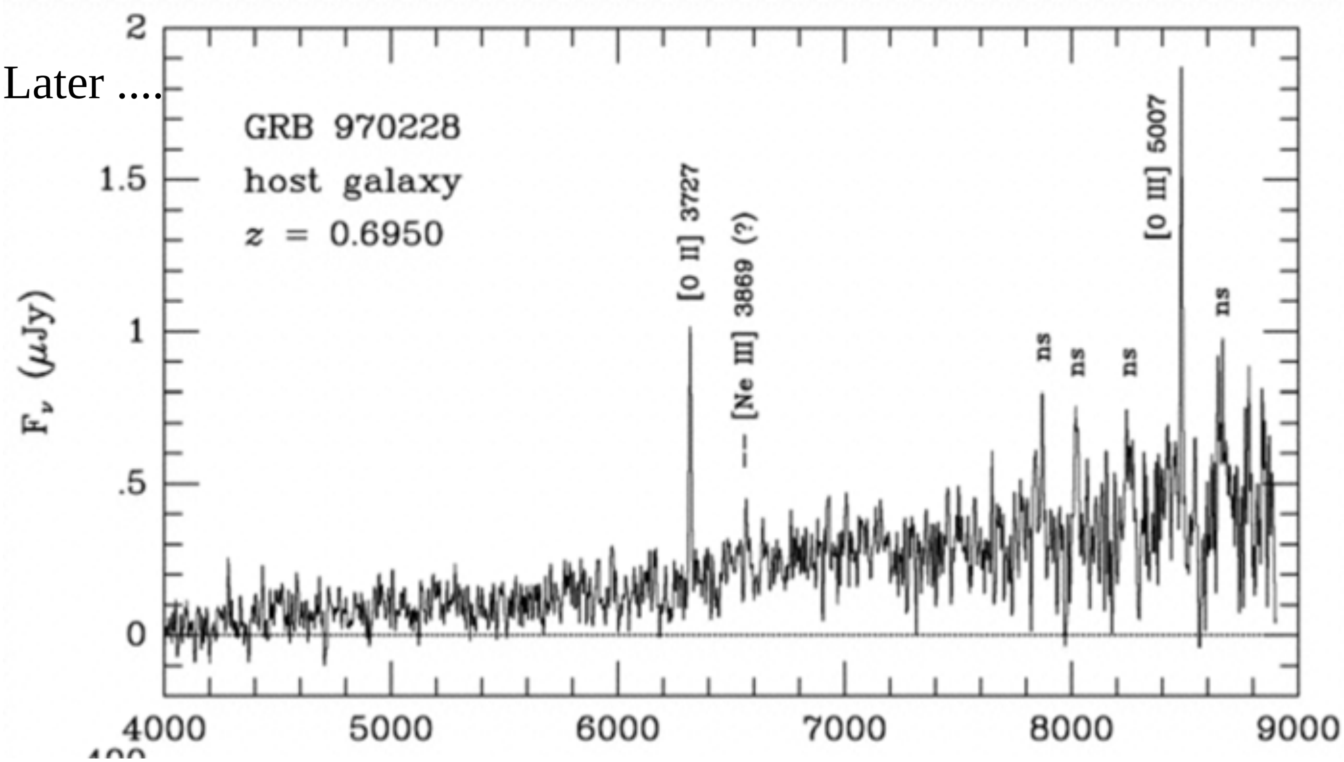
William Hershel Telescope　　　　Isaac Newton Telescope



Groot, Galama, von Paradijs, et al IAUC 6584, March 12, 1997

Looked hard and found a little faint galaxy when the OT faded

Later ....



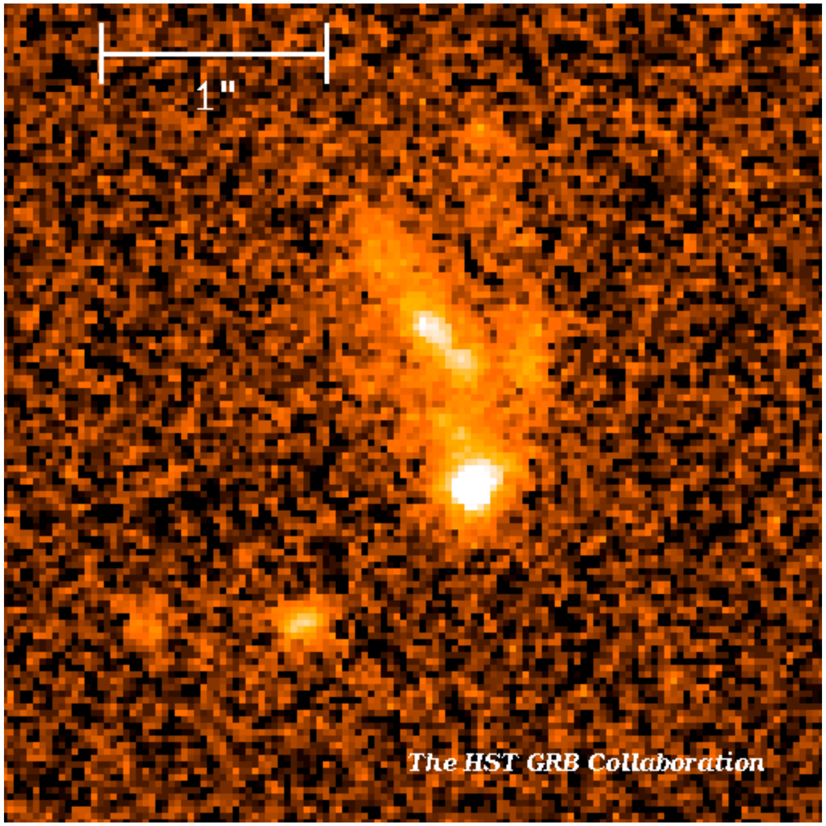
Spectrum of the host galaxy of GRB 970228 obtained at the Keck 2 Telescope.Prominent emission lines of oxygen and neon are indicated and show that the galaxy is located at a redshift of z = 0.695.
(Bloom, Djorgovski, and Kulkarni (2001), ApJ, 554, 678.
See also GCN 289, May 3, 1999.

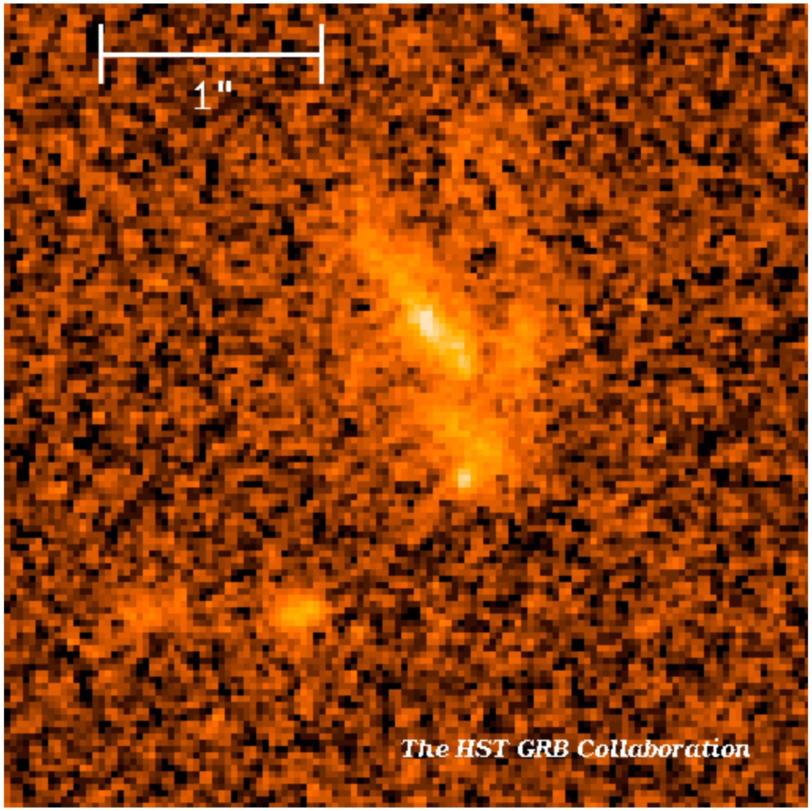
From the red shift a distance can be inferred – billions of light years. Far, far outside our galaxy.

From the distance and brightness an energy can be inferred.

1.6 x 10^{52} erg in gamma rays alone

This is 13 times as much energy as the sun will radiate in its ten billion year lifetime, but emitted in gamma-rays in less than a minute. It is 2000 times as much as a really bright supernova radiates in several months.





Two HST images of GRB 990123. The image on the left was taken February 8, 1999, the one on the right March 23, 1999. Each picture is 3.2 arc seconds on a side. Three orbits of HST time were used for the first picture; two for the second – hence the somewhat reduced exposure.

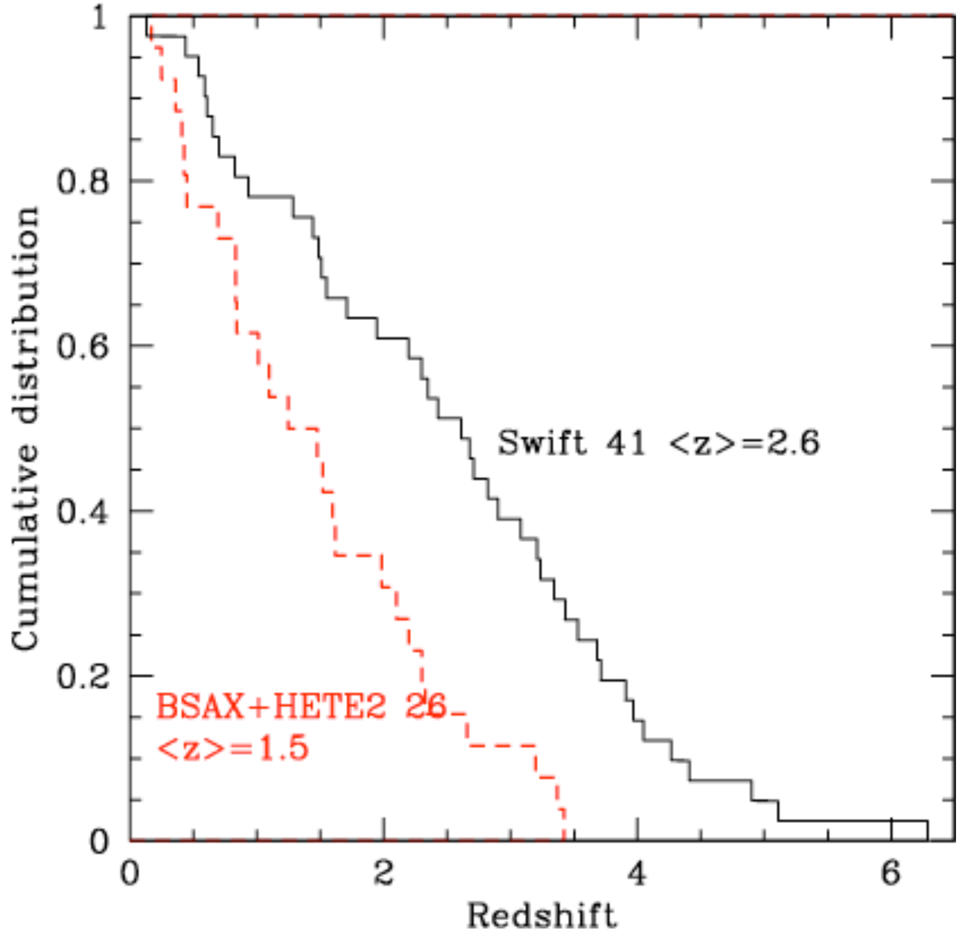
The spectrum of host galaxy (Kelson et al, IAUC 7096) taken using the Keck Telescopes gives a redshift of 1.61.

