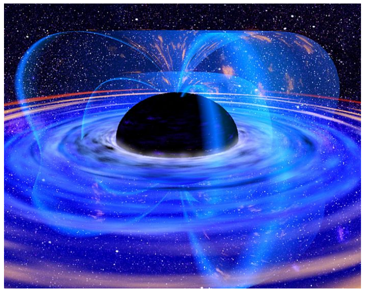


Lecture 19

Black Holes and Gamma-Ray Bursts

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

Black holes in nature – end points of stellar evolution

- In our galaxy alone, theory suggests 50 million black holes (2 SN per century for 10^{10} years ¼ of which make black holes
- Most massive galaxies have massive black holes at their centers (10^9 galaxies)
- Dozens of black hole binary x-ray sources per galaxy – at least
- One gravitational radiation detection so far

They are out there…

Some Properties of Black Holes

- Entirely defined by their mass, rotation rate, and charge. All memory of how the hole was made is lost. Almost like an elementary particle. "Black holes have no hair" (Wheeler, Israel, Hawking, etc.)
- Believed that all the mass is concentrated at the center in a small quantum-mechanical "singularity"
- The effective density of stellar mass black holes, as defined by their event horizons is very high, but there are supermassive black hole in active galactic nuclei with "average densities" no greater than water. they are just very big (this ignores the central concentration in a singularity though.) The average density matters to tidal forces.
- 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. Of course there's no light.

Kinds of black holes:

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

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

Event Horizon

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

Note that this "size" is proportional to M.
Very massive black holes - the maximum is 4 x 10^{10} solar masses have been inferred to exist in some Galactic centers. These black holes would be ~10 AU in size.

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

$$\rho = \frac{M}{(4/3)\pi R^3} \propto \frac{M}{M^3} \propto \frac{1}{M^2}$$
$$= 1.8 \times 10^{16} \left(\frac{M_\odot}{M}\right)^2 \text{ g cm}^{-3}$$

Tidal Force

$$\Delta F_{tidal} = \frac{dF_{grav}}{dr} \times d = \frac{2GMm}{r^3} d$$
$$= \left(\frac{GMm}{r^2}\right)\left(\frac{2d}{r}\right) = \text{ your weight } \times \frac{2d}{r} \propto \frac{1}{M^2}$$

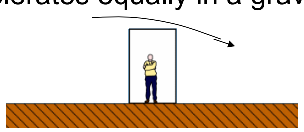
The tidal force would be reduced by $1/M^2$.

A rocket crossing the event horizon of a 100,000 solar mass black hole might just survive and black holes of 10^{10} solar masses are known in the nuclei of active galaxies

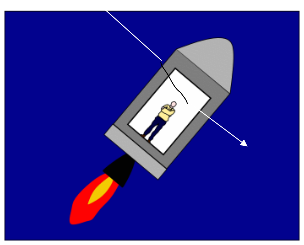
http://en.wikipedia.org/wiki/Spaghettification

But once inside the black hole the tidal forces would continue to grow even in a supermassive black hole.

EQUIVALENCE PRINCIPLE
(anything regardless of mass accelerates equally in a gravitational field)

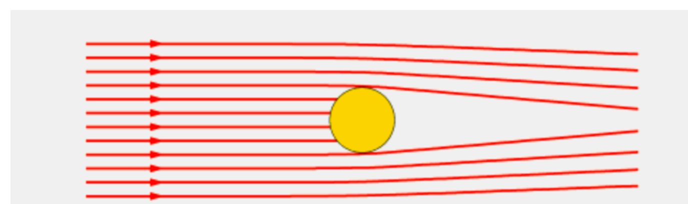


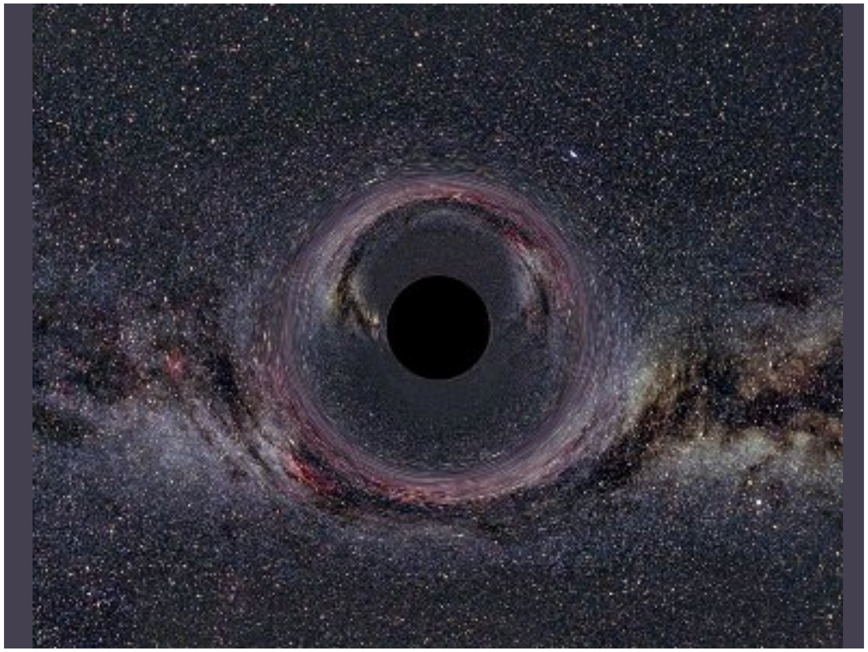
equals

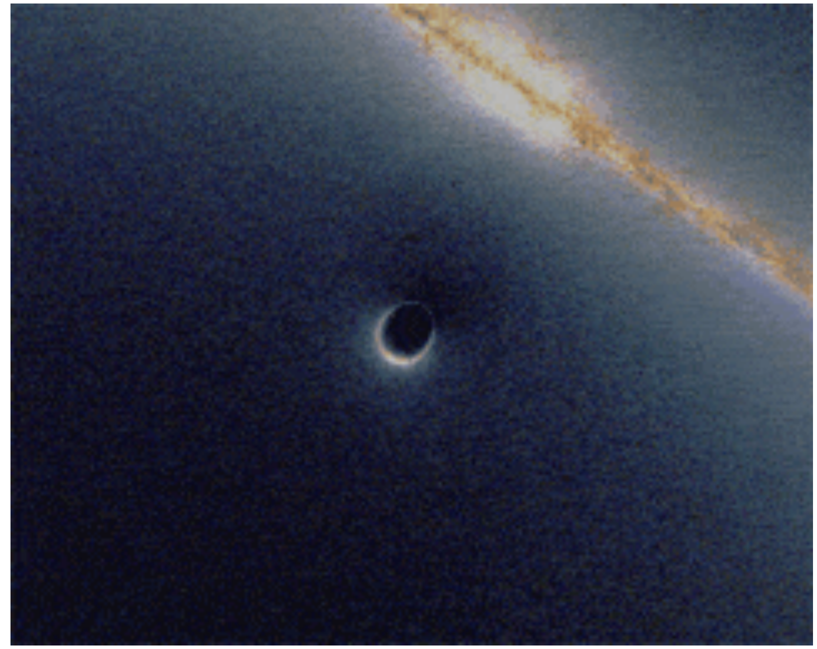


some deflection just because you are moving but even more if you are accelerating

Gravity "bends" light







Gravitational time dilation.

