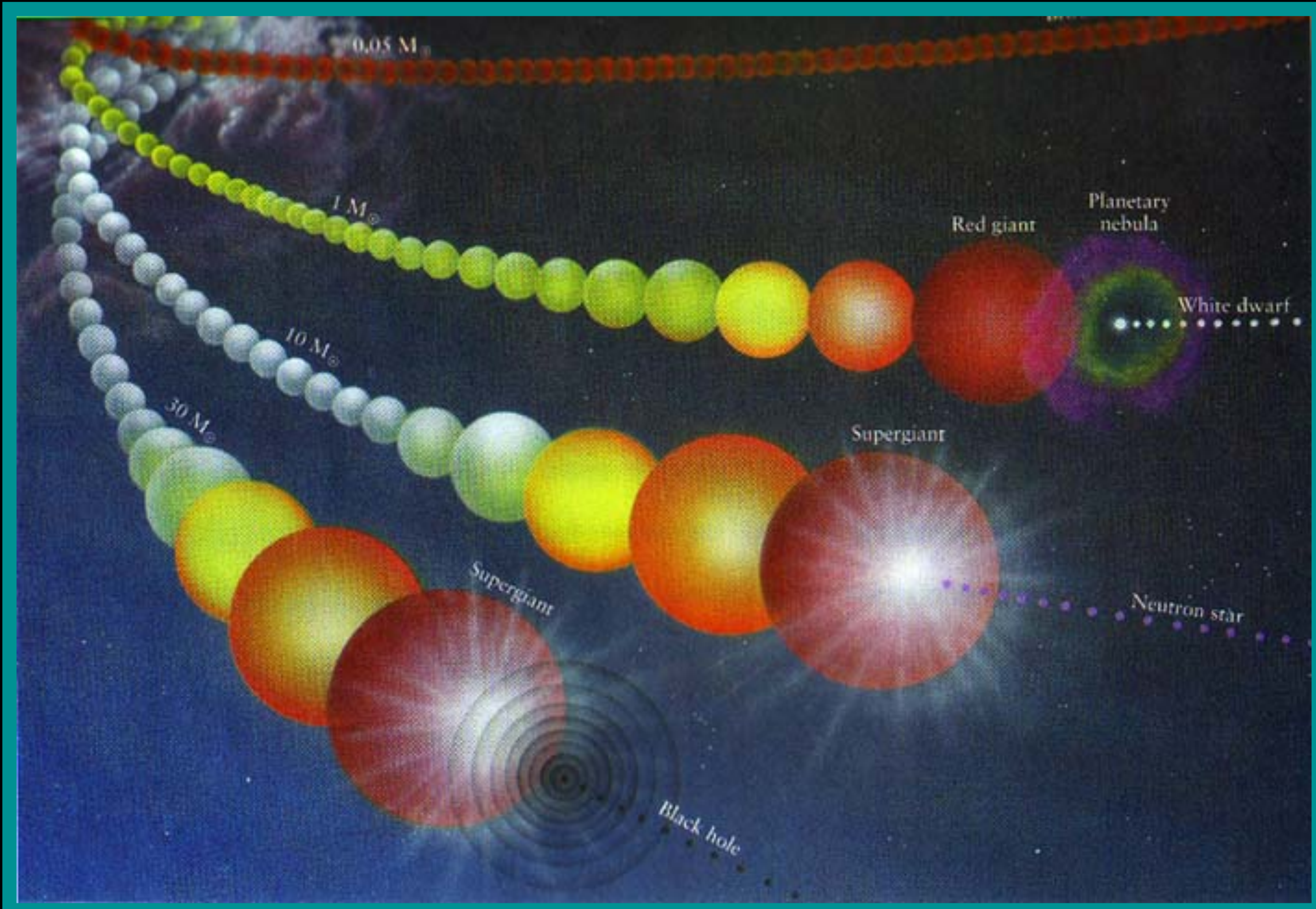
Termination of Stars



Some Quantum Concepts

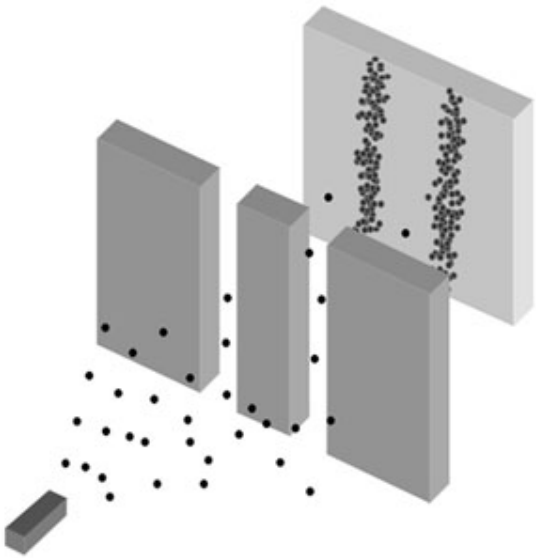
- ***Pauli Exclusion Principle:***

  Effectively limits the amount of certain kinds of stuff that can be crammed into a given space (particles with "personal space").
- When densities approach this limit, matter becomes "degenerate".
- Gas pressure depends on density only, and not temperature.

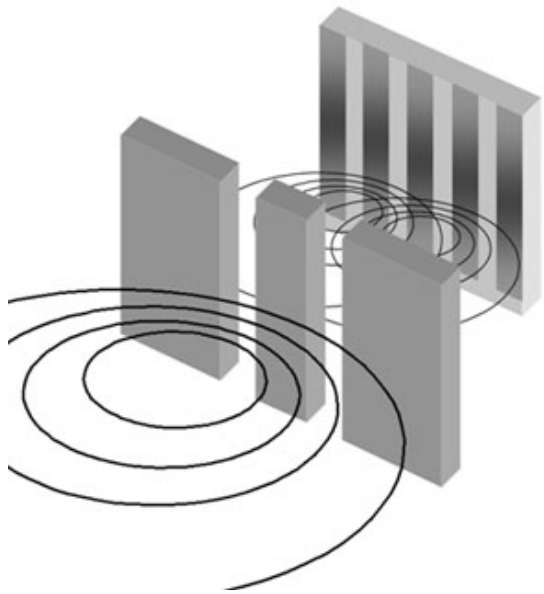
- ***Heisenberg Uncertainty Principle:***

  Cannot simultaneously know both particle position and momentum exactly. Particles can have large speeds when densely packed, and so high pressure, regardless of temperature.

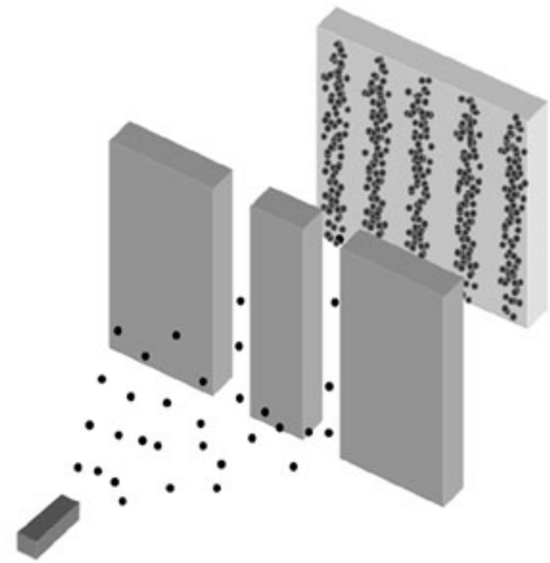
Wave-Particle Duality: The Two-Slit Experiments



Particles - Mud stripes



Waves - fringe pattern



Electrons - both!!!

Types of Degeneracy

- Electron Degeneracy:
  - Atoms are crammed.
  - Occurs at $\rho \sim 10^6$ g/cm^3.
  - White Dwarf stars halt collapse via this pressure.