Given the known brightness of the burst (in gamma-rays) this distance implies an energy of over several times 10^{54} erg. About the mass of the sun turned into pure energy.

Had this burst occurred on the far side of our Galaxy, at a distance of 60,000 light years, it would have been as bright – in gamma-rays – as the sun. This is ten billion times brighter than a supernova and equivalent to seeing a one hundred million trillion trillion megaton explosion.

Now from the study of many GRBs

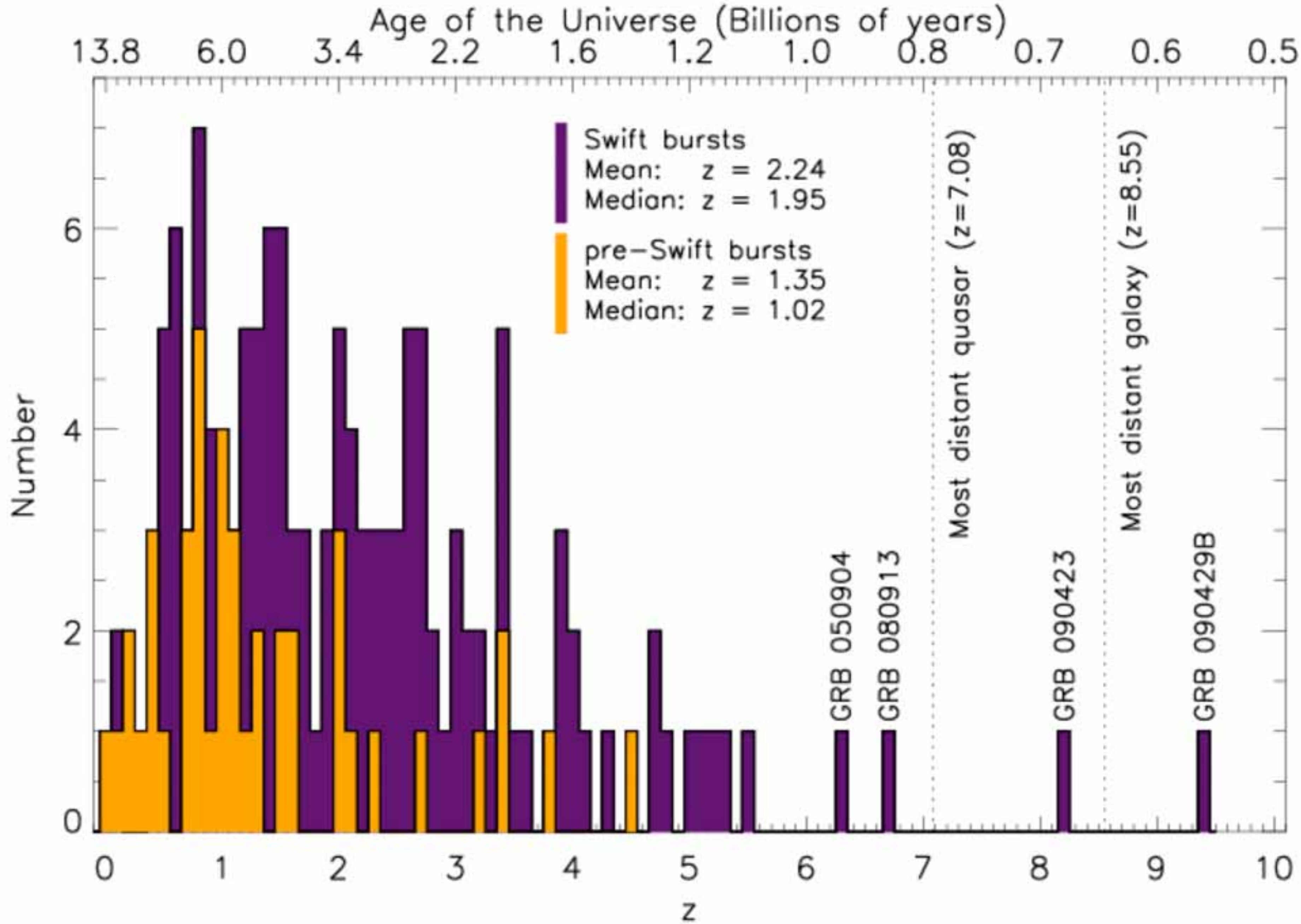
- "Long-soft" bursts are at cosmological distances



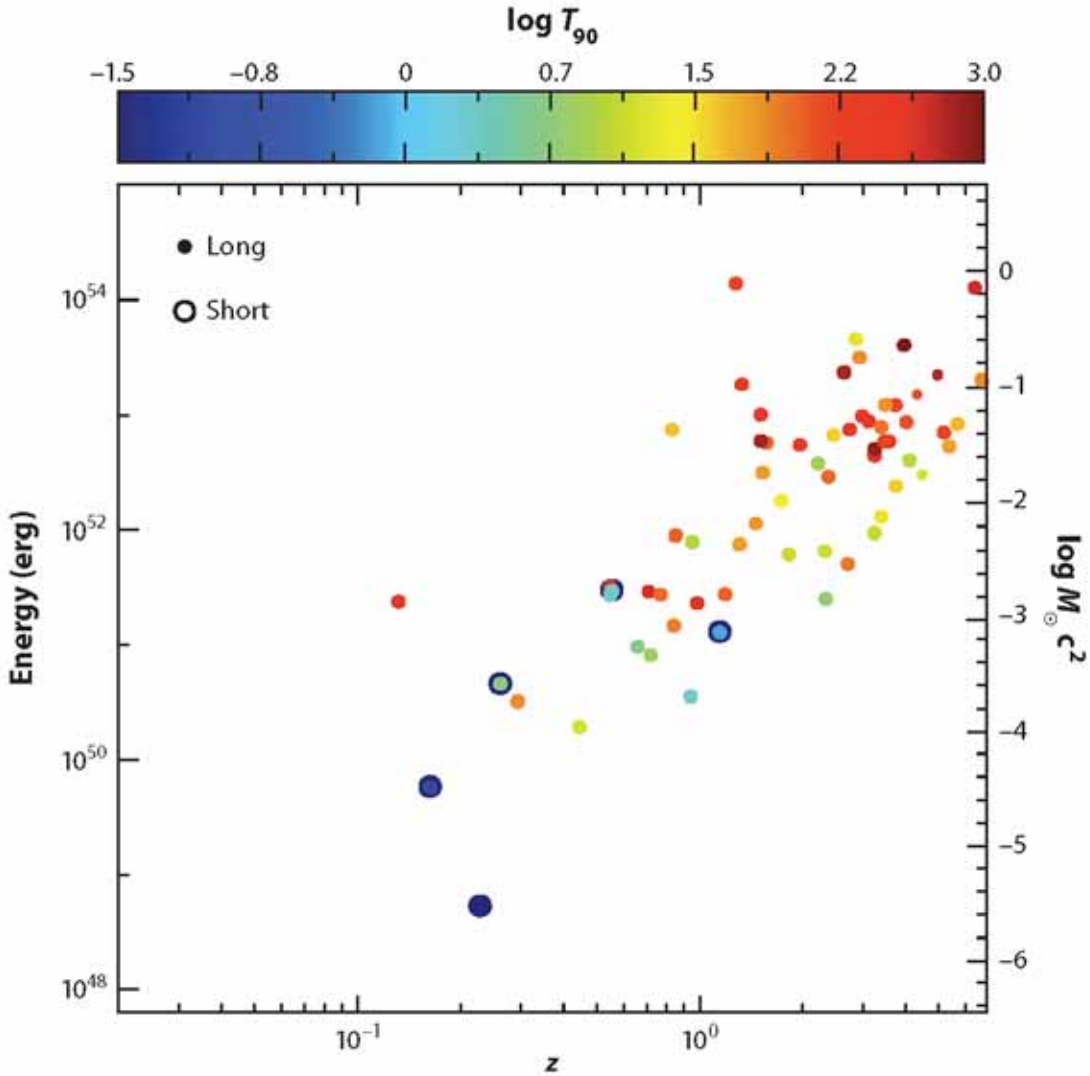
SWIFT gives an average z for 41 bursts with good distance determinations of 2.6

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

Fiore et al (2007)

