# Endpoints of Stellar Evolution

**Ay20 - Lecture 10**

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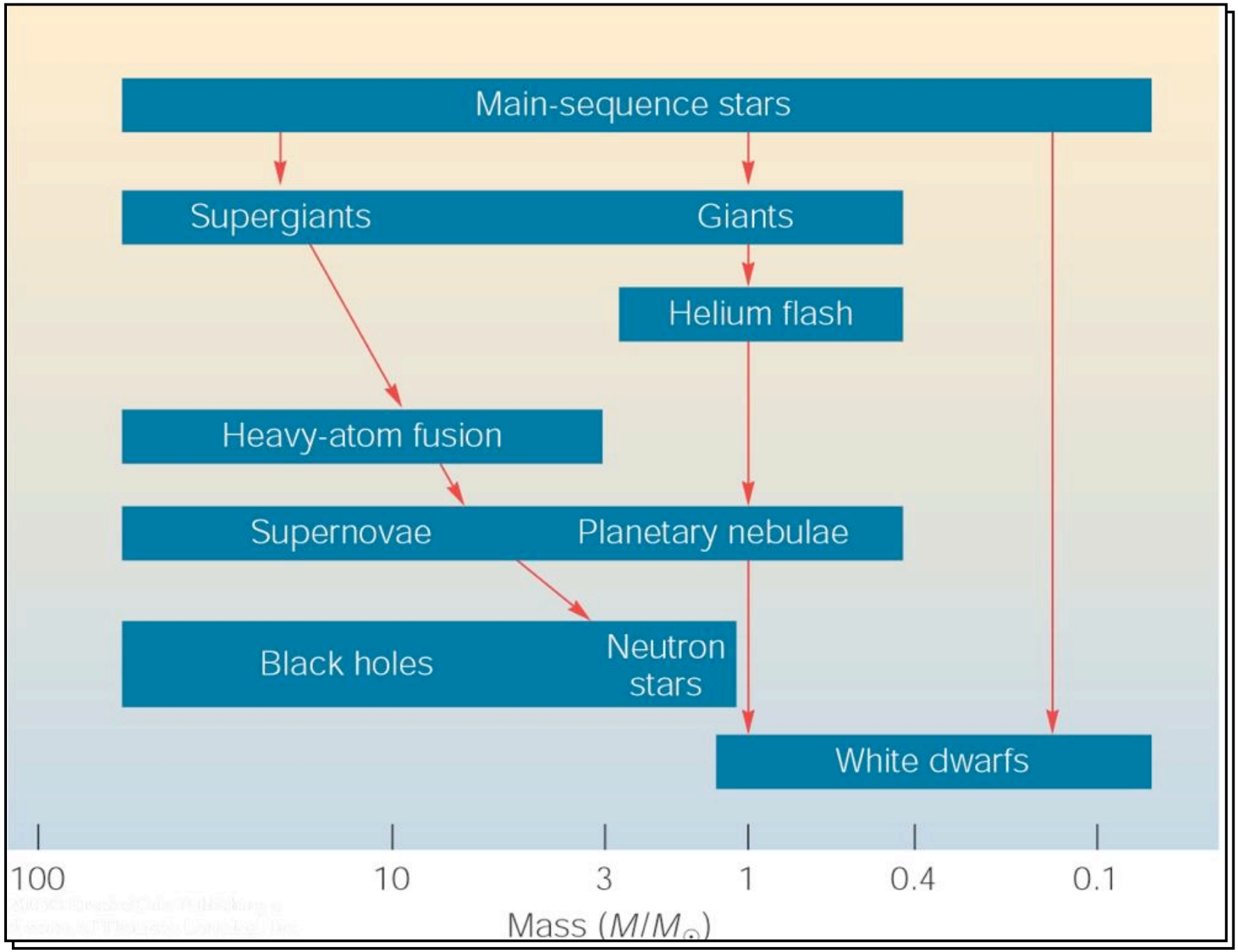
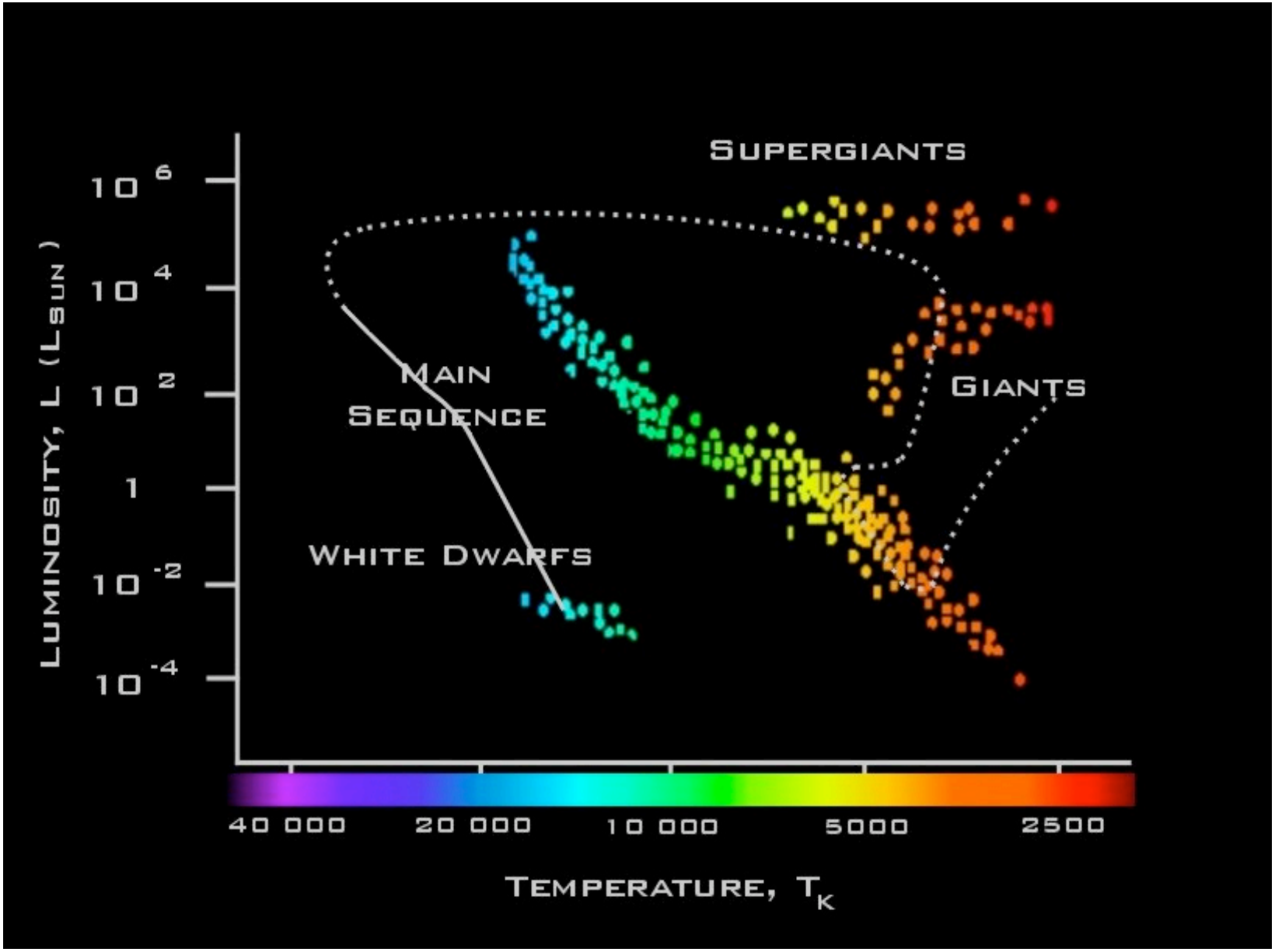
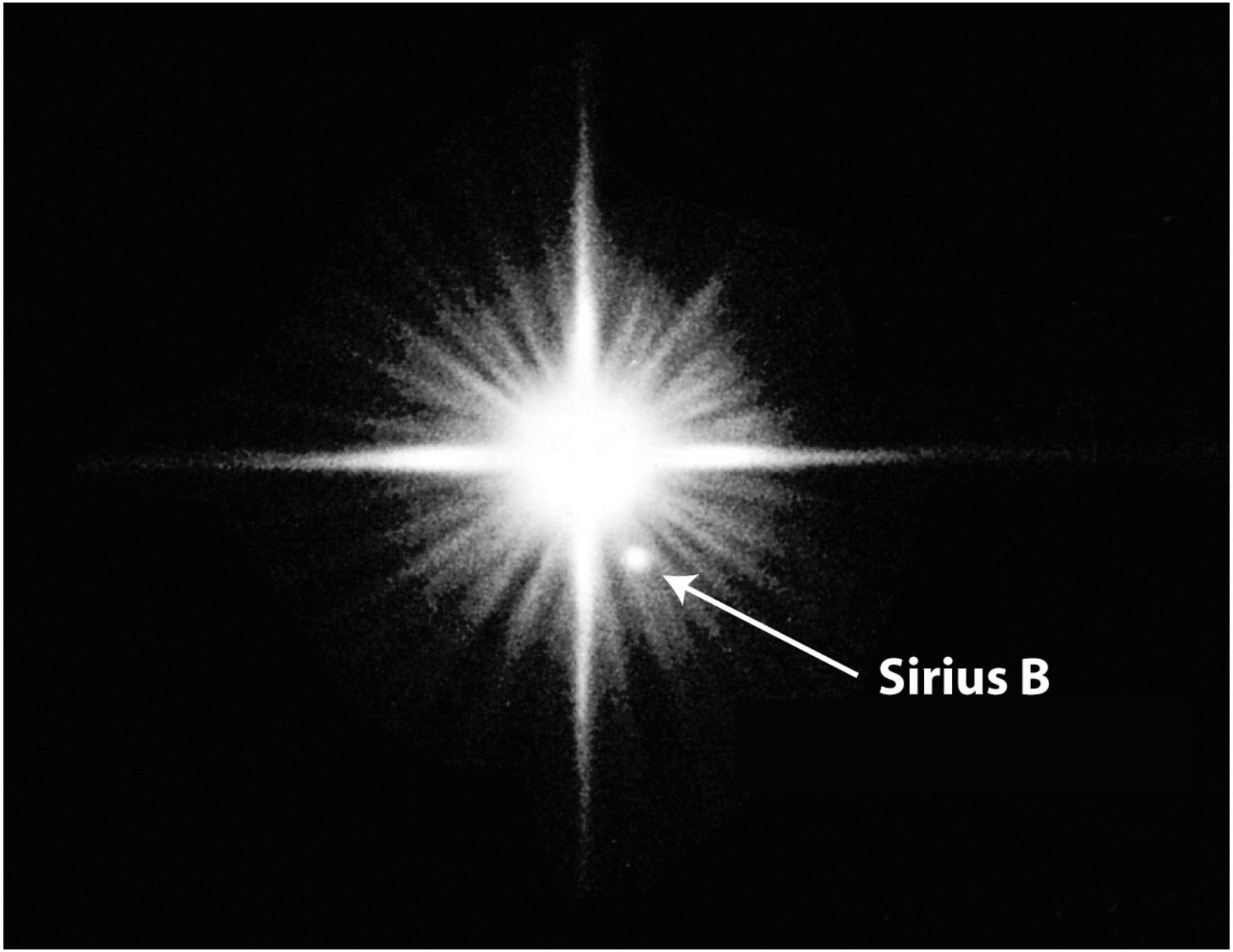
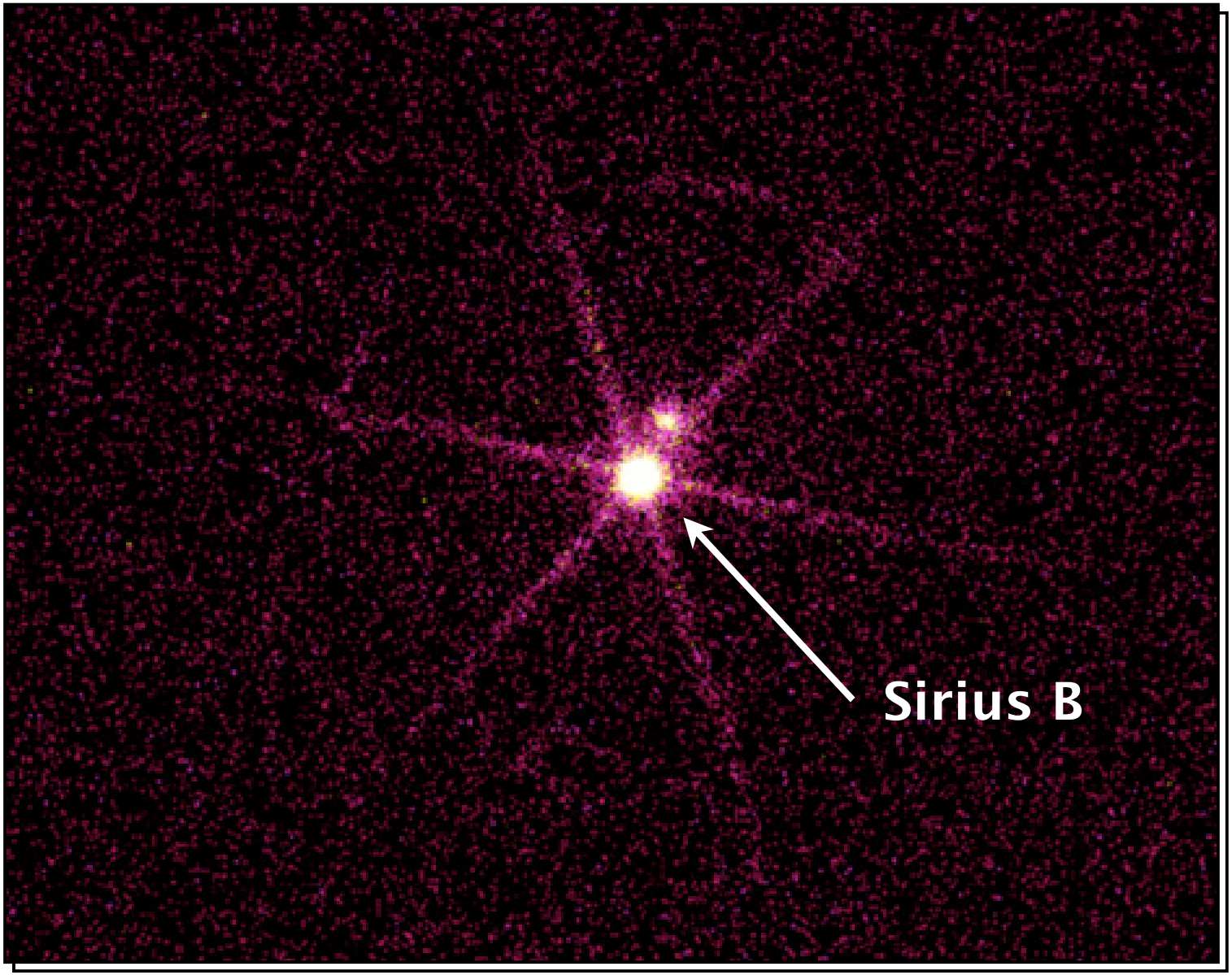
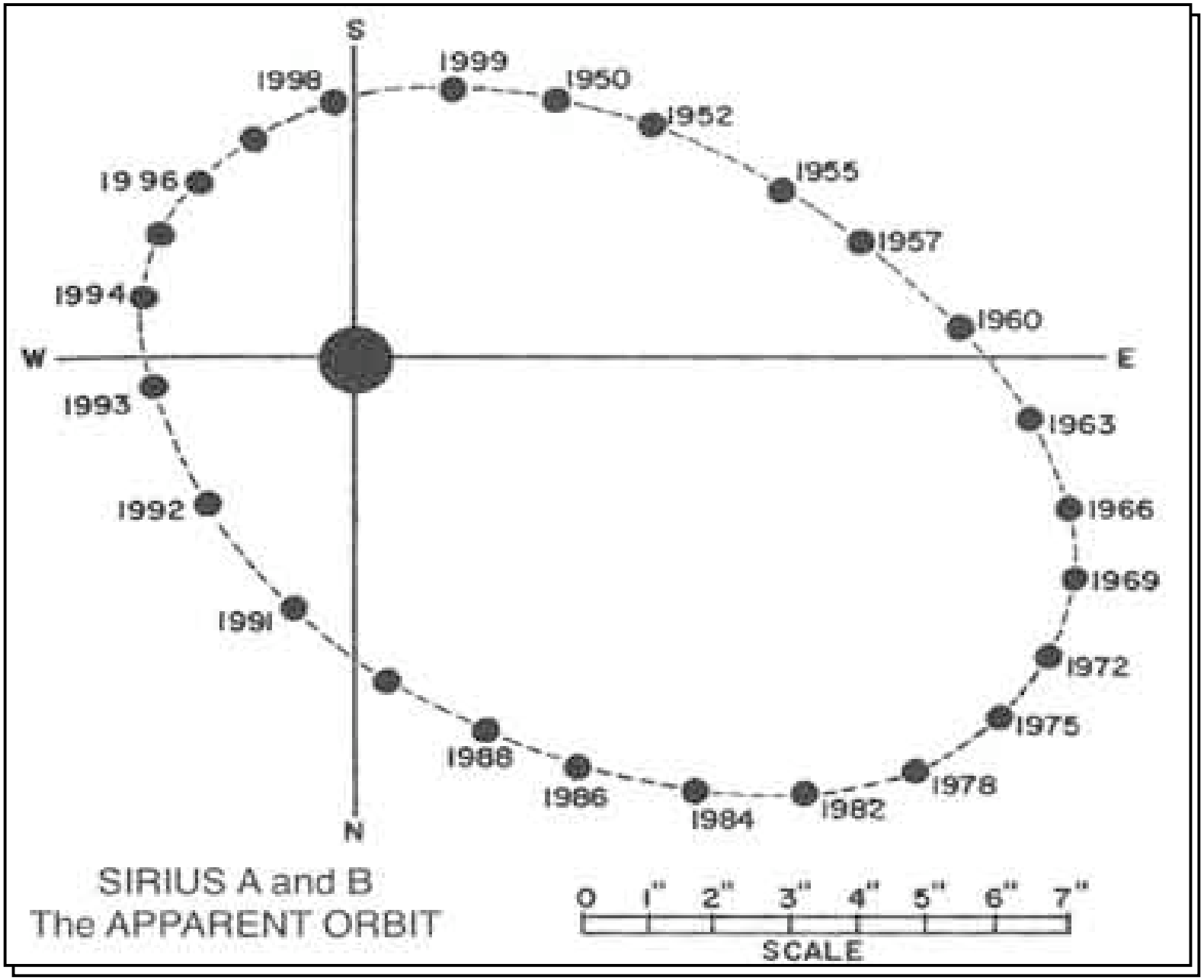