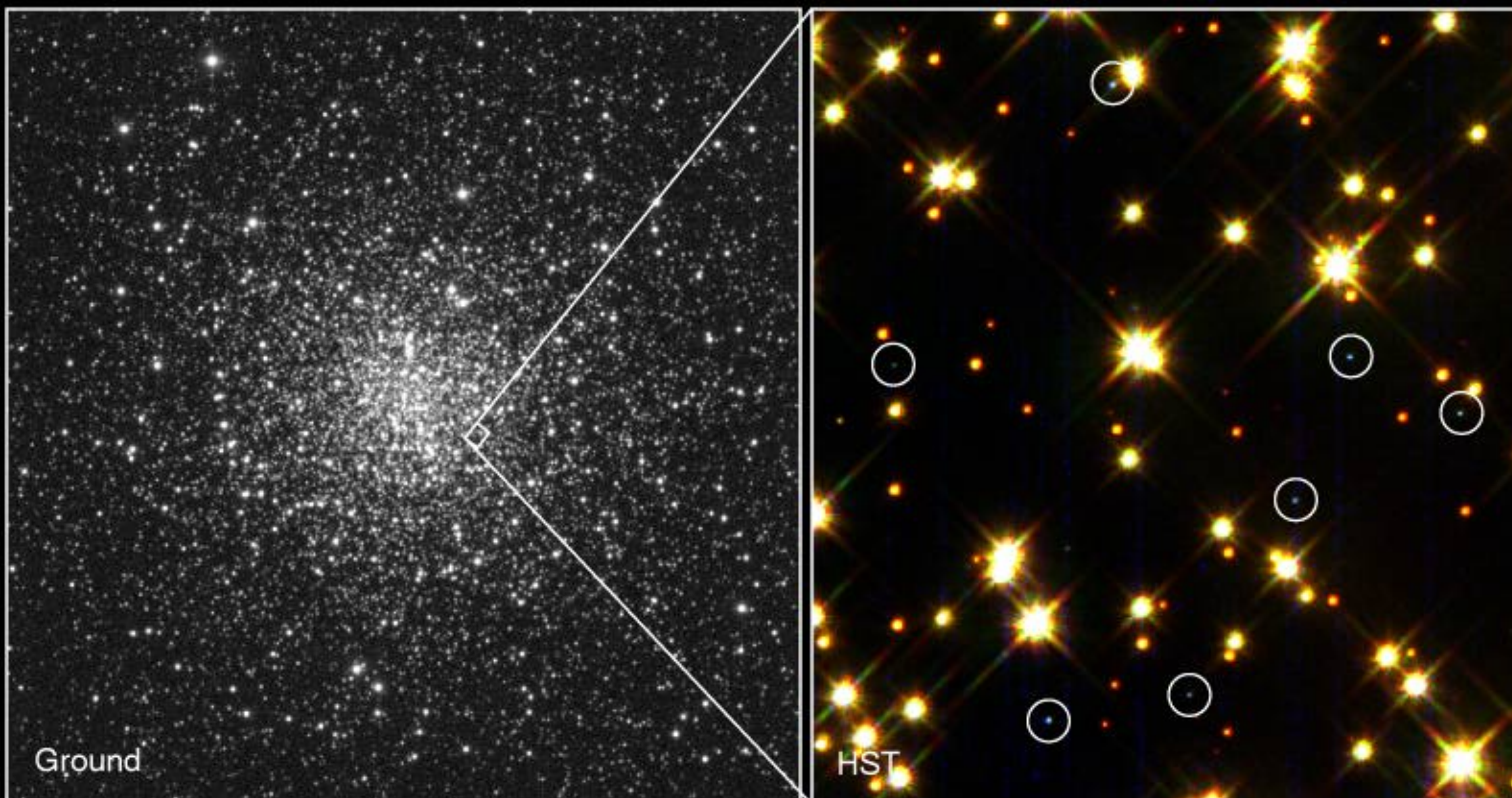
- Neutron Degeneracy:
  - If gravity is too strong, electrons forced into nucleus with protons to make neutrons.
  - Now nuclei are crammed.
  - Occurs at $\rho \sim 10^{15}$ g/cm^3!
  - This pressure supports Neutron stars.

Stellar Corpses – Low Mass Stars

Stars with $M < 8M_o$ become White Dwarfs (WDs)

1. Chandrasekhar Limit: $M_{WD} < 1.4M_o$, otherwise gravity overwhelms electron degeneracy pressure
2. For normal stars, bigger M yields bigger R, but opposite for WDs
3. Radius is fixed, and WD still glows, so it just continues to cool and fade (i.e., temperature drops over time)