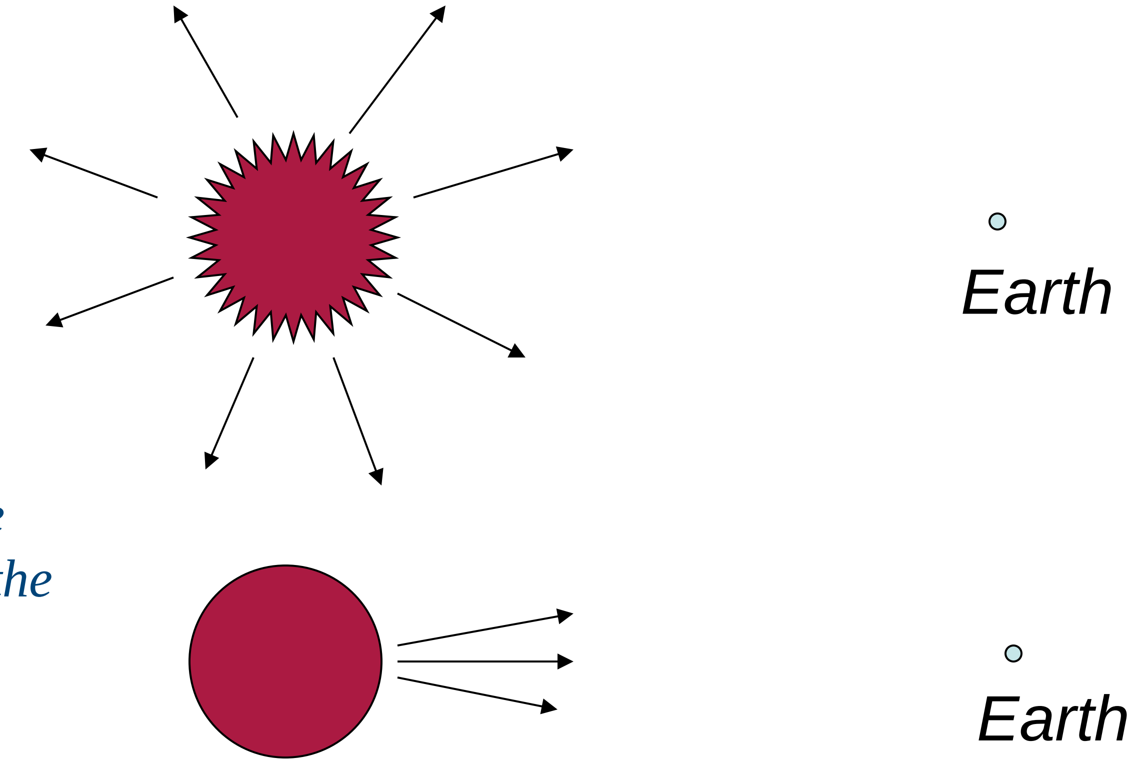

Age of the Universe (Billions of years)
13.8
6.0
3.4
2.2
1.6
1.2
1.0
0.8
0.7
0.6
0.5
Swift bursts
Mean: z = 2.24
Median: z = 1.95
pre-Swift bursts
Mean: z = 1.35
Median: z = 1.02
Most distant quasar (z=7.08)
Most distant galaxy (z=8.55)
GRB 050904
GRB 080913
GRB 090423
GRB 090429B
Number
0
2
4
6
0
1
2
3
4
5
6
7
8
9
10
z

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



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

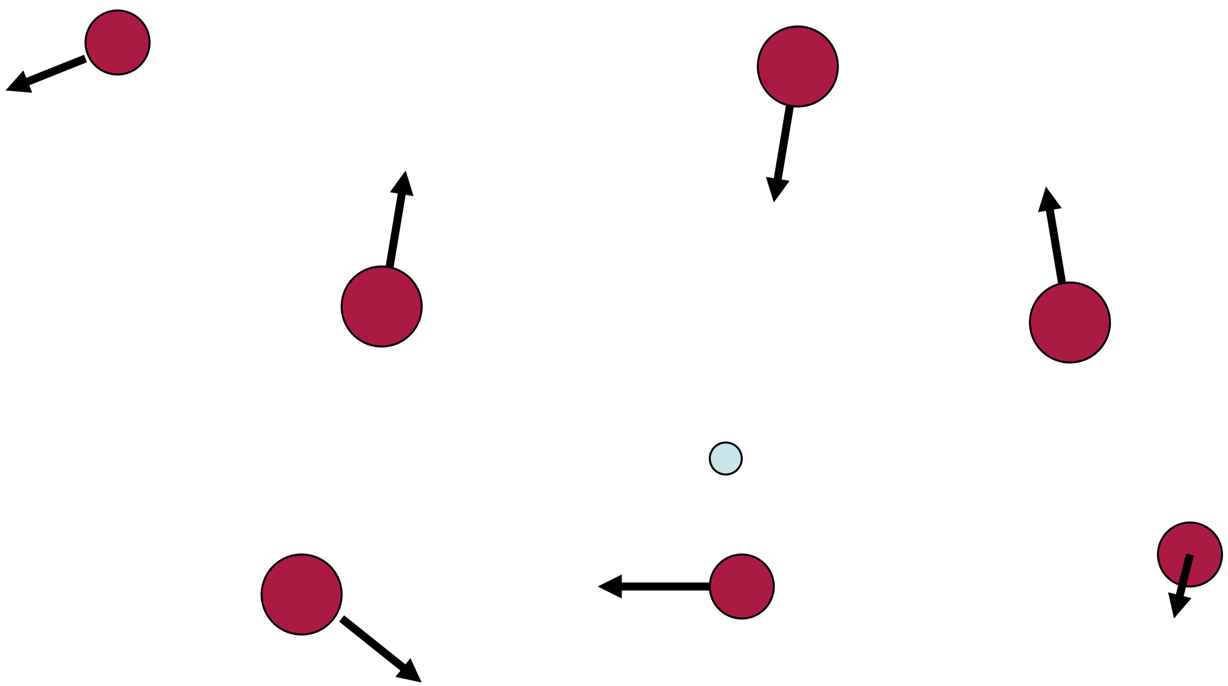
But are the energies required really as great as 10^{54} erg?



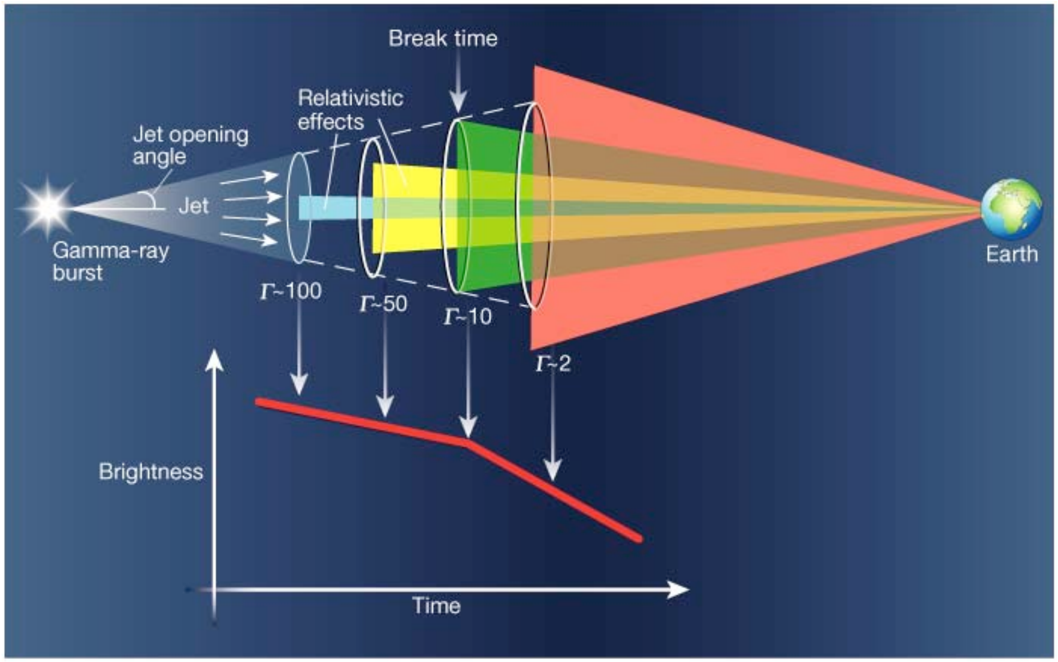
If the energy were beamed to 0.1% of the sky, then the total energy could be 1000 times less

Nothing seen down here

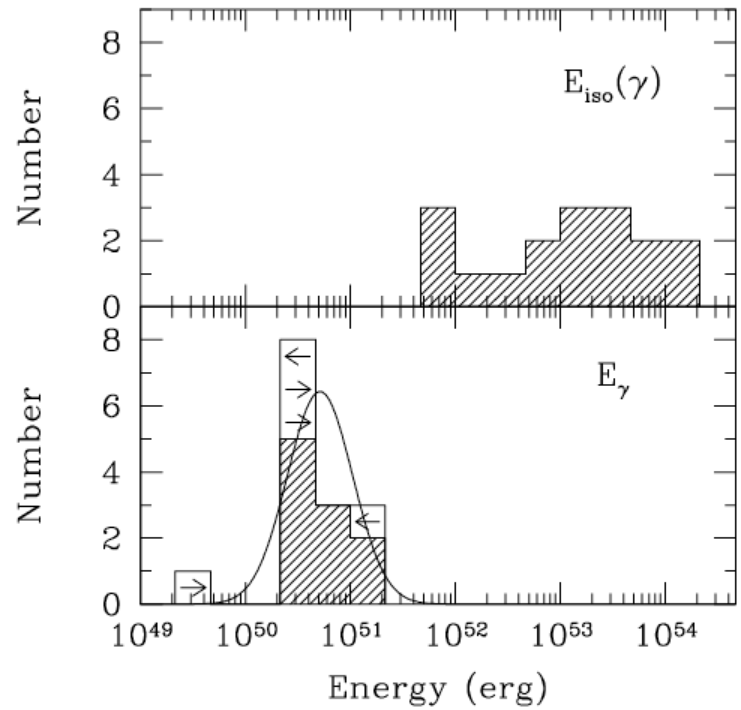
But then there would be a lot of bursts that we do not see for every one that we do see. About 300 in fact.