Main-sequence stars
Supergiants
Giants
Helium flash
Heavy-atom fusion
Supernovae
Planetary nebulae
Black holes
Neutron stars
White dwarfs
100
10
3
1
0.4
0.1
Mass ($M/M_\odot$)

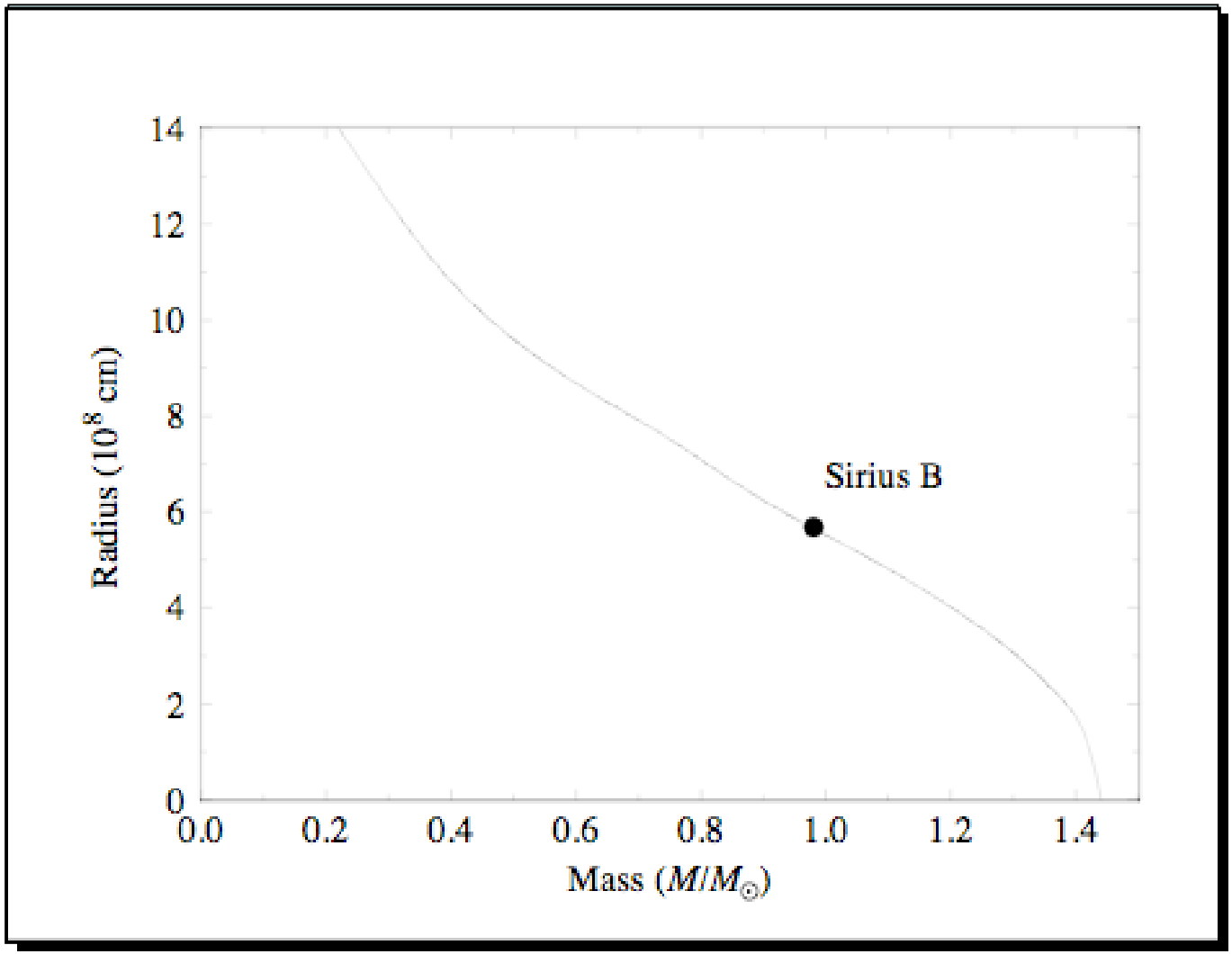

Supergiants
Main
Sequence
Giants
White Dwarfs
Luminosity, L (Lsun)
10 6
10 4
10 2
1
10 -2
10 -4
40 000
20 000
10 000
5000
2500
Temperature, TK