White Dwarfs in Space

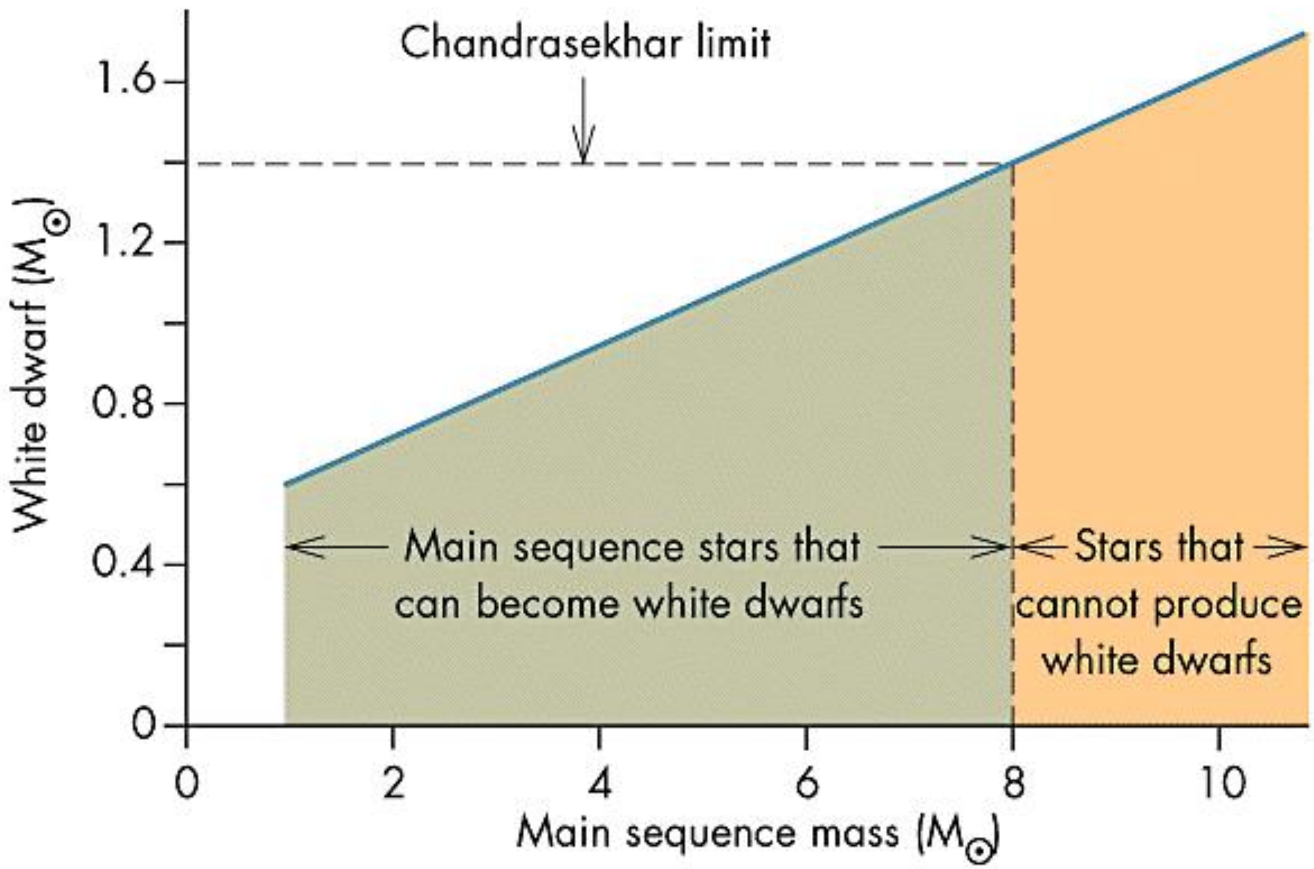


White Dwarf Stars in M4

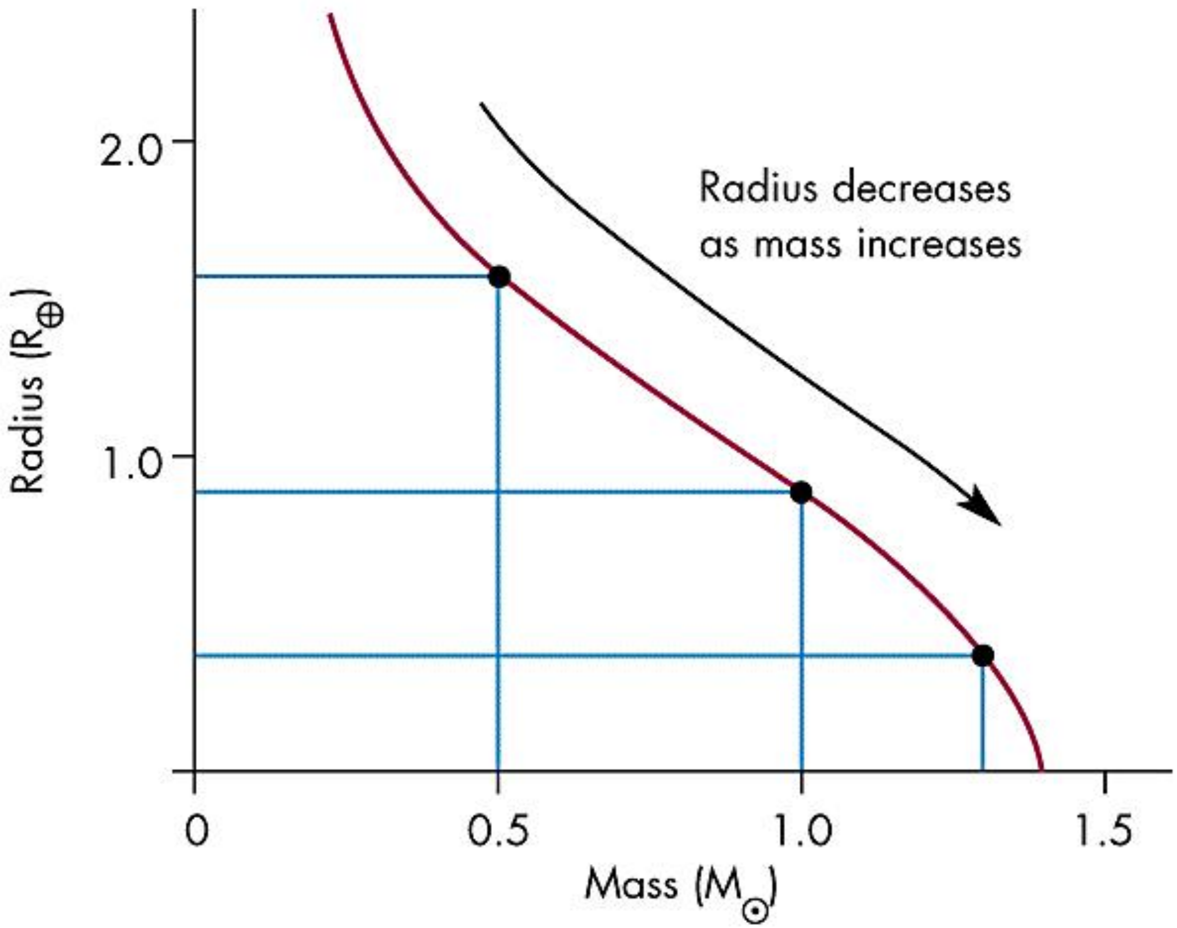
HST • WFPC2

PRC95-32 · ST ScI OPO · August 28, 1995 · H. Bond (ST ScI), NASA

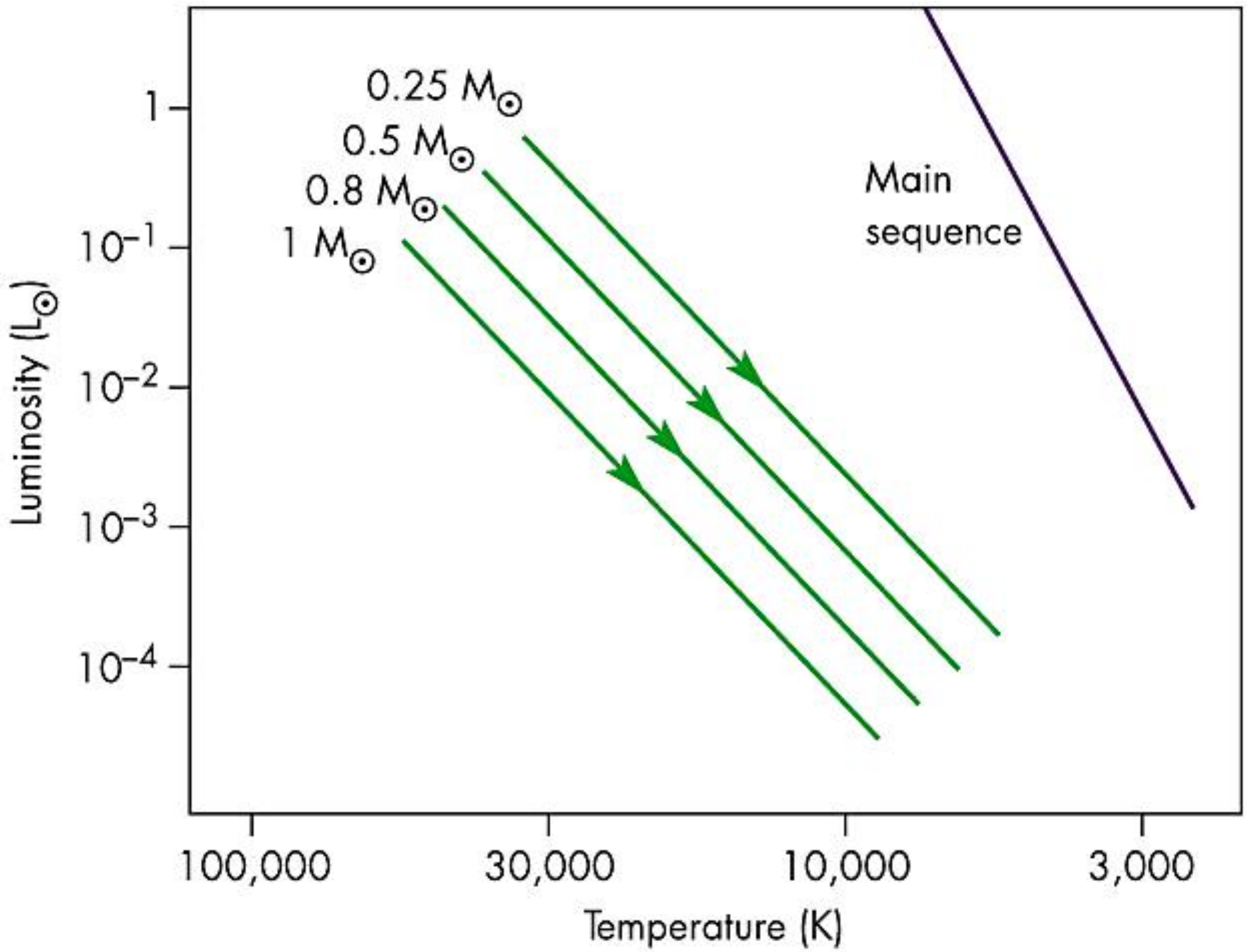
The Chandrasekhar Limit for White Dwarf Stars