An outcome of the equivalence principle, without derivation

$$t_{remote} = t_{near\,BH} \,/\, \sqrt{1 - r_s / r} \qquad r_s = \frac{2GM}{c^2}$$

$$r > r_s$$

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

has been measured on Eath with atomic clocks ~ nanoseconds

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

If you could go inside what would you see? I don't know

According to one view, mostly vacuum. The collapse continues to a "point" at the center. The event horizon is just a cloak that prohibits (outwards) communication with the universe. Roger Penrose (1960's) proved a theorem that all black holes have "singularities". Quantum mechanics was neglected.

The matter piles up at the center and the density classically can approach infinity. But quantum mechanics does not allow an infinite mass energy density to exist at a geometrical point.

At this time there is no agreed upon theory that unites the basics of quantum mechanics and general relativity.

However, combinations of the fundamental constants, G, c, and h set some scales for quantum gravitational effects.

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

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

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

$\approx R_S$ for the Planck mass

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

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

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

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

$$\frac{\hbar c}{G} = \frac{(2.99\times10^{10})(1.05\times10^{-27})}{(6.67\times10^{-8})} \frac{\text{cm}}{\text{s}} \frac{\text{gm}^2}{\text{dyne cm}^2} \text{erg s}$$

$$= 4.70\times10^{-10} \frac{\text{gm}^2 \text{ erg}}{\text{dyne cm}} = 4.70\times10^{-10} \text{ gm}^2$$

$$\left(\frac{\hbar c}{G}\right)^{1/2} = 2.17\times10^{-5} \text{ gm}$$

Uncertainty Principle

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

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

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

Space time viewed on a scale of the Planck length can be expected to look very unlike the space-time of common experience:

- Curled up dimensions?
- Quantum foam?
- Time undefined

Can the constants G, c, and h be assumed to stay constant across so many decades of extrapolation?

Is every black hole that forms the birth of a new universe? I don't know

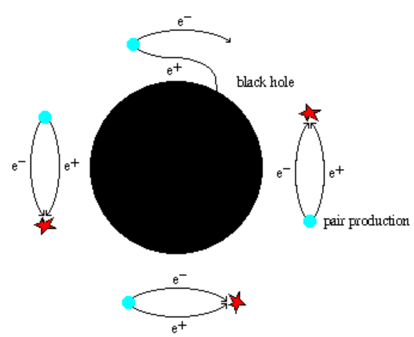
e.g. http://phys.org/news/2012-05-black-hole-universe-physicist-solution.html

The singularity inside a black hole resembles that at the beginning of the universe, but it is very difficult to do experiments. Is this science?

The next 50 years is going to be very interesting in this field – maybe.

Hawking Radiation

the strong gravitational field around a black hole causes pair production



if a pair is produced outside the event horizon, then one member will fall back into the black hole, but the other member will escape and the black hole loses mass

the amount of mass lost is greater for small black holes, therefore quantum sized black holes disintegrate in very short timescales

Hawking Penrose radiation

$$\tau \sim \frac{5120\pi G^2 M^3}{\hbar c^4} = 8.4\times 10^{-17}\left(\frac{M}{kg}\right)^3 \text{ sec}$$

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

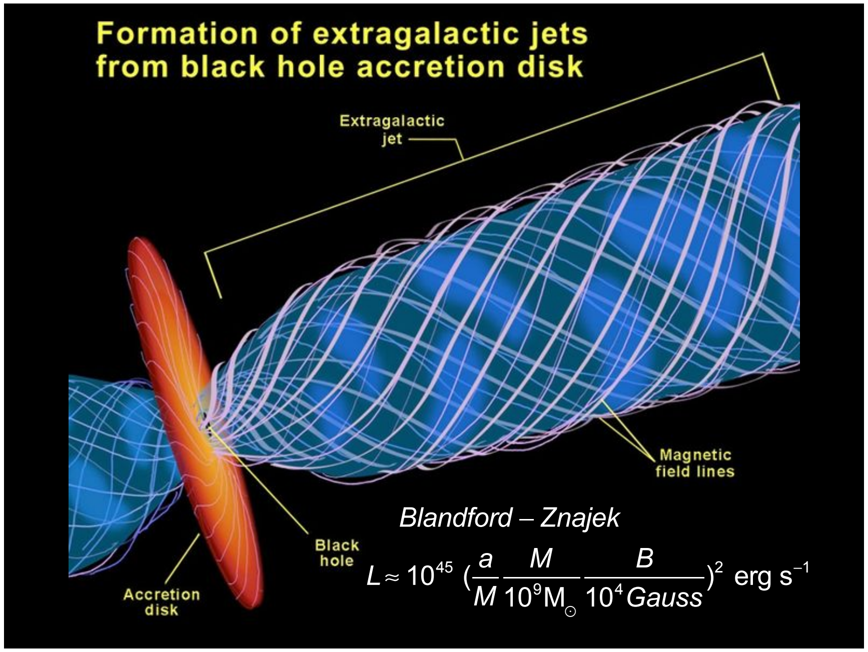
but a Hubble time for 10^{14} *gm*

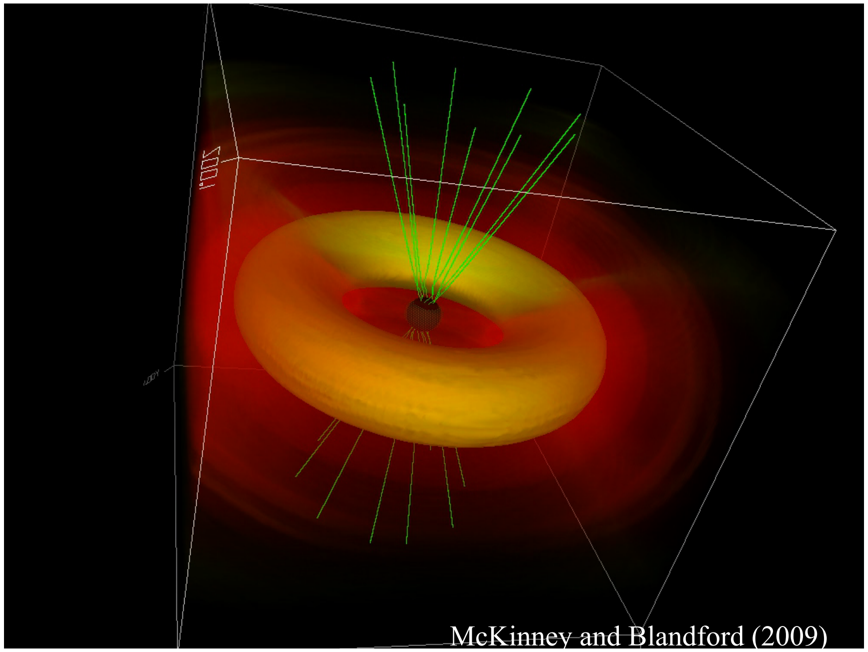
https://en.wikipedia.org/wiki/Hawking_radiation