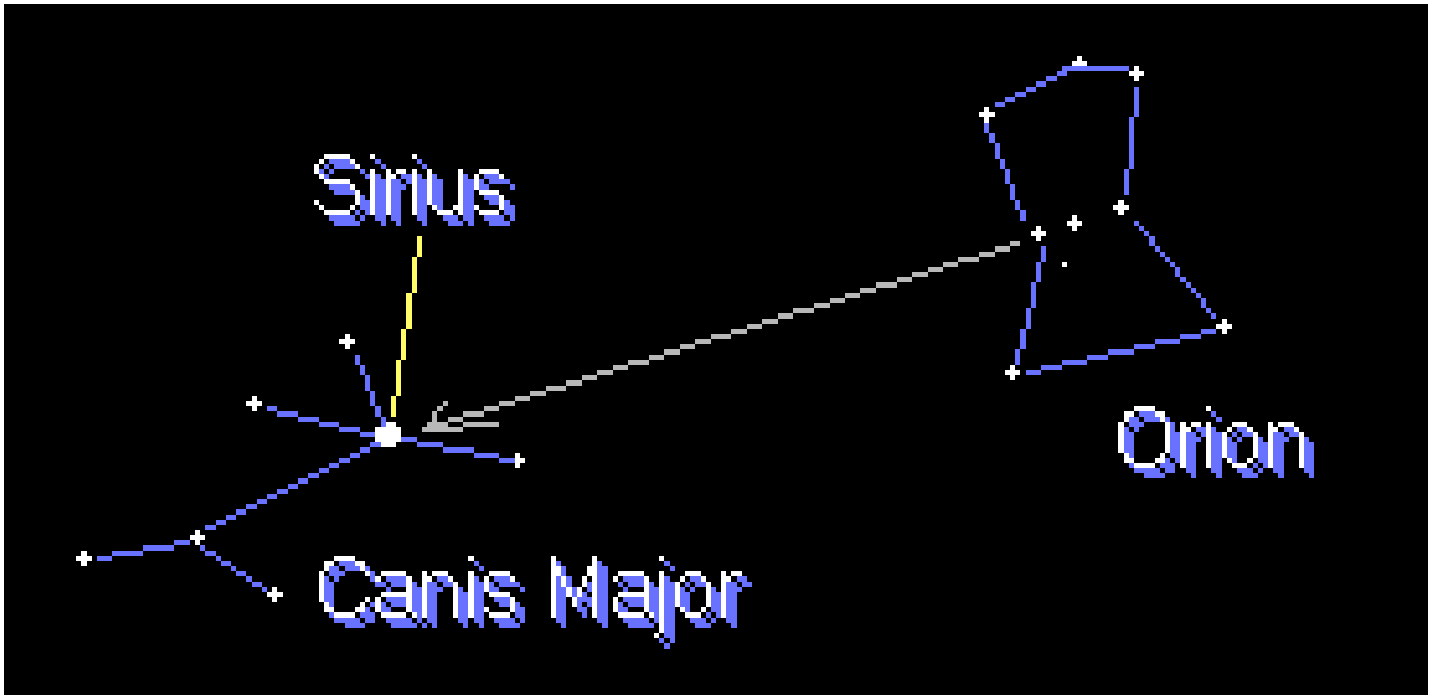

Sirius B

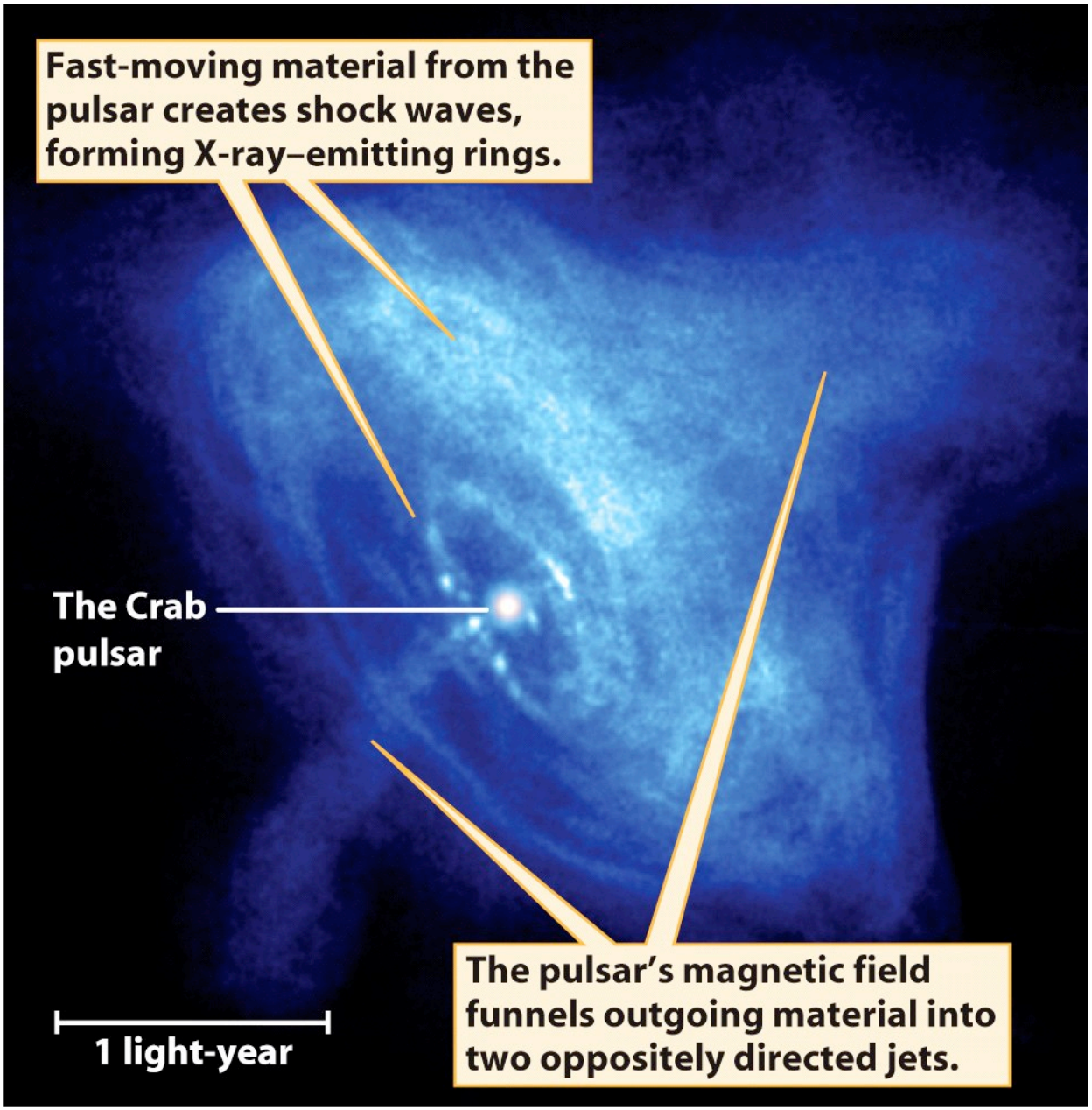


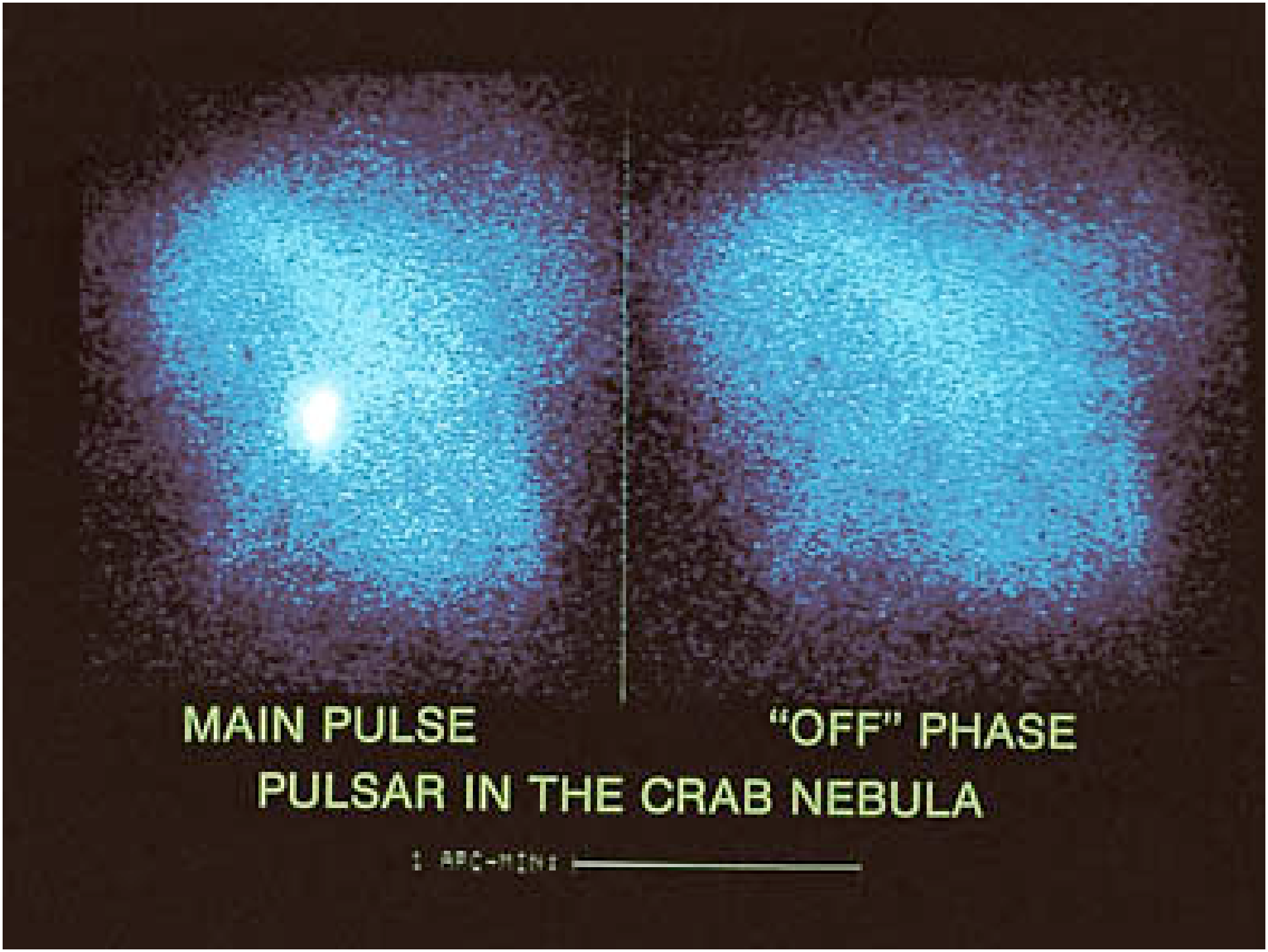

*Chandra* X-ray Image

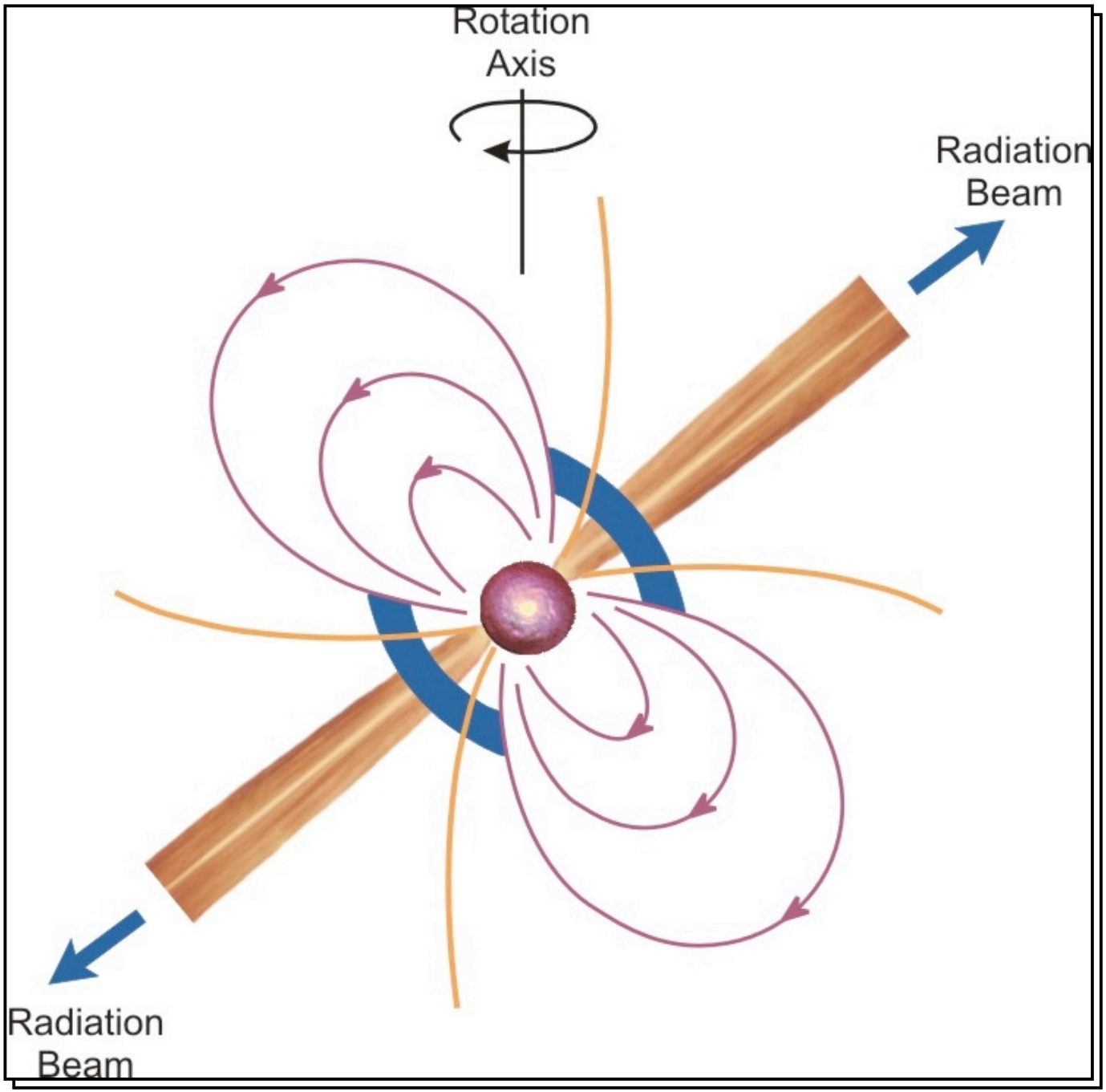

S
1998
1999
1950
1952
1955
1957
1960
1963
1966
1969
1972
1975
1978
1982
1984
1986
1988
1991
1992
1993
1994
1996
W
E
N
SIRIUS A and B
The APPARENT ORBIT
0 1" 2" 3" 4" 5" 6" 7"
SCALE

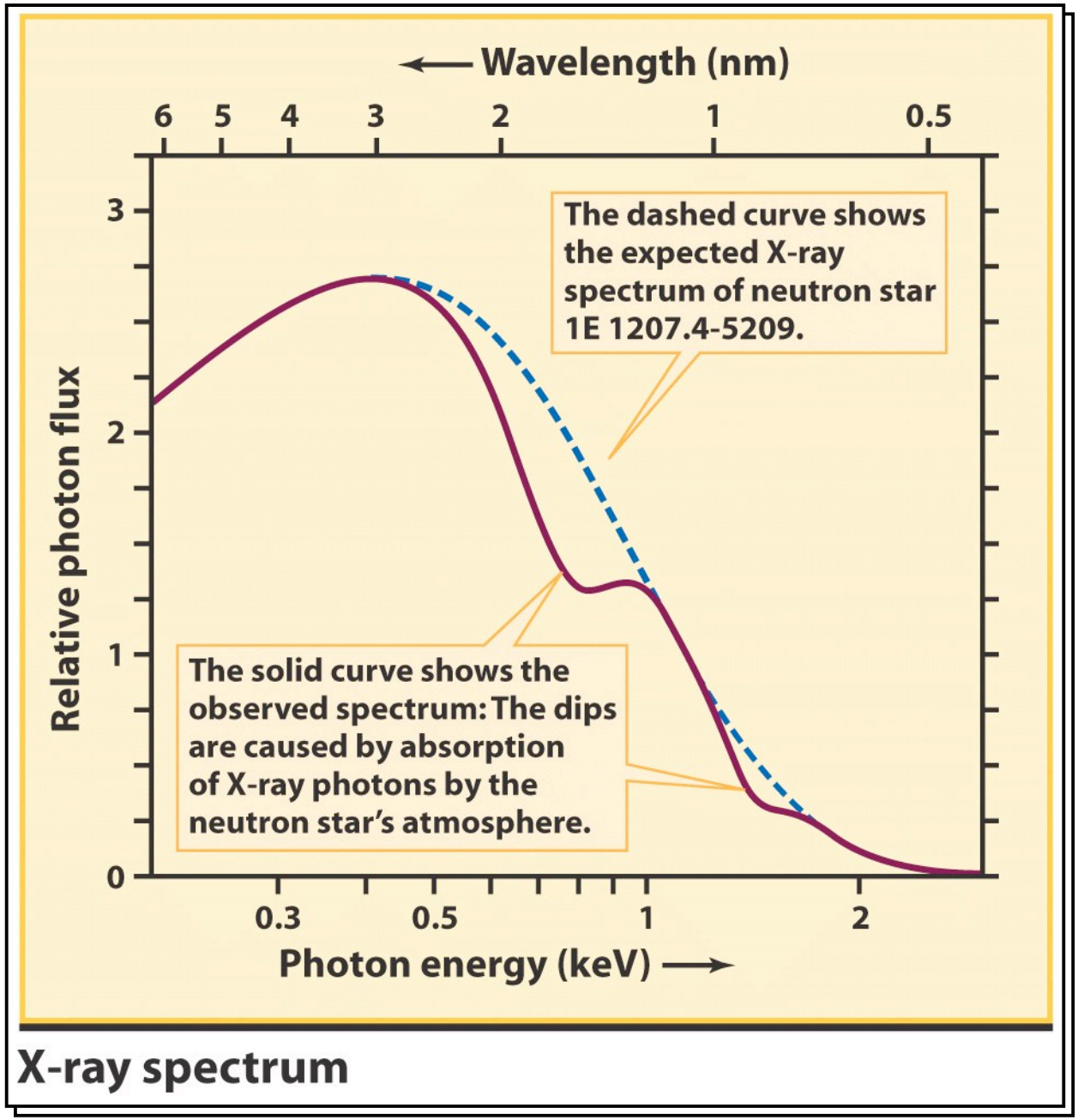

