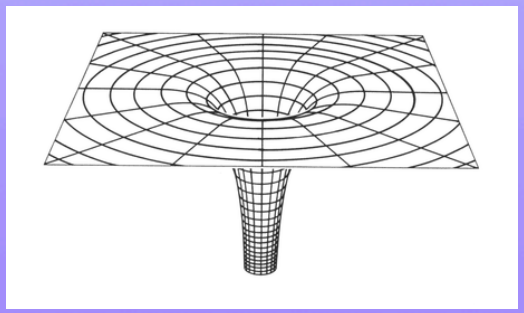
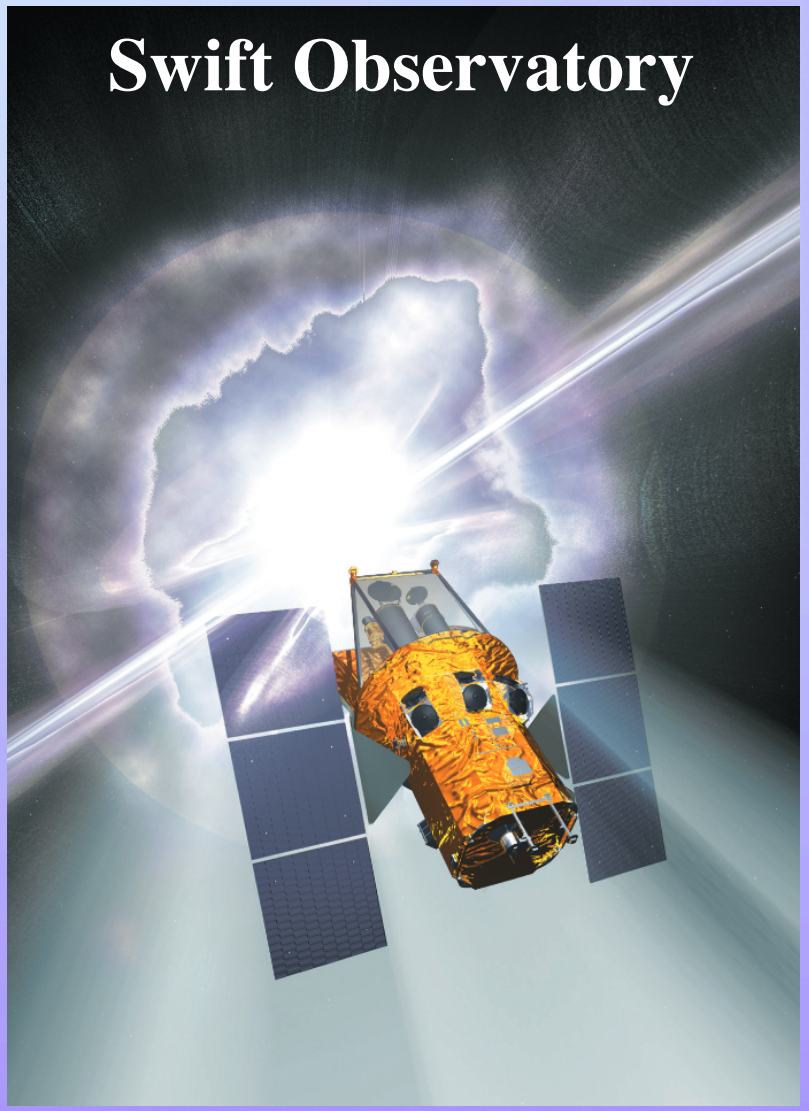
Black Holes: From Einstein to Gamma-Ray Bursts

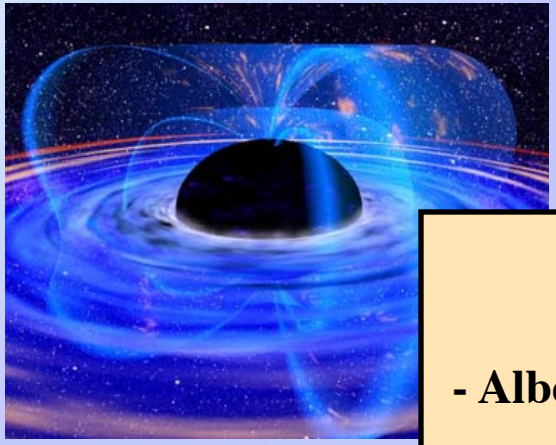
Neil Gehrels
NASA-GSFC & PSU



Public Lecture
March 21, 2012

Swift Observatory

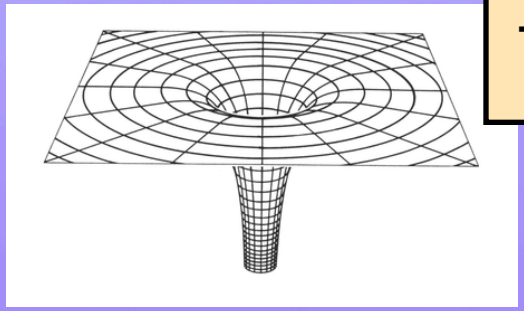




G
The S

OUTLINE

- Albert Einstein
- What is a Black Hole?
- Observations of BHs
- Wormholes
- Hawking radiation
- Gamma Ray Bursts: BH birth and death
- What is a Black Hole?

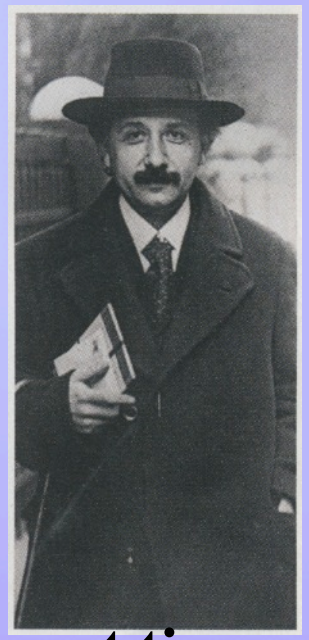


Penn State
March 21, 2012

Einstein Theoretical Breakthroughs

1905

1916



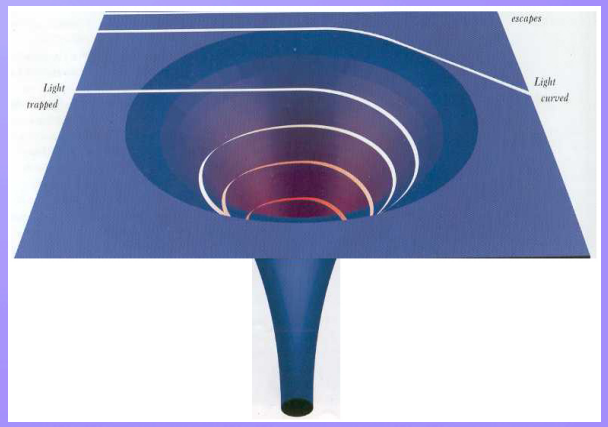
better Einstein picture next time

1905
Annus Mirabilis

- particle nature of light
- Brownian motion
- special relativity
- $E = mc^2$

1916
General Relativity

- equivalence of gravity and acceleration
- gravity = curvature of space-time



Karl Schwarzschild

1916

First solution of Einstein's equation

- solution outside of a spherical star at rest
- special solution exists with singularity
- Schwarzschild radius = 3 km for sun-sized BH
- distance at which light can not escape

father of Martin Schwarzschild

Karl Schwarzschild

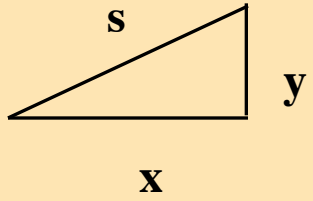
The *Equations*

- Einstein field equation of general relativity

$$G_{\mu\nu} = (8\pi G/c^4)\ T_{\mu\nu} - g_{\mu\nu}\ \Lambda$$

$$s^2 = x^2 + y^2$$

- Schwarzschild solution



Without mass

$$s^2 = t^2 - r^2$$

With mass

$$s^2 = (1 - 2Gm/rc^2)\ t^2 - \frac{1}{(1 - 2Gm/rc^2)}\ r^2$$

- The Schwarzschild equation has a singularity at

$$1 - 2Gm/rc^2 = 0 \quad \text{or} \quad r = 2\,Gm / c^2$$

Karl Schwarzschild

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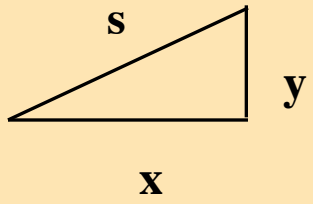

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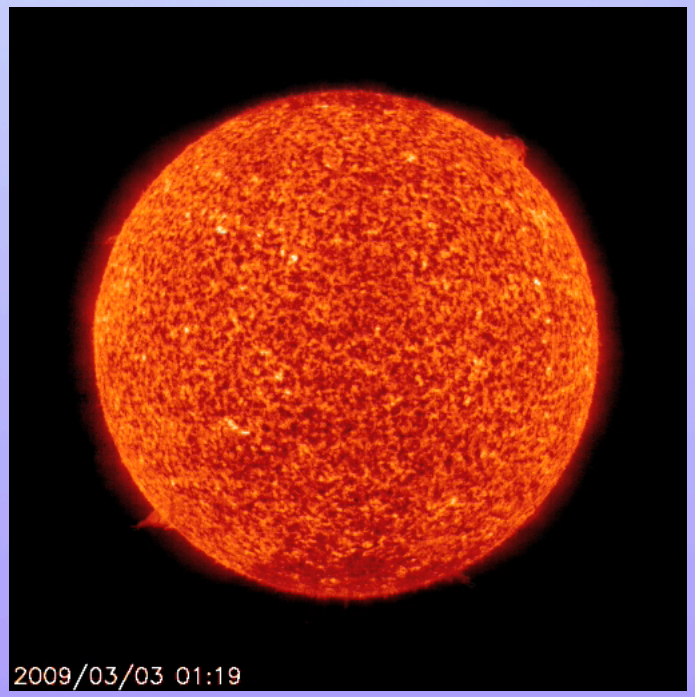
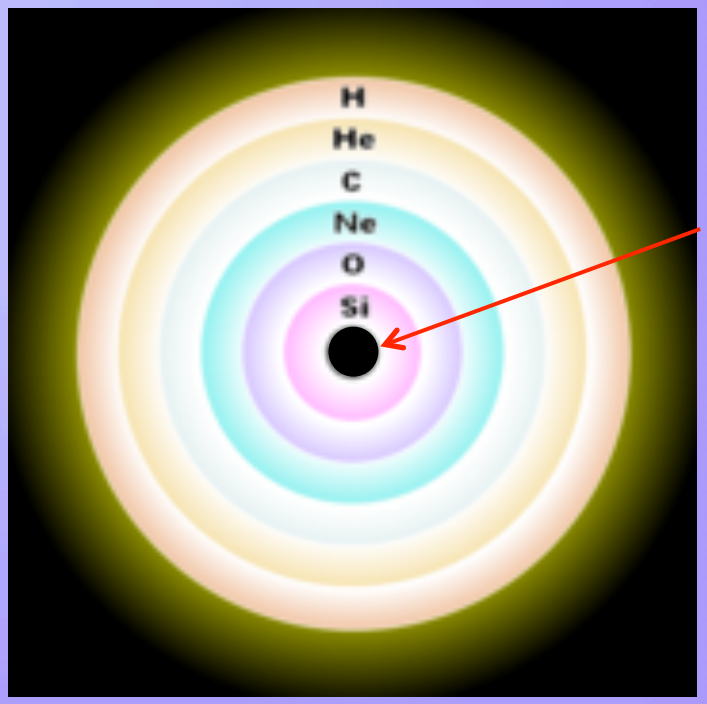
Massive Star Evolution

SOHO movie of
Our Sun



Star evolves over millions of years
to onion layer configuration



iron core

When core burns to iron, there is no more energy to be gained and the core collapses

AGAIN JONES' COLLEAGUES AIMED THE TELESCOPE SNEAKY AT THE SUN ....

Massive Star Evolution

SOHO movie of
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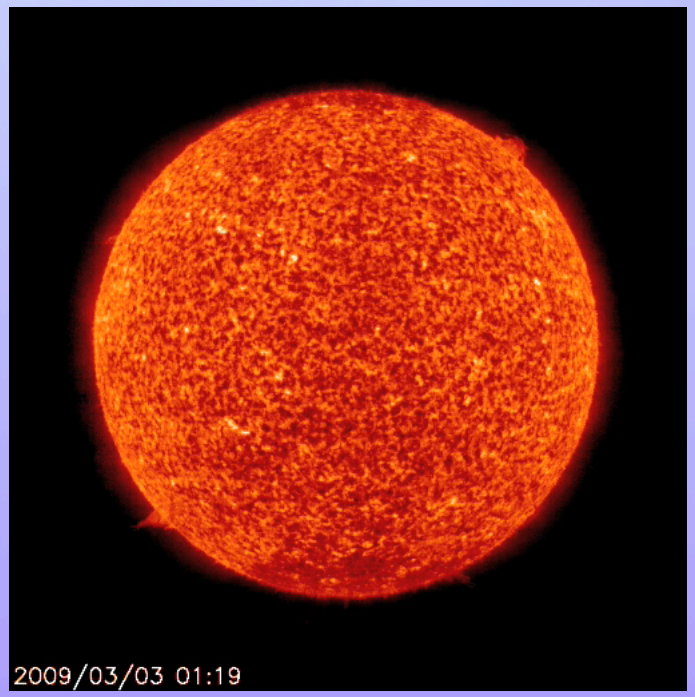

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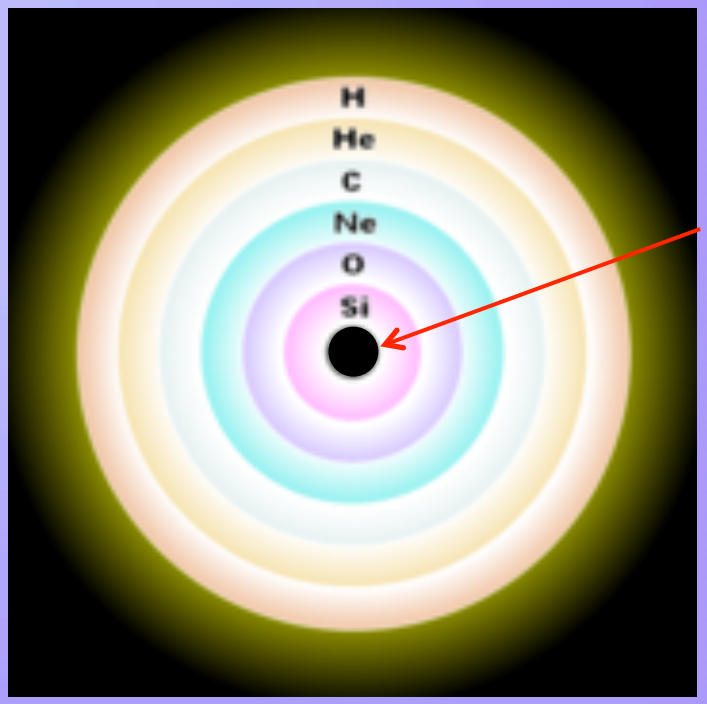

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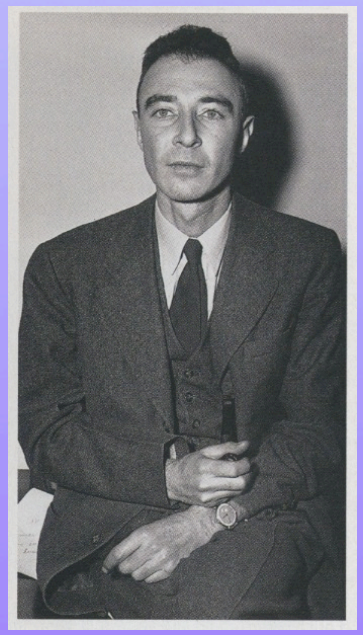
Black Holes

- Oppie and student Hartland Snyder showed how black holes can form with stars more massive than ~2 solar masses
- Gravity overwhelms nuclear and quantum forces and star collapses
- Wheeler coined the term "black hole"

Robert Oppenheimer
1939



John Wheeler
1967

Black Hole of Calcutta

1756

Nawab of Bengal

The dungeon was a strongly barred room and was not intended for the confinement of more than two or three men at a time. There were only two windows and thick iron bars within impeded the ventilation. The prisoners were packed so tightly that the door was difficult to close.