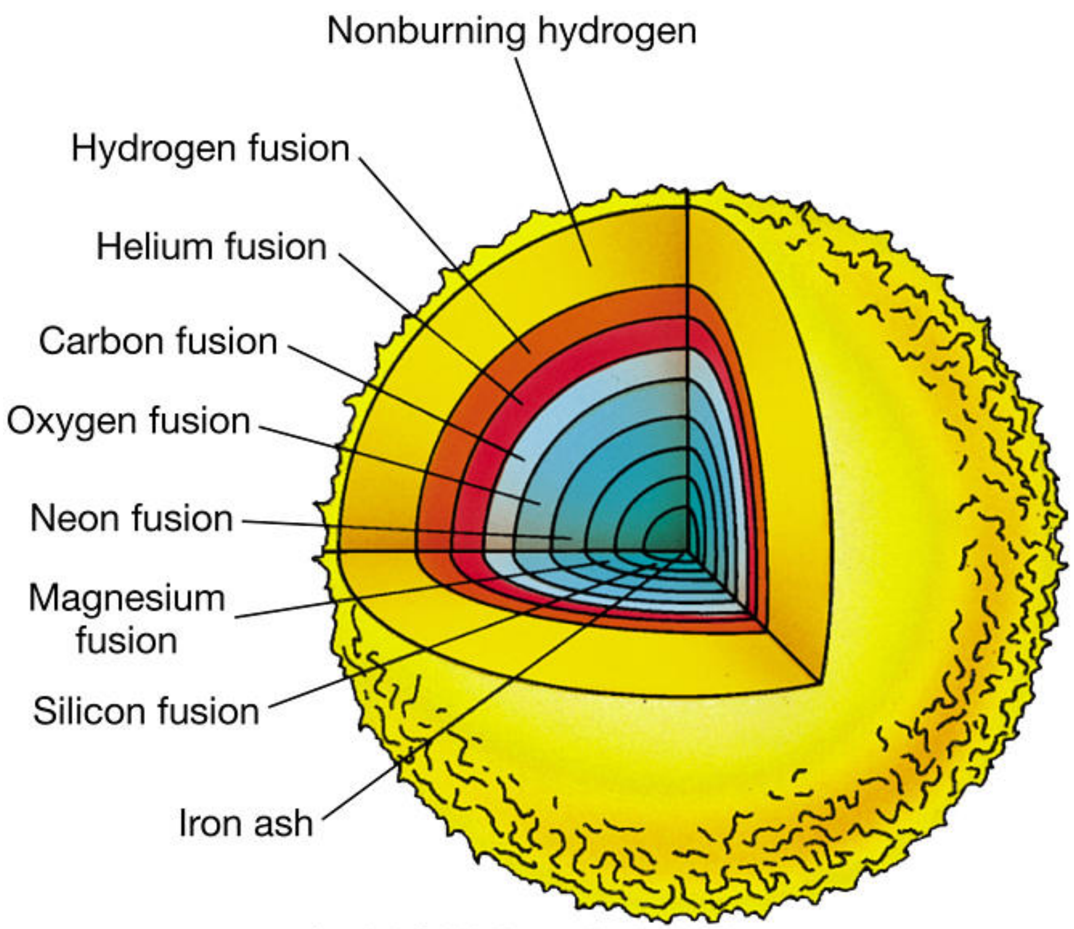
Mass-Radius for White Dwarfs



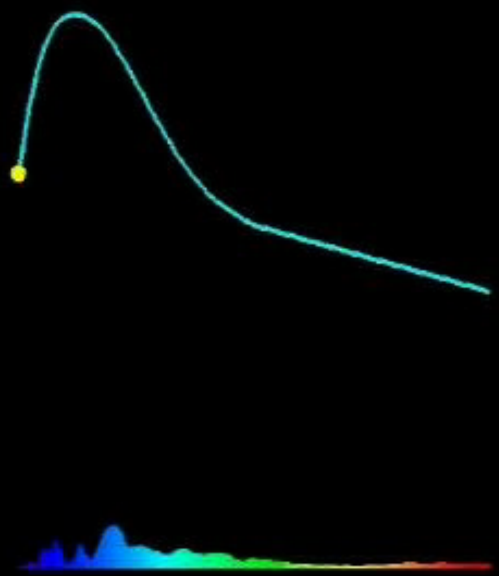
White Dwarf Tracks in the HRD



Massive Star at Life's End

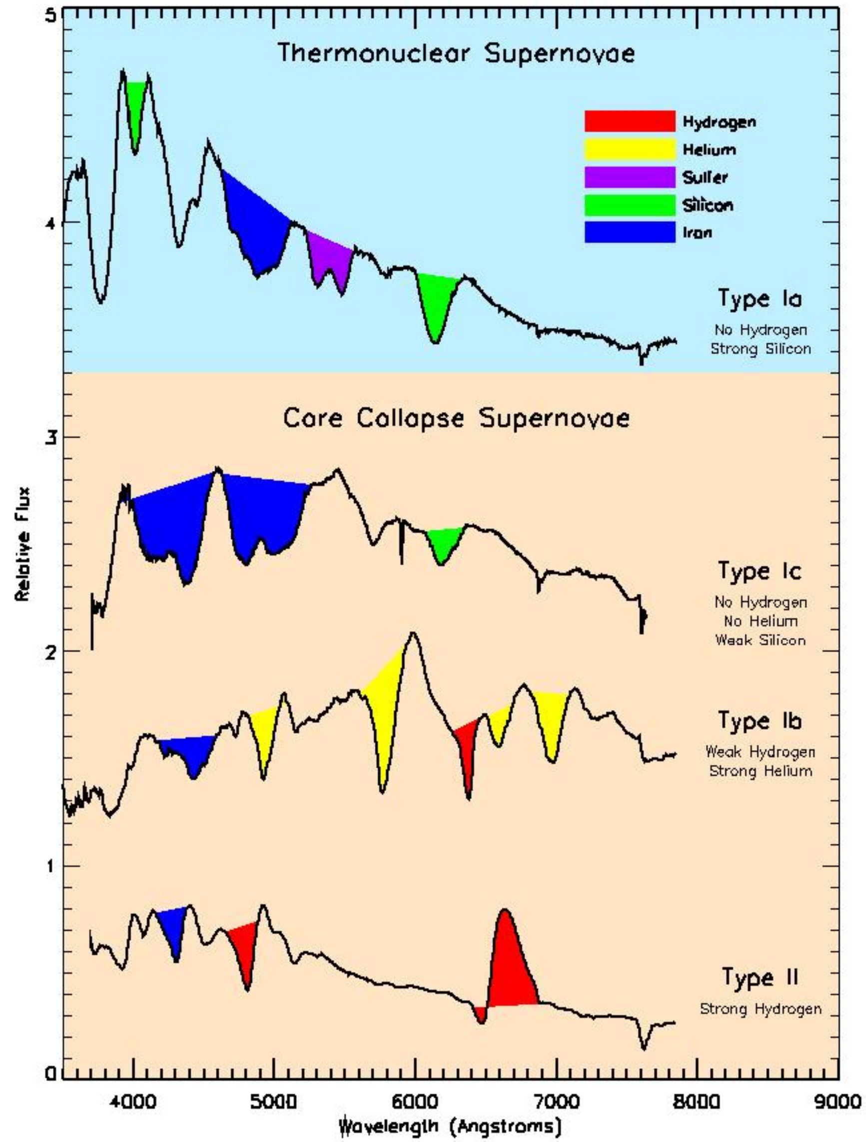


A Supernova



Supernova Types

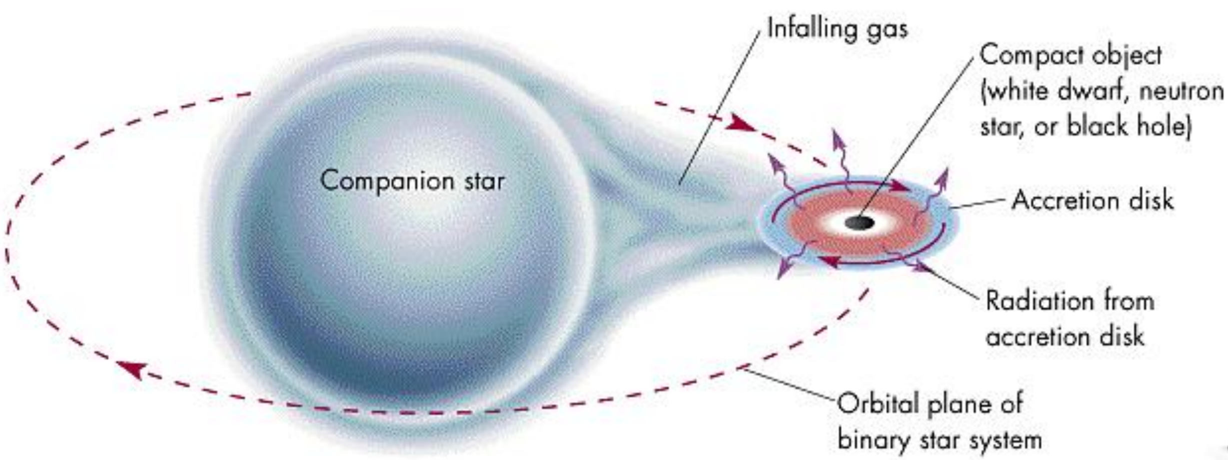
- Type Ia
  - Lacks hydrogen
  - Consists of a WD in a binary with mass transfer
  - Used as standard candle
- Type II
  - Shows hydrogen
  - Explosion of a single massive star



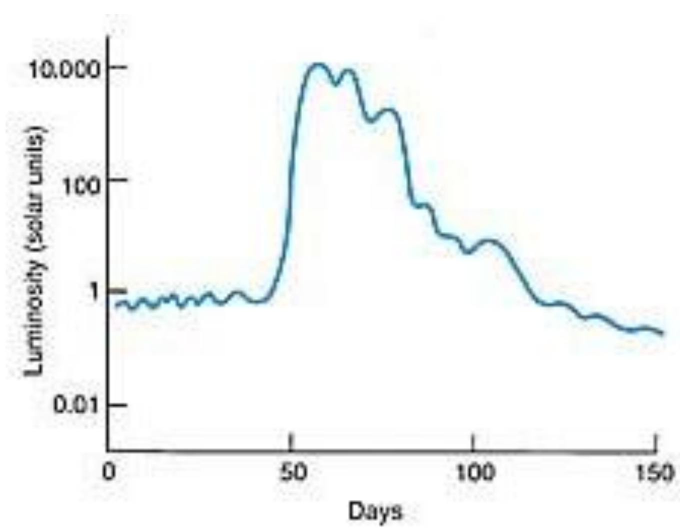
WDs in Binaries

- Mass can transfer from a normal star to a WD, resulting in an accretion disk.
- This is a disk of gas orbiting the WD with gas slowly "seeping" inward to the WD.
- **NOVAE**: Hydrogen gas accumulates and heats up until fusion switches on. Leads to an explosion and ejection of mass. Repeats.
- **SUPERNOVAE**: (Type Ia) Transfer is rapid so fusion is ongoing. Mass accumulates until Chandra limit is exceeded which leads to a catastrophic explosion. SNe can become brighter than a galaxy for a time.