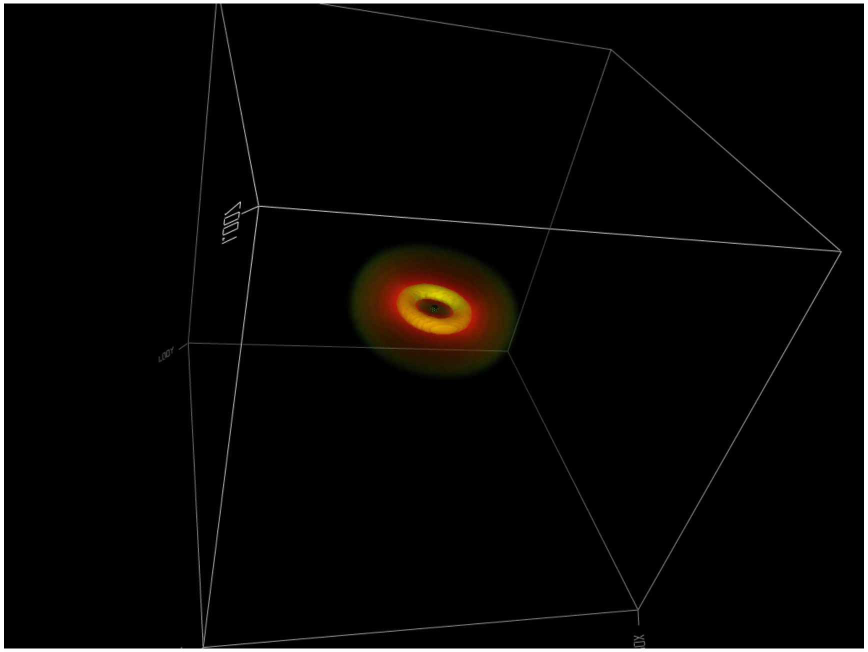
$$T_\infty = \frac{\hbar c^3}{8\pi G M k_B} \quad \left(\approx \frac{1.227\times 10^{23}\ \text{kg}}{M}\ \text{K} = 6.169\times 10^{-8}\ \text{K}\times\frac{M_\odot}{M}\right)$$

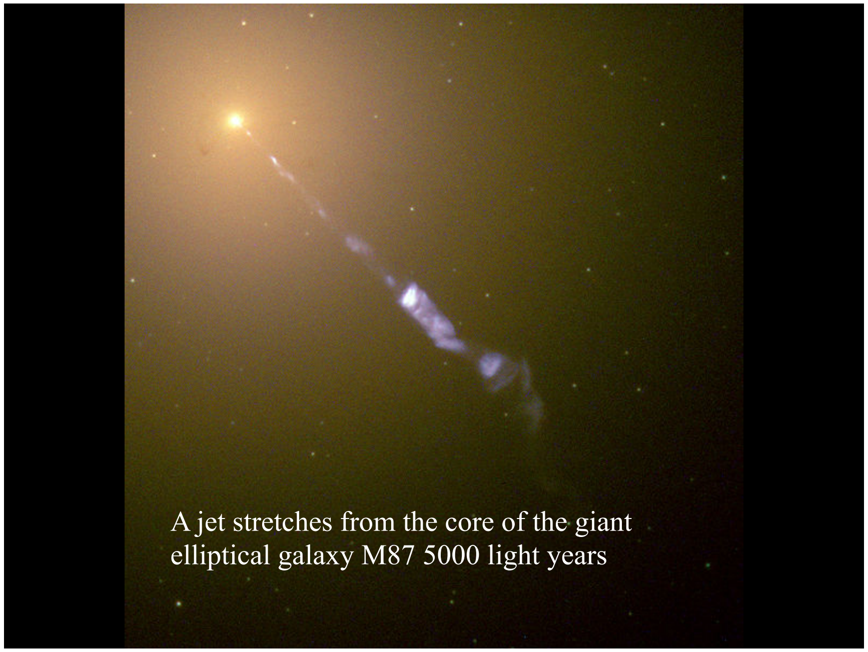
$$L = \frac{\hbar c^6}{15360\pi G^2 M^2} = 9x10^{-22}\left(\frac{M_\odot}{M}\right)\text{erg s}^{-1}$$

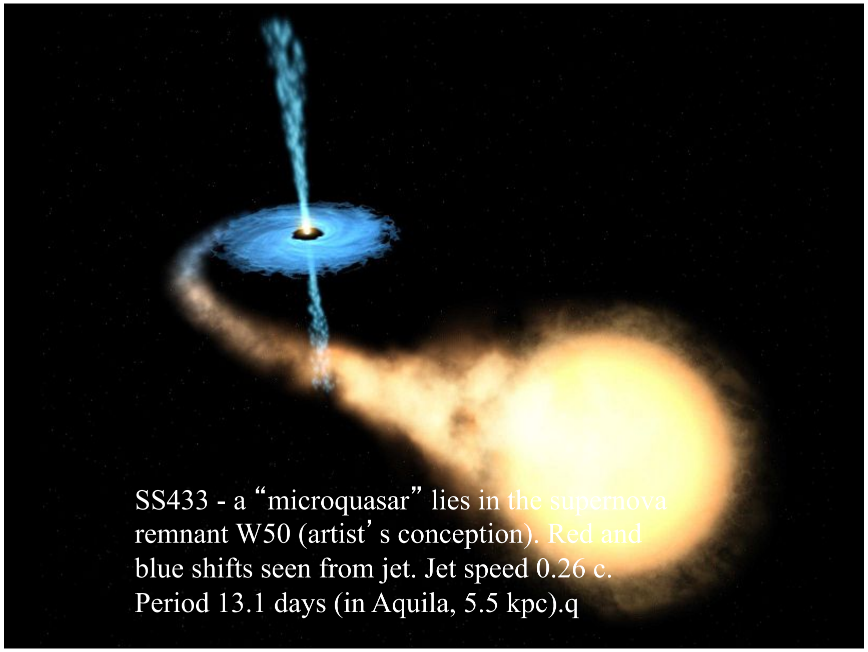
ignoring the microwave background radiation!


Formation of extragalactic jets
from black hole accretion disk
Extragalactic jet
Magnetic field lines
Black hole
Accretion disk
Blandford – Znajek
$L \approx 10^{45} \left(\frac{a}{M} \frac{M}{10^9 M_\odot} \frac{B}{10^4 Gauss}\right)^2$ erg s^{-1}


McKinney and Blandford (2009)



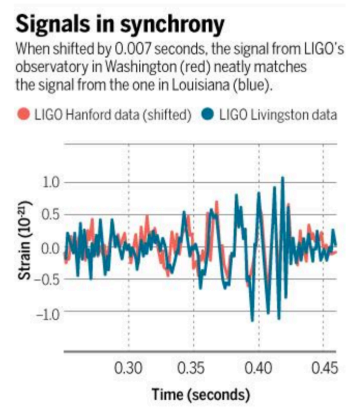

A jet stretches from the core of the giant
elliptical galaxy M87 5000 light years