John Archibald Wheeler
in Black Hole Nova Scotia

What is a Black Hole?

- Compact object with all mass at center point - singularity
- No particles or light can escape
- Construct of general relativity
- "black holes have no hair" [John Wheeler]:
  only 3 observable properties (mass, spin and charge)

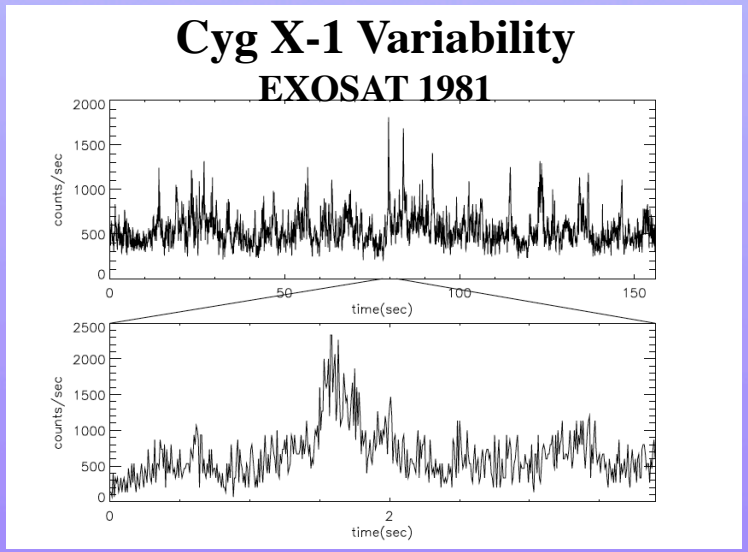
artist depiction

Schwarzschild radius

Black Holes Really Exist

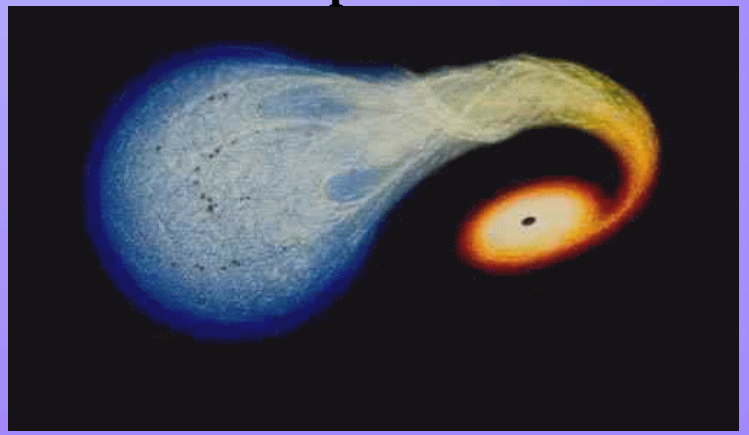
- First suspected black hole was Cygnus X-1 in 1970's
  - * erratic flaring
  - * massive compact star (about 10 times solar mass)

- In 1990's mass measurements of compact stars showed some were very compact with masses more than 2 solar mass



Pottschmidt & König

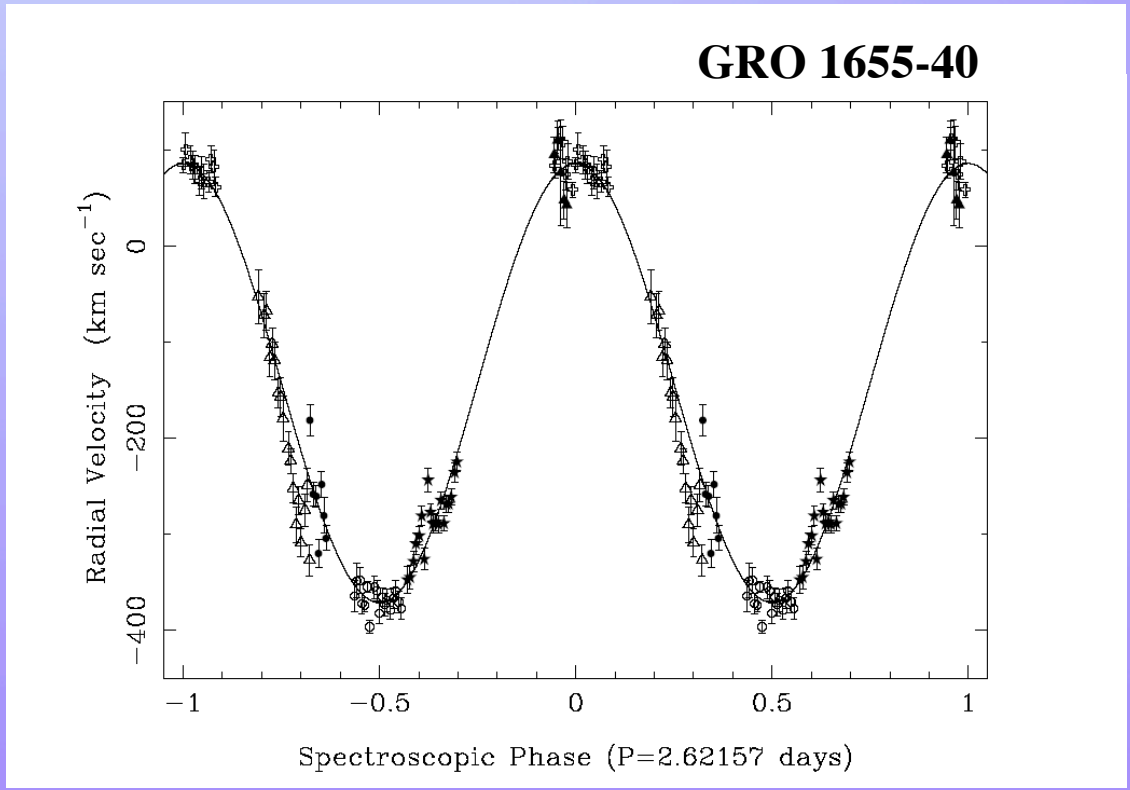
Cyg X-1 Accreting from Companion Star

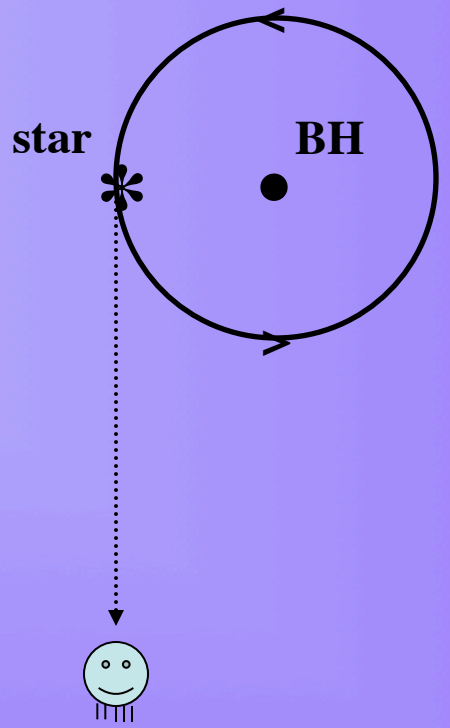


Radial Velocity of BH Companion Star

Radial velocity of companion to BH derived from optical Doppler observations

Velocity curve gives BH mass = 6.0 - 6.6 solar masses





J. A. Orosz & C. D. Bailyn 1997: Astrophysicsal Journal, 477, 876

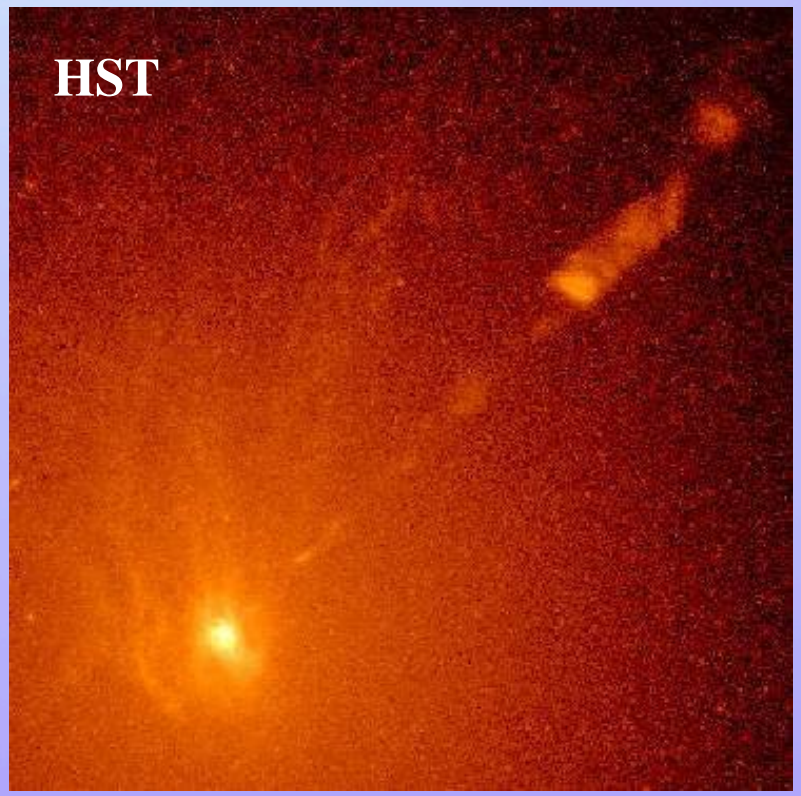
20 Black Holes Known

Table 1 Twenty confirmed black holes and twenty black-hole candidates[a]

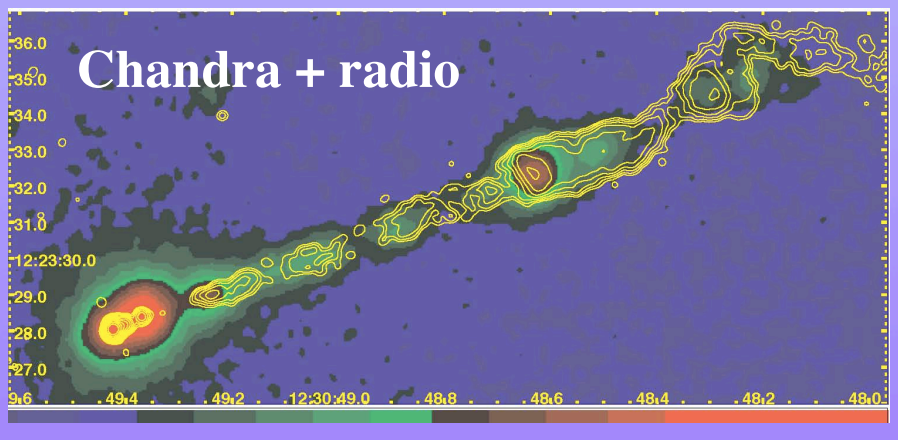
Coordinate Name	Common[b] Name/Prefix	Year[c]	Spec.	P_{orb} (hr)	$f(M)$ ($M_\odot$)	M_1 ($M_\odot$)
0422+32	(GRO J)	1992/1	M2V	5.1	1.19 ± 0.02	3.7–5.0
0538–641	LMC X–3	–	B3V	40.9	2.3 ± 0.3	5.9–9.2
0540–697	LMC X–1	–	O7III	93.8[d]	0.13 ± 0.05[d]	4.0–10.0:[e]
0620–003	(A)	1975/1[f]	K4V	7.8	2.72 ± 0.06	8.7–12.9
1009–45	(GRS)	1993/1	K7/M0V	6.8	3.17 ± 0.12	3.6–4.7:[e]
1118+480	(XTE J)	2000/2	K5/M0V	4.1	6.1 ± 0.3	6.5–7.2
1124–684	Nova Mus 91	1991/1	K3/K5V	10.4	3.01 ± 0.15	6.5–8.2
1354–64[g]	(GS)	1987/2	GIV	61.1[g]	5.75 ± 0.30	–
1543–475	(4U)	1971/4	A2V	26.8	0.25 ± 0.01	8.4–10.4
1550–564	(XTE J)	1998/5	G8/K8IV	37.0	6.86 ± 0.71	8.4–10.8
1650–500[b]	(XTE J)	2001/1	K4V	7.7	2.73 ± 0.56	–
1655–40	(GRO J)	1994/3	F3/F5IV	62.9	2.73 ± 0.09	6.0–6.6
1659–487	GX 339–4	1972/10[i]	–	42.1[j,k]	5.8 ± 0.5	–
1705–250	Nova Oph 77	1977/1	K3/7V	12.5	4.86 ± 0.13	5.6–8.3
1819.3–2525	V4641 Sgr	1999/4	B9III	67.6	3.13 ± 0.13	6.8–7.4
1859+226	(XTE J)	1999/1	–	9.2:[e]	7.4 ± 1.1:[e]	7.6–12.0:[e]
1915+105	(GRS)	1992/Q[l]	K/MIII	804.0	9.5 ± 3.0	10.0–18.0
1956+350	Cyg X–1	–	O9.7Iab	134.4	0.244 ± 0.005	6.8–13.3
2000+251	(GS)	1988/1	K3/K7V	8.3	5.01 ± 0.12	7.1–7.8
2023+338	V404 Cyg	1989/1[f]	K0III	155.3	6.08 ± 0.06	10.1–13.4
1524–617	(A)	1974/2	–	–	–	–