Sketch of a Cataclysmic Variable



Example
Nova lightcurve



Stellar Corpses – High Mass Stars

If 8 M_o < M < 25 M_o, stars explode as Type II SNe

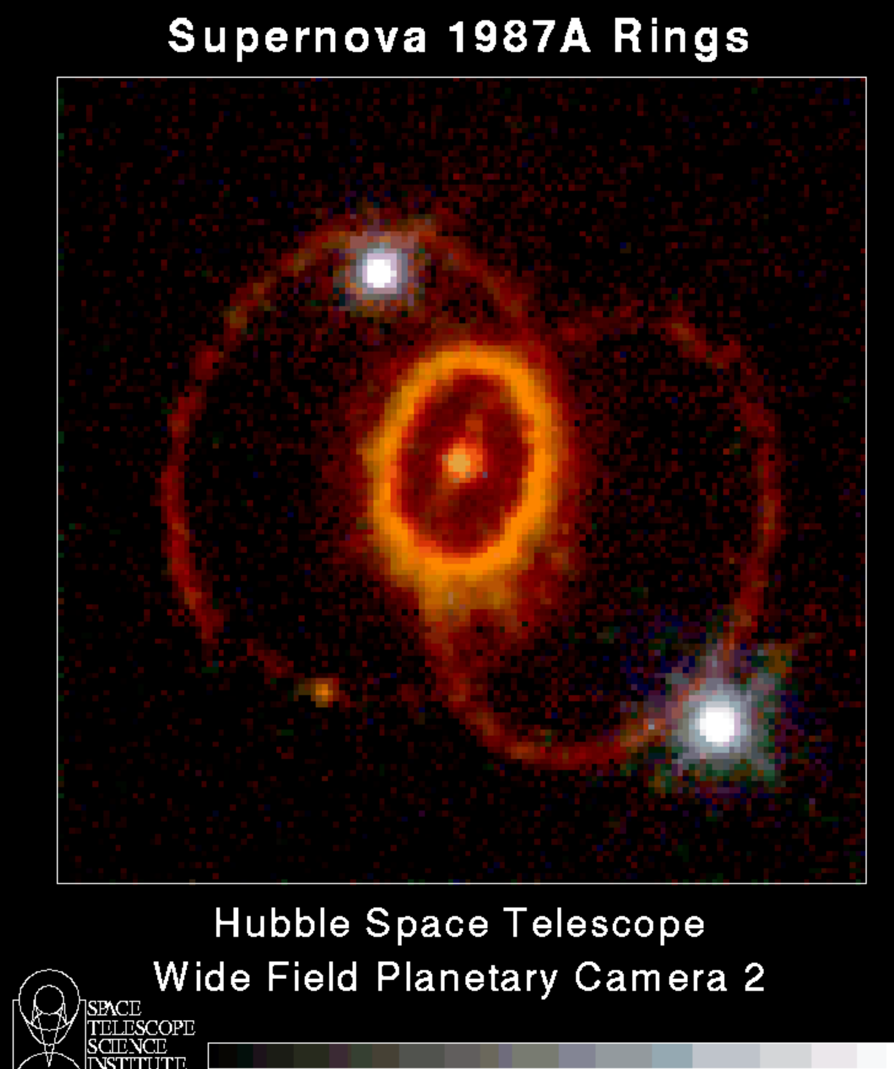
- Nuclear fusion of elements up to iron
- Central core becomes a WD, then a NS. Gravitational contraction is resisted, and a violent "shudder" lifts outer gas layers
- LOTS of neutrinos made to accelerate material away
- A NS remains, with
  - R ~ 10–15 km
  - M ~ 1.5–3 M_o
  - Fast rotation and strong magnetic fields

Historical Supernovae

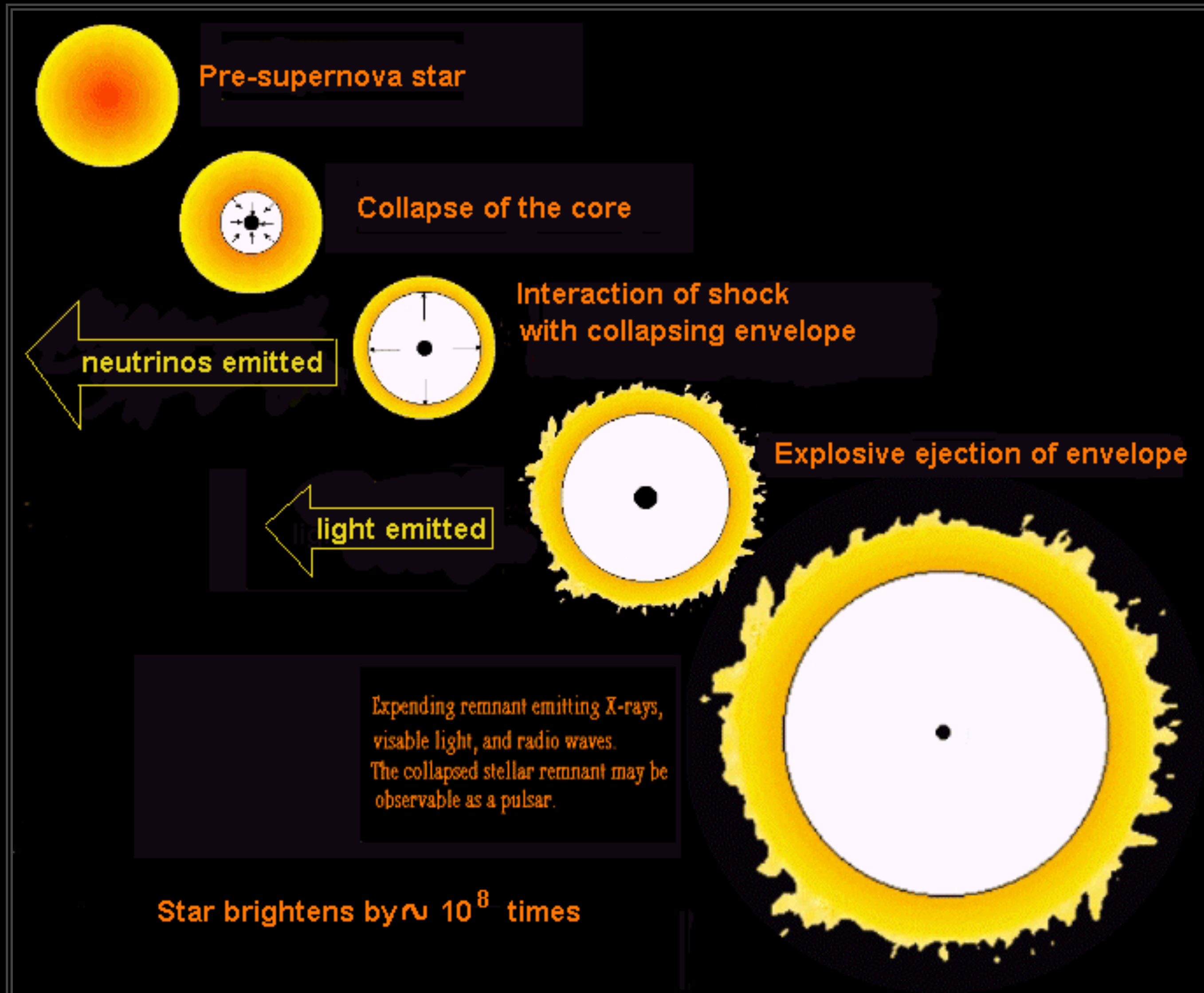
1006	Chinese
1054	Chinese
1572	Brahe
1604	Kepler
1987A	in LMC

- 1967, first Pulsar was discovered
- These are fast rotating NS's that beam radiation out (nearly) along the magnetic poles
  - ➢ The effect is like a lighthouse Beacon