14
12
10
8
6
4
2
0
Radius ($10^8$ cm)
Sirius B
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Mass ($M/M_\odot$)


Sirius
Orion
Canis Major

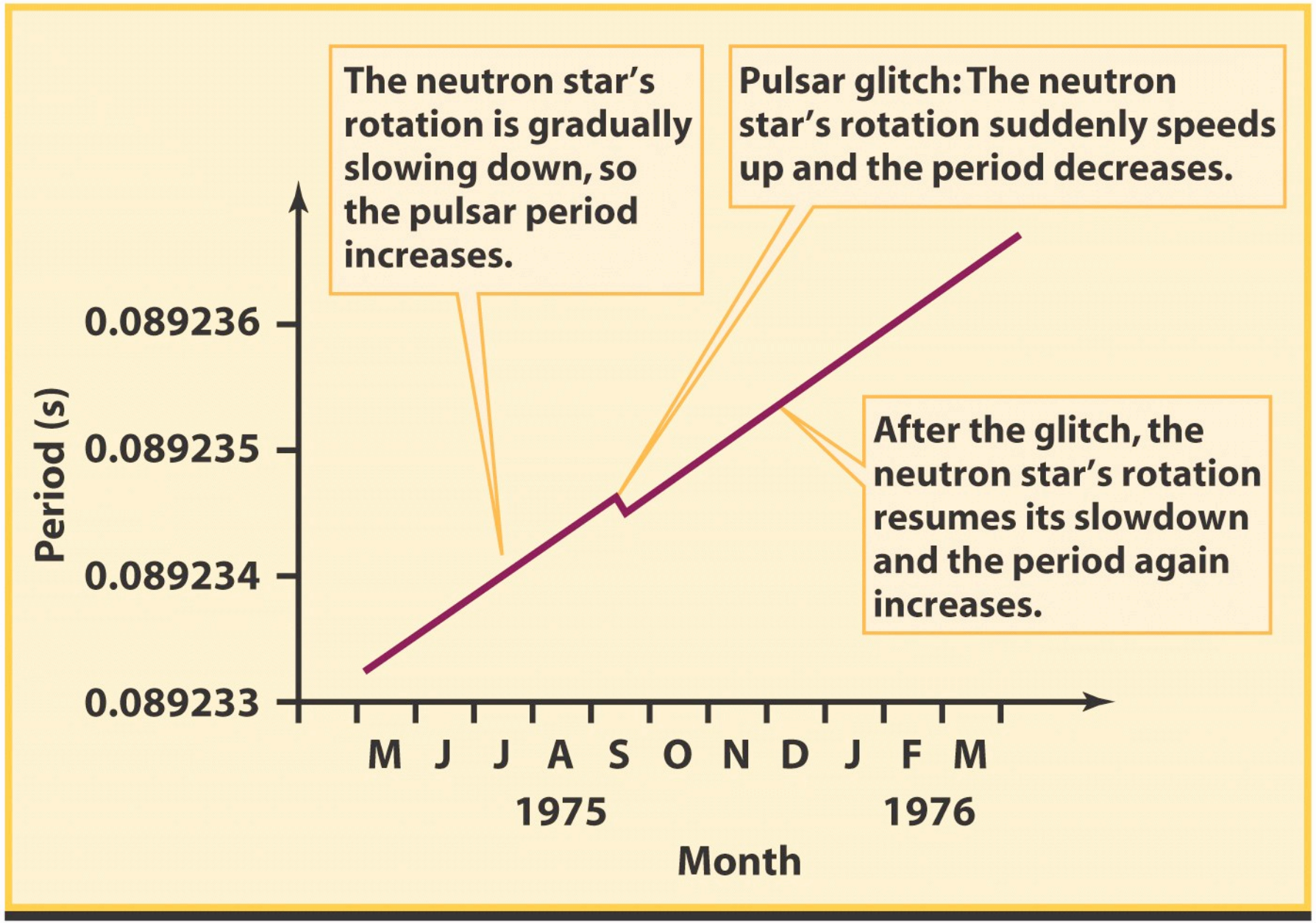

Fast-moving material from the pulsar creates shock waves, forming X-ray–emitting rings.
The Crab pulsar
1 light-year
The pulsar's magnetic field funnels outgoing material into two oppositely directed jets.