R. A. Remillard & J. E. McClintock 2006 Ann. Rev. Astron. Astrophys. 44:49-92

"Image" of a Black Hole

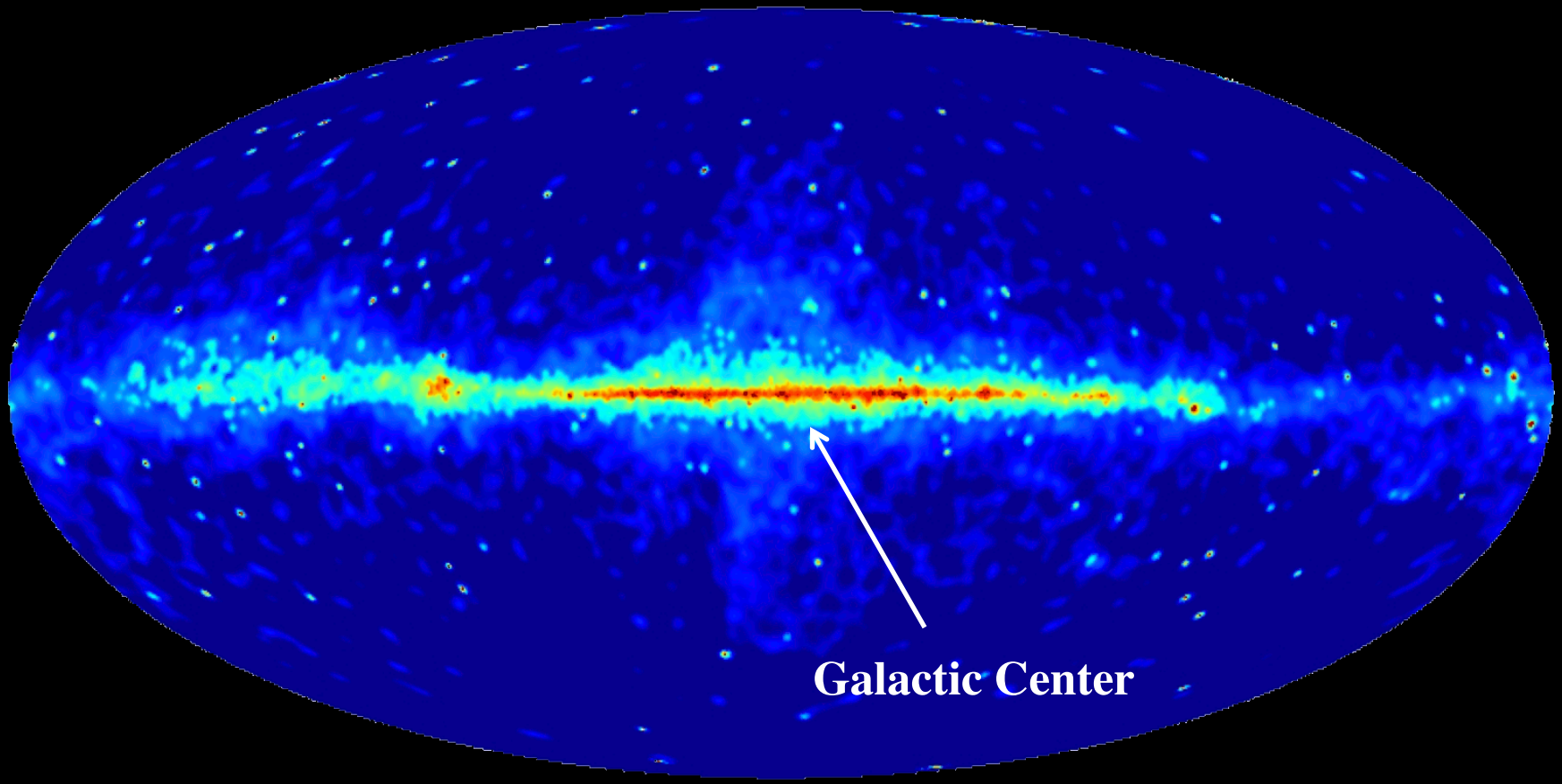


- Images of M87
- Giant elliptical galaxy in Virgo cluster (brightest Virgo galaxy)
- Quasar
- BH mass of 3 billion solar masses
- Jet is seen in optical, radio and X-rays



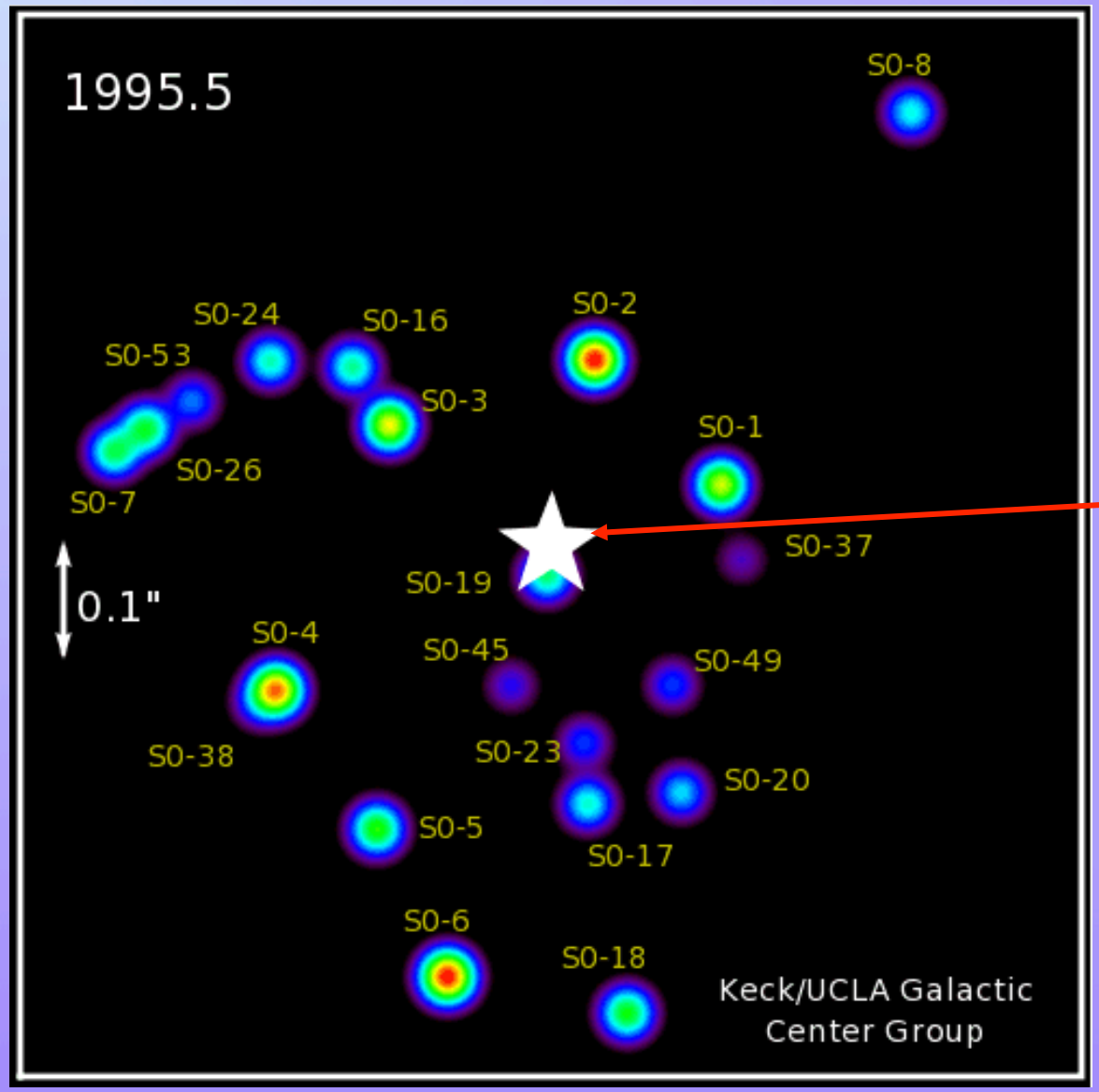
artist conception
BH & accretion disk

Fermi Sky Map
Black Holes Everywhere



> 10 GeV

Infrared Stars Near Milkyway BH



Sgr A*

Dormant BH at Milkyway center

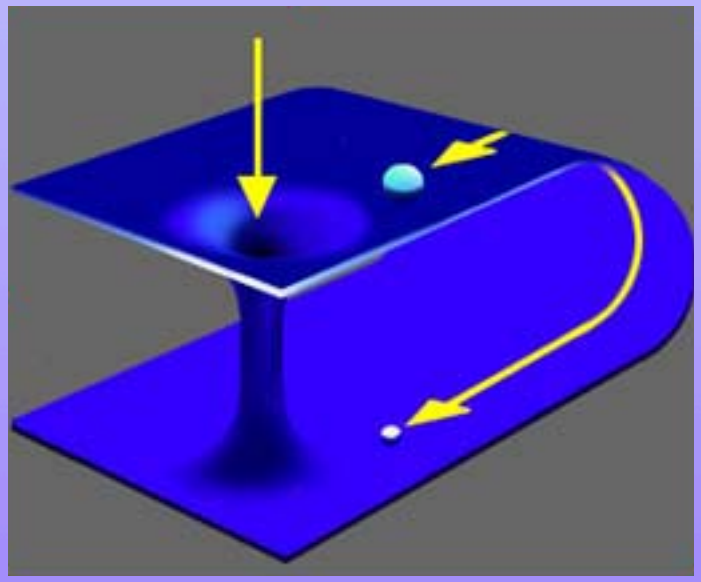
3 million solar mass

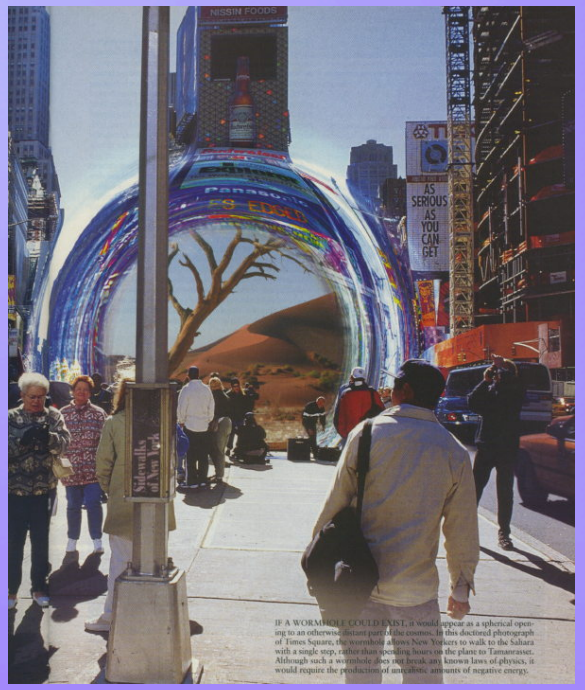
Wormholes

- Is it possible to travel between two disconnected parts of the universe?

- Schwarzschild wormhole is unstable

- Morris-Thorne wormhole must be held open by exotic matter - matter with negative energy density.





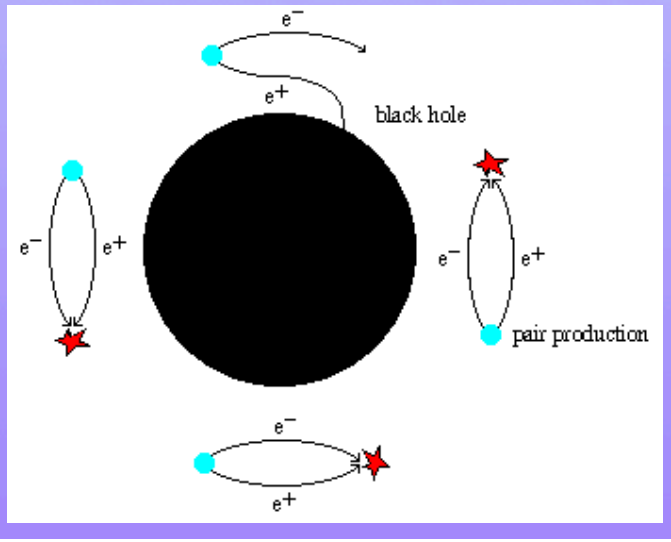
Hawking Radiation

- Virtual particle pairs can form near BH event horizon

- One disappears in BH and other is emitted

- Mass BHs would lose only tiny fractions of their energy

- Small BHs left over from the Big Bang could evaporate in our time



Stephen Hawking receiving Copley Medal

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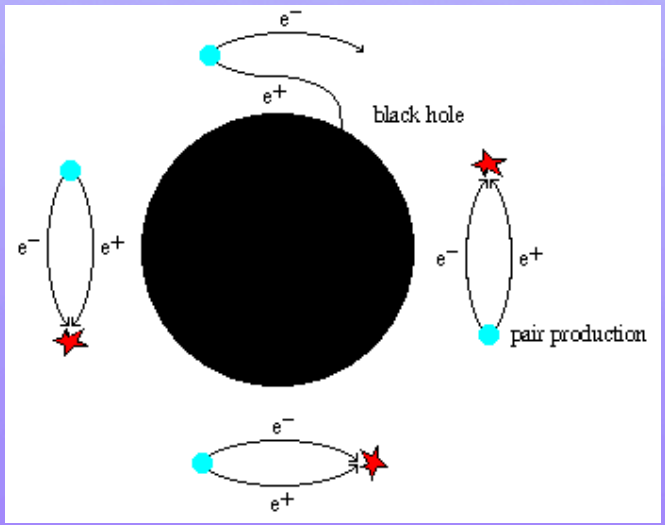
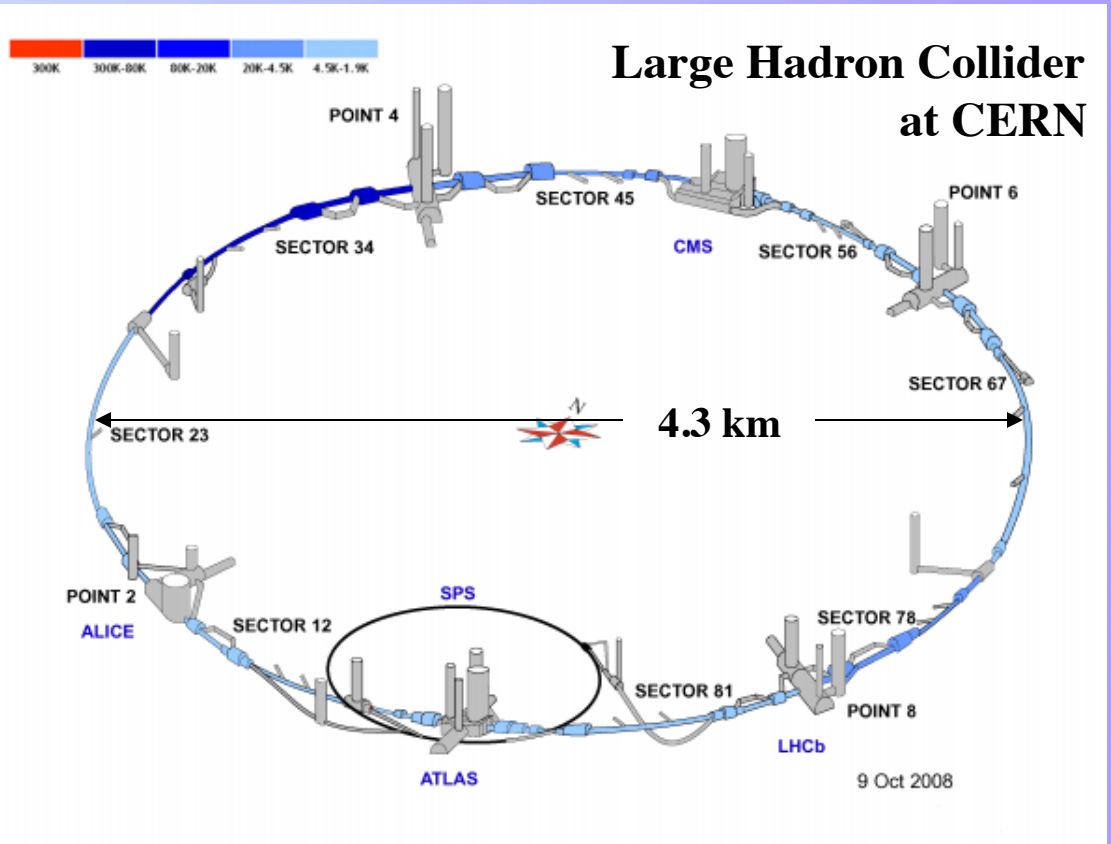