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

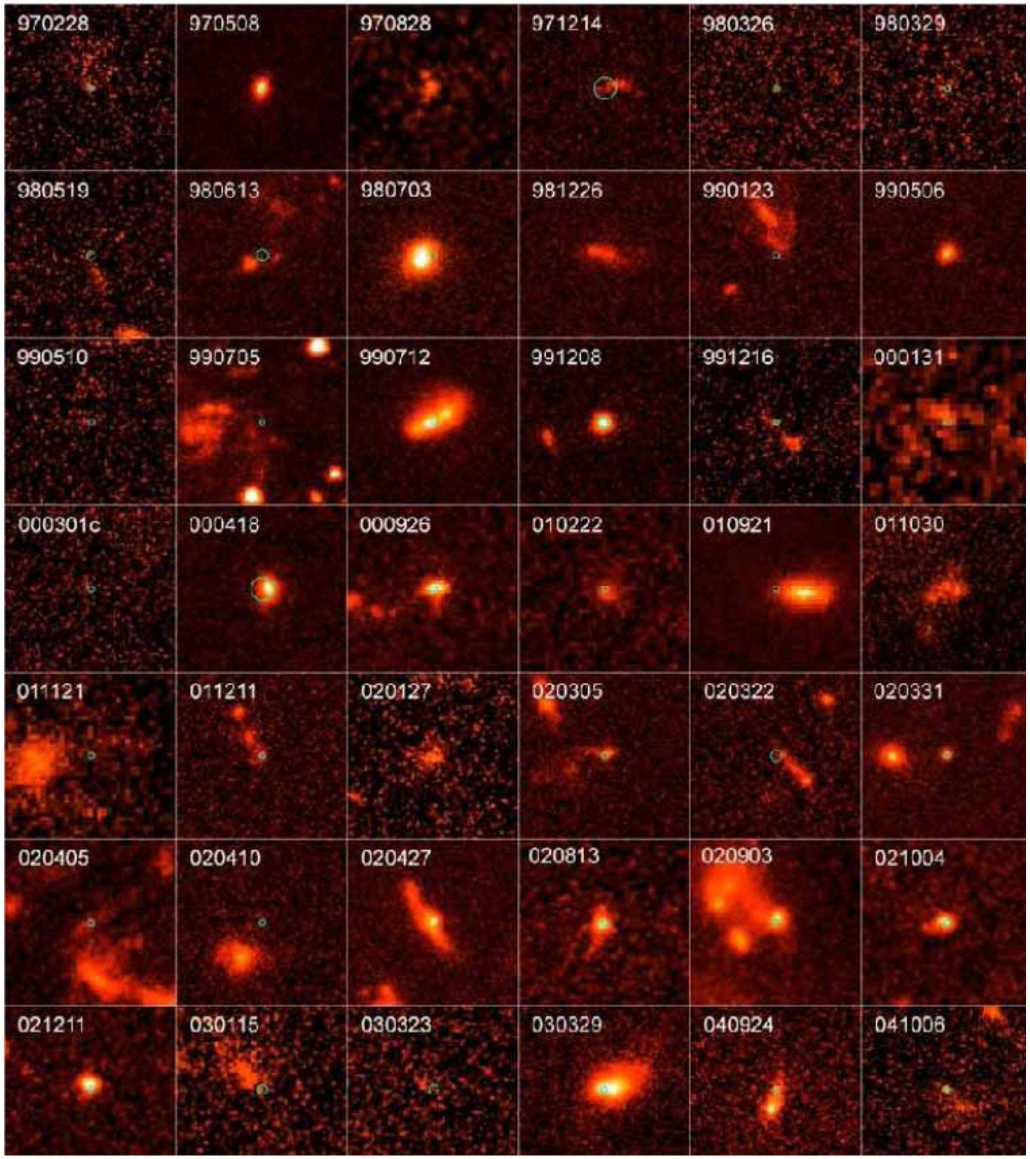


Frail et al. (2001)



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

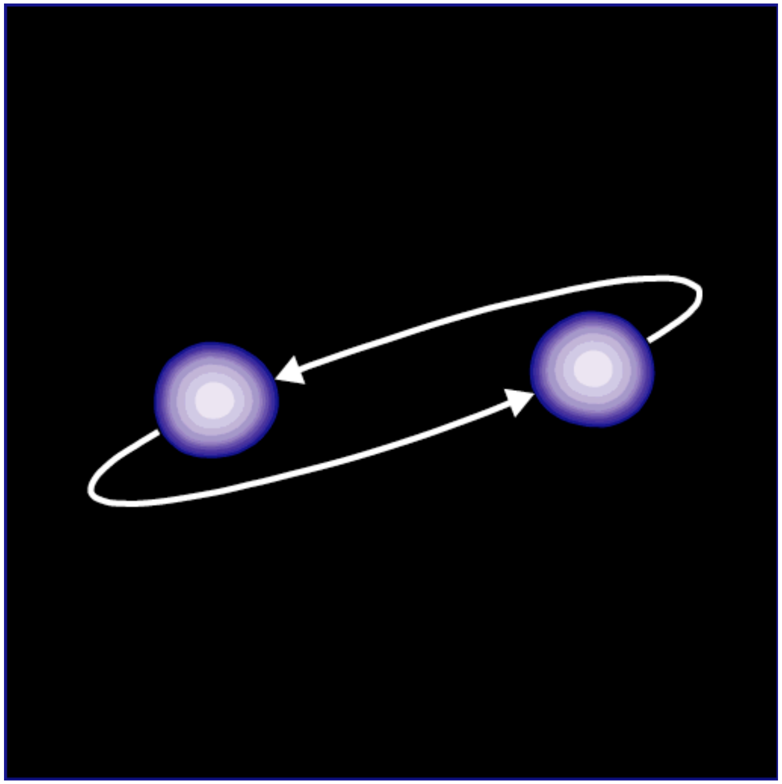


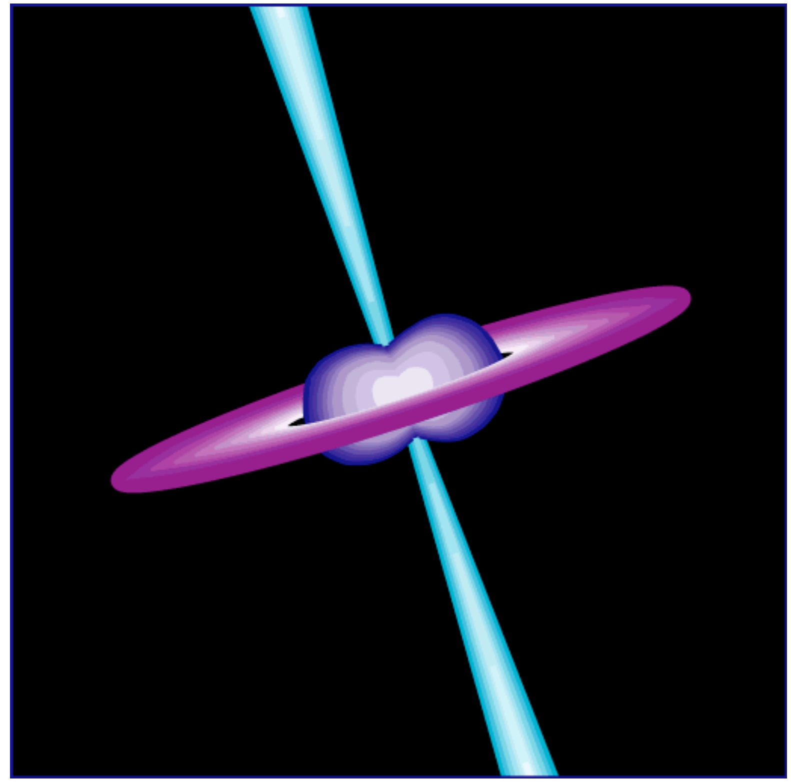
Fruchter et al (2005).

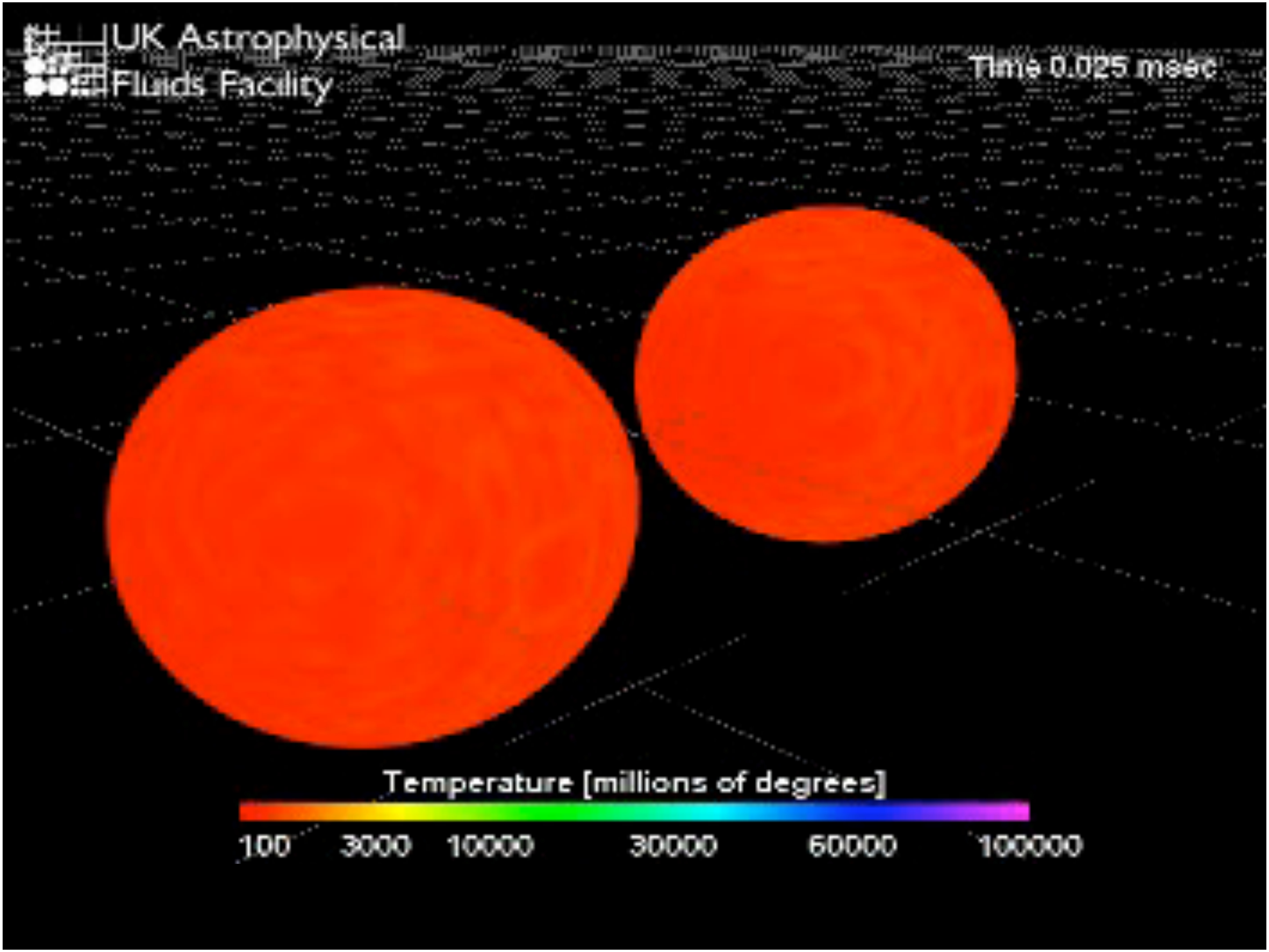
The green circles show GRB locations to an accuracy of 0.15 arc sec.