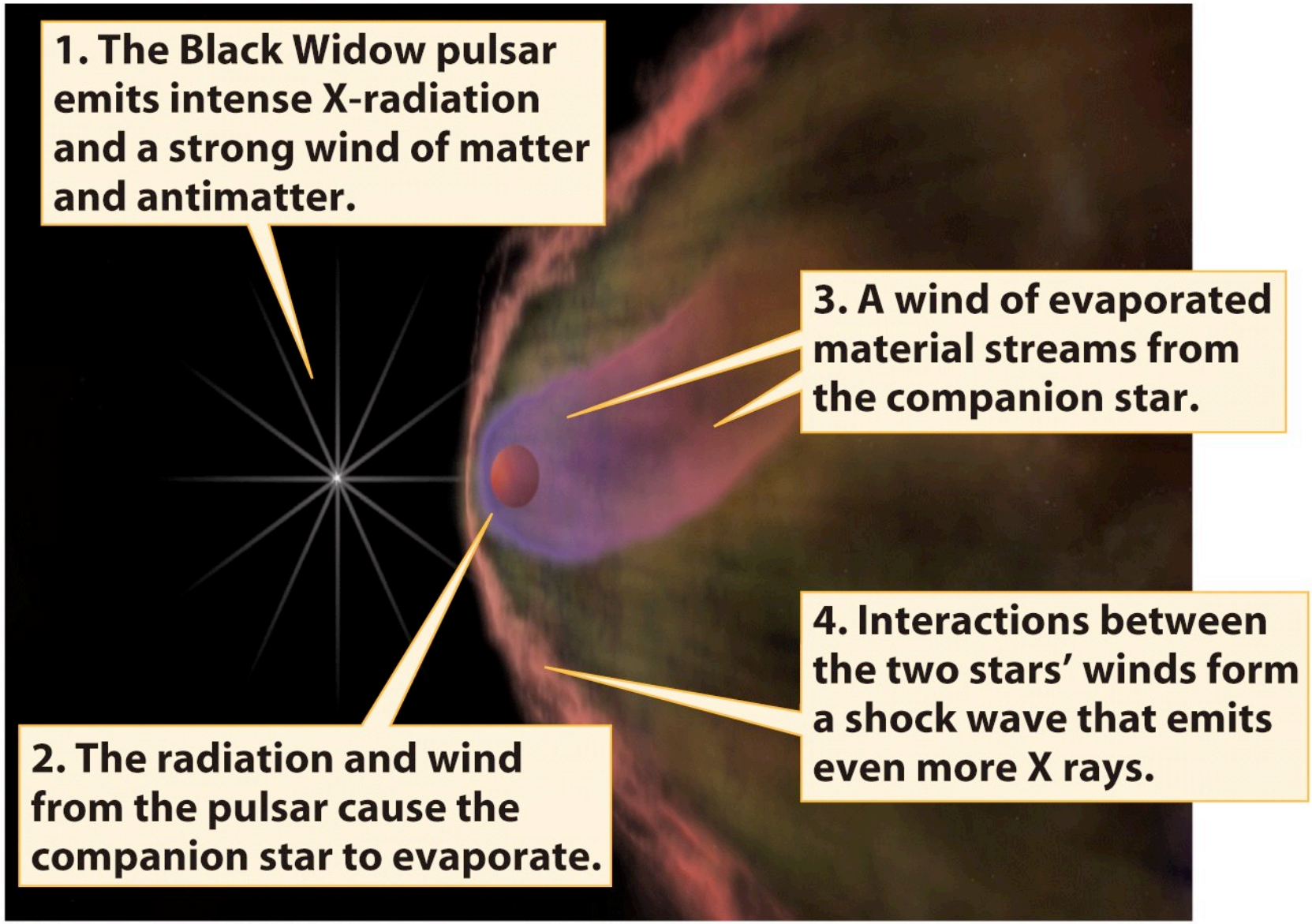

MAIN PULSE
"OFF" PHASE
PULSAR IN THE CRAB NEBULA
1 ARC-MIN


Rotation
Axis
Radiation
Beam
Radiation
Beam

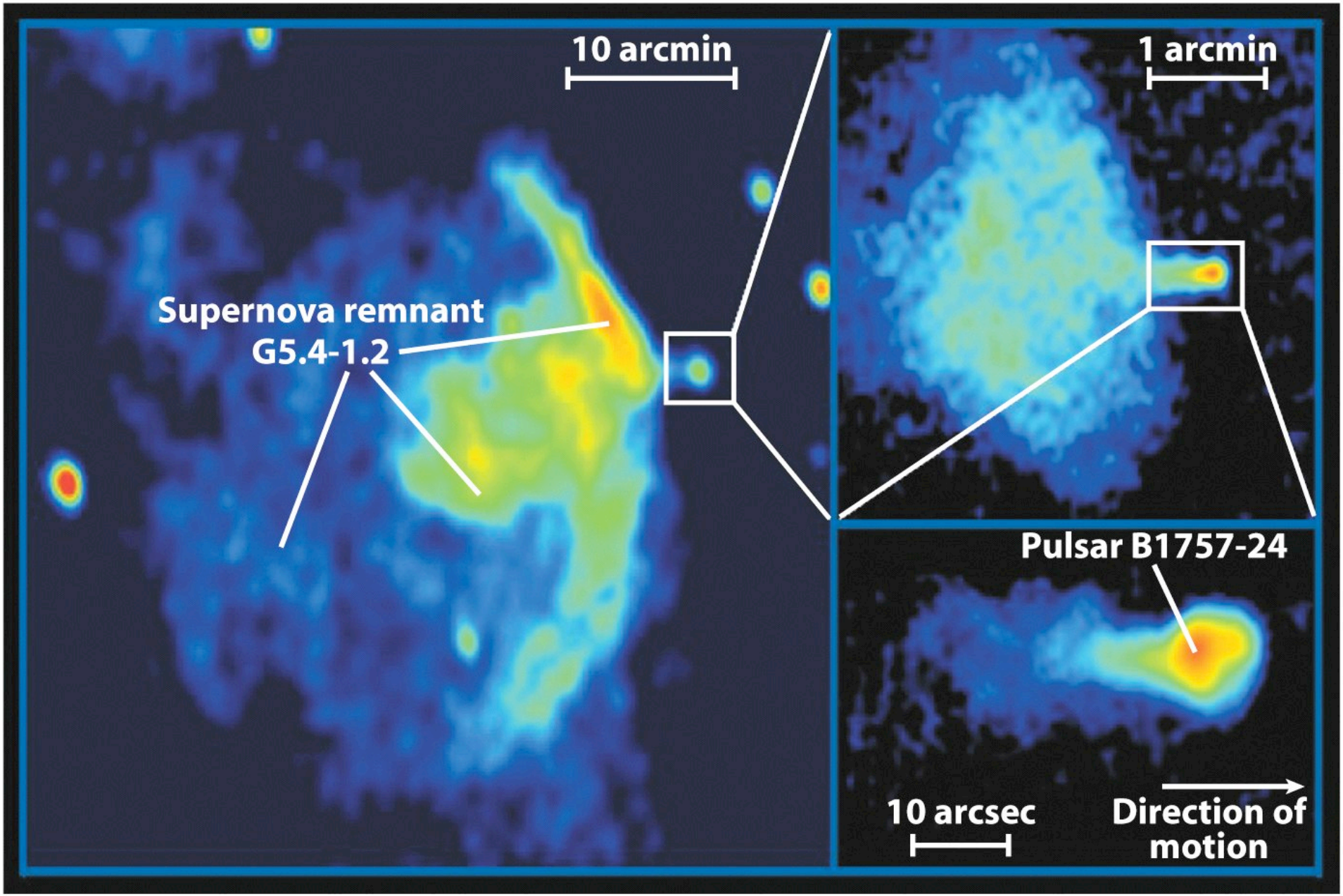



X-ray spectrum


The neutron star's rotation is gradually slowing down, so the pulsar period increases.
Pulsar glitch: The neutron star's rotation suddenly speeds up and the period decreases.
After the glitch, the neutron star's rotation resumes its slowdown and the period again increases.
Period (s)
0.089236
0.089235
0.089234
0.089233
M J J A S O N D J F M
1975
1976
Month




**An illustration of the pulsar and its companion**


10 arcmin
1 arcmin
Supernova remnant
G5.4-1.2
Pulsar B1757-24
10 arcsec
Direction of
motion

# Binary pulsar

In 1974, Russell Hulse and Joe Taylor discovered a pulsar in a close binary system. From analysis of the arrival time of the pulses, they determined that the orbit was eccentric (e = 0.62), with a period of 7.8 hours.

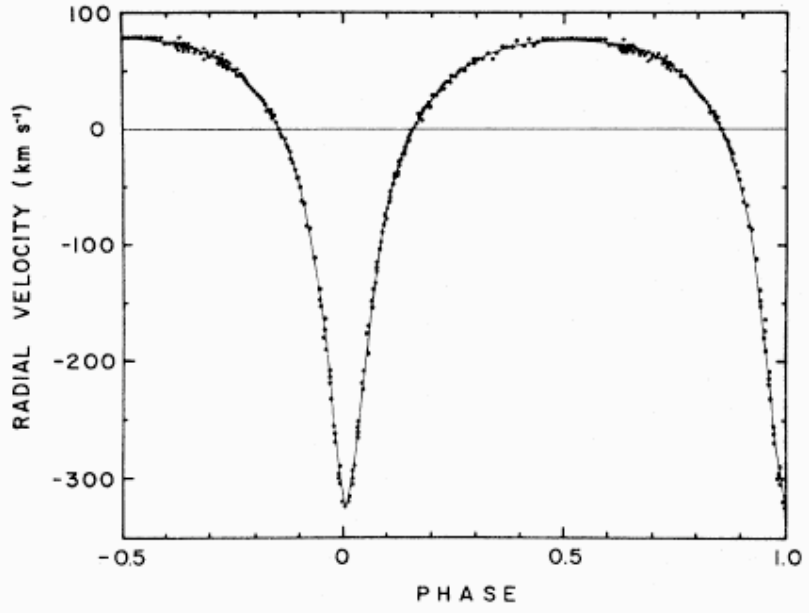
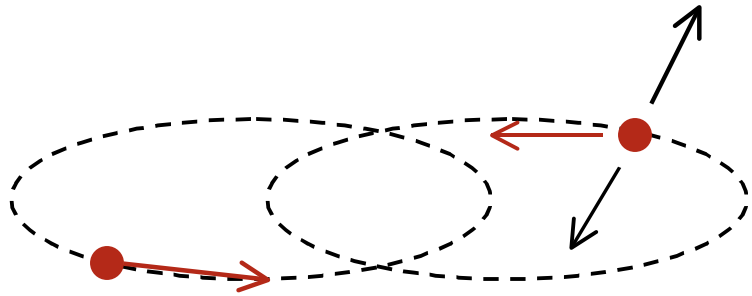



FIG. 12. The complete velocity curve for PSR 1913+16 from the discovery paper, fitted with a Keplerian orbital solution. The orbital phase is the fraction of a binary orbital period of $7^h45^m$ (from R. A. Hulse and J. H. Taylor, 1975a).