Lawsuit

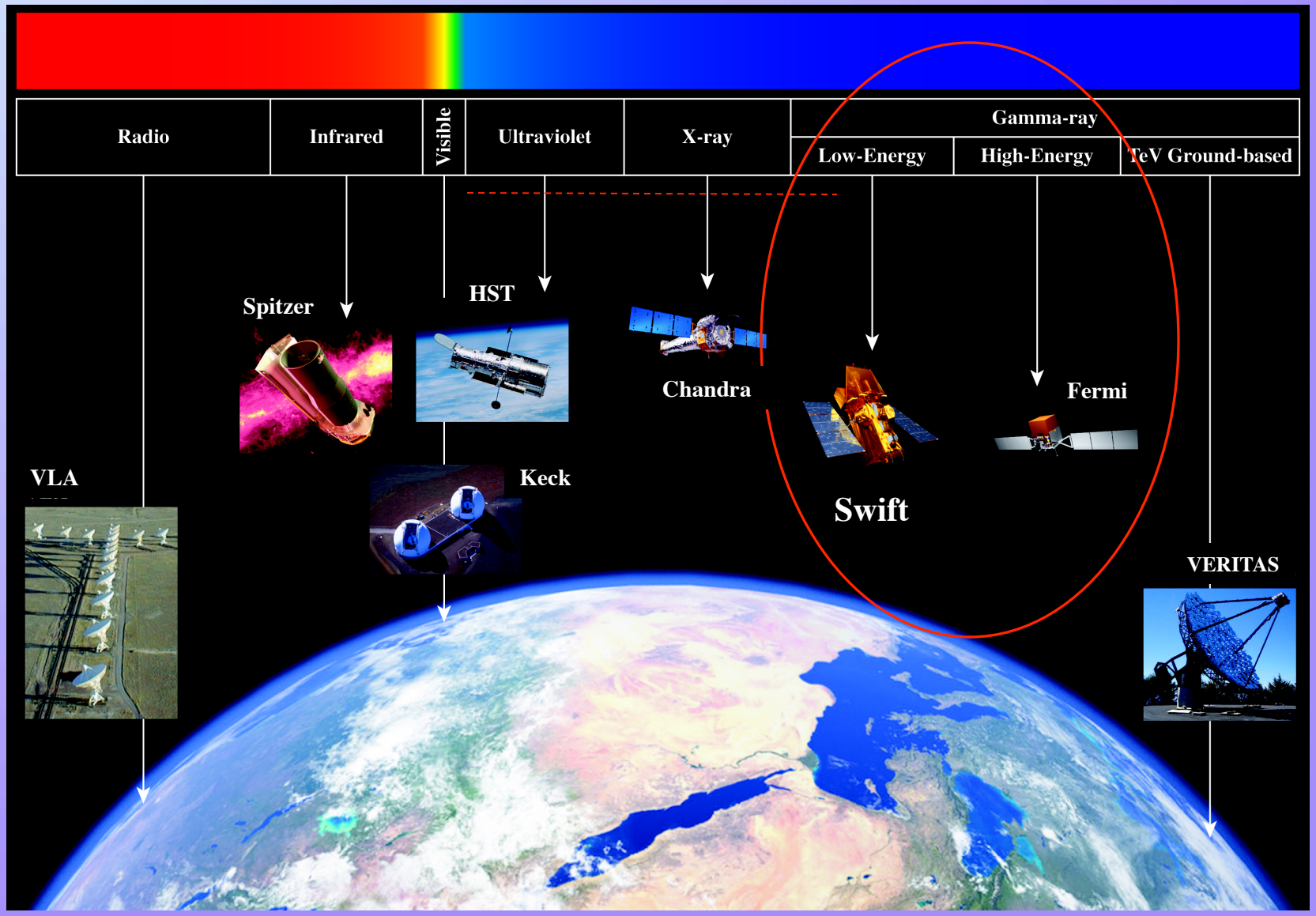


Could micro BHs be produced in LHC? (Walter Wagner)

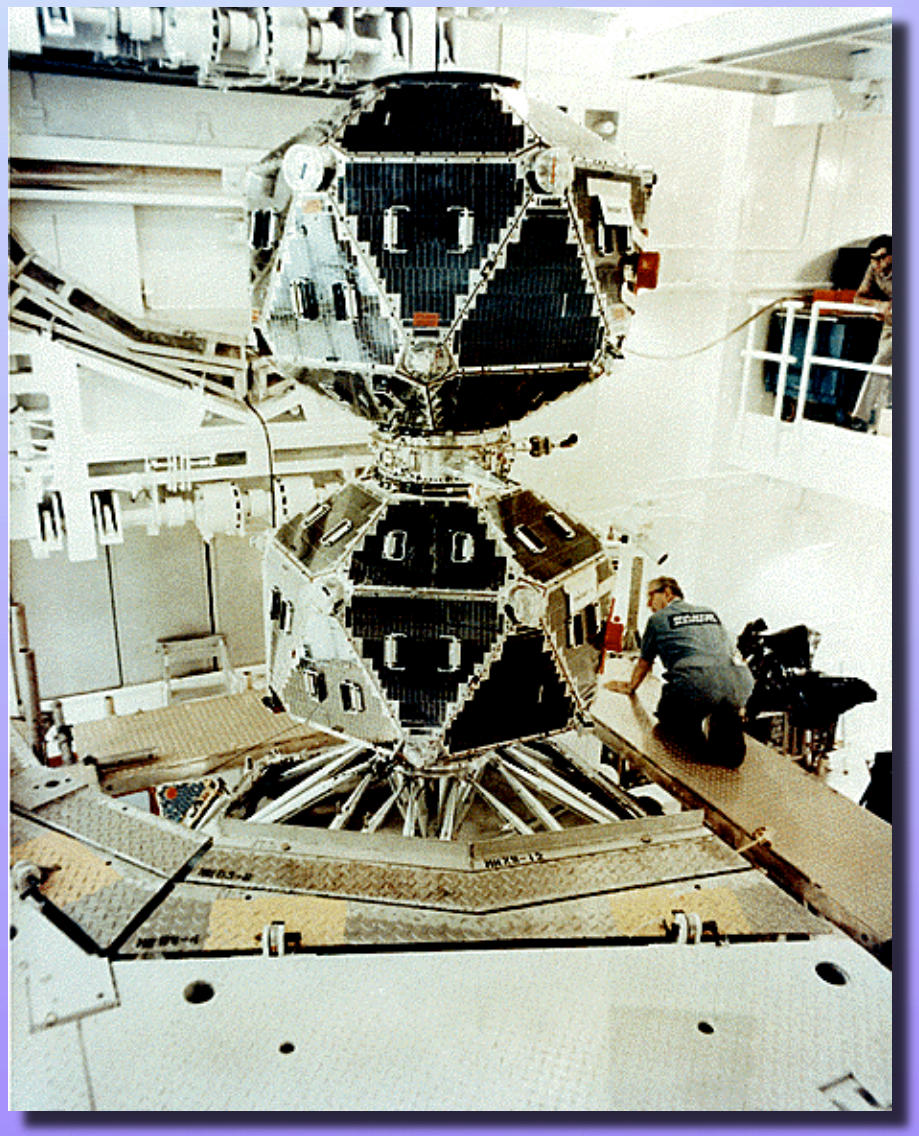
Even if produced they would evaporate immediately

Swift Observatory
Gamma Ray Bursts

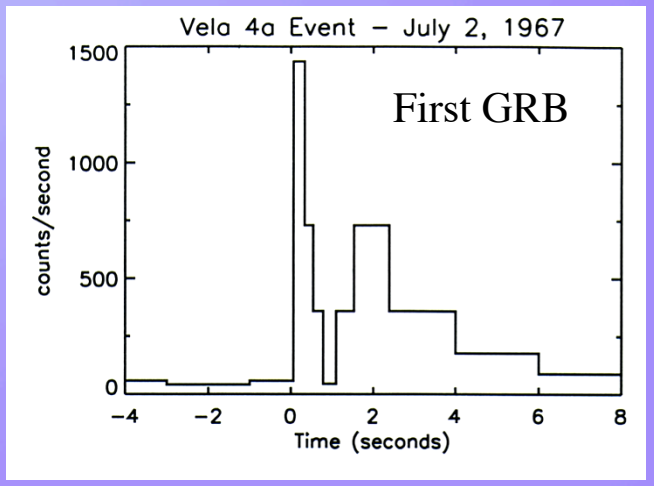
Electromagnetic Spectrum



First GRB Detection

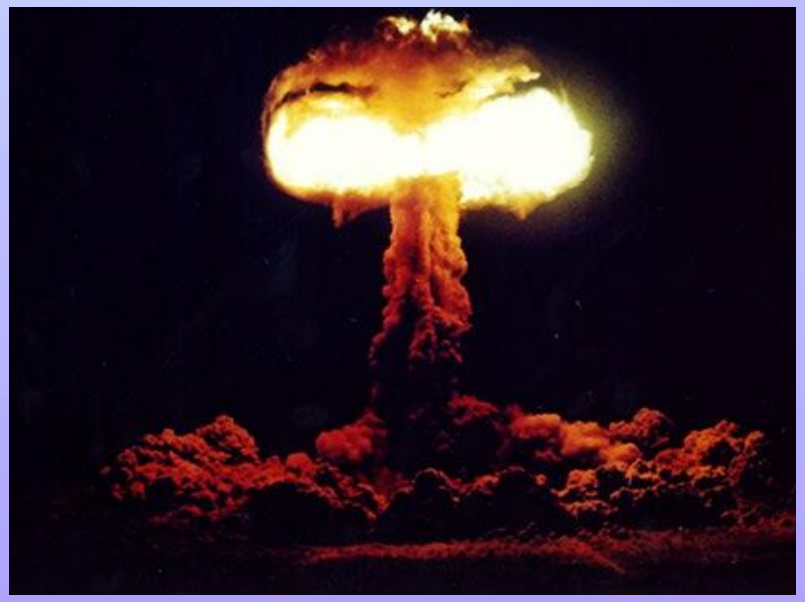


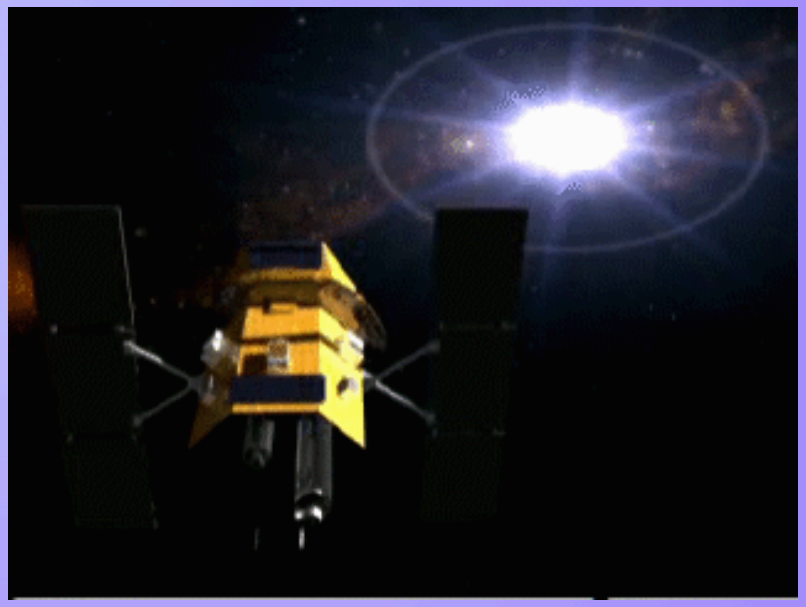
Vela Satellites - Los Alamos



(Klebesadel, Strong & Olson 1973)

Los Alamos View (E. Fenimore)