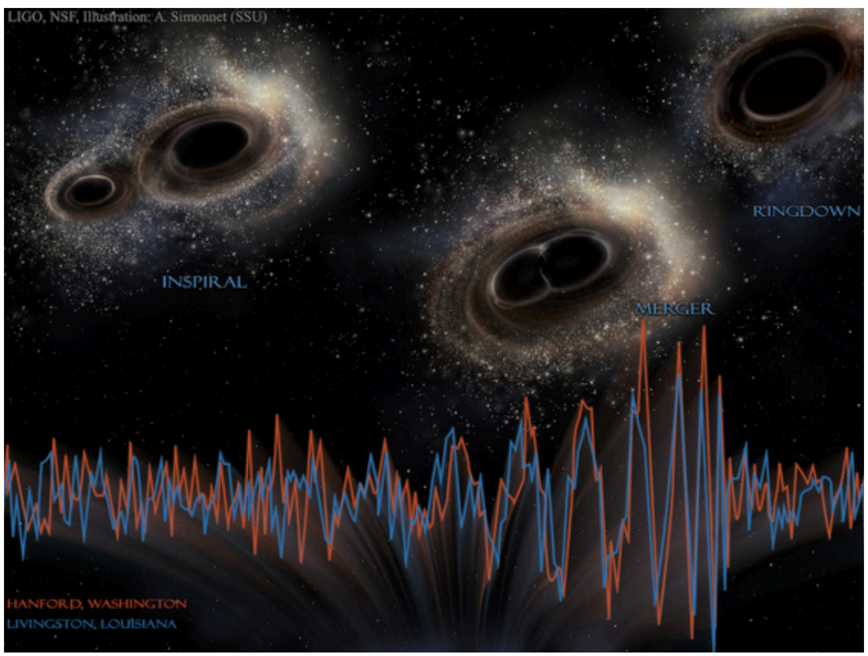


SS433 - a “microquasar” lies in the supernova remnant W50 (artist’s conception). Red and blue shifts seen from jet. Jet speed 0.26 c. Period 13.1 days (in Aquila, 5.5 kpc).q

And now …. gravitational radiation detected 9/14/15
announced 2/11/16

https://www.ligo.caltech.edu/news/ligo20160211





WHAT WE LEARNED

- Black holes exist
- Two of them, 29 and 36 solar masses, merged 1.3 million years ago (masses from period, distance from amlitude of the signal)
- From theory – the masses of the stars that made the black holes were about 70 and 90 solar masses respectively.
- May have evolved by common envelope. One of them may have been a pulsational-pair instability supernova along the way
- 0.4 s a gamma-ray burst may have been detecte by the Fermi gamma-ray telescope

Gamma-Ray Bursts
(which maybe related to BHs)

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.

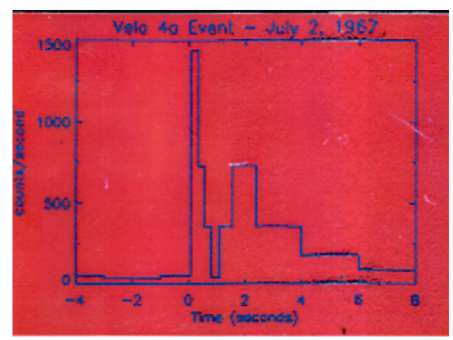
With appropriate instrumentation, we see about one of these per day at the Earth. They seem never to repeat from the same source.

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)

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 distance to the objects emitting the bursts – and hence no knowledge of their energy.

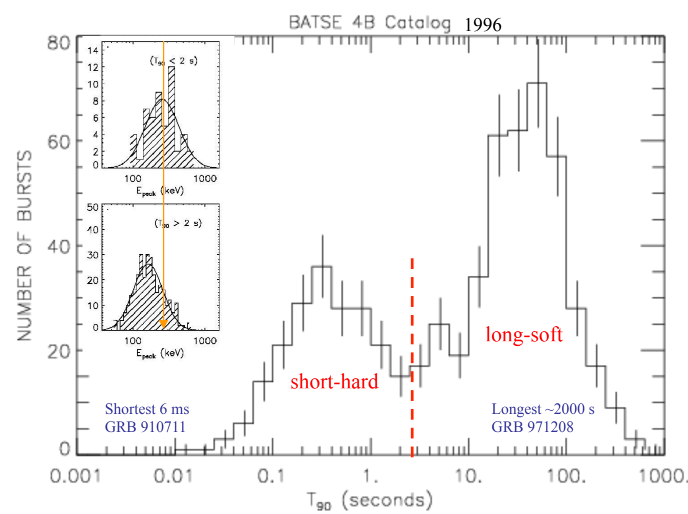
Early on some weak indication of association with the Galactic disk

- 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 ....

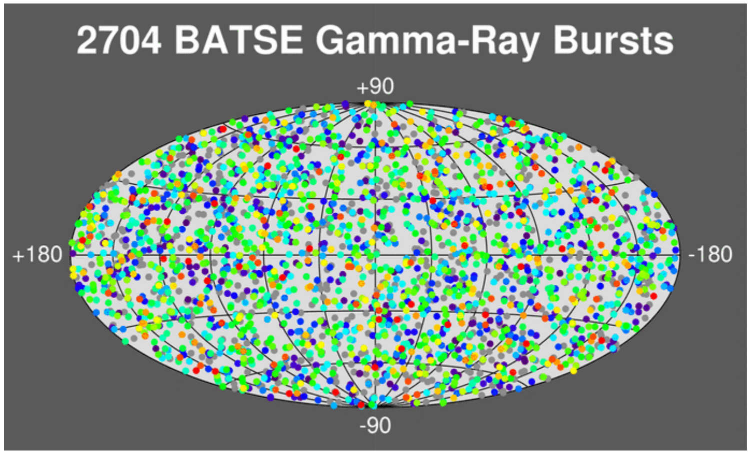
During the 1970's until the early 90's. uncertainty in distance – a factor of one billion.

By the late 90's we knew …

GRBs come in at least two flavors



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.

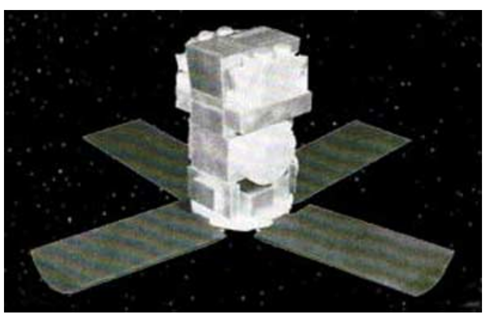
What could do that?

The high degree of isotropy – with us at its "center" implied either an extremely close source (Ooort cloud? nearby stars?) or something so far away that the distance from here to the center of the Milky Way (8.5 kpc) meant nothing.

Debate Lamb vs Paczynski (1995) similar to Curtis Shapley debate of (1920)

Intermezzo – HETE – 1 (High Energy Transient Explorer)

Launch April 11, 1996; died April 14, 1996



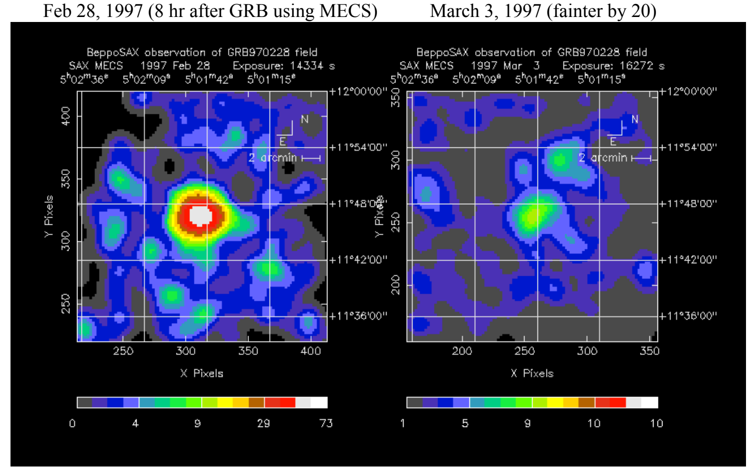
http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1996-061A

175 kg; Instruments – FREGATE, WXM, UVC, SXC
$27 M

(HETE – 2 – launched September 9, 2000)

BeppoSax GRB 970228 (discovered with WFC)