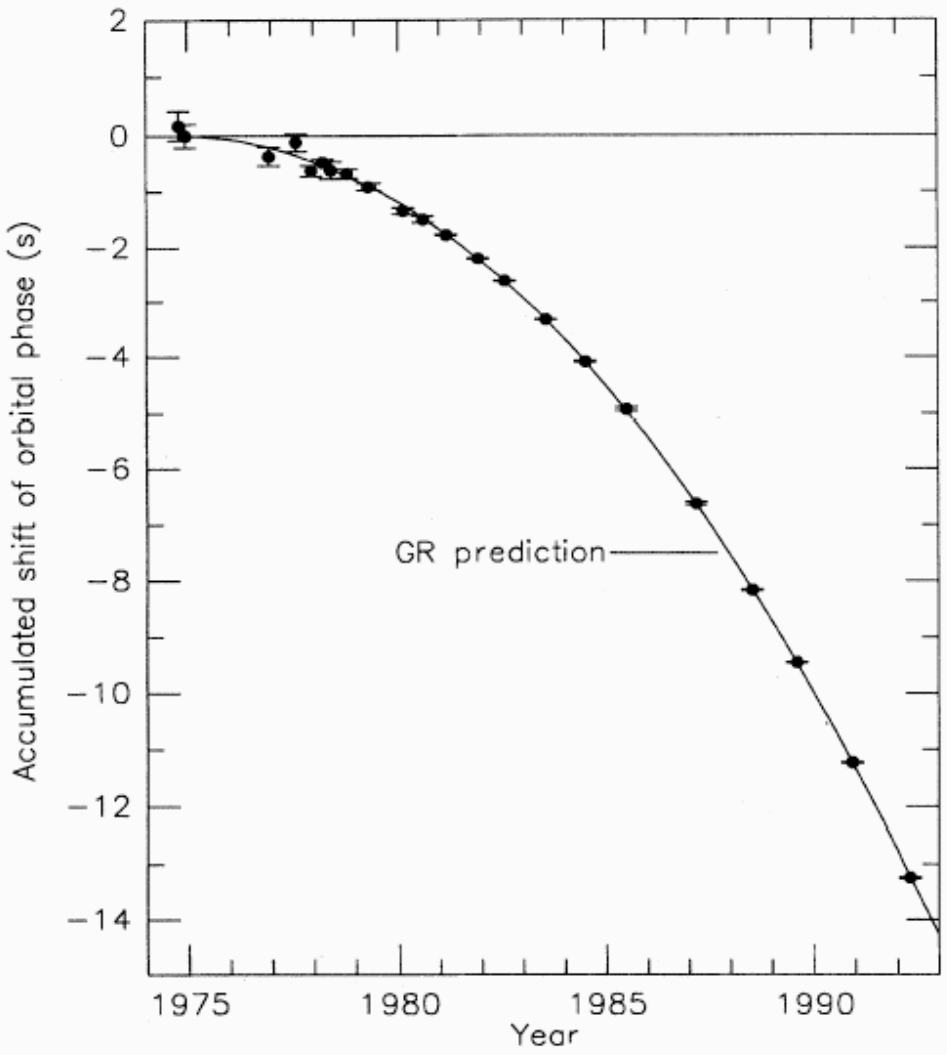
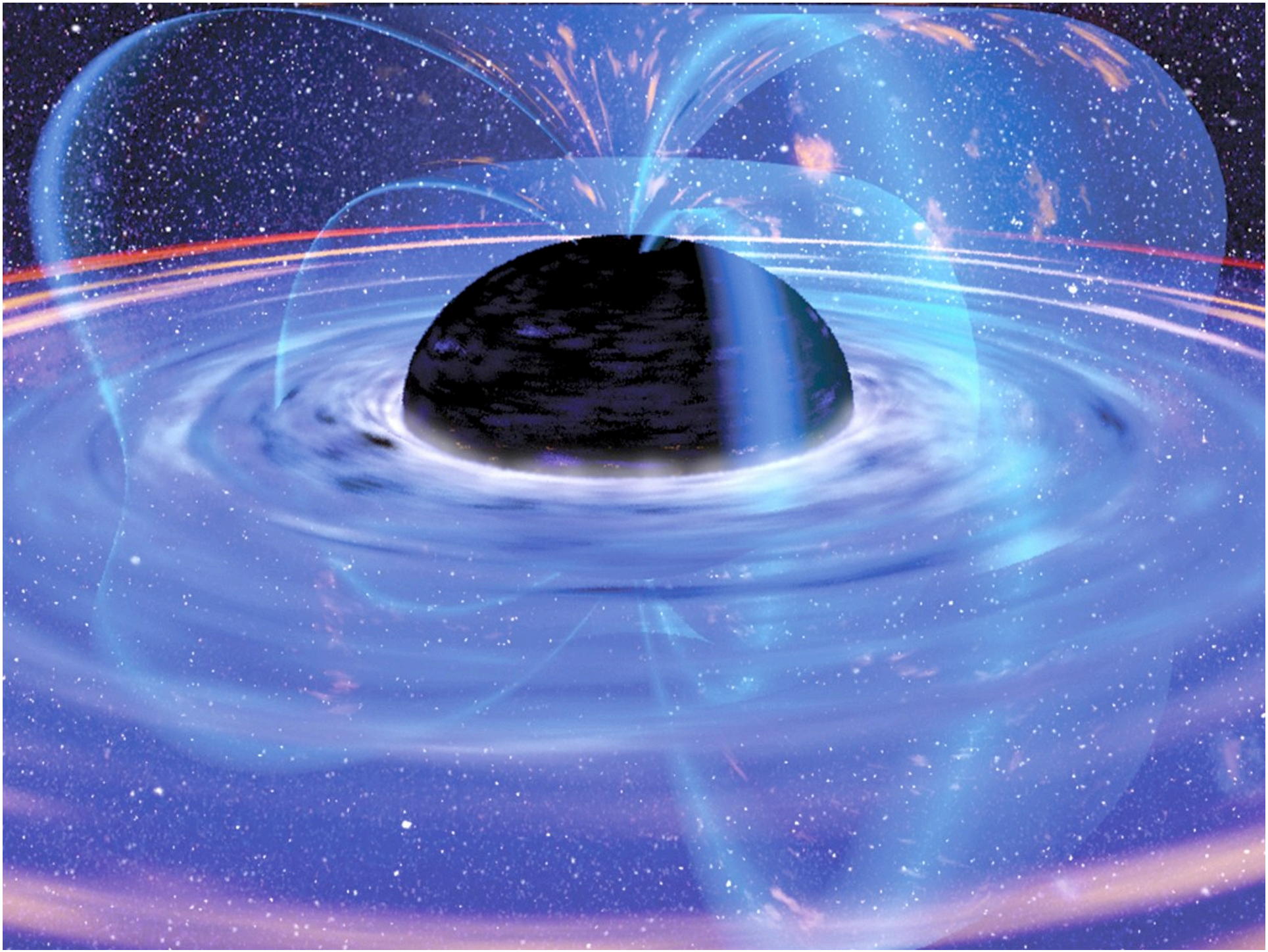
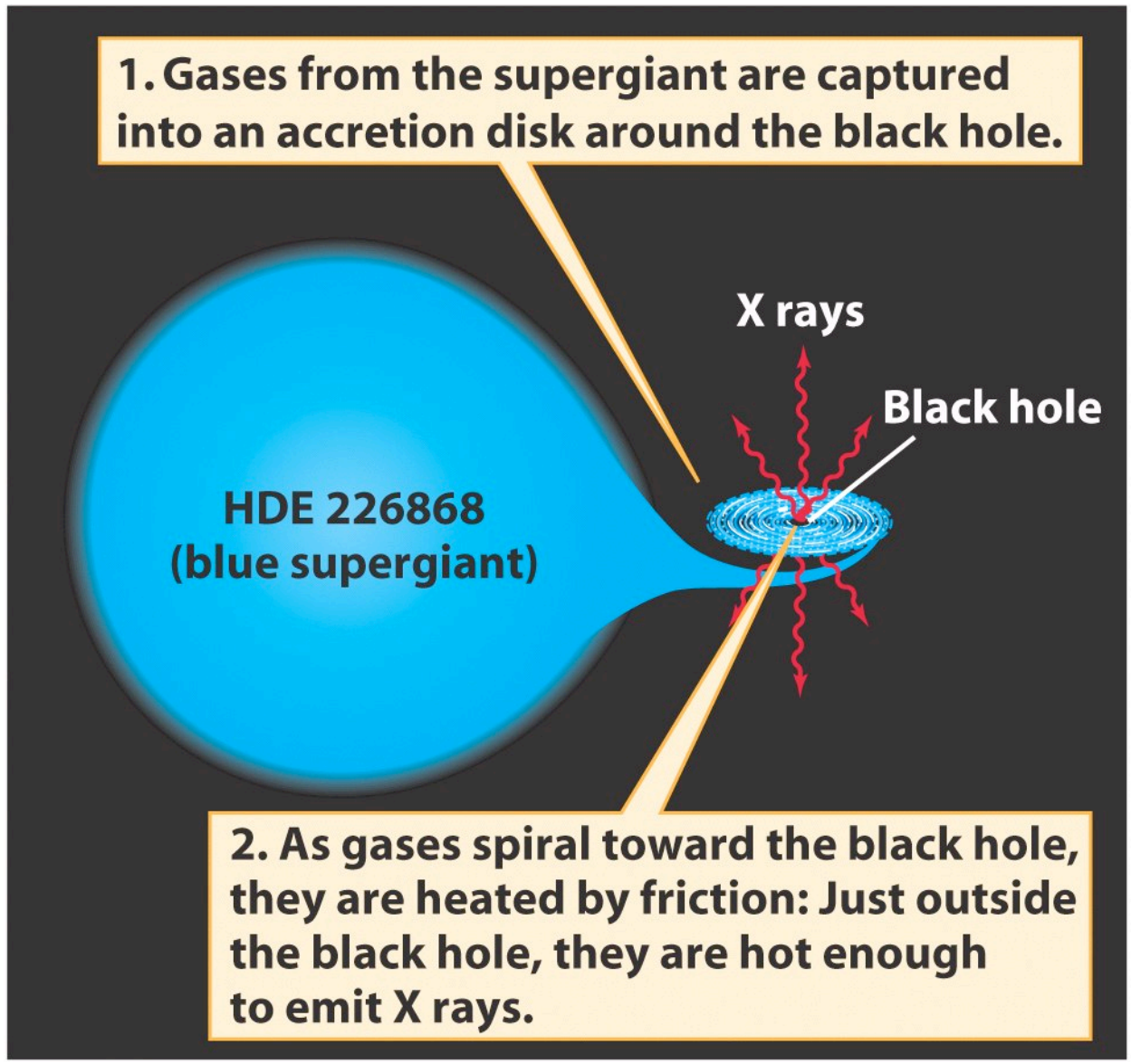



FIG. 10. Accumulated shift of the times of periastron in the PSR 1913+16 system, relative to an assumed orbit with constant period. The parabolic curve represents the general relativistic prediction for energy losses from gravitational radiation.