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.*

One Model: Merging Neutron Stars





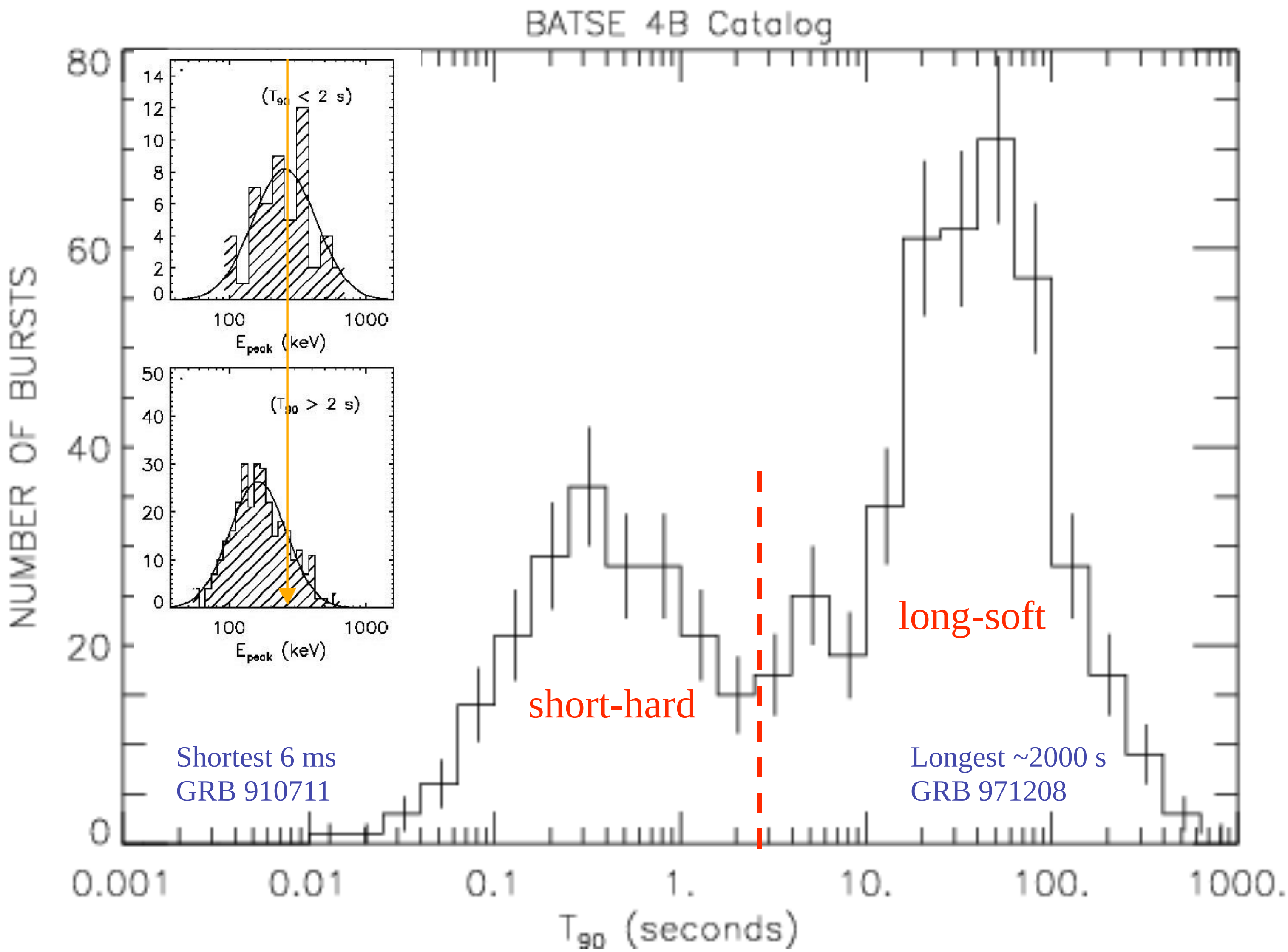

UK Astrophysical
Fluids Facility
Time 0.025 msec
Temperature [millions of degrees]
100
3000
10000
30000
60000
100000

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

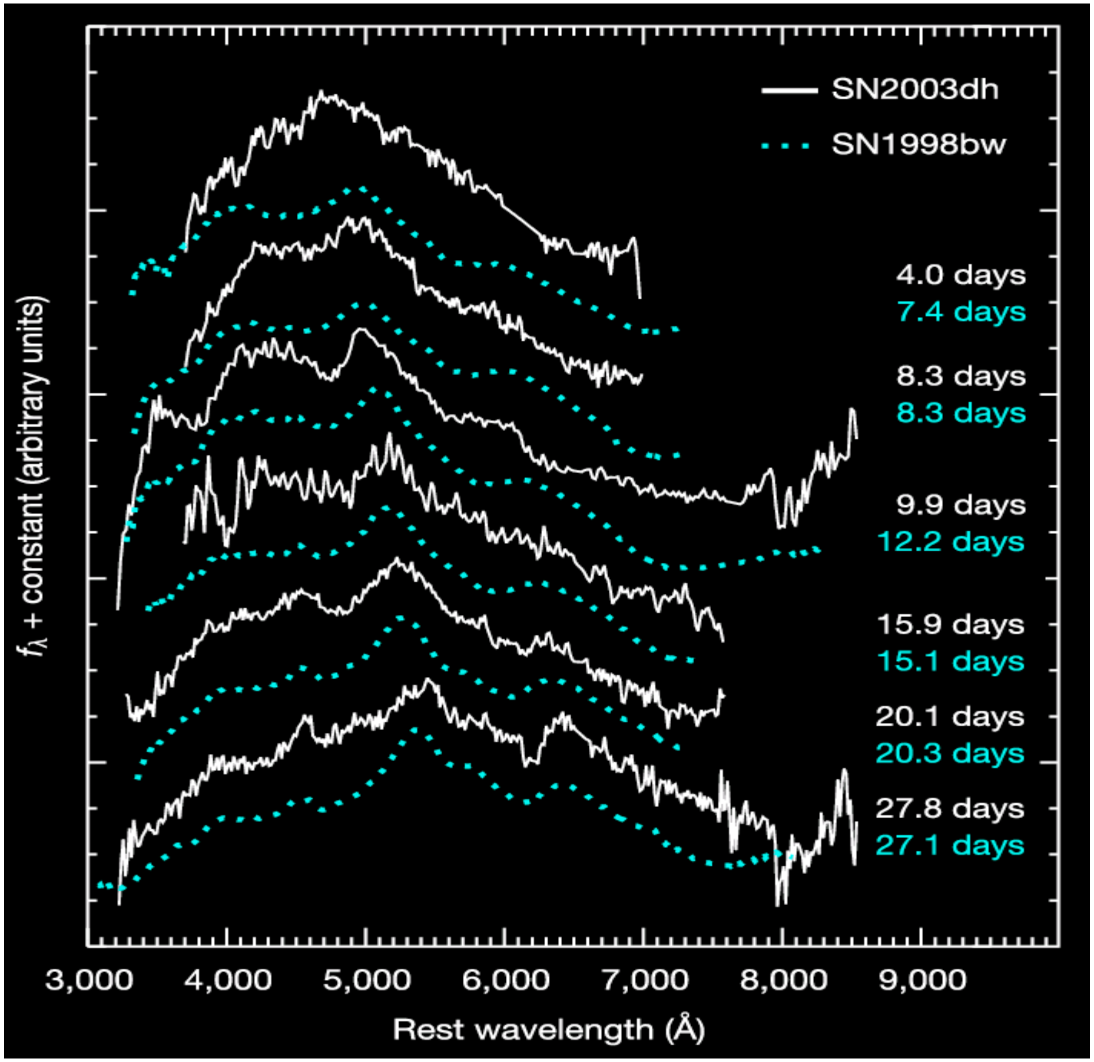
These bursts did not come from star forming regions, and in fact showed all the characteristics expected of merging neutron stars. It is widely believed that merging neutron stars (and neutron stars merging with black holes) have now been observed as short hard gamma-ray bursts. In the next 10 - 15 years,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

These GRBs are much closer than the LS GRBs and have ~30 times less energy.

But what about the long soft bursts?



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



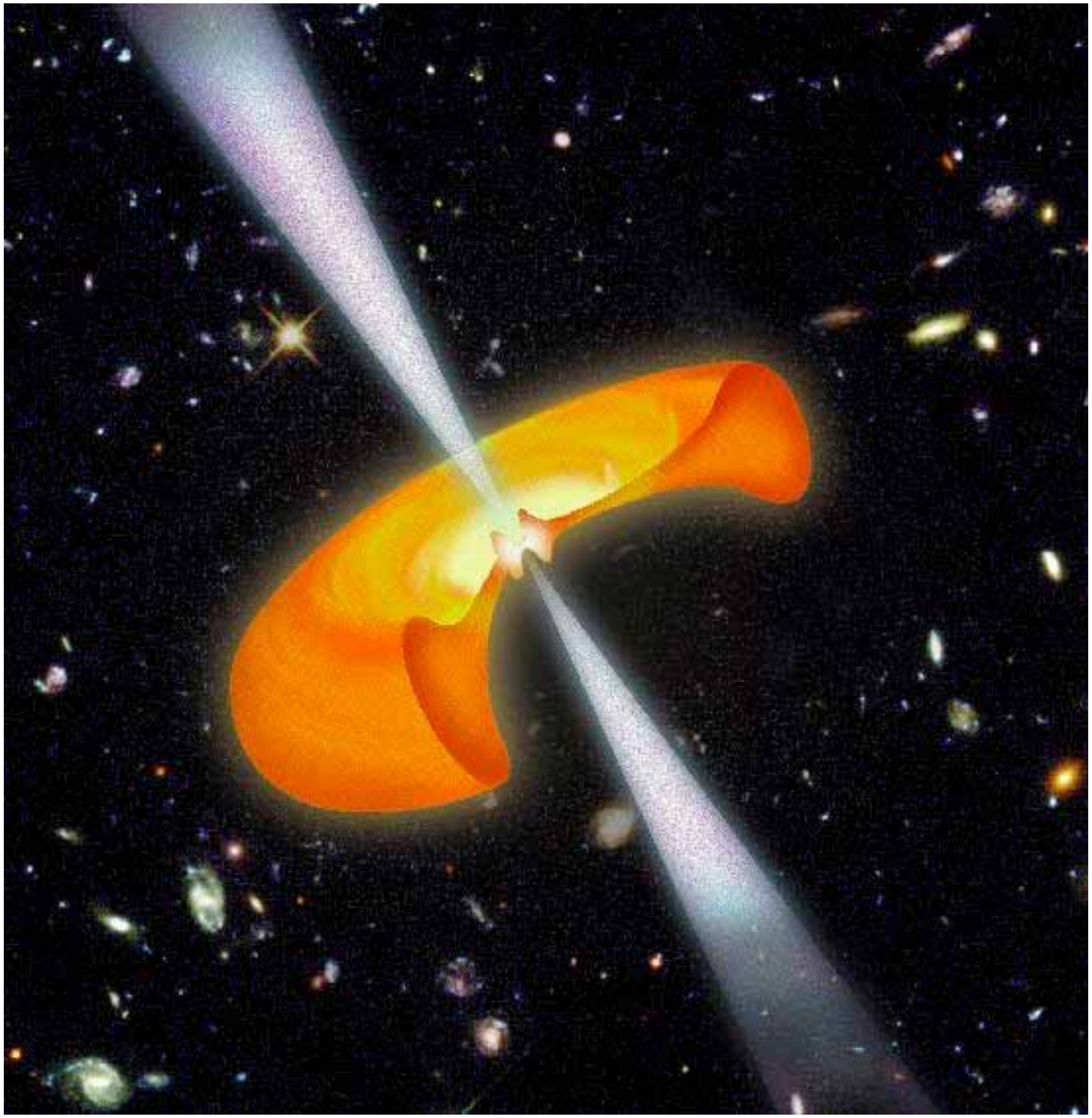
GRB980425/ SN1998bw

GRB030329/ SN2003dh

GRB031203/ SN2003lw

GRB060218/ SN2006aj

The Collapsar Model
(Woosley 1993)