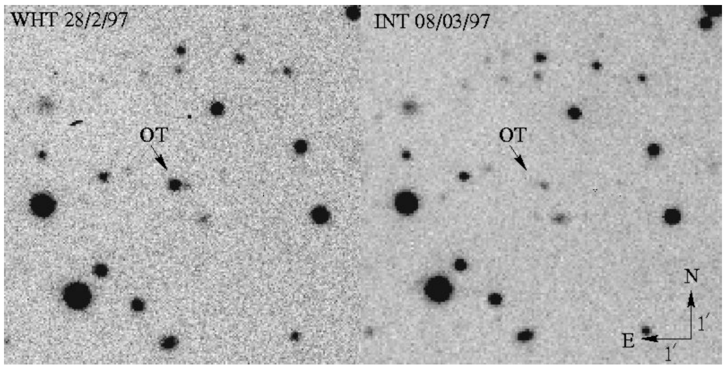
Feb 28, 1997 (8 hr after GRB using MECS) March 3, 1997 (fainter by 20)



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

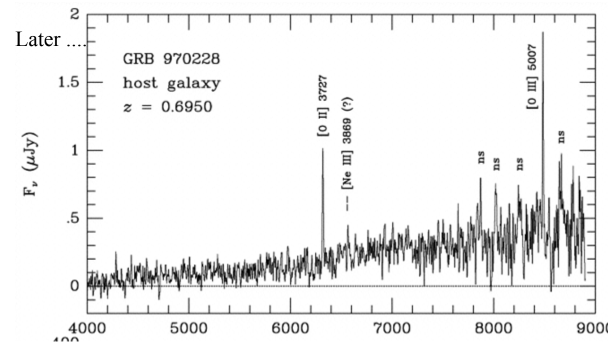
GRB 970228

William Herschel 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



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 could be inferred – billions of light years. Far, far outside our galaxy.

From the distance and brightness an energy could be inferred.

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

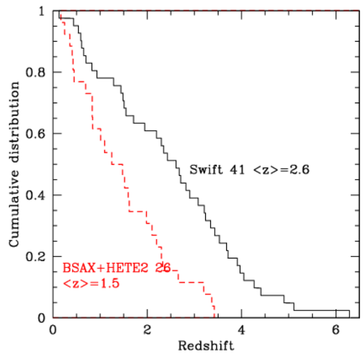
This is 13 times as much energy as the sun will radiate in its ten billion year lifetime, but emitted in gamma-rays in less than a minute. It is 2000 times as much as a really bright supernova radiates in several months.

Even brighter was GRB 990123 at redshift 1.6

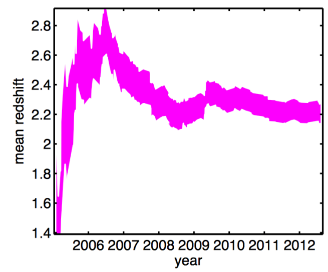
Given the known brightness of the burst (in gamma-rays) this distance implies an energy of over several times 10^{54} erg. About the mass of the sun turned into pure energy.

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.

After a new satellite, SWIFT, was launched in November 2004, much more and better data was obtained

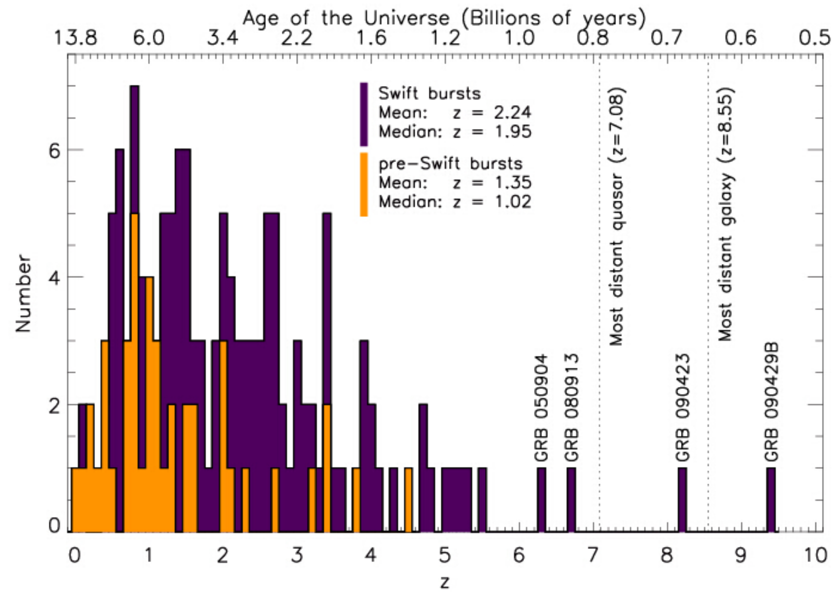


In 2007

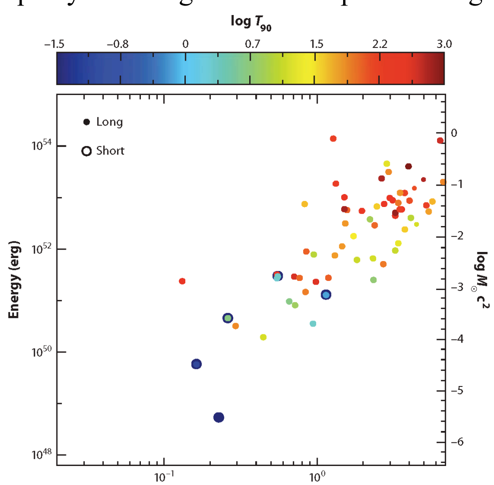


Average redshift with time shows convergence on z = 2.2 (Coward et al. 2012)

Tracks star formation

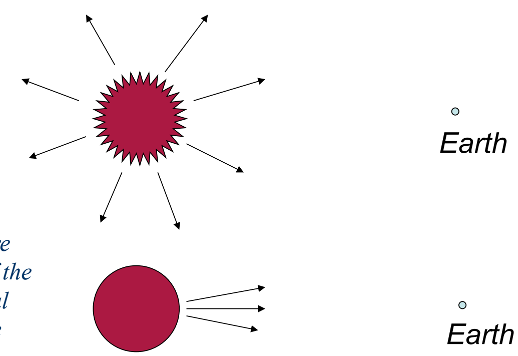


Inferred energy if bursts emit their radiation equally at all angles extends up to 10^{54} erg



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

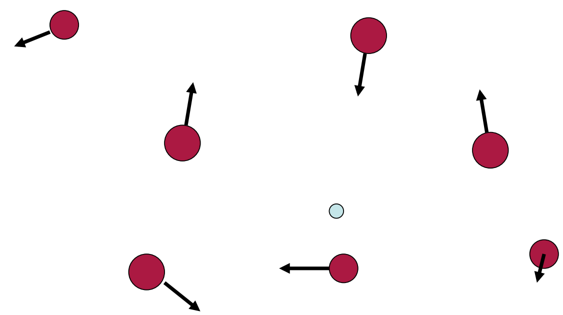
But are the energies required really as great as 10^{54} erg?