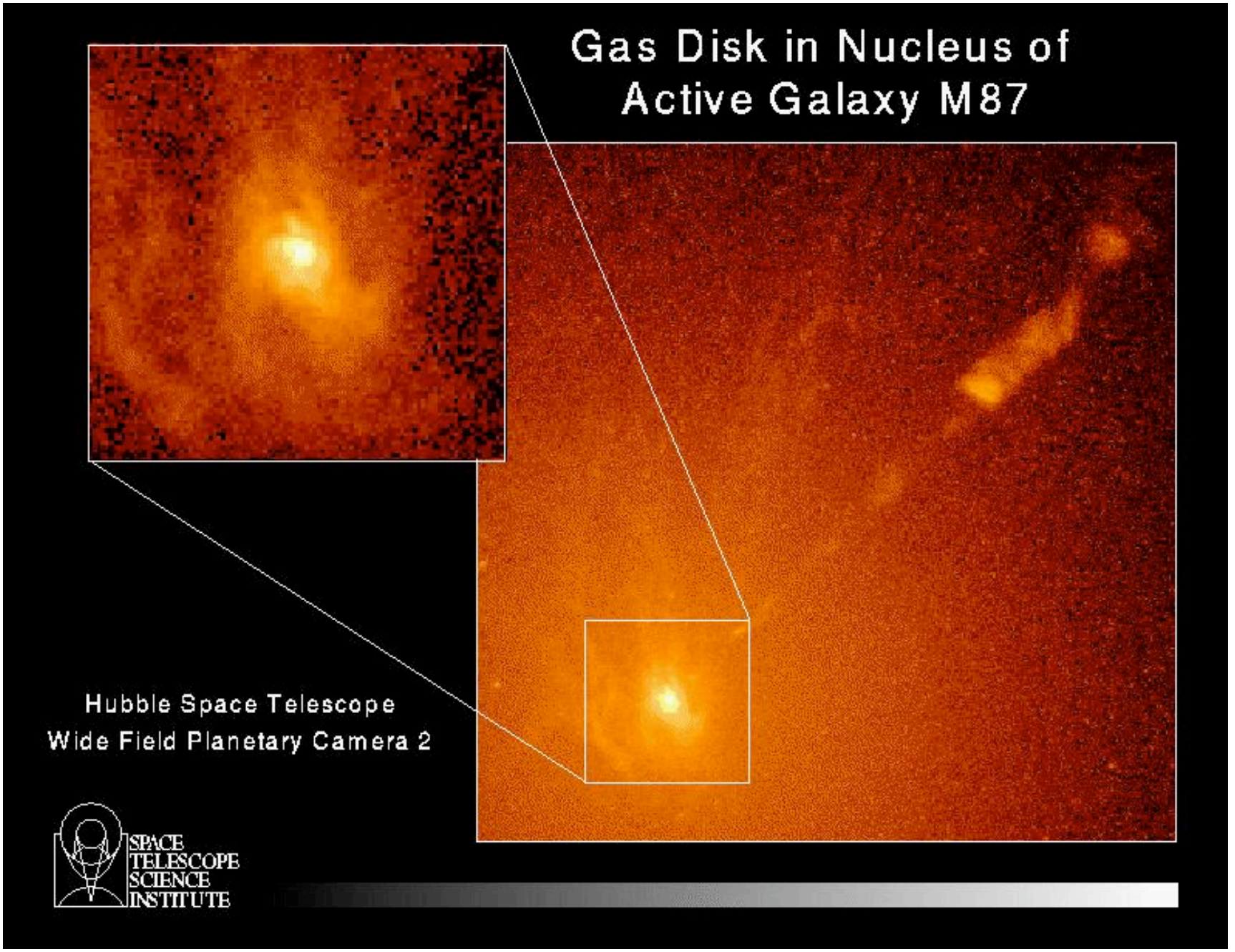
Observed change in time of closest approach matches the General Relativity prediction.

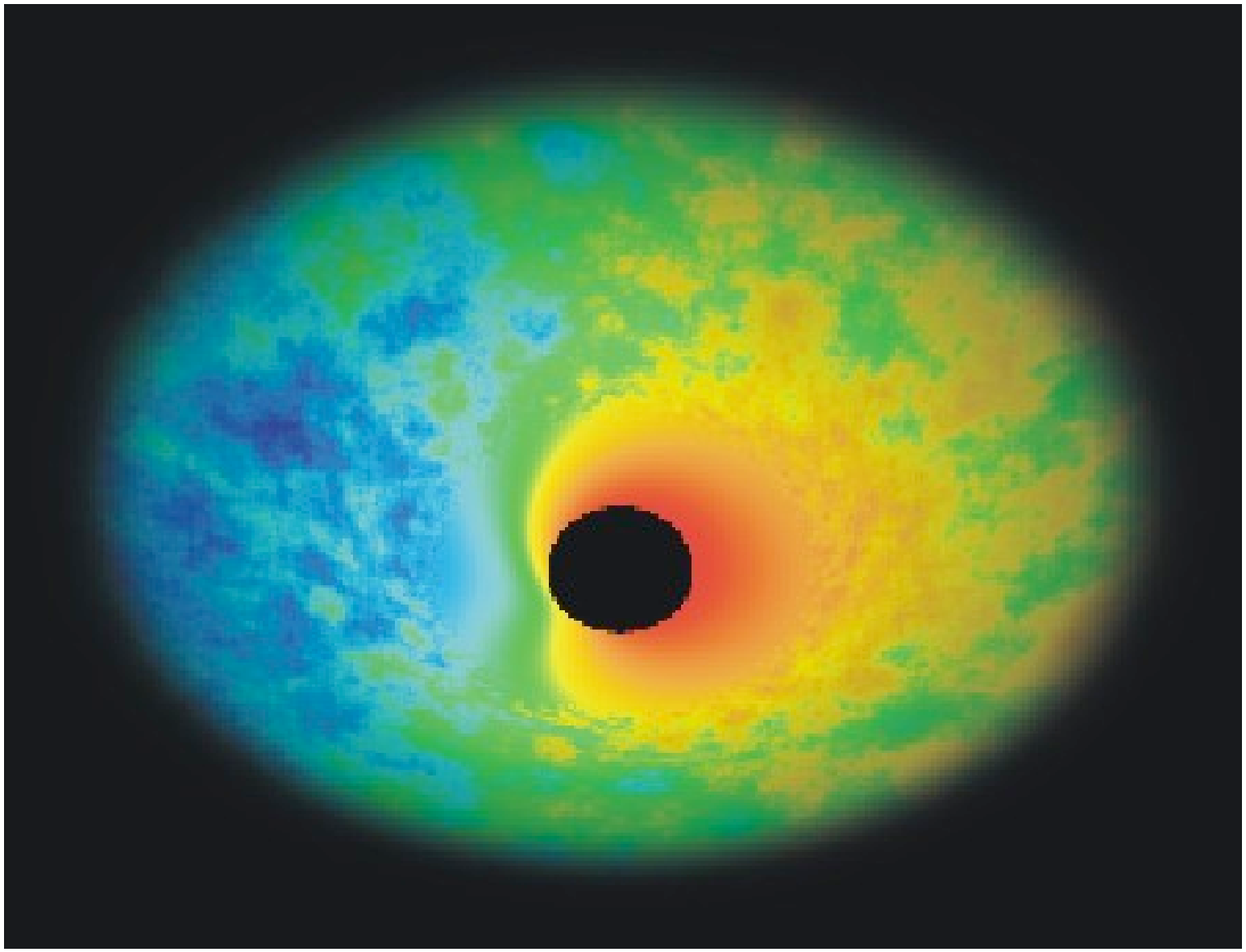
Orbit shrinks by ~3 mm per orbit of the binary system.