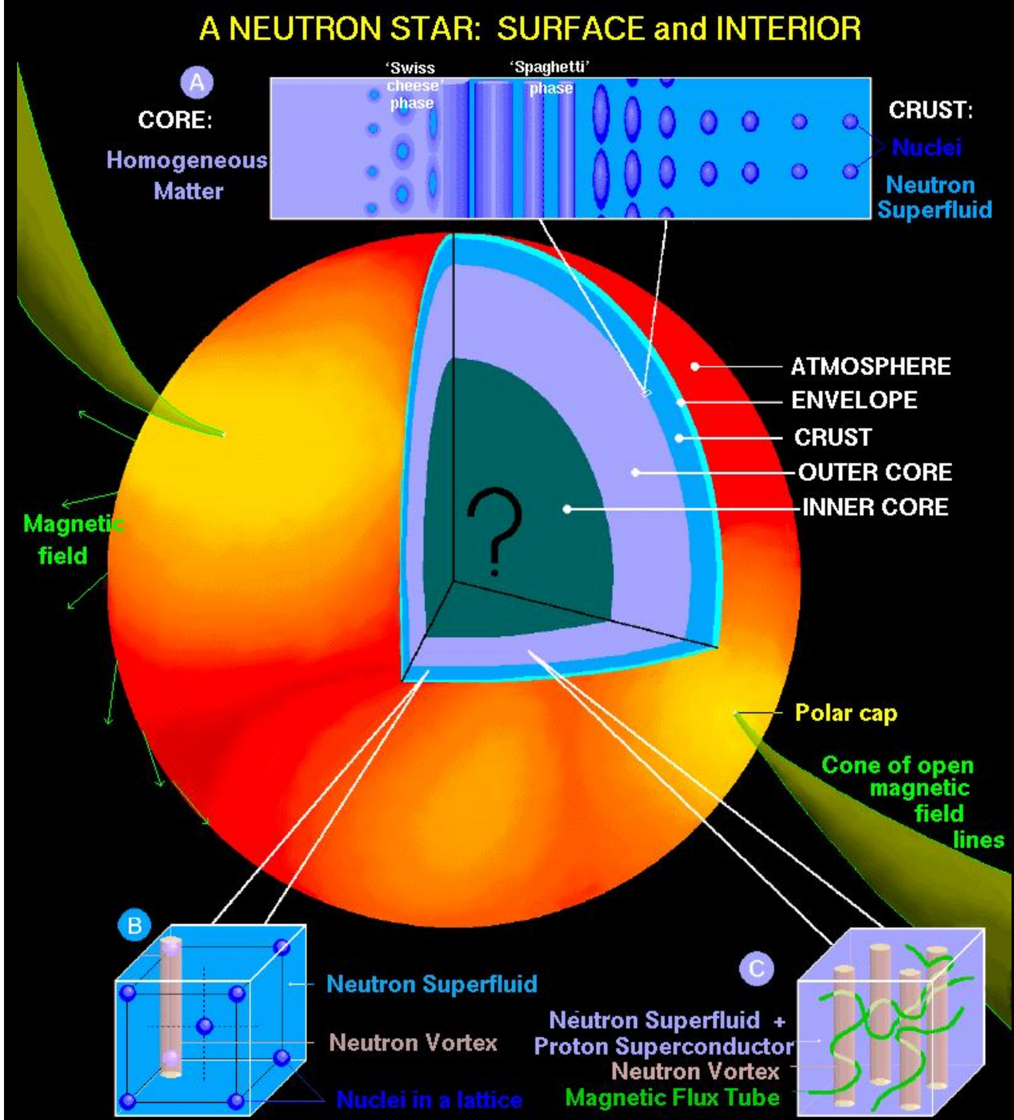
Bizarre Rings Surrounding SN1987A

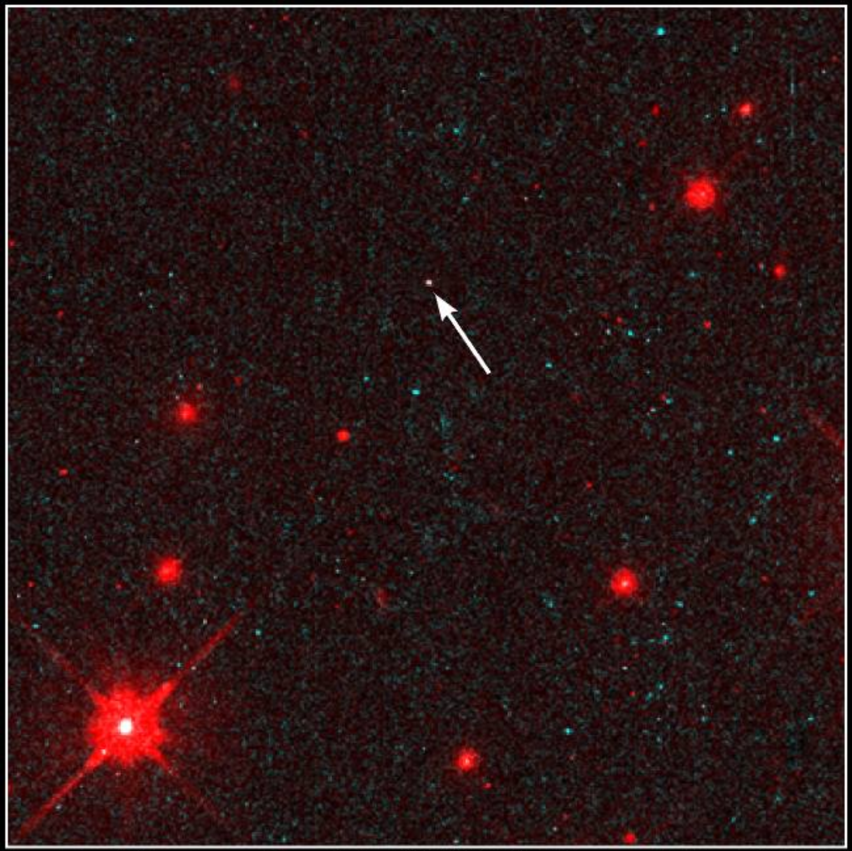


Stages in a Supernova



A Lone Neutron Star



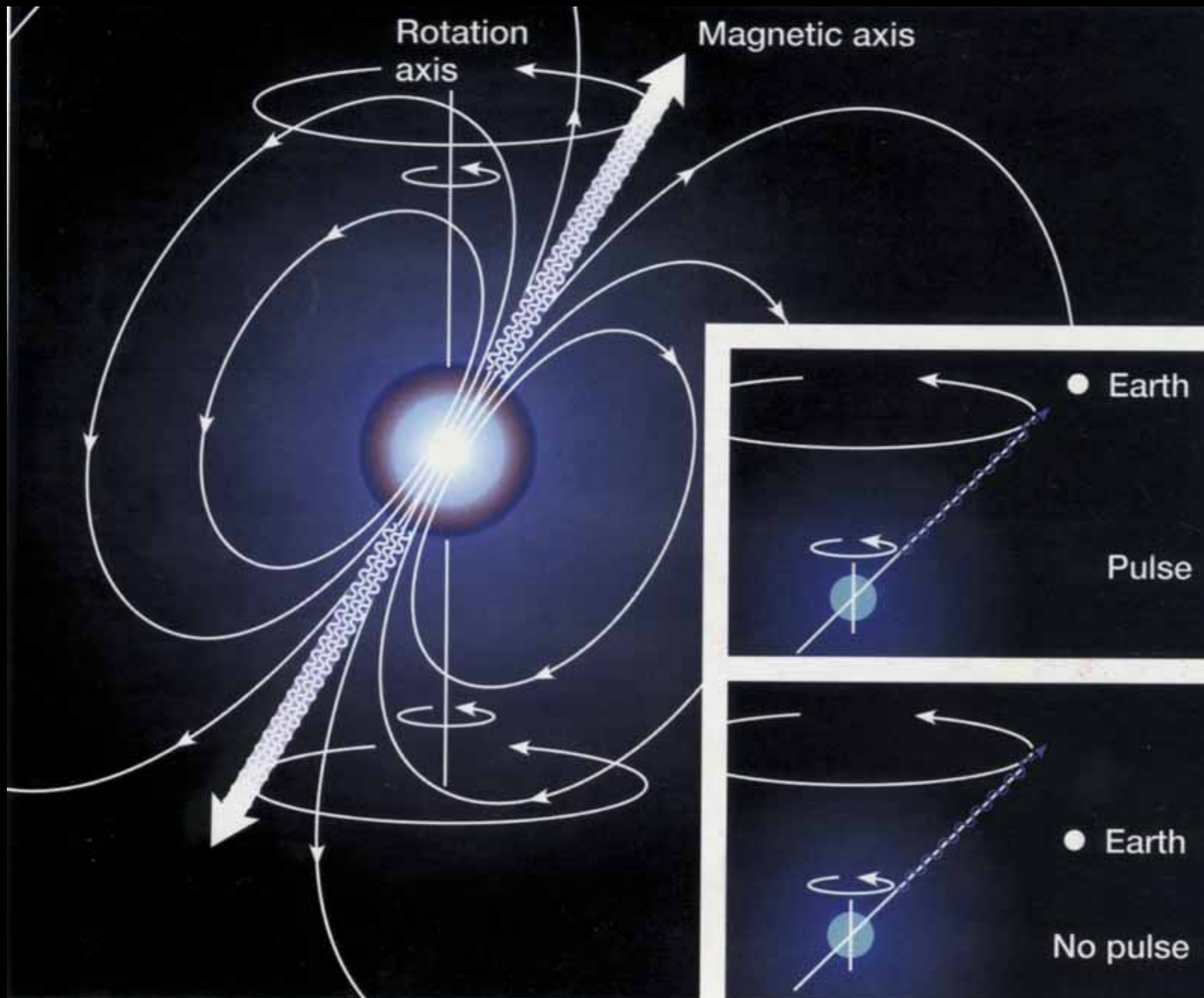


Isolated Neutron Star RX J185635-3754 HST • WFPC2

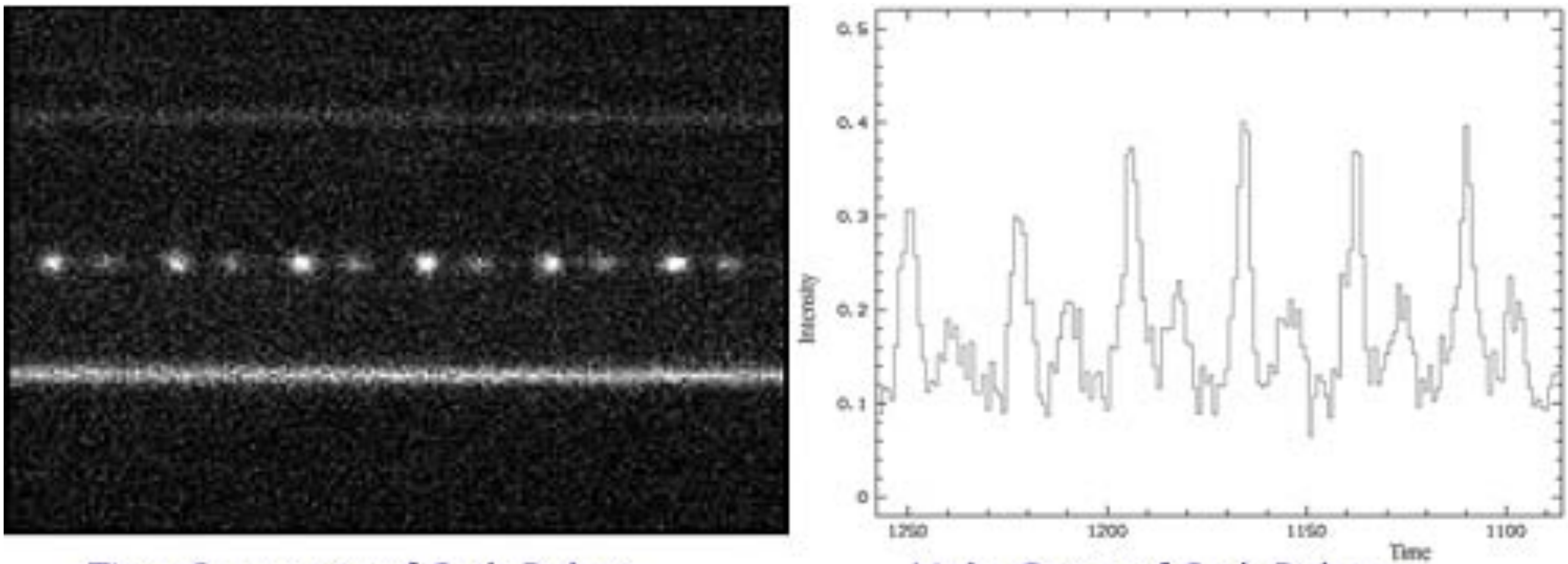
PRC97-32 • ST ScI OPO • September 25, 1997