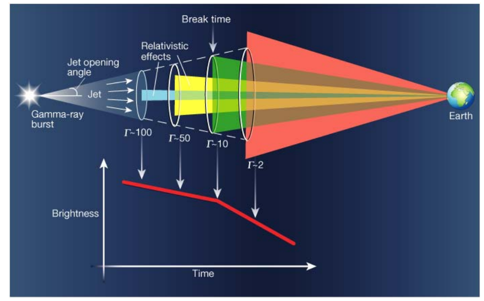
If the energy were beamed to 0.1% of the sky, then the total energy could be 1000 times less

Nothing seen down here

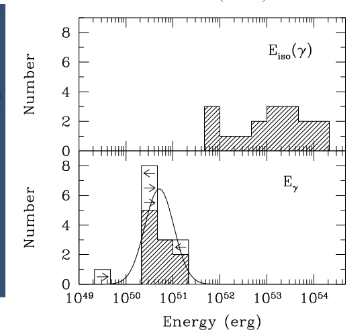
But then there would be a lot of bursts that we do not see for every one that we do see. About 300 in fact.



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

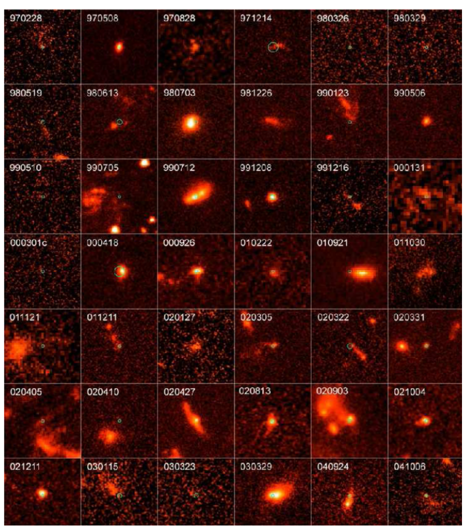


Frail et al. (2001)



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

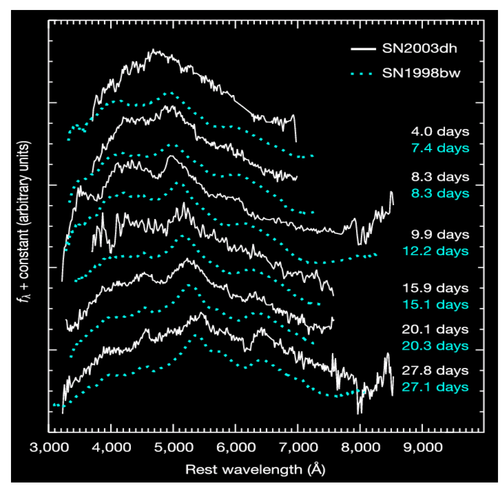


Fruchter et al (2005).

The green circles show 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



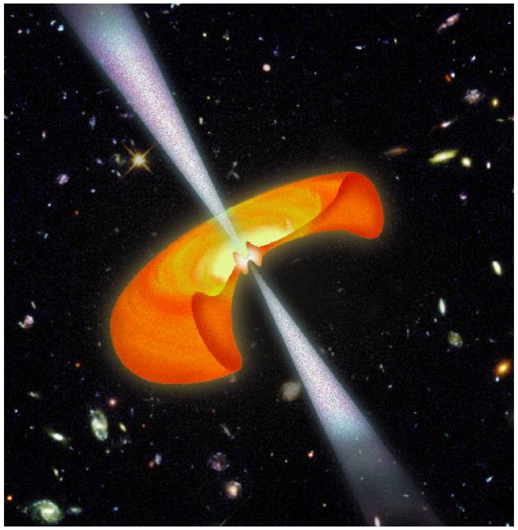
GRB980425/ SN1998bw

GRB030329/ SN2003dh

GRB031203/ SN2003lw

GRB060218/ SN2006aj

The Collapsar Model
(Woosley 1993)



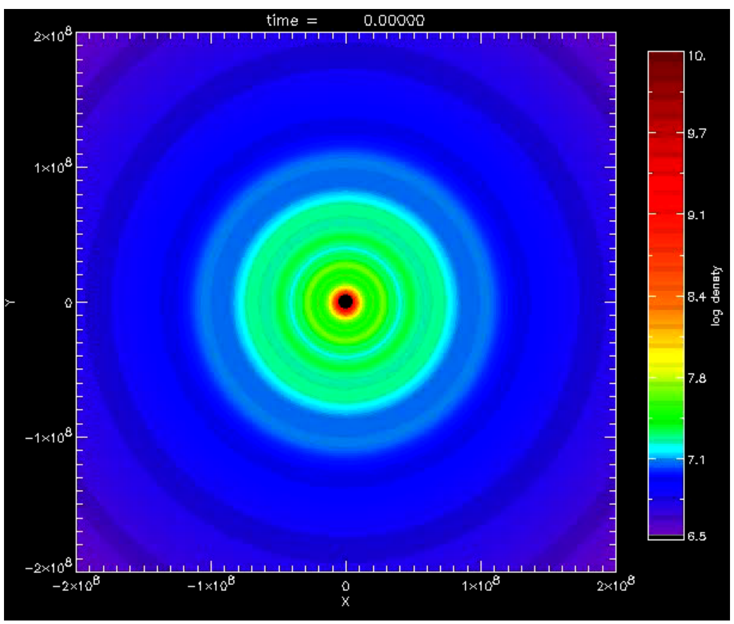
Usually massive stars make supernovae. Their iron core collapses to a neutron star and the energy released explodes the rest of the star.

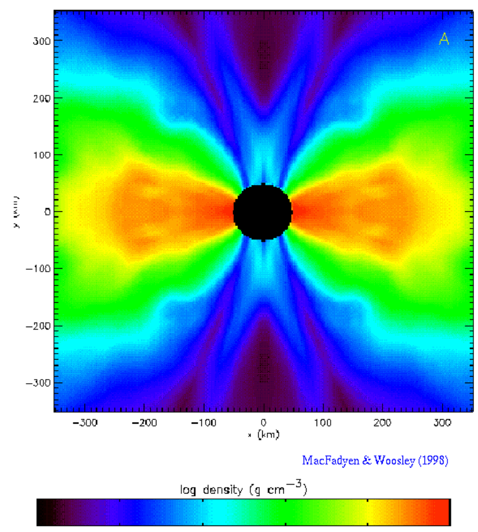
But what if the explosion fizzled? What if the iron core collapsed to an object too massive to be a neutron star – a black hole.

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?