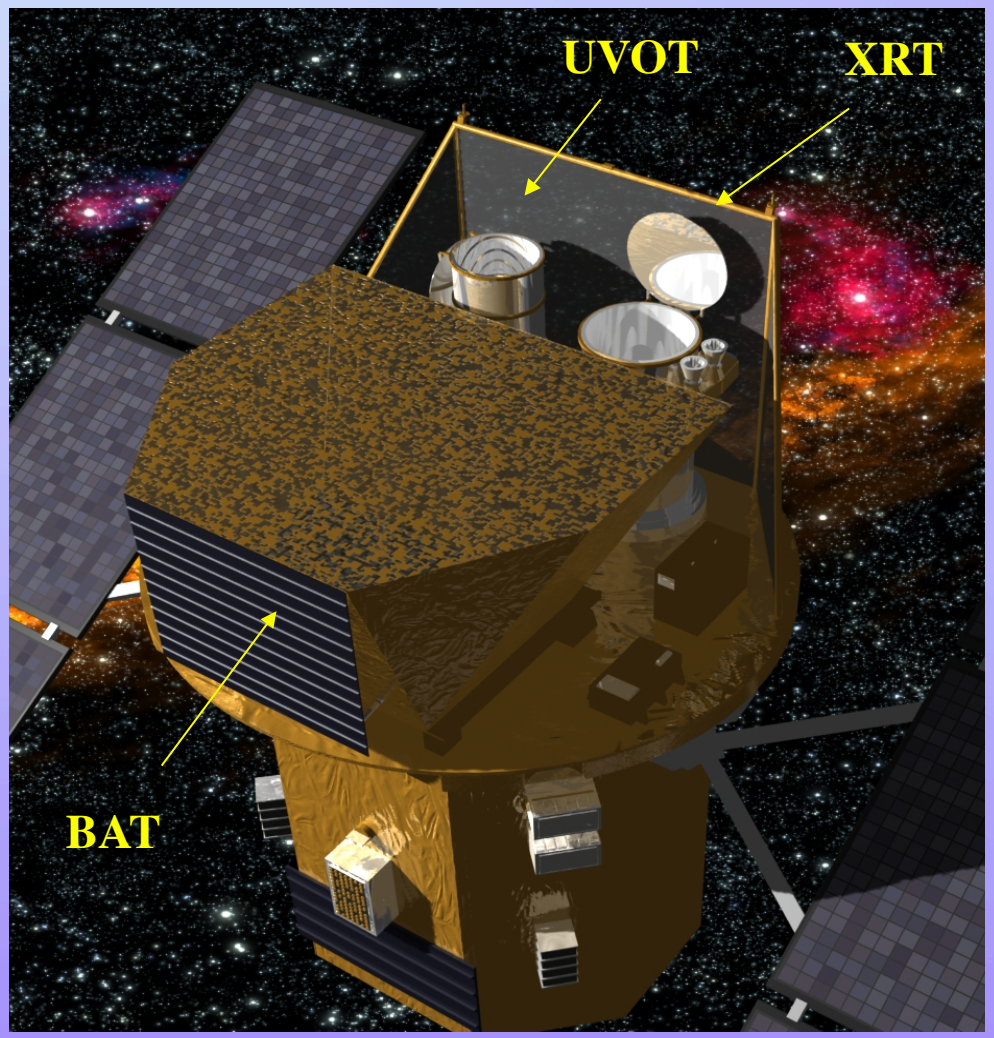




1 raisin * c^2 =
nuclear bomb energy

400,000 Earths * c^2 =
GRB Energy

Swift Mission

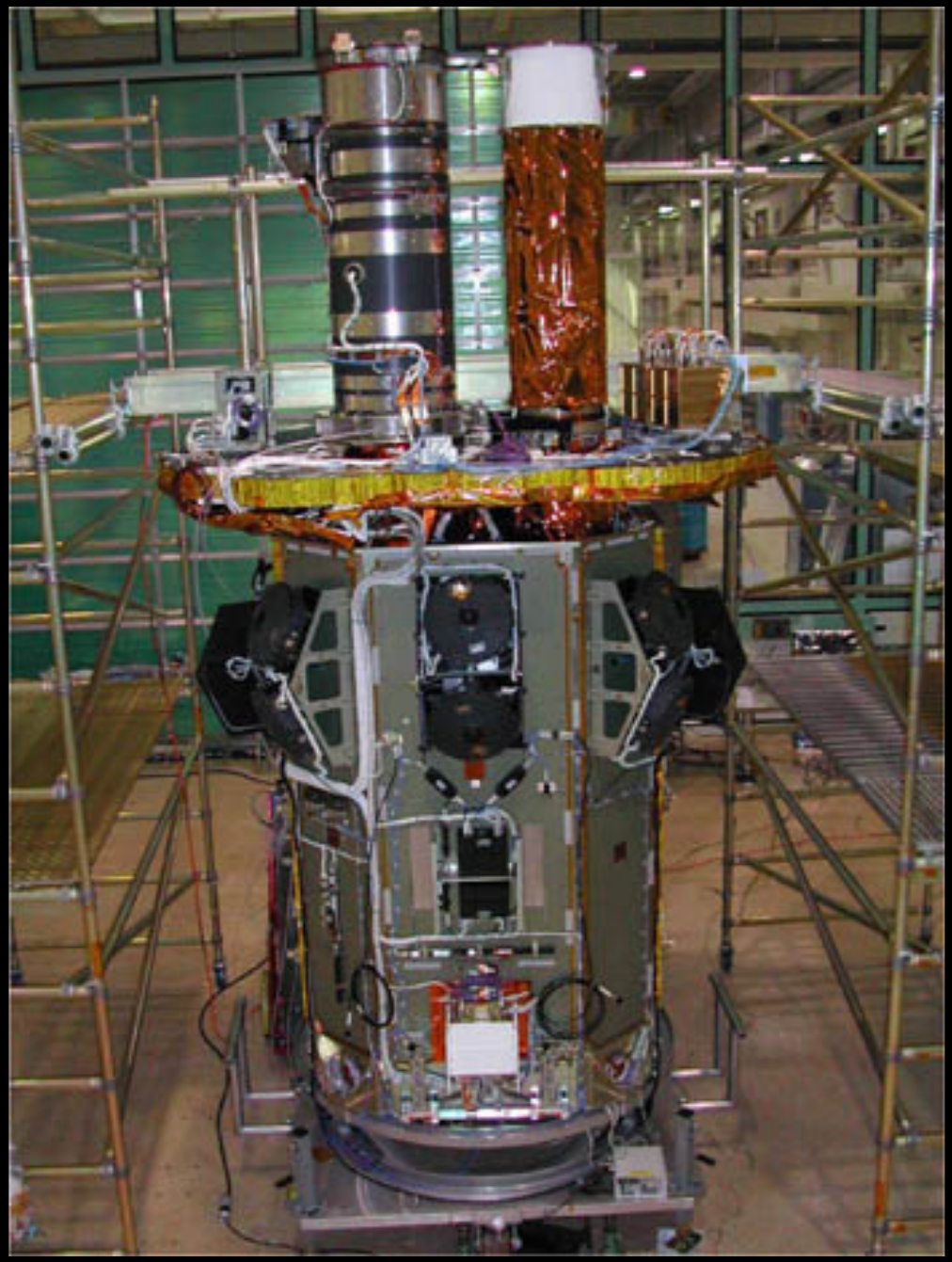


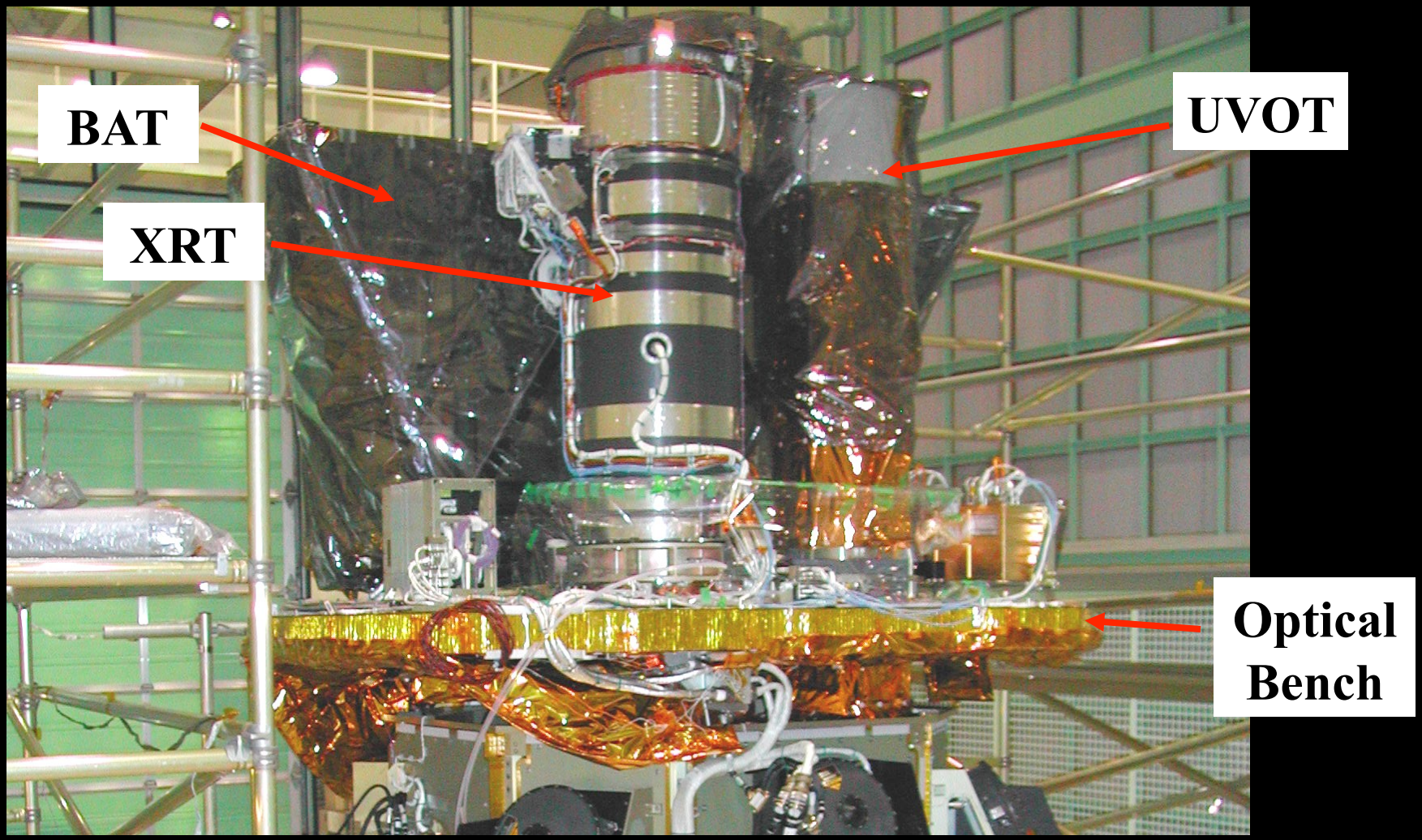
3 instruments, each with:

- lightcurves
- images
- spectra

Rapid slewing spacecraft






BAT
XRT
UVOT
Optical Bench

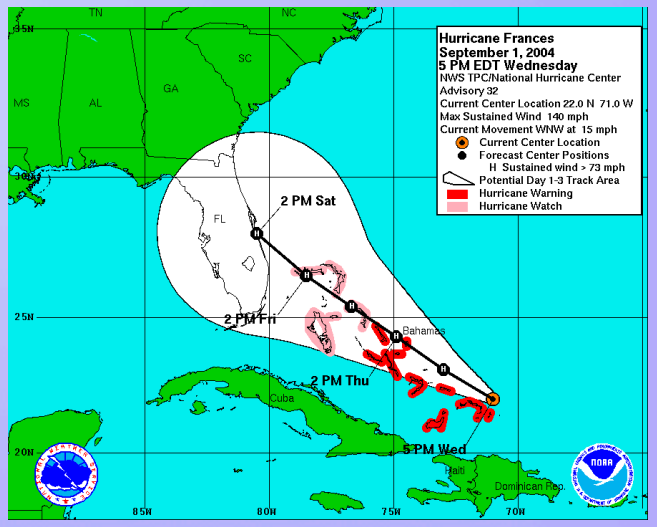

OVERSIZE LOAD

Florida 2004 - Hurricane Alley

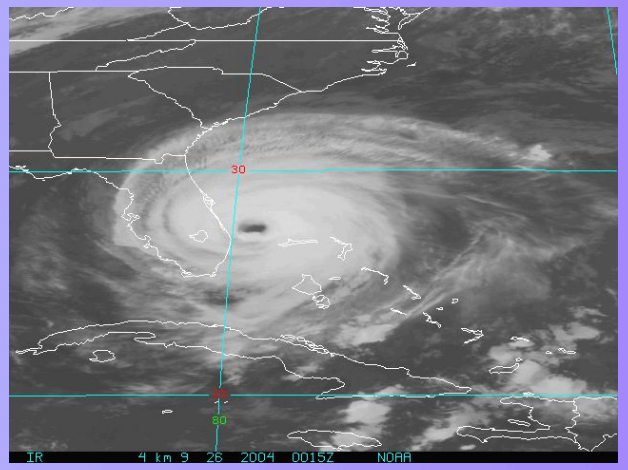
Hurricanes:

- Charley Aug 13
- Frances Sept 4
- Ivan Sept 10
- Jeanne Sept 25

Frances

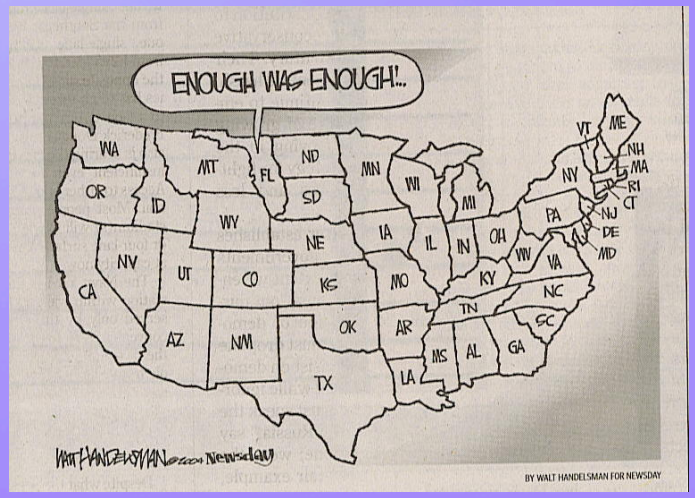


Jeanne

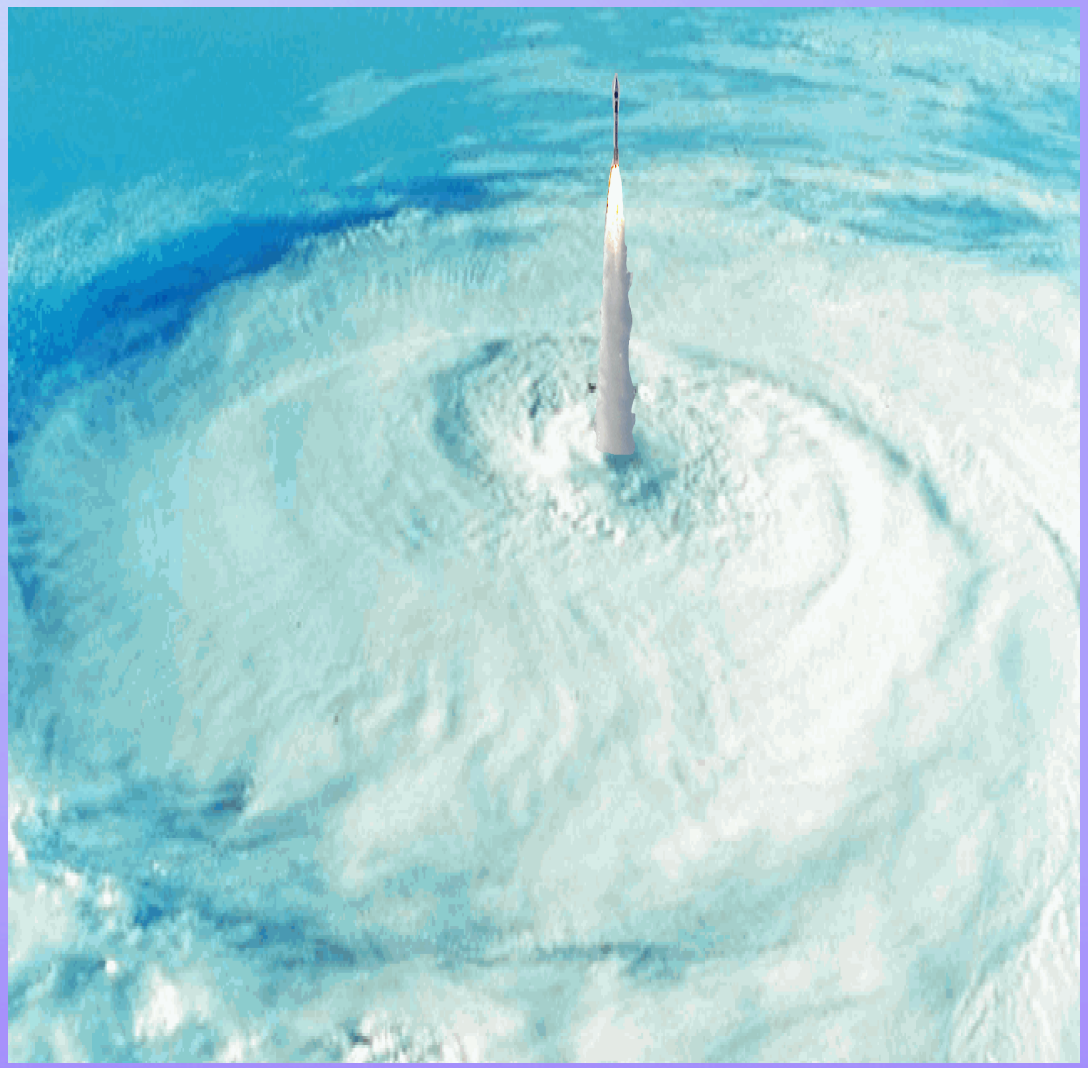


Jeanne

Vehicle Assembly Building damage

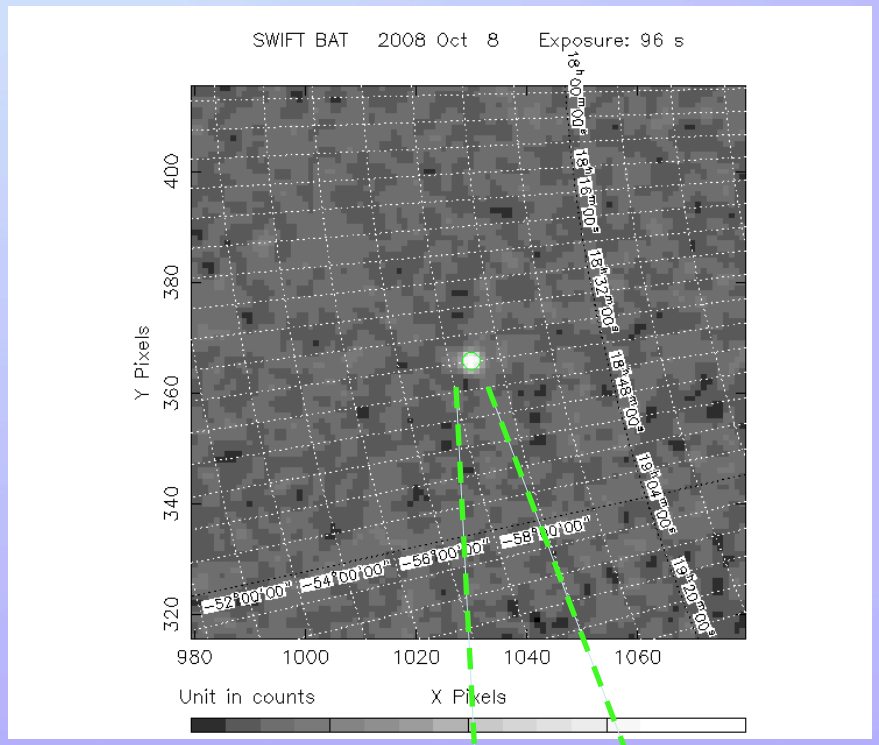


Let's Launch Anyway !!!

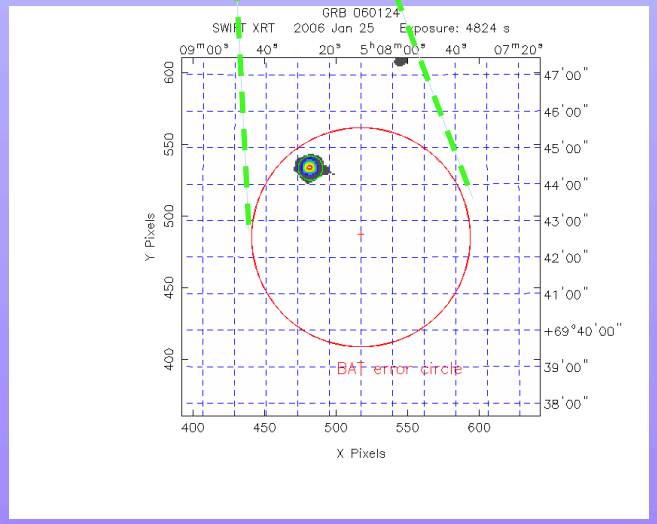


Swift
Gamma Ray Burst

gamma rays

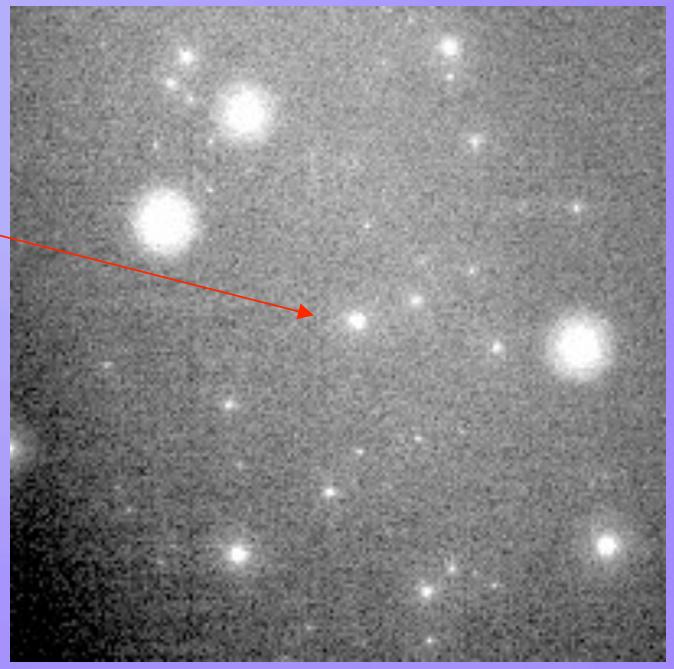


X-ray



visible **March 19, 2008**

"naked eye" GRB



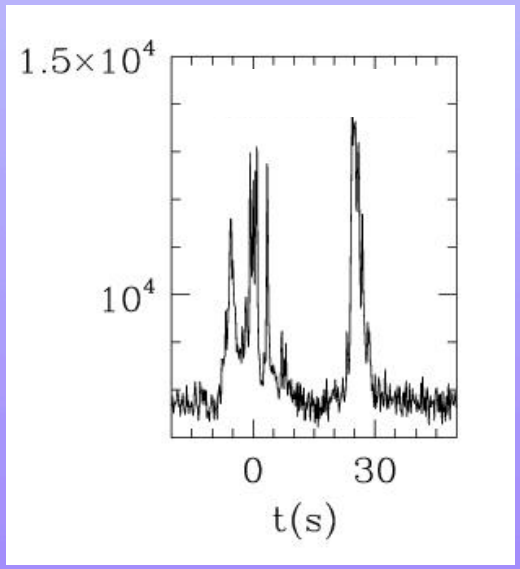
(Pi of the Sky telescope)