F. Walter (State University of New York at Stony Brook) and NASA

Light House Effect



The Pulsar Light Curve

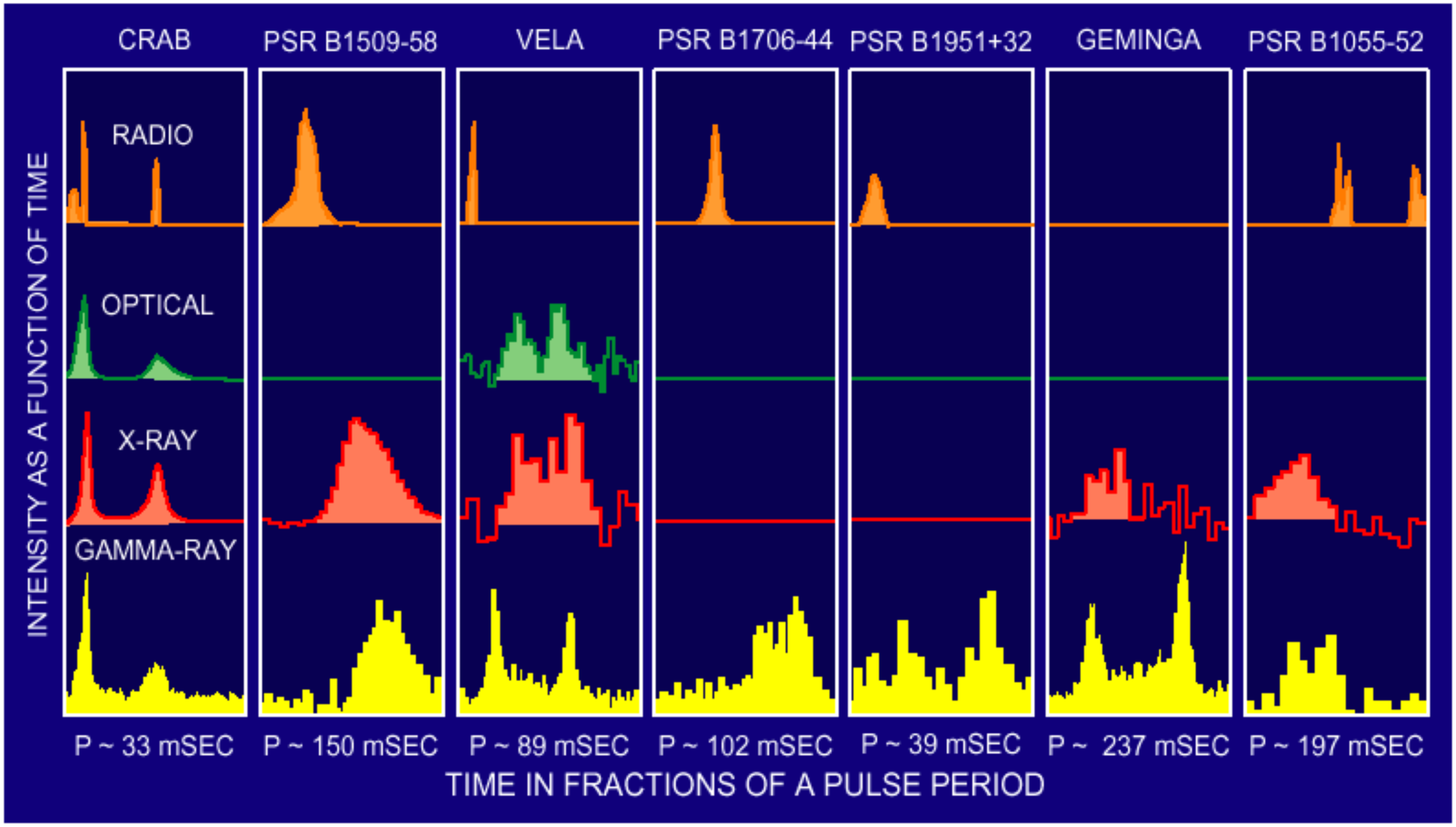


Time Sequence of Crab Pulsar

Light Curve of Crab Pulsar

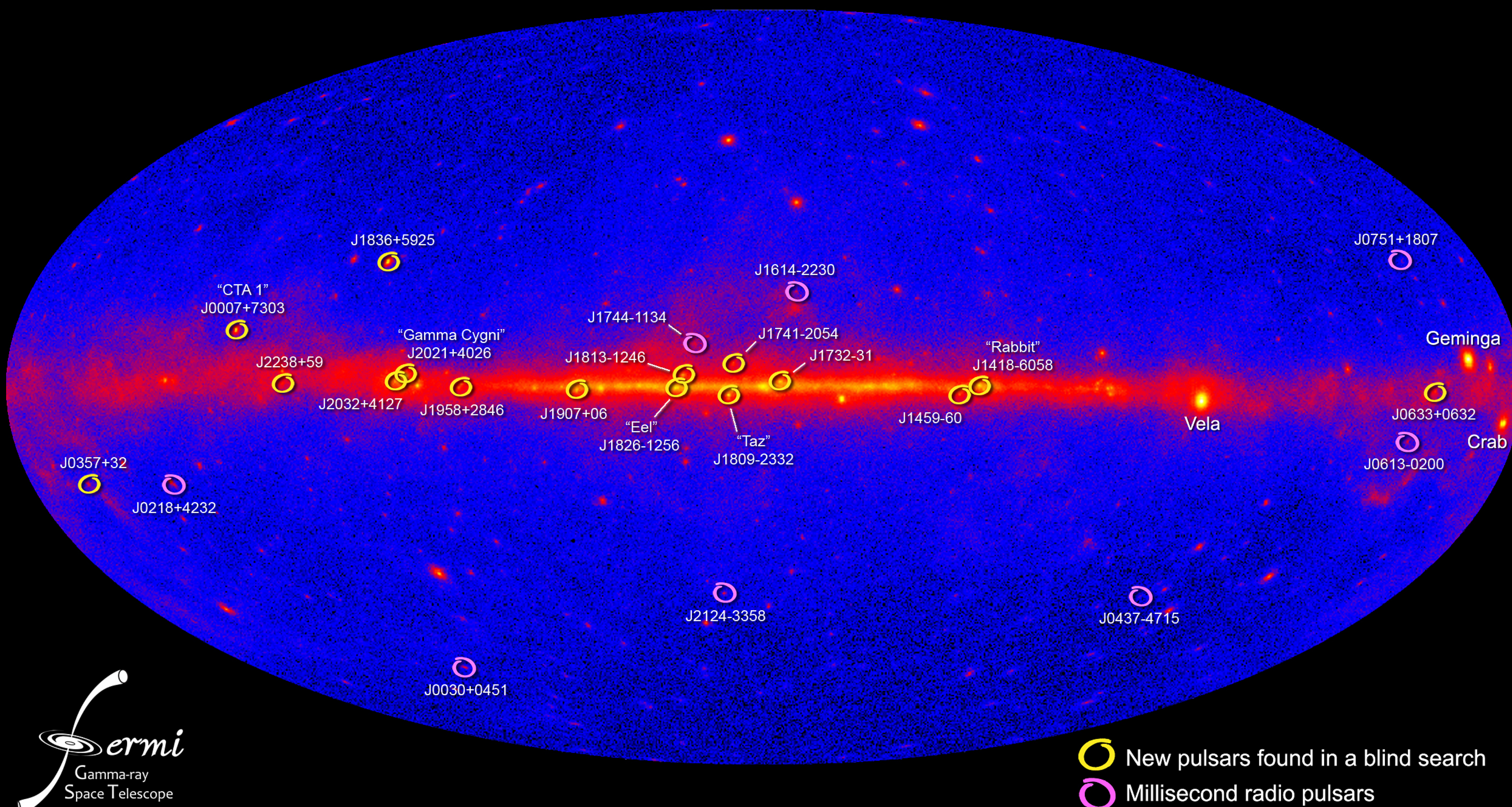
(VLT KUEYEN + FORS2 + FIERA) © ESO

Pulse Variations with Wavelength



Multiwavelength light curves of the seven pulsars detected with EGRET. A flat line in the radio, optical or X-ray bands means that no such pulsation has been detected. GLAST should provide gamma-ray light curves for several dozen pulsars, which combined with the pulse shapes measured at other energies will severely constrain theoretical models for pulsar emission.

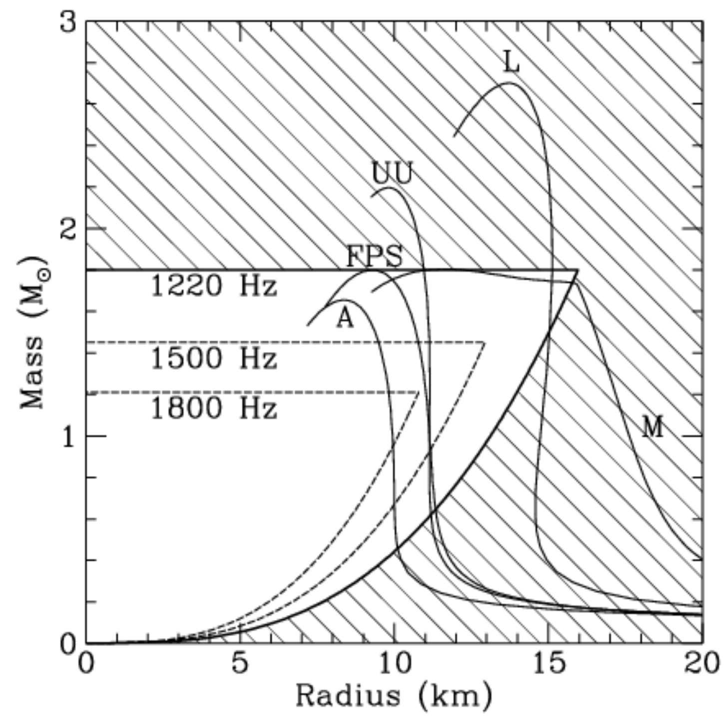
Pulsars Seen in Gamma-Rays