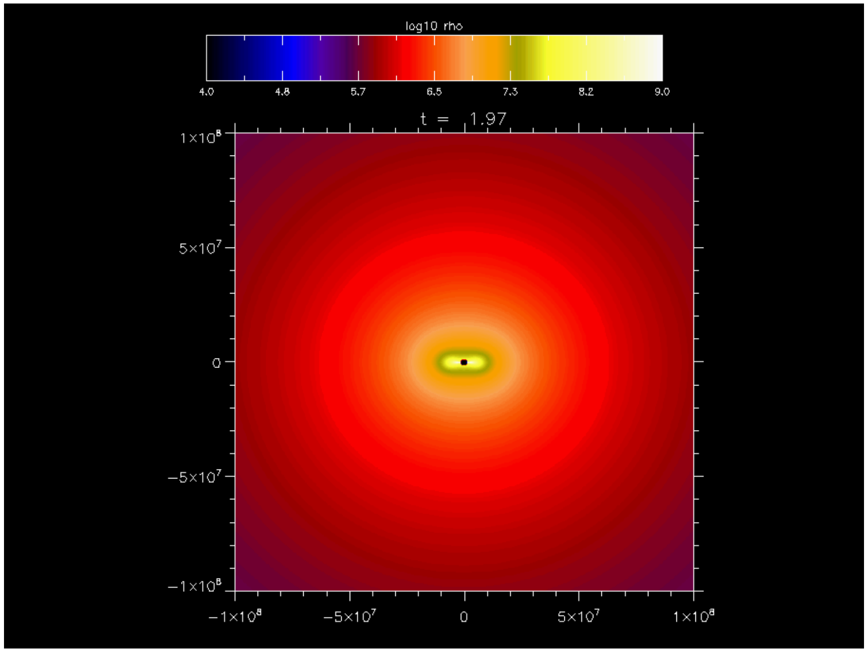


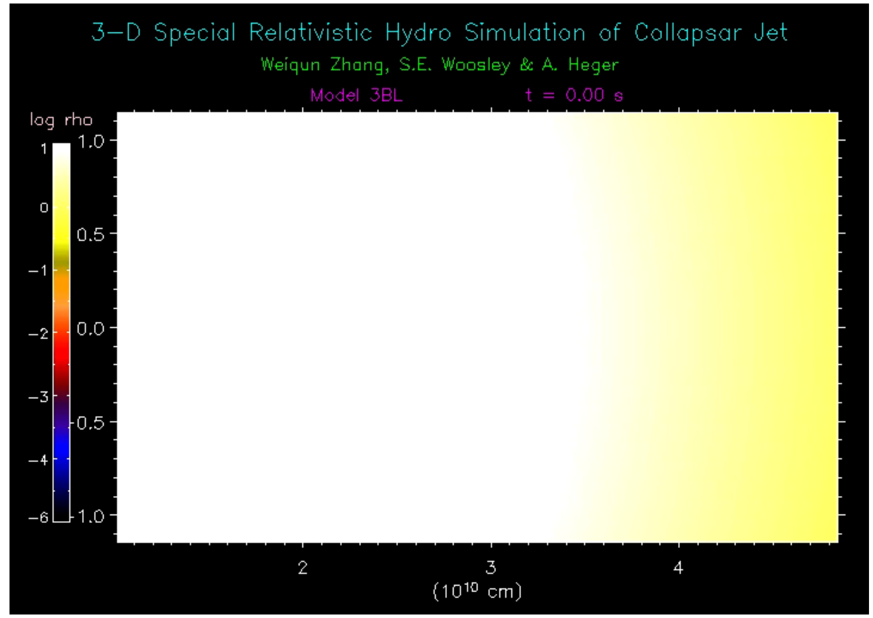
MacFadyen & Woosley (1998)

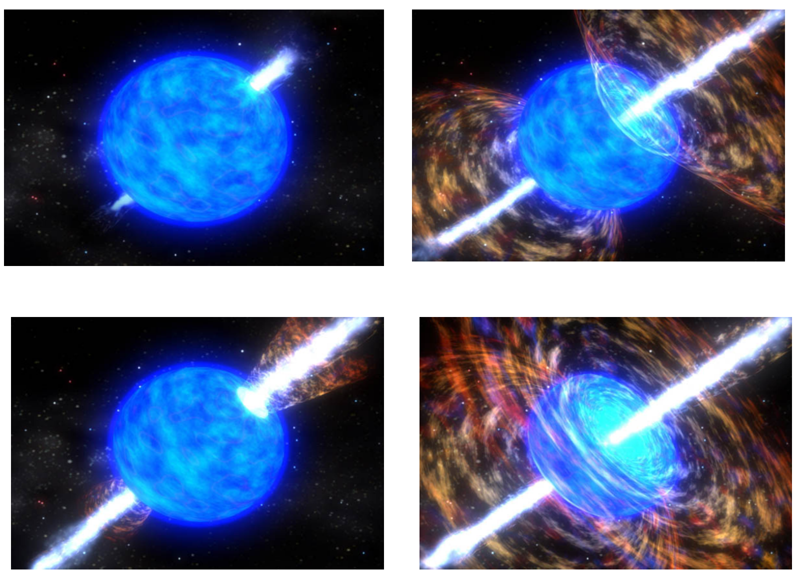
7.6 s after core collapse; high viscosity case.

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

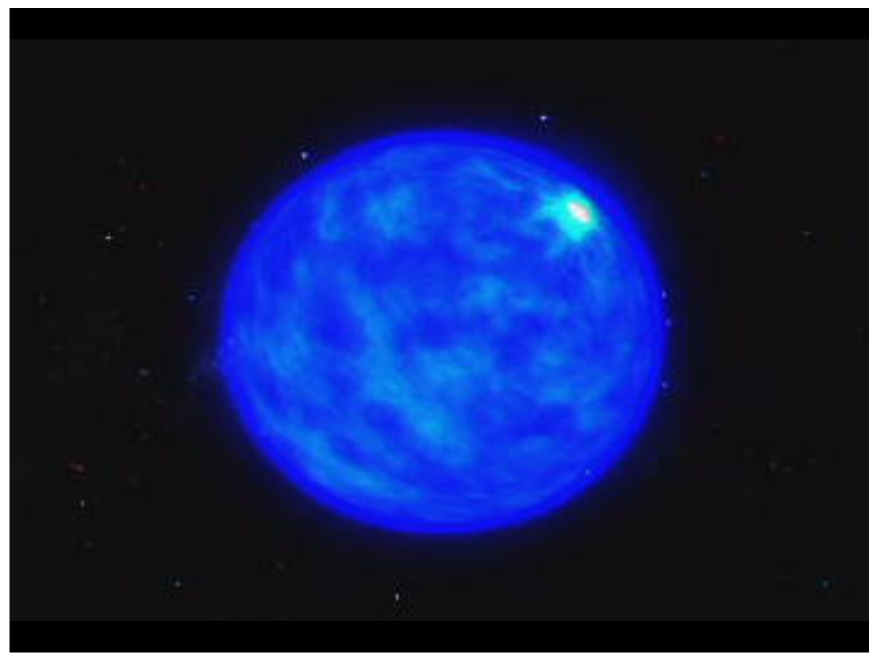
The exact mechanism for extracting this energy either from the disk or the rotation of the black hole is fascinating physics, but is not crucial to the outcome, so long as the energy is not contaminated by too much matter.