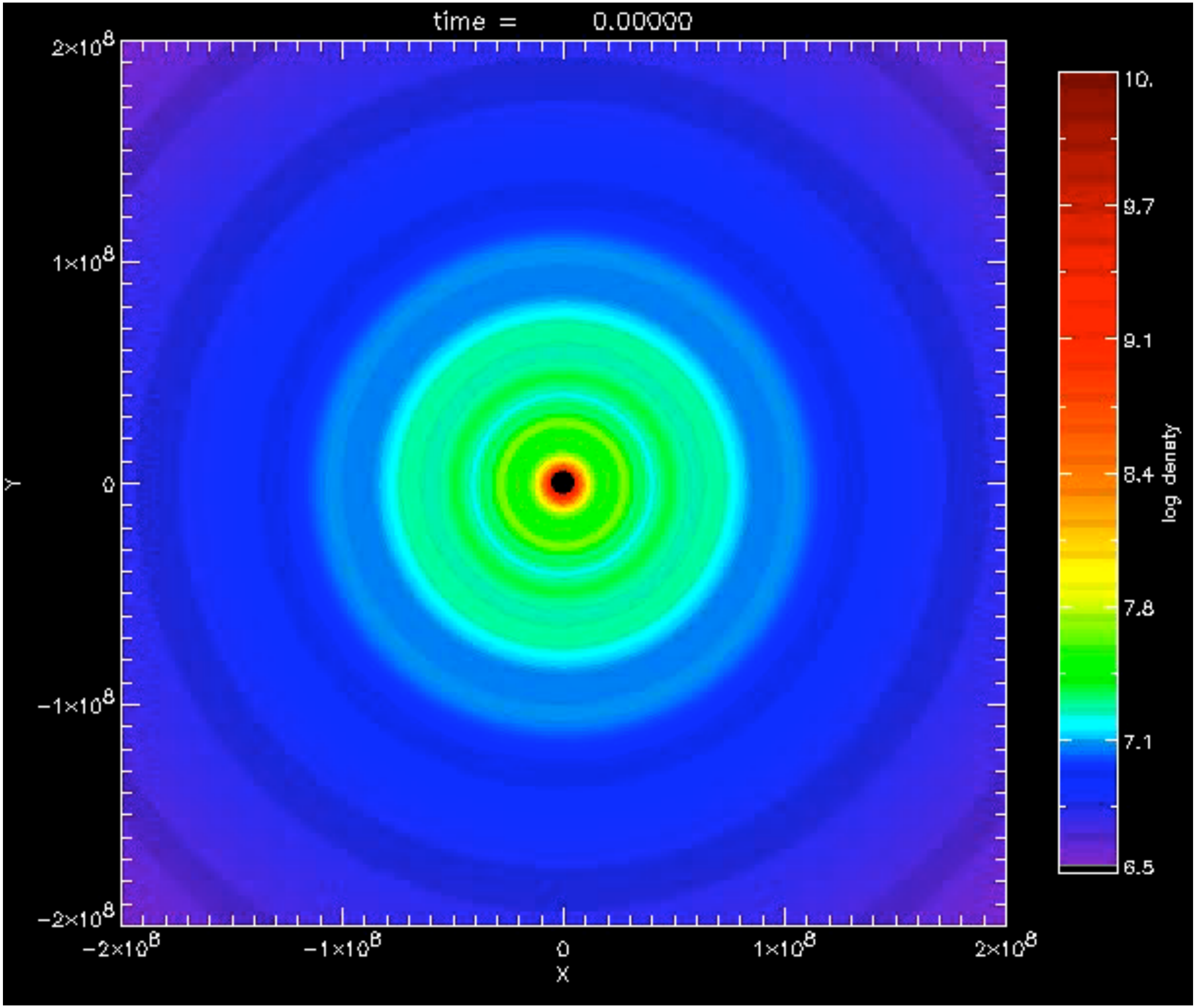
Usually massive stars make supernovae. Their iron core collapses to a neutron star and the energy released explodes the rest of the star.

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.

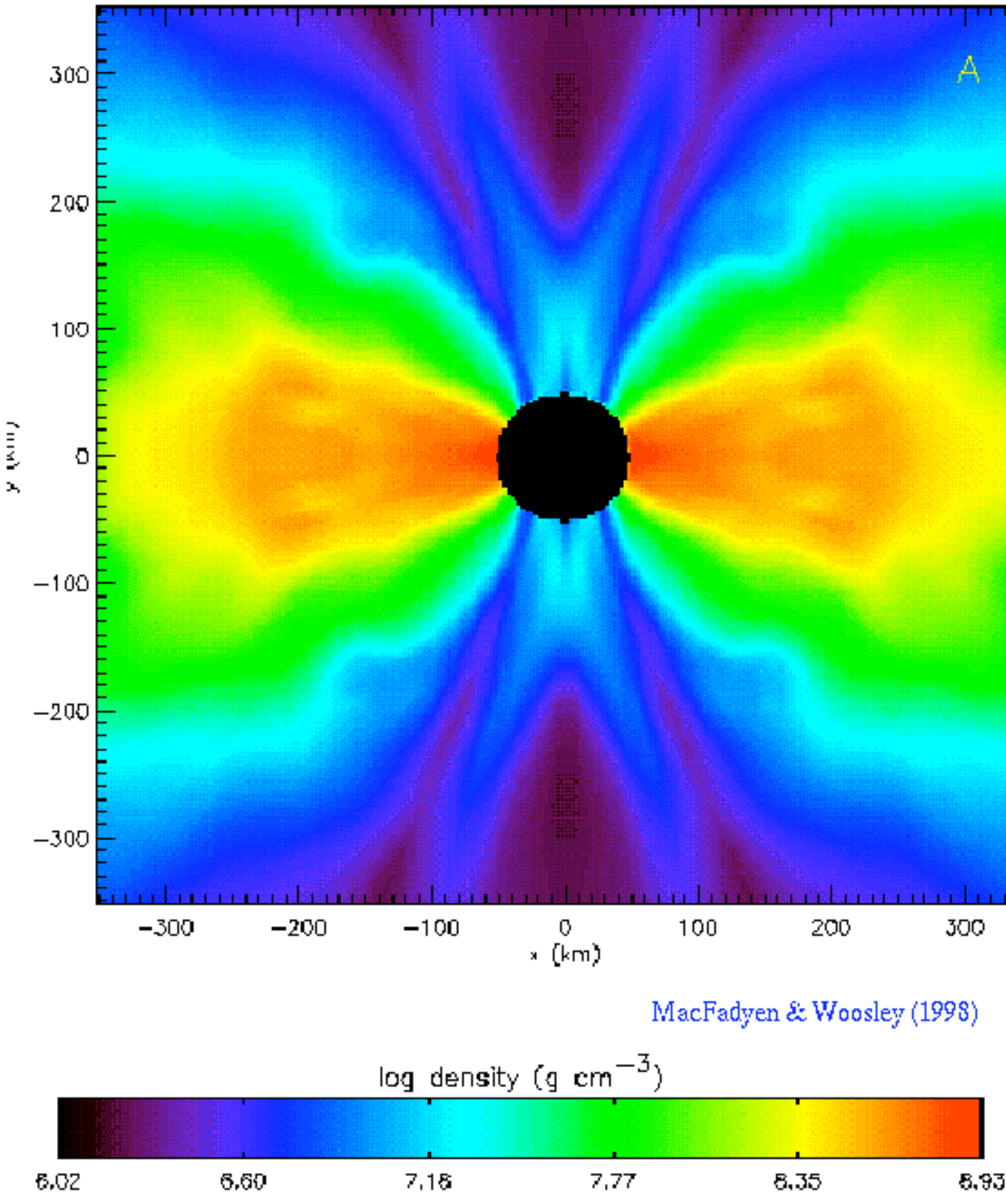
A star without rotation would then simply disappear....

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?