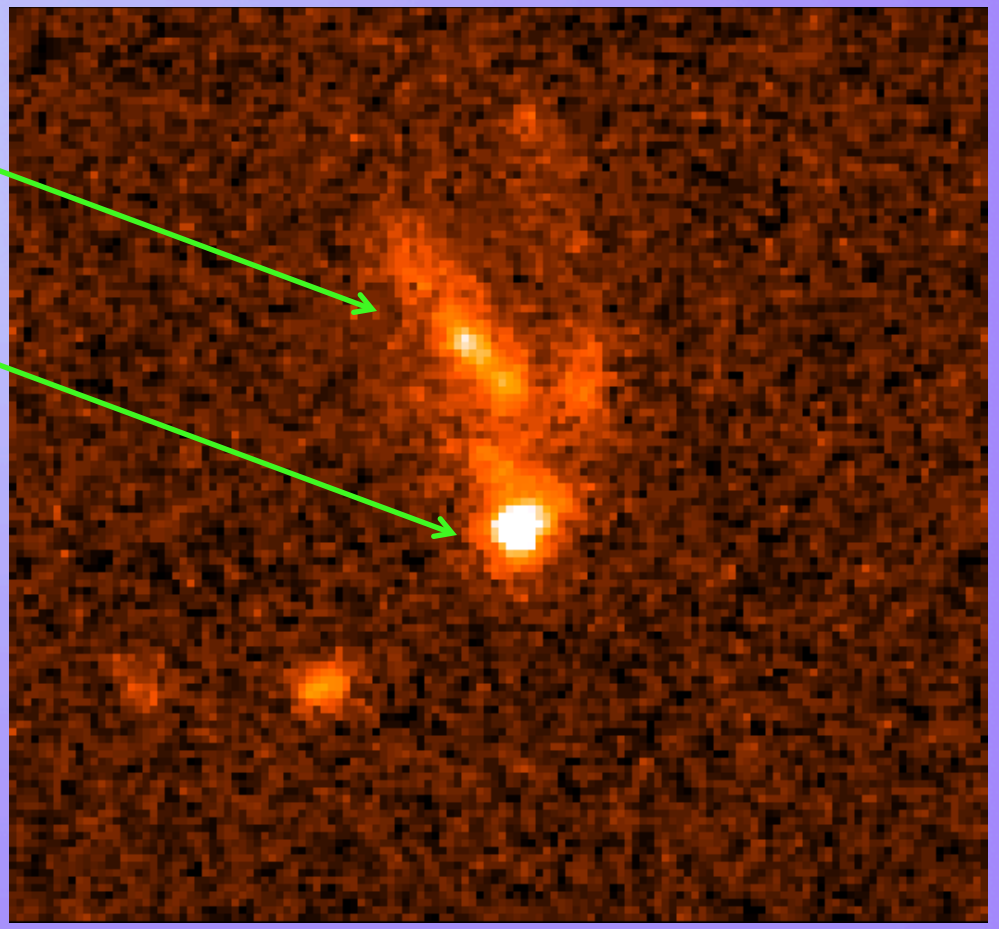
Explosions in Distant Galaxies

Hubble Space Telescope Image

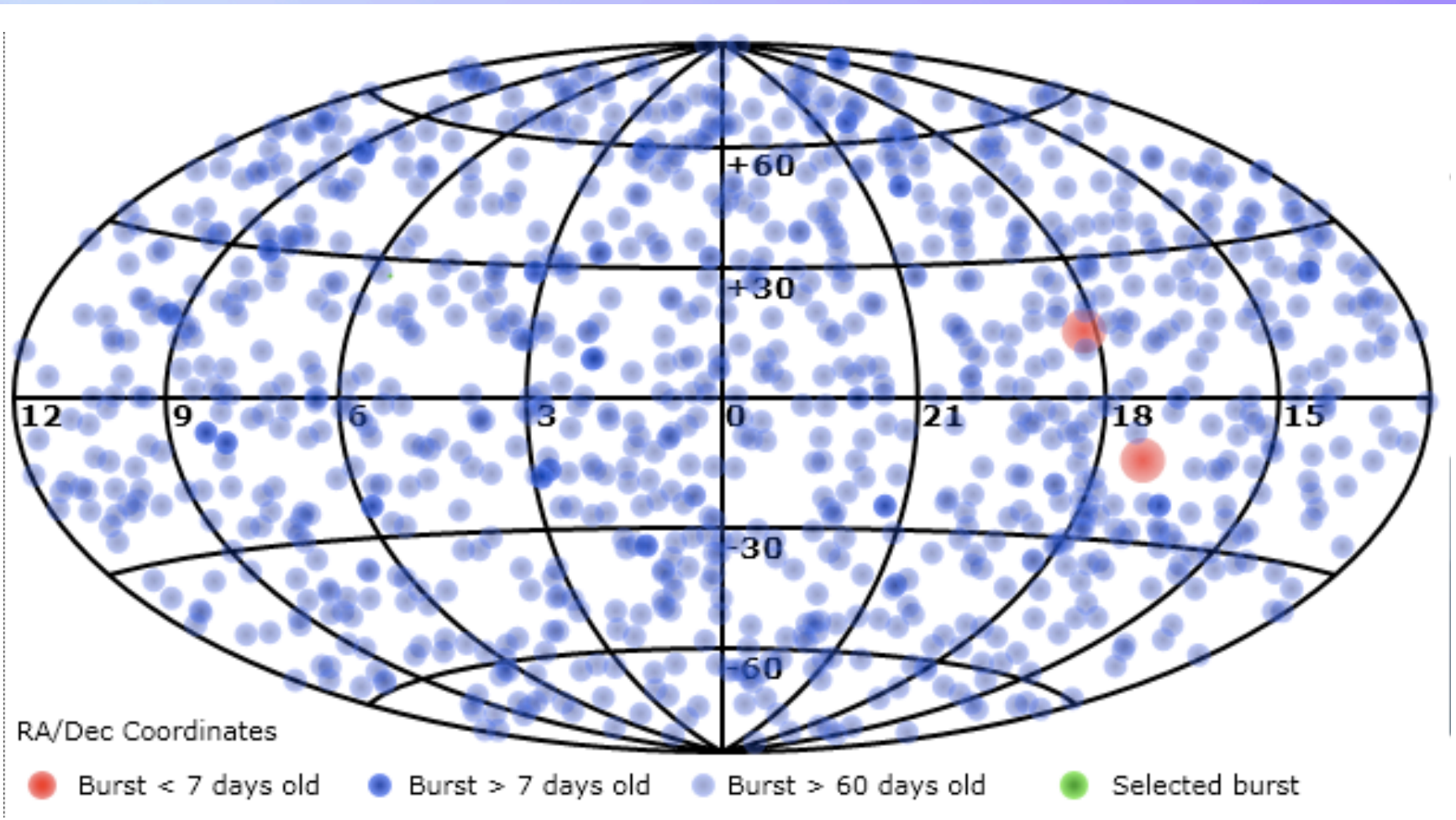
galaxy

gamma ray burst





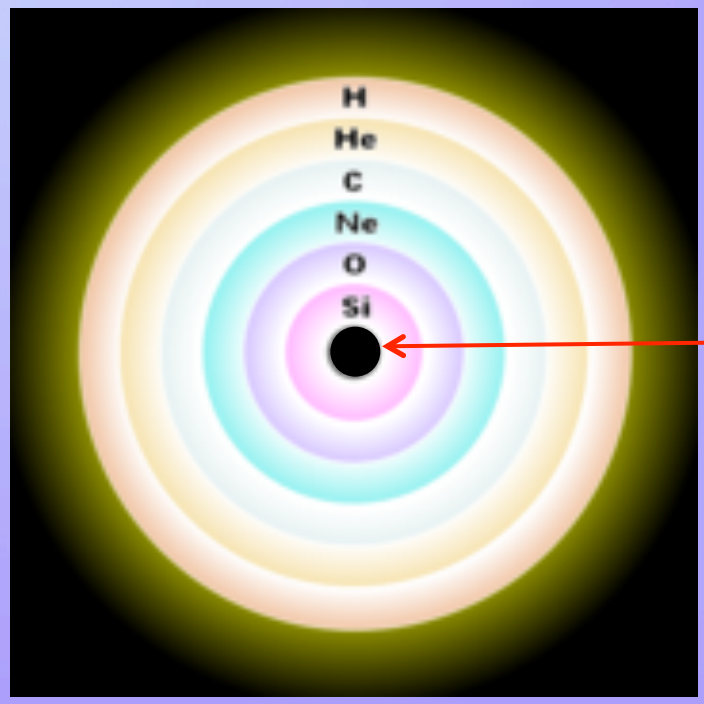
665 Gamma Ray Bursts



http://grb.sonoma.edu/

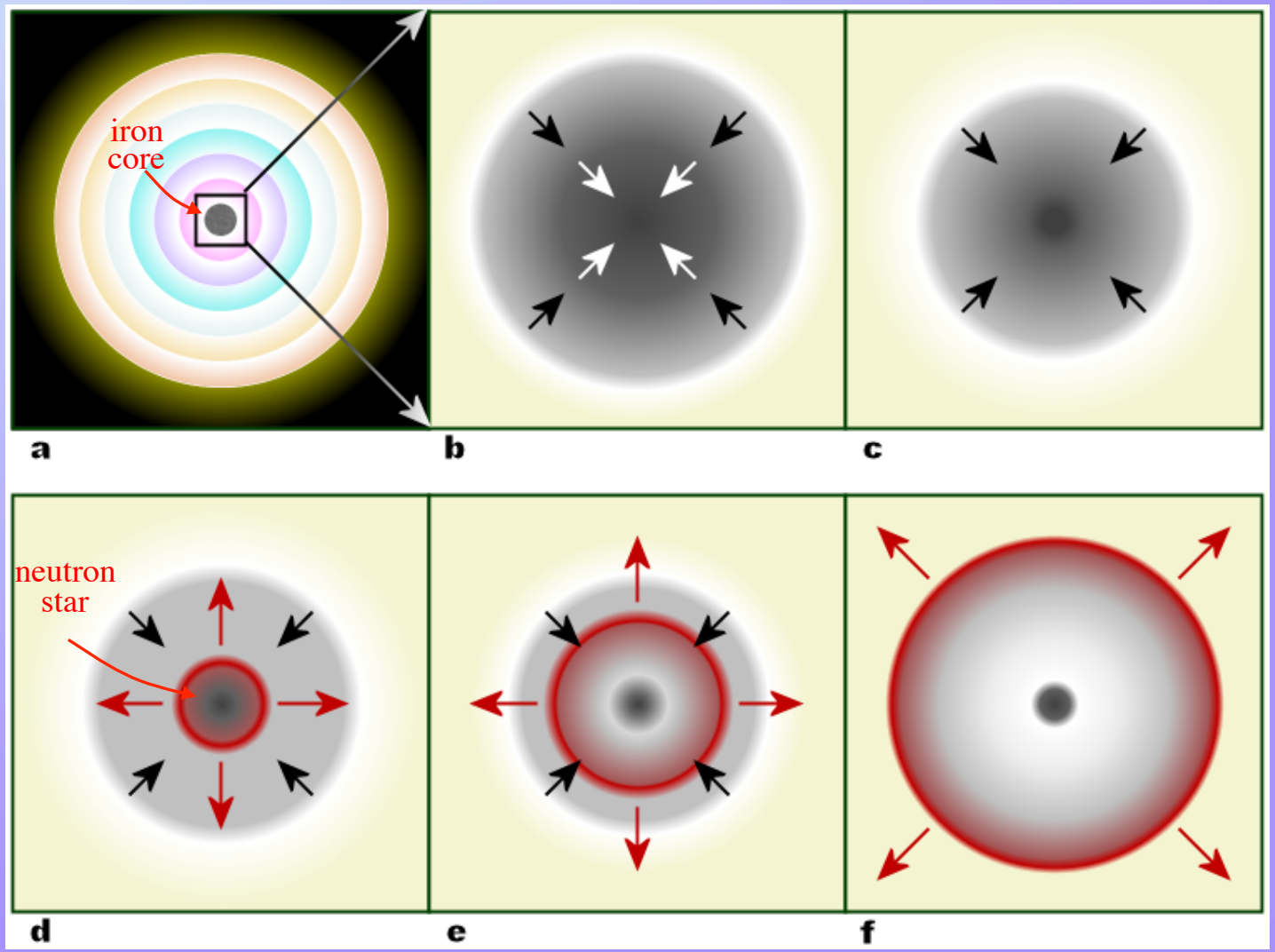
Massive Star Evolution

Star evolves over millions of years
to onion layer configuration

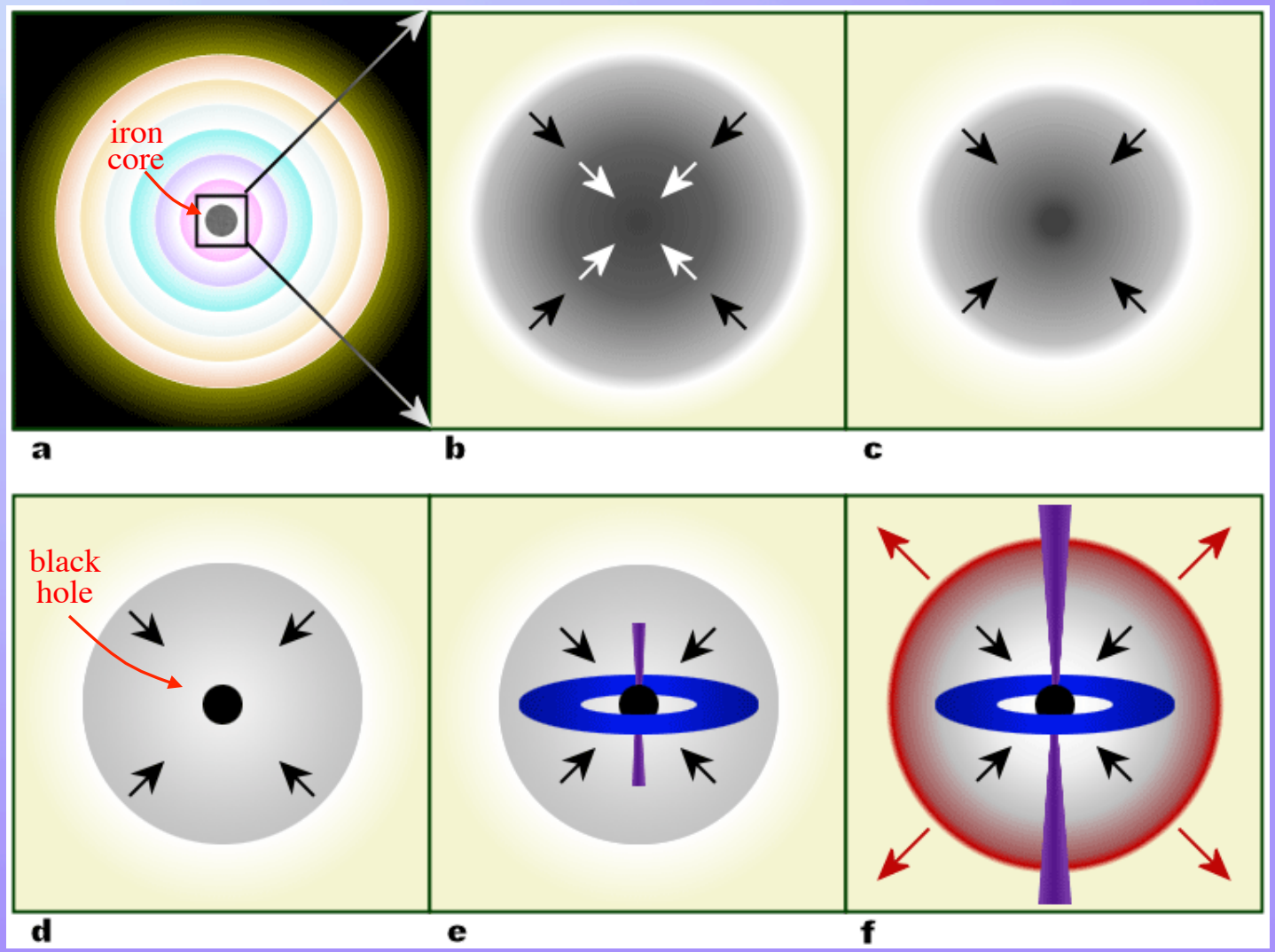


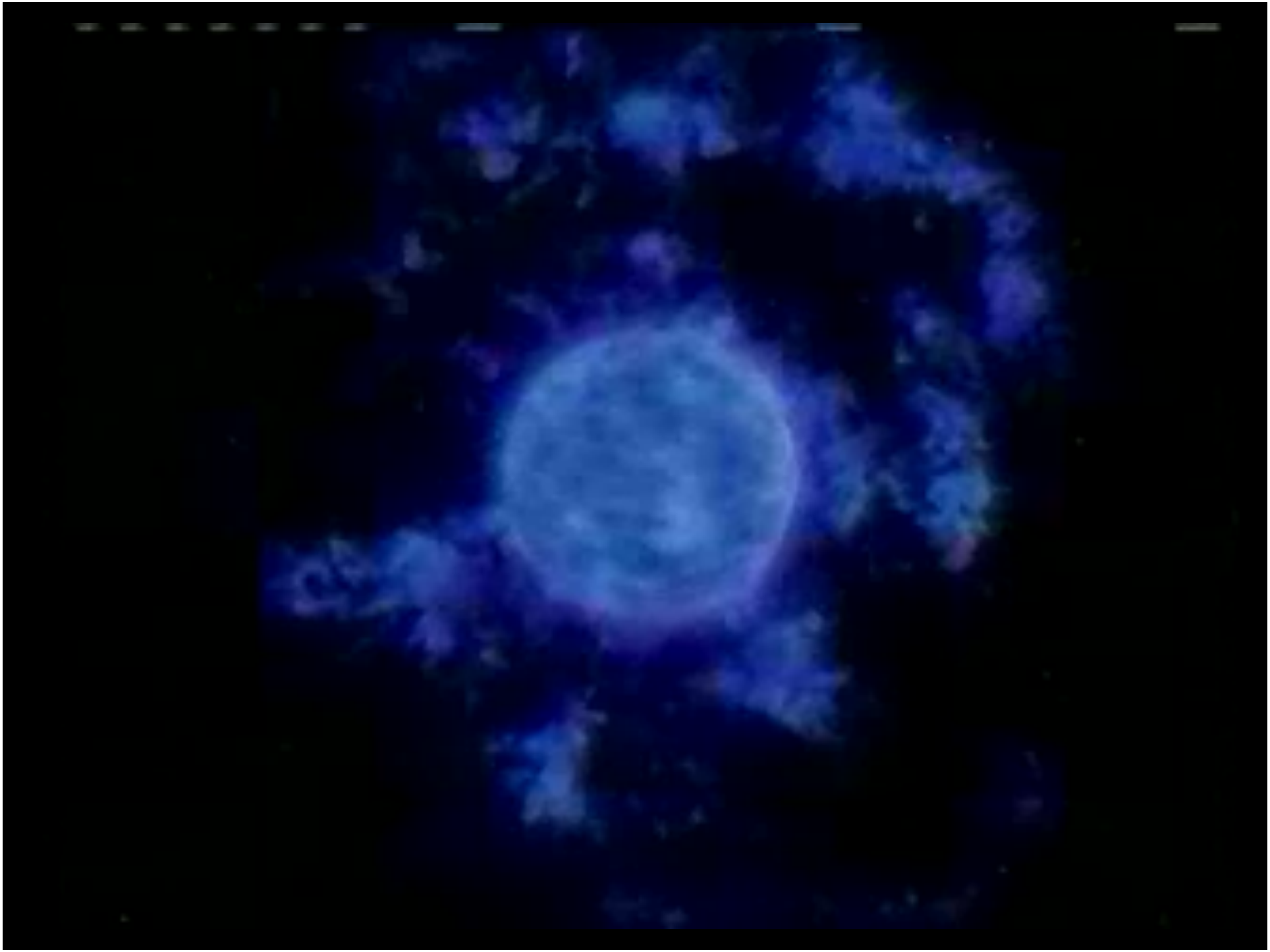
When core burns to iron, there is no more energy to be gained and the core collapses