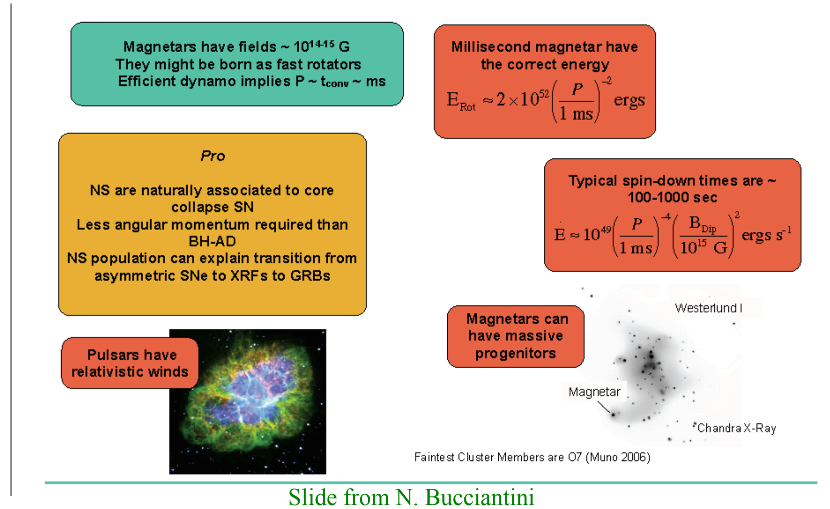
Dana Berry (Skyworks) and SEW



Predictions of the Collapsar Model

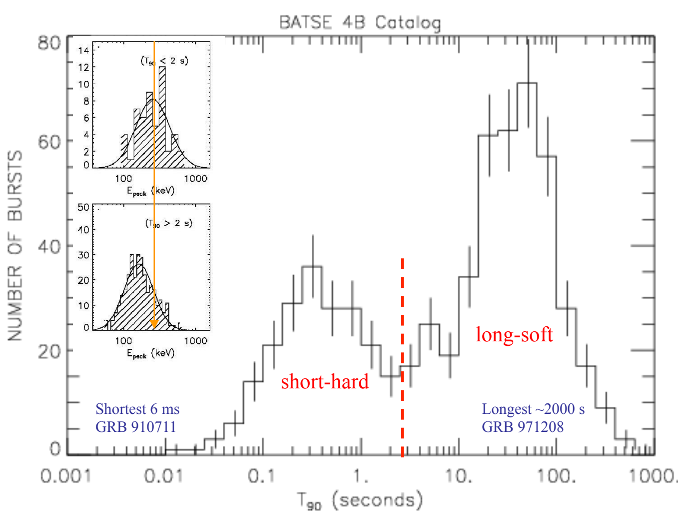
- ✓ Gamma-ray bursts should occur in star regions
- ✓ GRBs should be accompanied by Type I b or c supernovae (the jet doesn't get out of a giant star in time, need to lose envelope)
- ✓ GRBs should be favored by low metallicity and high redshift

But there is an alternative: Millisecond Magnetars

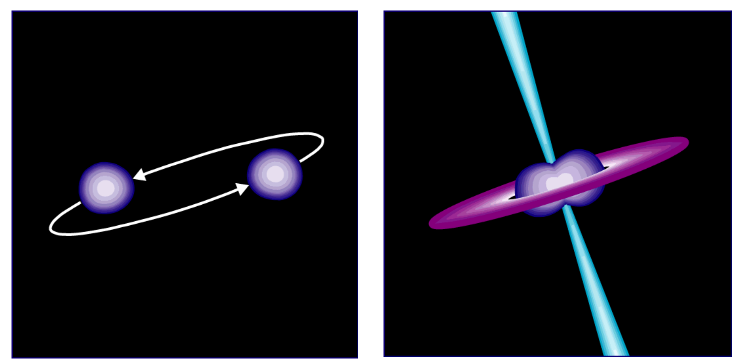


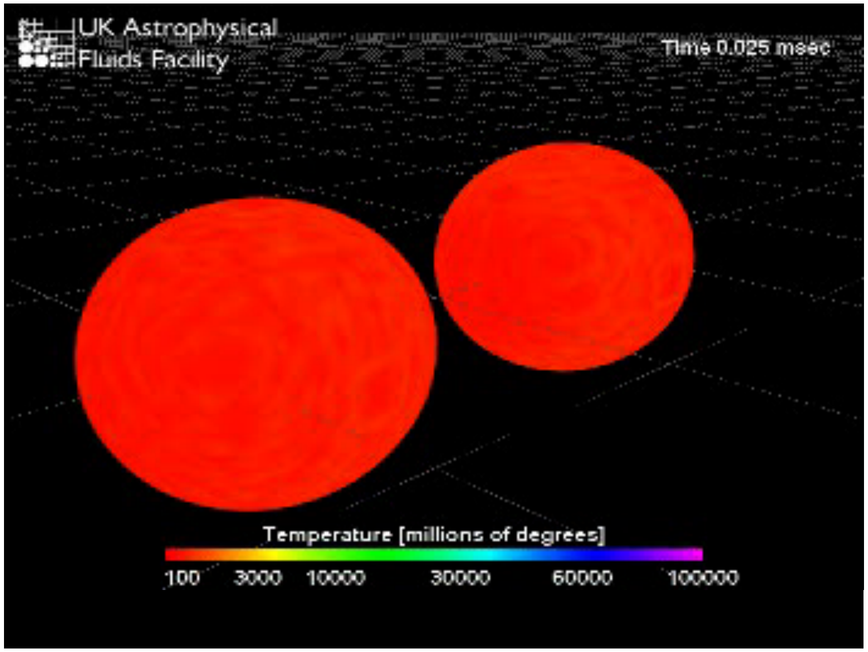
Slide from N. Bucciantini

But what about the short hard bursts?



One Model: Merging Neutron Stars

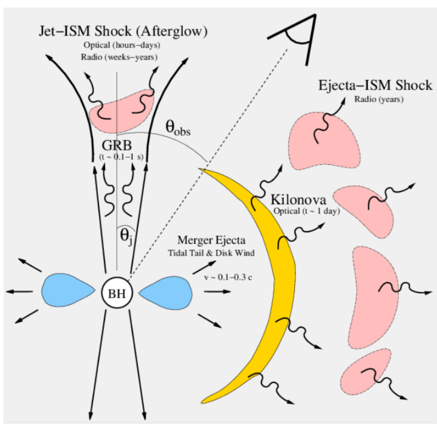




Starting in May 2005, about a half dozen short hard bursts were localized by the HETE-2 and SWIFT satellites.

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 ~30 times less energy.

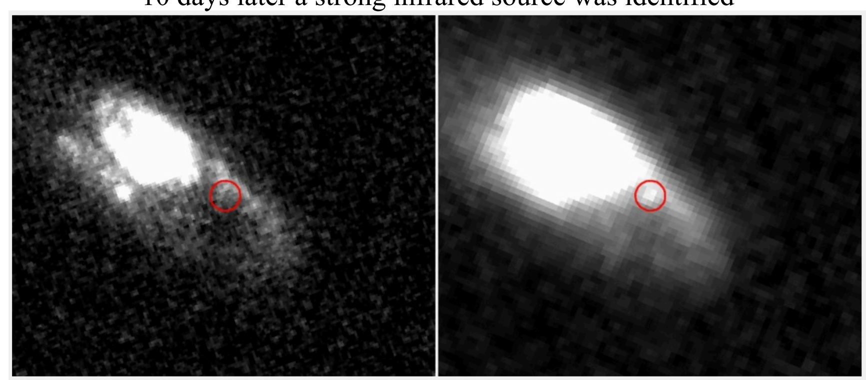


A cartoon of the electromagnetic radiation emitted by a black hole after the merger of two compact objects. The GRB is produced by the shock generated after the accretion of material into the black hole. The kilonova is produced by radioactive decay of the ejecta around the black hole. The pink blobs 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

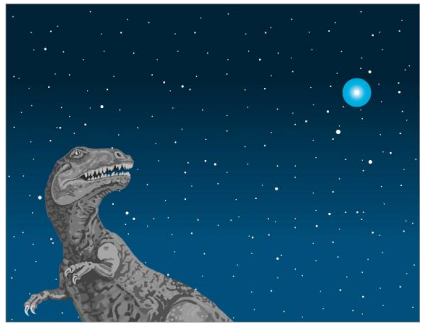
Point source identified in a galaxy 3 hours later

10 days later a strong infrared source was identified



The position where the short GRB occured 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, Tanvir et al. detect a source in coincidence with the position of the short GRB. Figure 1 of Tanvir et al.

Afterglow or kilonova??



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