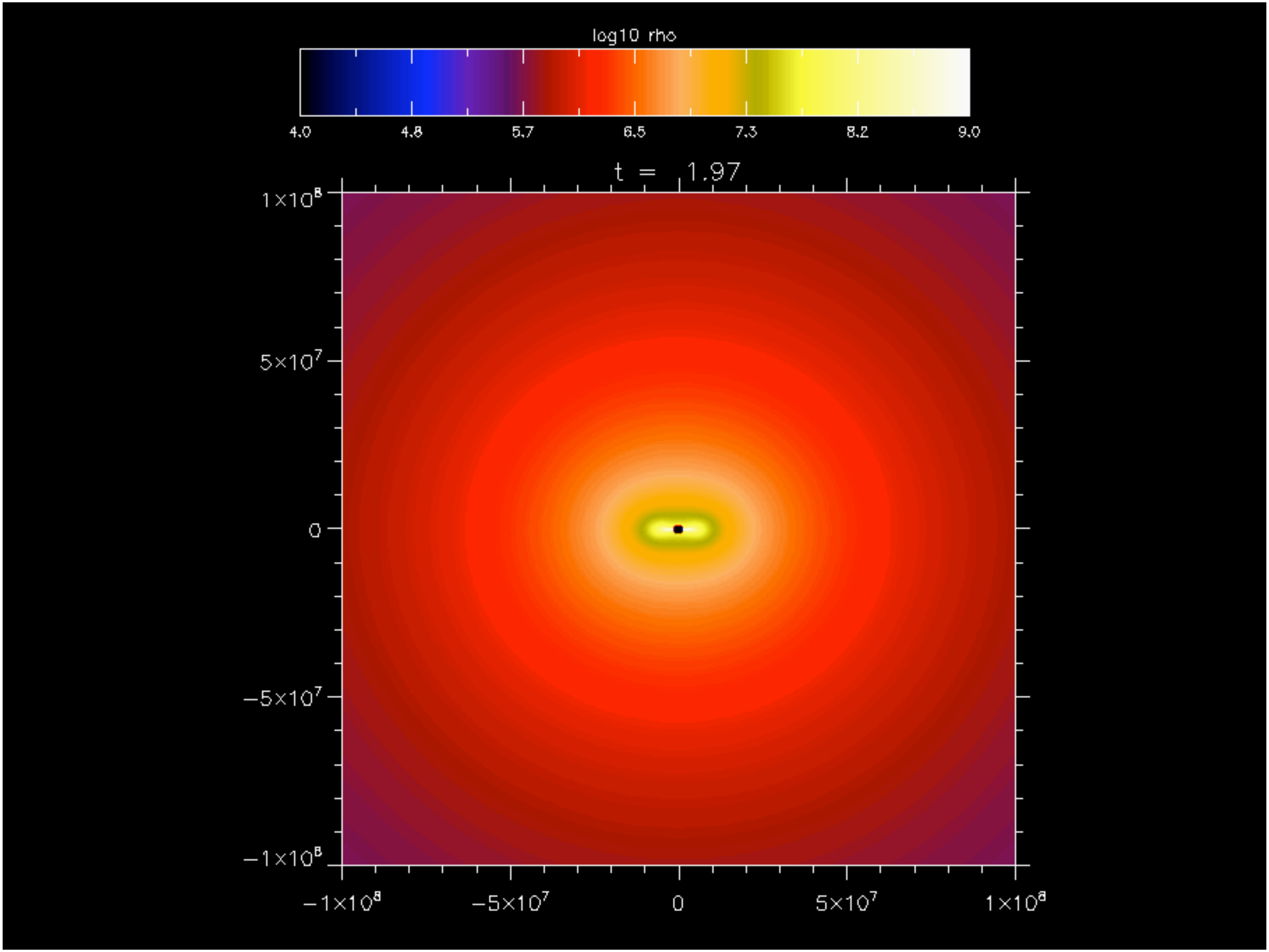
time = 0.00000
2×10^8
1×10^8
0
−1×10^8
−2×10^8
Y
X
10.
9.7
9.1
8.4
7.8
7.1
6.5
log density

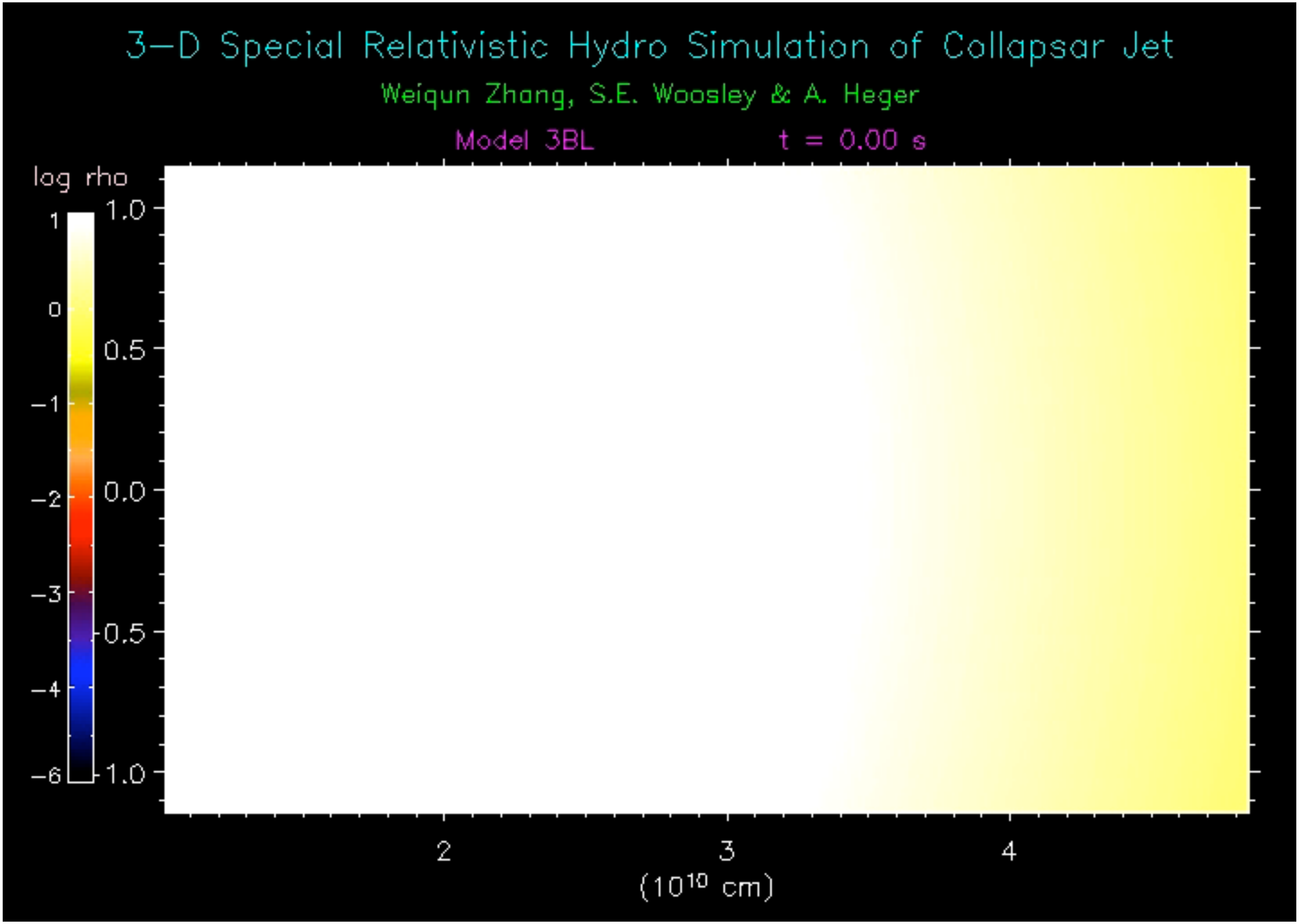


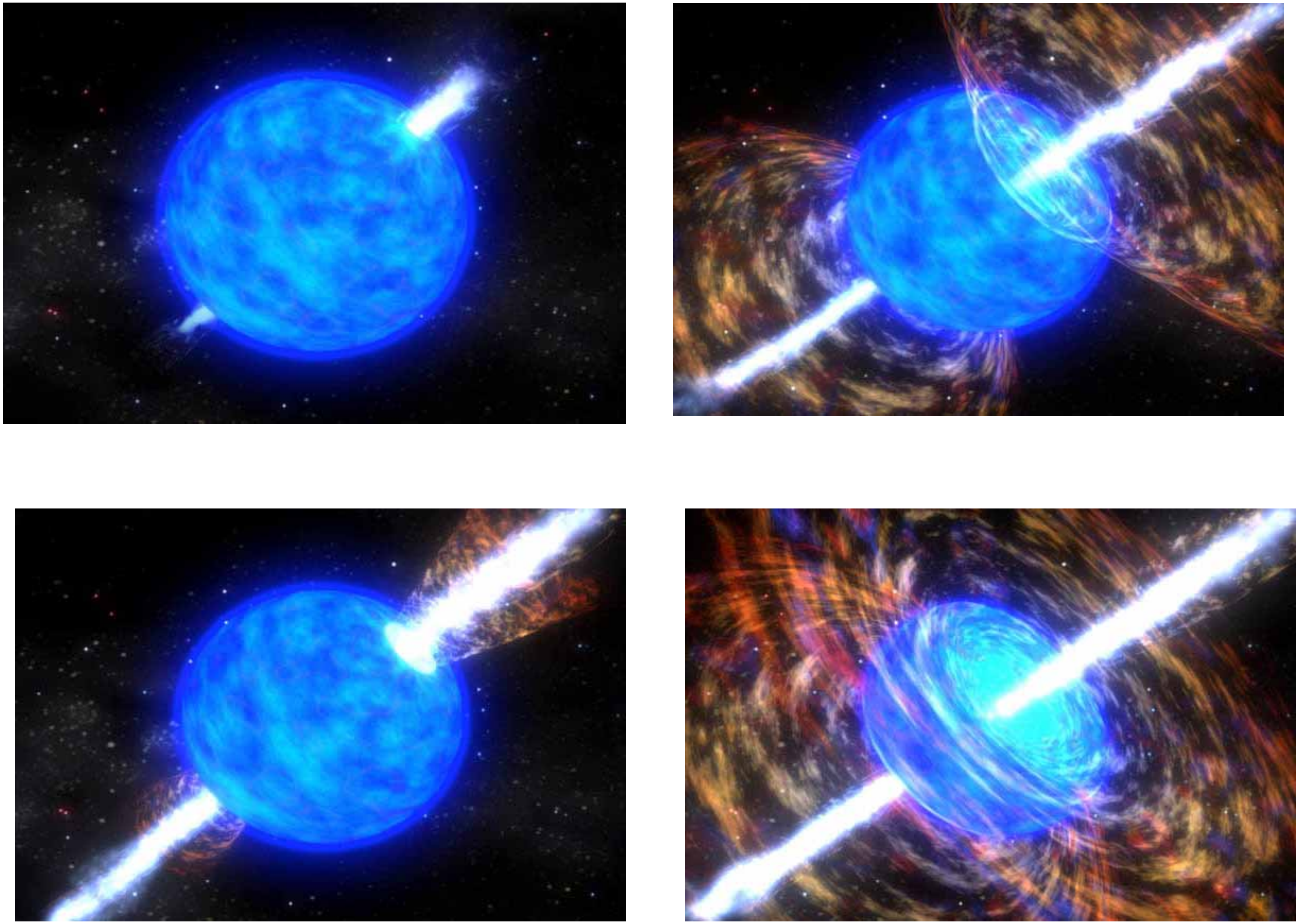
7.6 s after core collapse; high viscosity case.