Normal Supernova



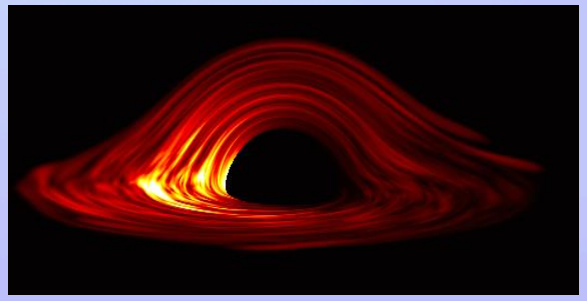
Gamma Ray Burst



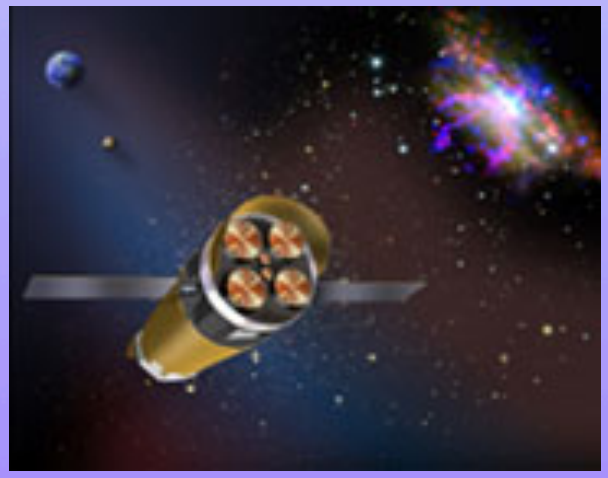


Future Measurements

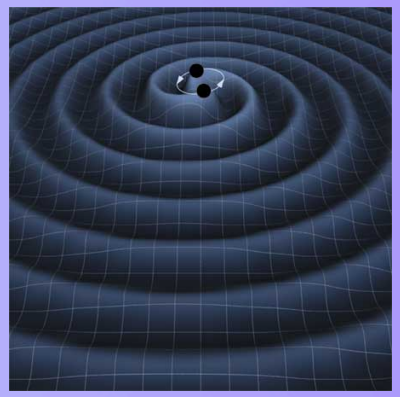
X-rays - Accretion Disks



Athena

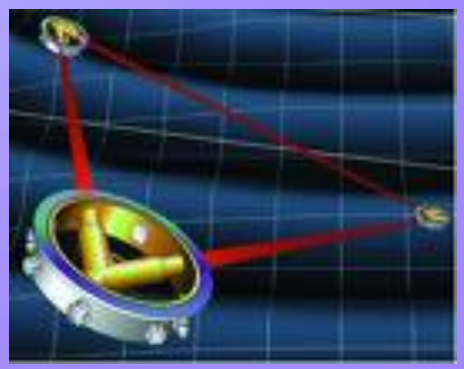


Gravitational Waves - Mergers

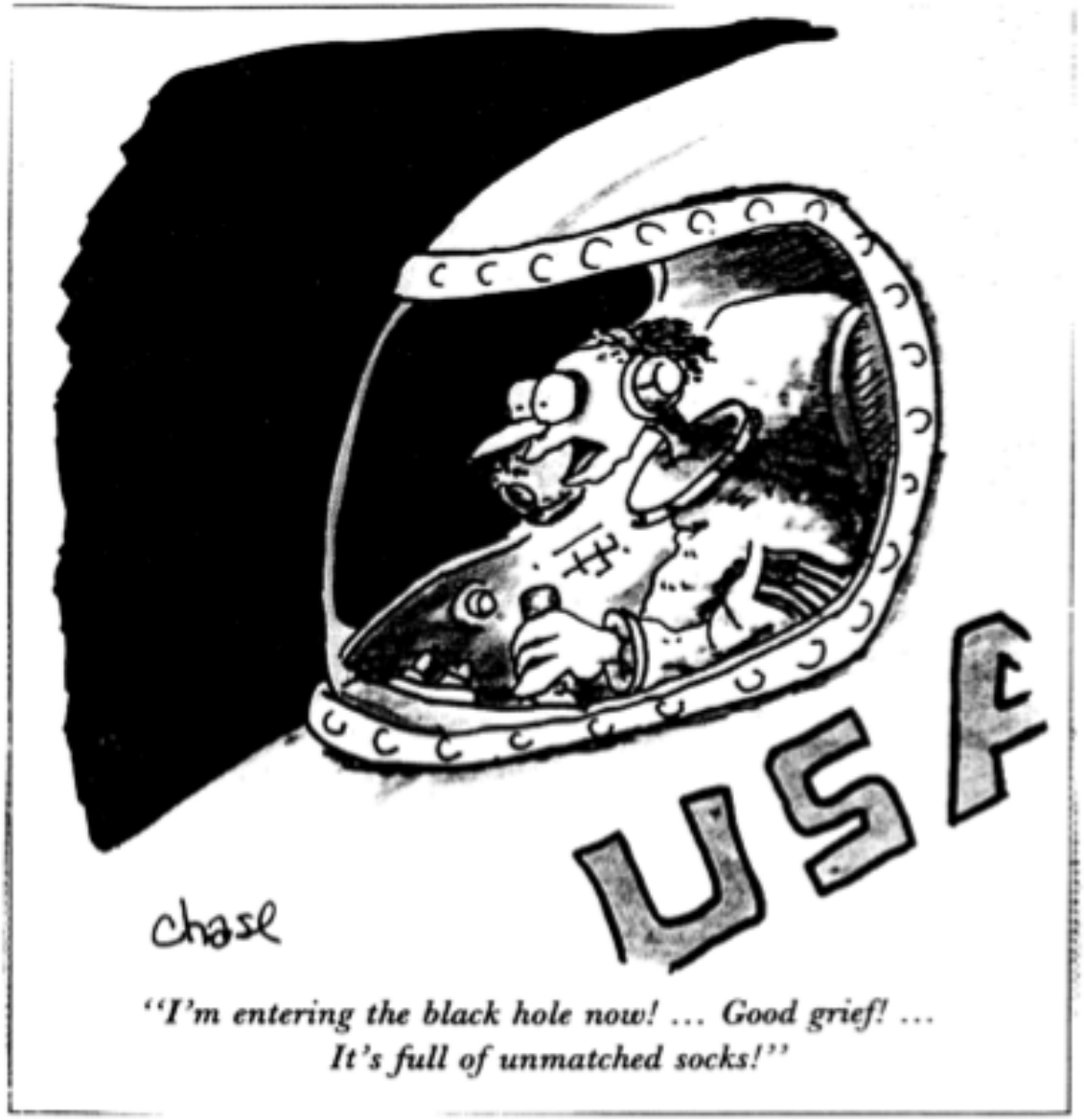


LIGO & VIRGO

NGO - LISA



What is a black hole?

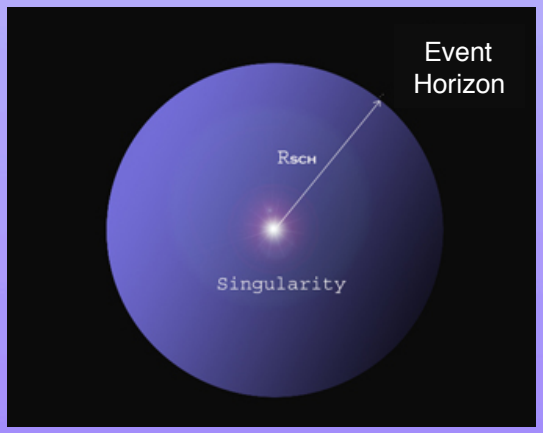


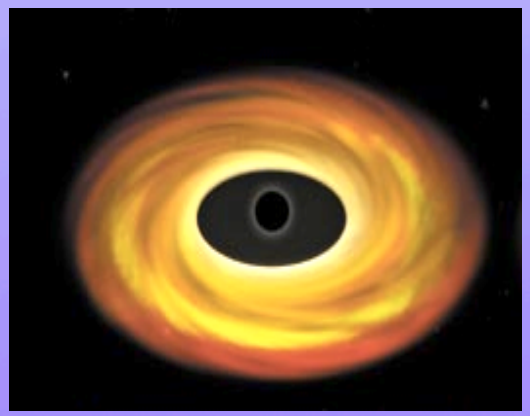
"I'm entering the black hole now! ... Good grief! ... It's full of unmatched socks!"

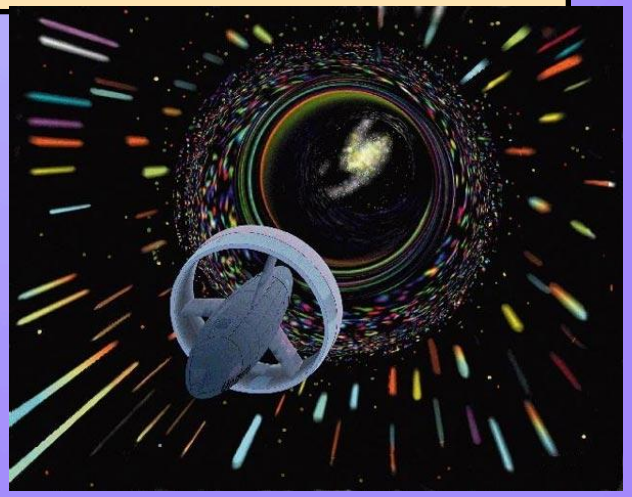
Black Hole Structure

Theoretical Models

- Point mass at center (general relativity)
- All mass relativistically accumulated at event horizon (Zhang 2008)
- "Fuzzy ball" of strings from "string theory" (Mathur et al. 2002)
- Wormhole portals to parallel universes (Damour & Solodukin 2007)
- Birth of universes and evolution (Smolin 1997)







Falling in to a Black Hole

Special relativity: "moving clocks run slowly"

General relativity: "clocks near massive objects run slowly"

Vastly different views in different frames:

- From a distance, traveler never goes past event horizon
- For the traveler, event horizon crossing is possible

Space and Time reverse

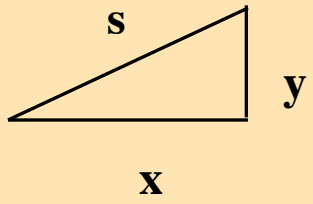
The *Equations*

- Einstein field equation of general relativity

$$G_{\mu\nu} = (8\pi G/c^4)\ T_{\mu\nu} - g_{\mu\nu}\ \Lambda$$

$$s^2 = x^2 + y^2$$

- Schwarzschild solution



Without mass

$$s^2 = t^2 - r^2$$

With mass

$$s^2 = (1 - 2Gm/rc^2)\ t^2 - \frac{1}{(1 - 2Gm/rc^2)}\ r^2$$

- The Schwarzschild equation has a singularity at

$$1 - 2Gm/rc^2 = 0 \quad \text{or} \quad r = 2\,Gm / c^2$$

Falling in to a Black Hole

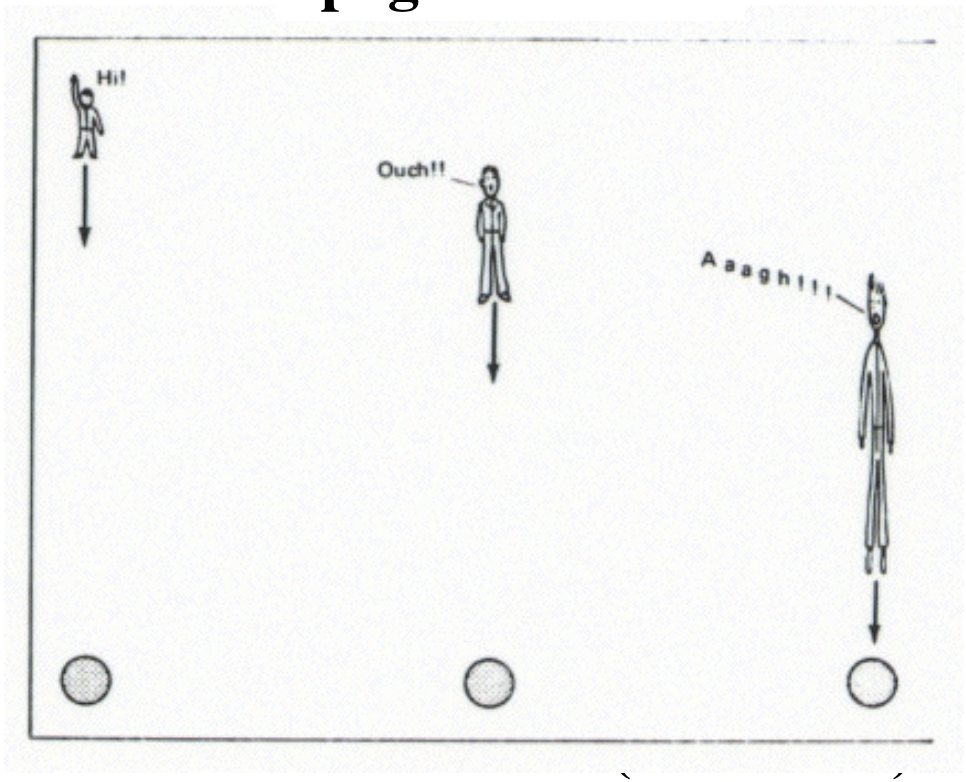
Special relati

General rela **slowly”**

Vastly differe

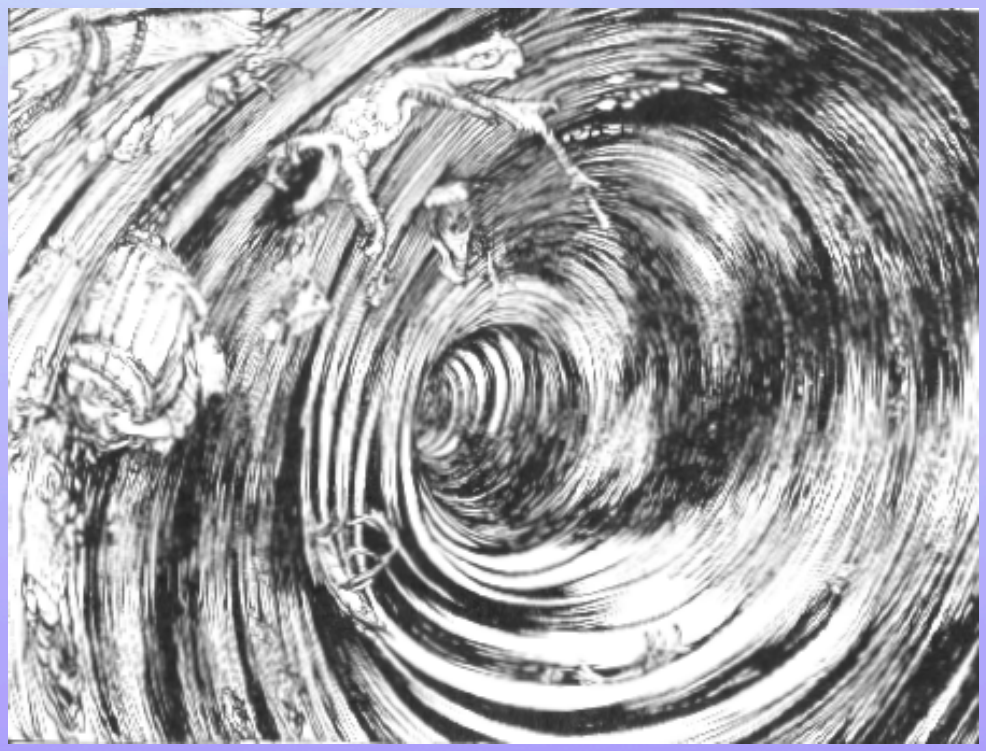
- From a dista
- For the trav

spaghetification



J. Safko

The Old & The New



Miguel Duga 2007

Conclusions

- Objects exist that look & behave like the BHs predicted by Einstein's theory

- They are common in the universe

- Fiery explosions mark their birth

- We do not yet know what the true nature is of these "black holes"

- Observations by future observatories will probe down to the event horizon