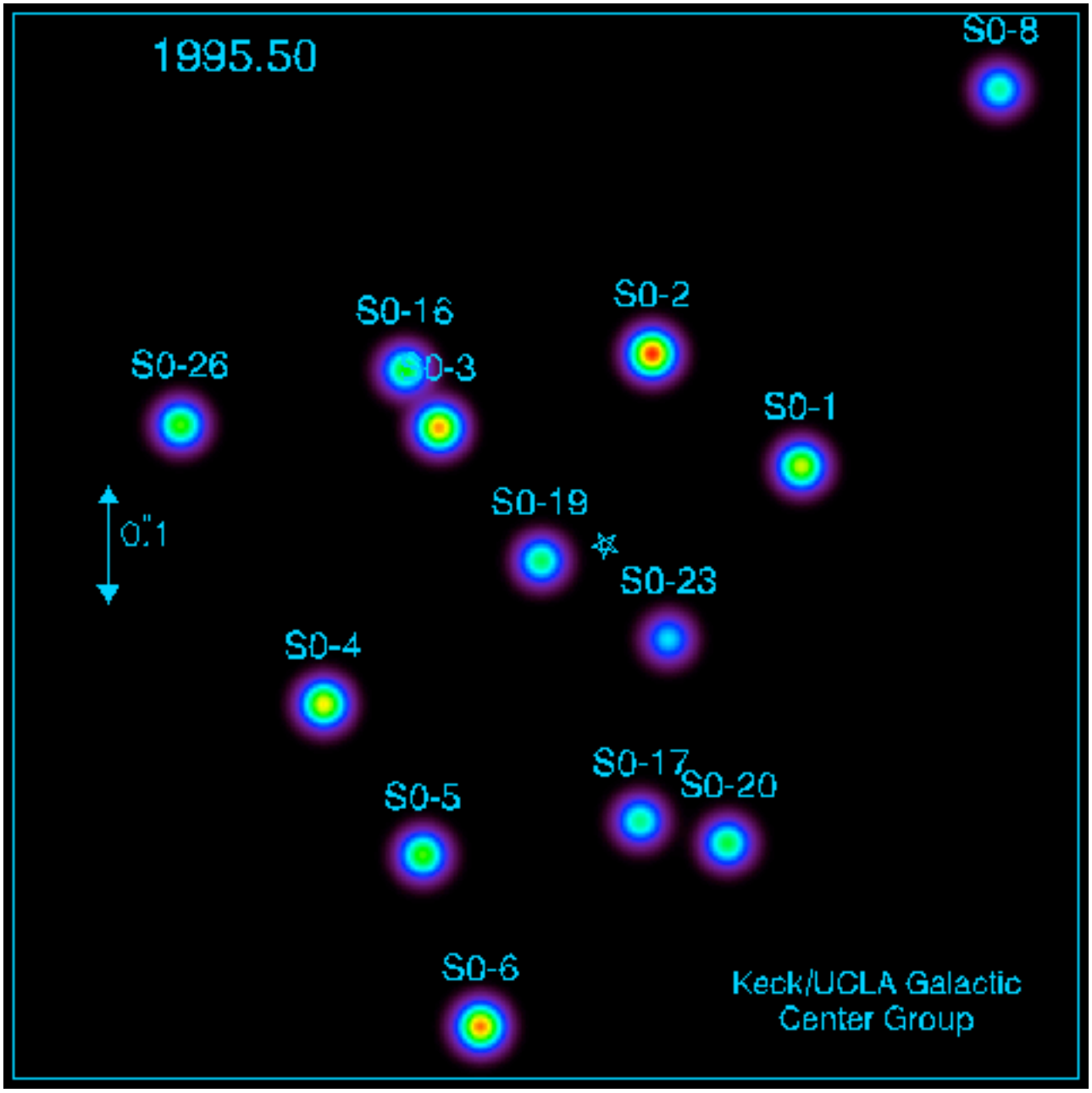


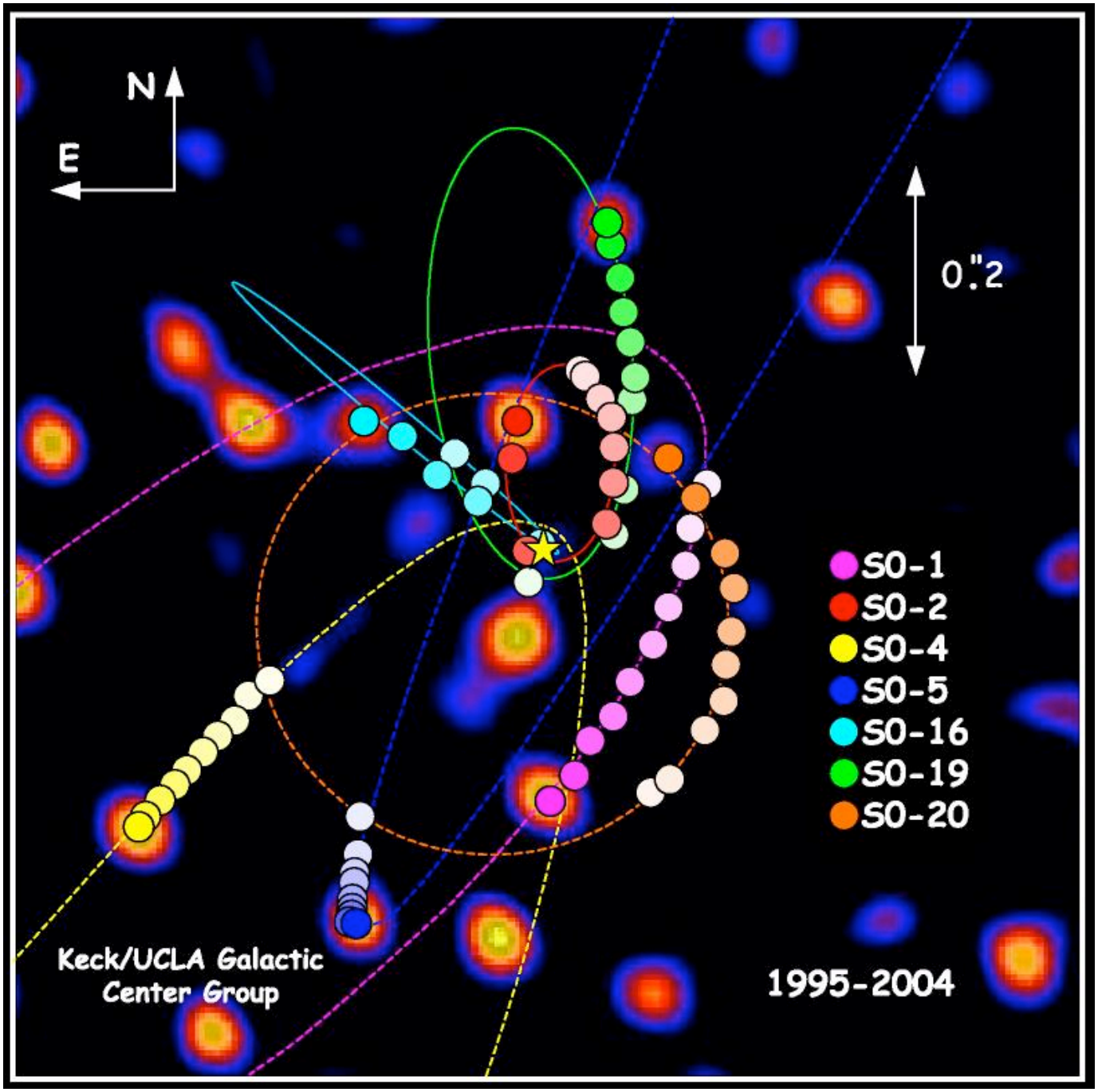

A schematic diagram of Cygnus X-1

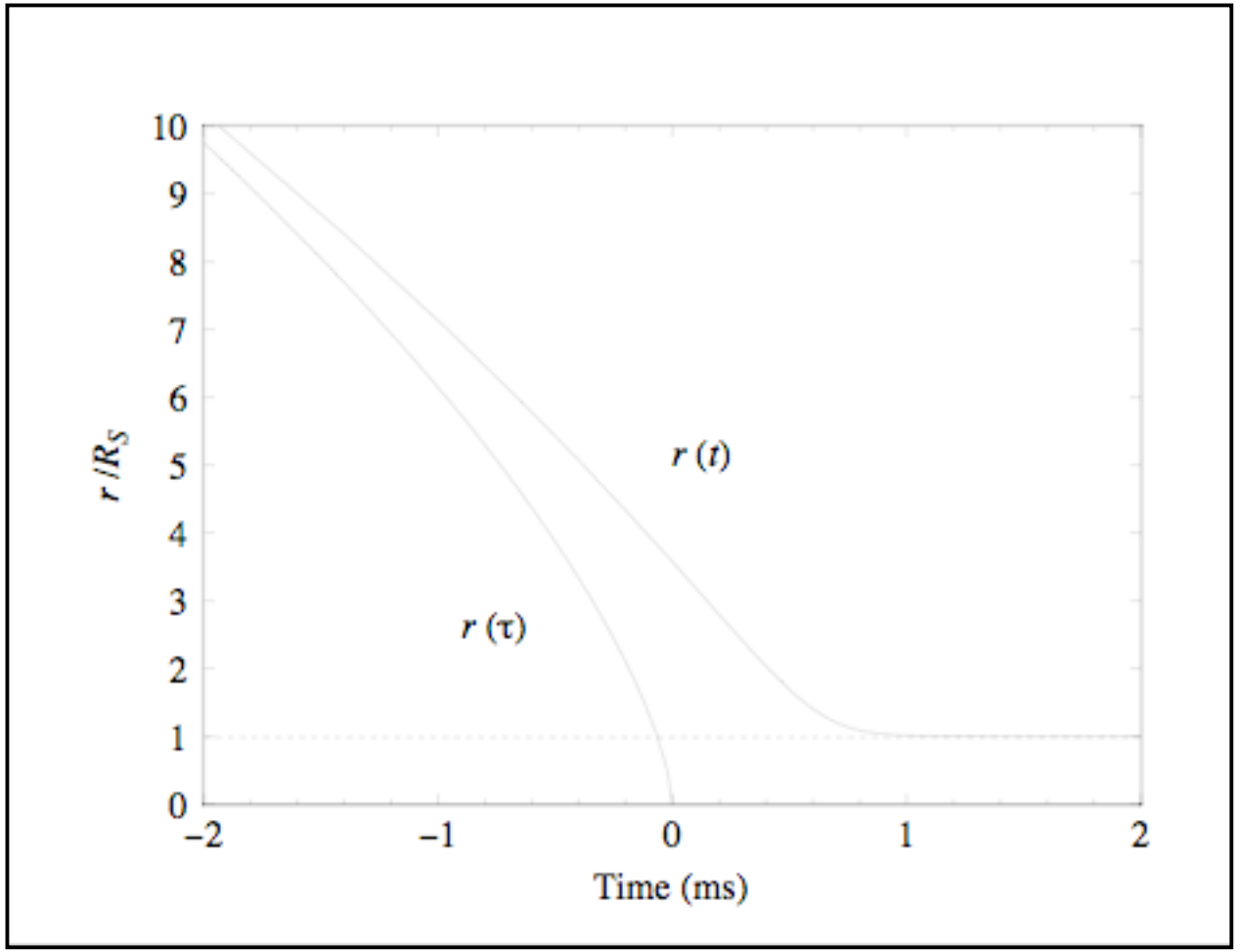

Gas Disk in Nucleus of
Active Galaxy M87
Hubble Space Telescope
Wide Field Planetary Camera 2
SPACE
TELESCOPE
SCIENCE
INSTITUTE

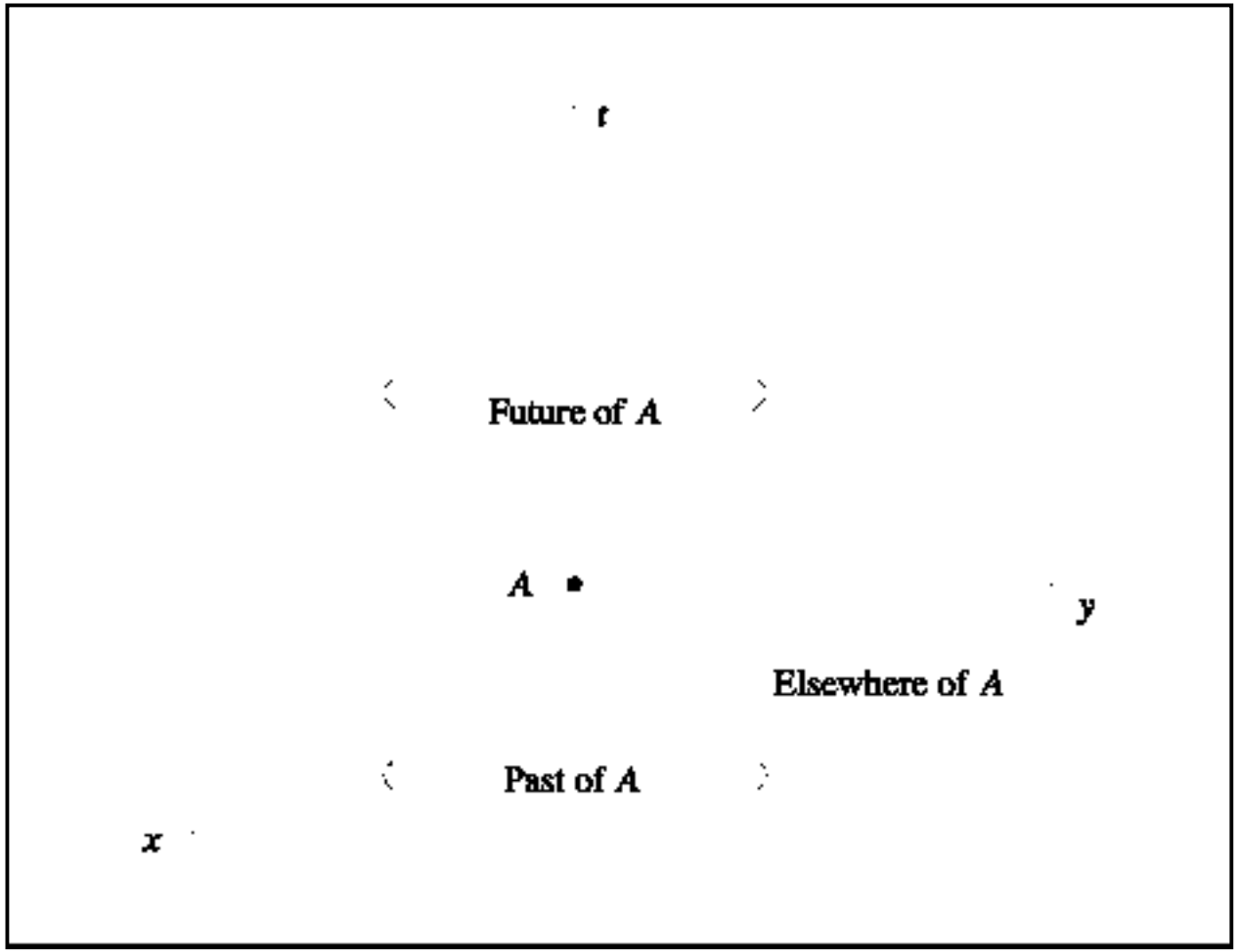


*Ben Bromley (Harvard CfA)*


1995.50
S0-8
S0-16
S0-2
S0-26
S0-3
S0-1
0."1
S0-19
S0-23
S0-4
S0-17
S0-20
S0-5
S0-6
Keck/UCLA Galactic
Center Group


N
E
0."2
S0-1
S0-2
S0-4
S0-5
S0-16
S0-19
S0-20
Keck/UCLA Galactic
Center Group
1995-2004


10
9
8
7
6
5
4
3
2
1
0
$r/R_S$
$r(t)$
$r(\tau)$
−2
−1
0
1
2
Time (ms)


t
Future of A
A
y
Elsewhere of A
Past of A
x