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.


log10 rho
4.0
4.8
5.7
6.5
7.3
8.2
9.0
t = 1.97
1×10^8
5×10^7
0
−5×10^7
−1×10^8
−1×10^8
−5×10^7
0
5×10^7
1×10^8


3–D Special Relativistic Hydro Simulation of Collapsar Jet
Weiqun Zhang, S.E. Woosley & A. Heger
Model 3BL
t = 0.00 s
log rho
1
0
−1
−2
−3
−4
−6
1.0
0.5
0.0
0.5
1.0
2
3
4
(10^10 cm)



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 ~ $10^{14\text{-}15}$ G
They might be born as fast rotators
Efficient dynamo implies P ~ t_{conv} ~ ms

Millisecond magnetar have the correct energy

$$E_{Rot} \approx 2\times10^{52}\left(\frac{P}{1\ \mathrm{ms}}\right)^{-2}\ \mathrm{ergs}$$

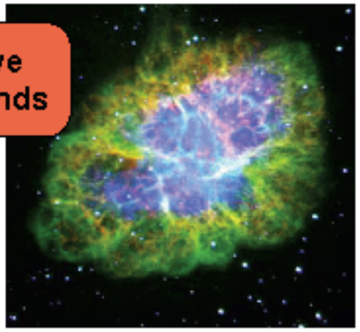
Pro

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

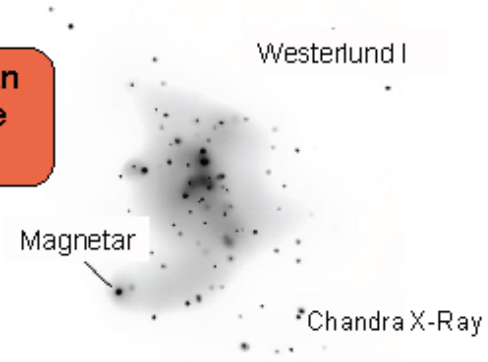
Typical spin-down times are ~ 100-1000 sec

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

Pulsars have relativistic winds

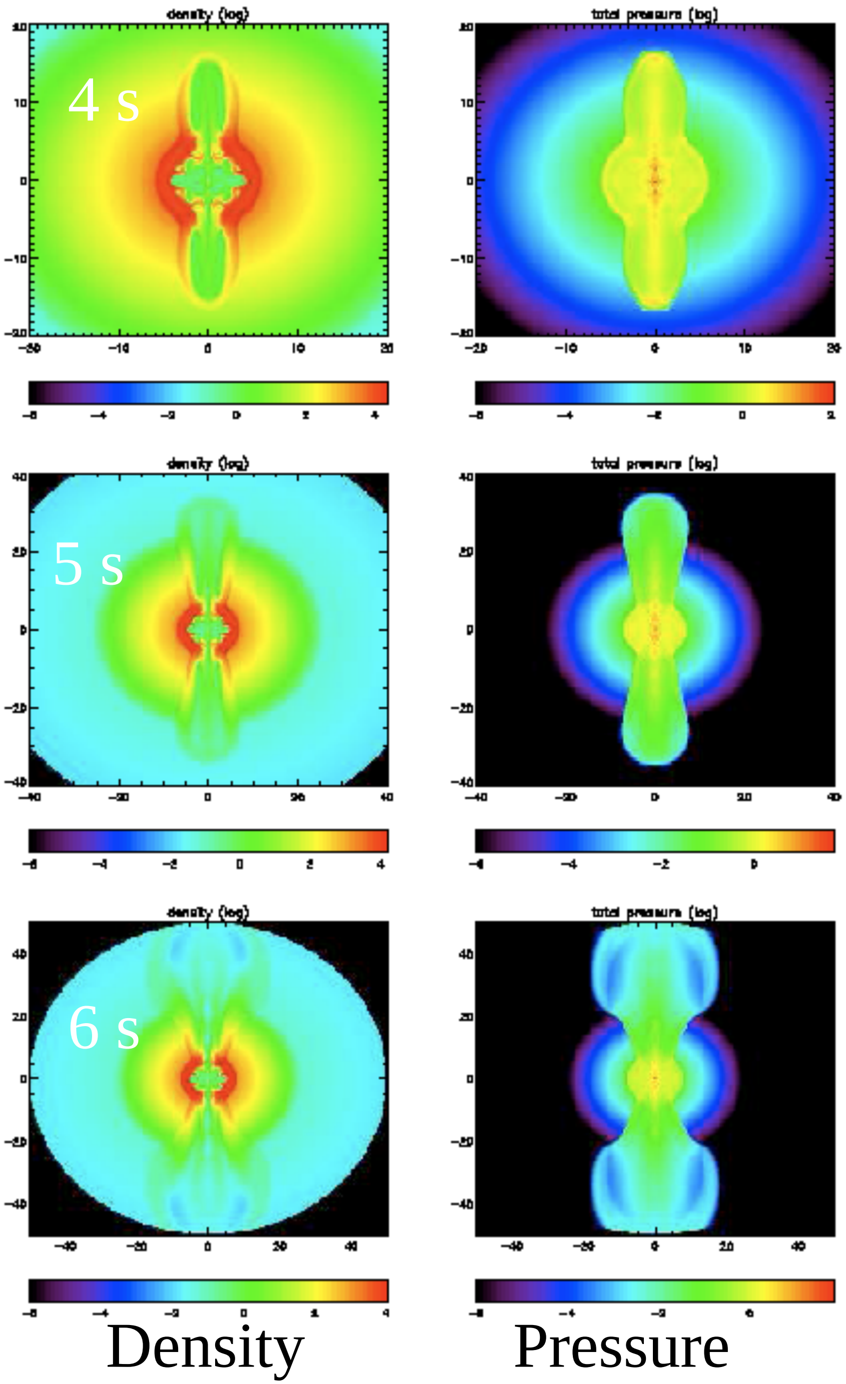


Magnetars can have massive progenitors



Faintest Cluster Members are O7 (Muno 2006)

Slide from N. Bucciantini



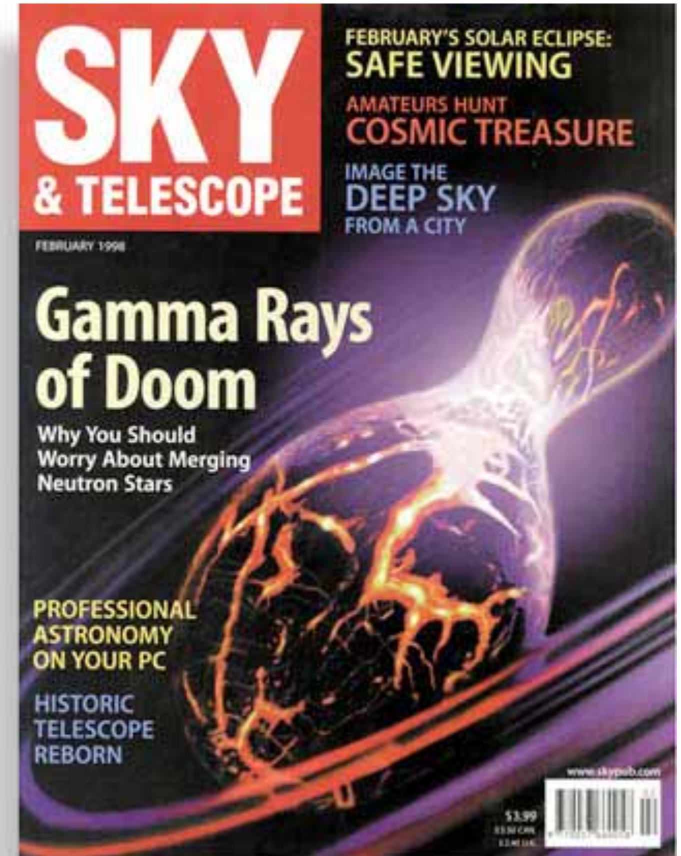
Assume a pre-existing supernova explosion in the stripped down core of a 35 solar mass star.

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

Two phase wind:

Initial magetar-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.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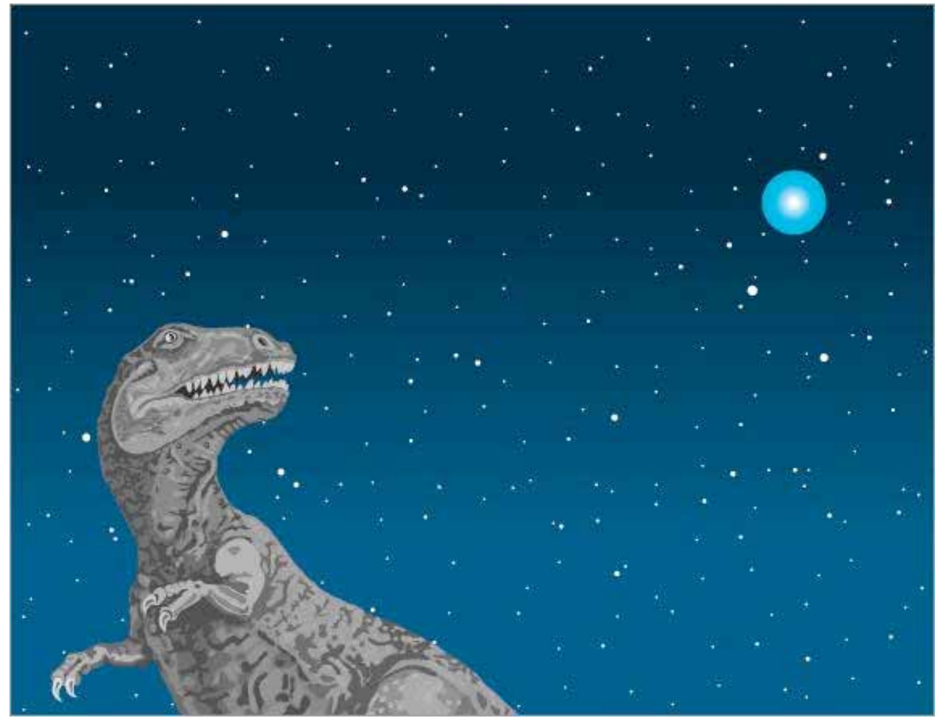

A 10^{53} erg event situated 30,000 light years away (distance from here to the Galactic center) would give as much energy to the earth in 10 seconds as the sun – equivalent to a 200 megaton explosion.

Does it matter having an extra sun in the sky for 10 seconds?

Probably not. This is spread all over the surface of the earth and the heat capacity of the Earth's atmosphere is very high. Gamma-rays would deposit their energy about 30 km up. Some bad nitrogen chemistry would happen.

Noticeable yes, deadly to all living things – No.

Biological Hazards of Gamma-Ray Bursts

Distance (kpc)	Events /10 by	Megatons	Results
10	100 – 1000	200	Some ozone damage, EMP acid rain
1	1 – 10	20,000	Ozone gone, acid rain, blindness 2nd and 3rd degree burns*
0.1	0.01 – 0.1	two million	Shock waves, flash incineration, tidal waves, radioactivity (^{14}C) End of life as we know it.

* Depends on uncertain efficiency for conversion of energetic electrons to optical light