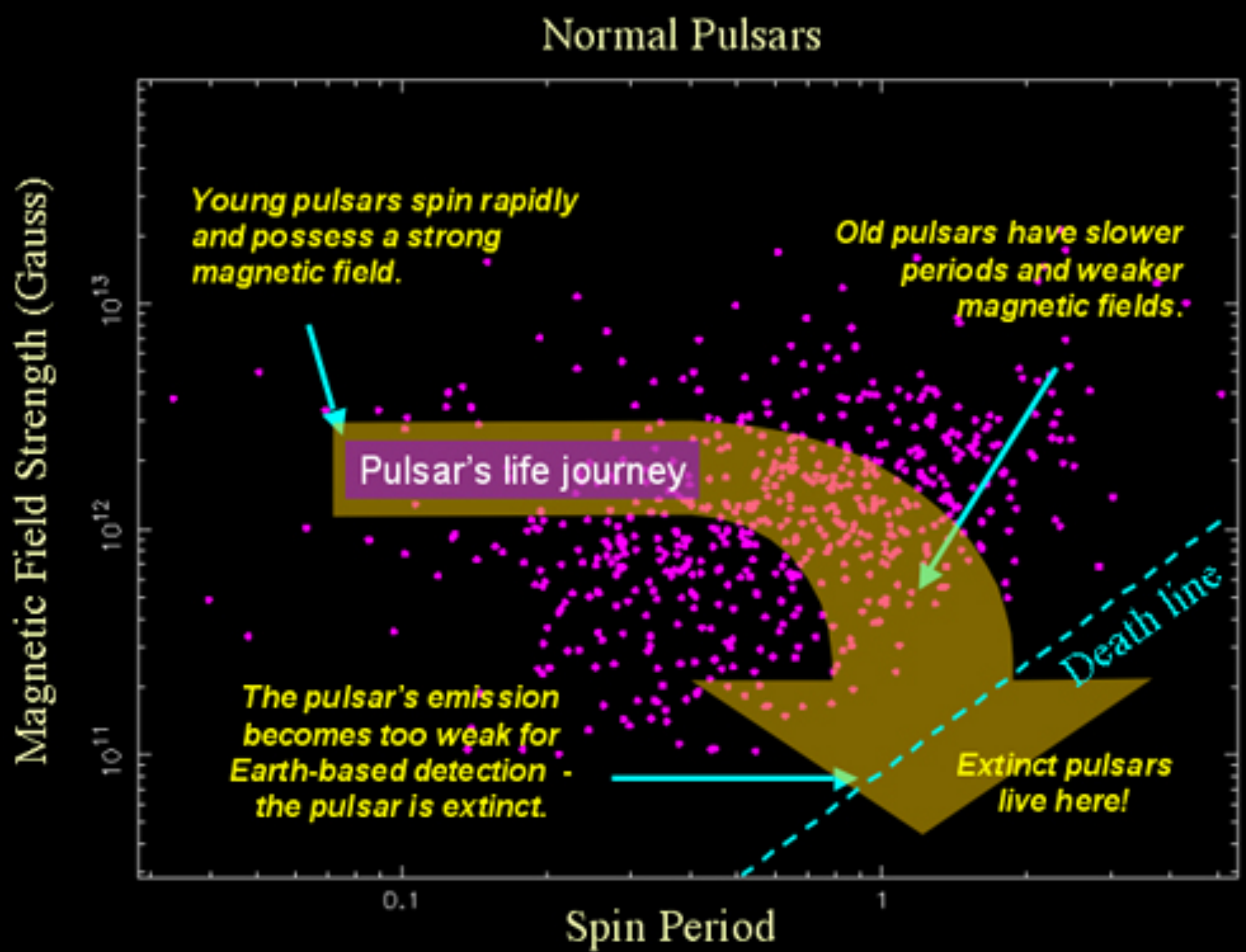
Fermi
Gamma-ray Space Telescope

Mass-Radius for Neutron Stars

- Right shows a mass-radius relation for neutron stars.
- Curves are for different models
- Frequencies relate to rotation periods and help to constrain neutron star sizes and structure.
- Shaded regions of figure are observationally disallowed.



The Evolution of Pulsars



Stellar Corpses – Real High Mass

- For $M > 25M_o$, stars also explode as Type II SNe, but the remnant mass exceeds the NS mass limit of ~ $3M_o$

  Gravity wins!

- Remnant collapses to a BLACK HOLE (BH)
- A BH is an object with a sufficient concentration of mass that light cannot escape it. (Does not mean a BH is a cosmic "vacuum".)

Schwarzschild Radius

- Recall escape speed:

$$v_{esc}^2 = \frac{2GM}{r}$$

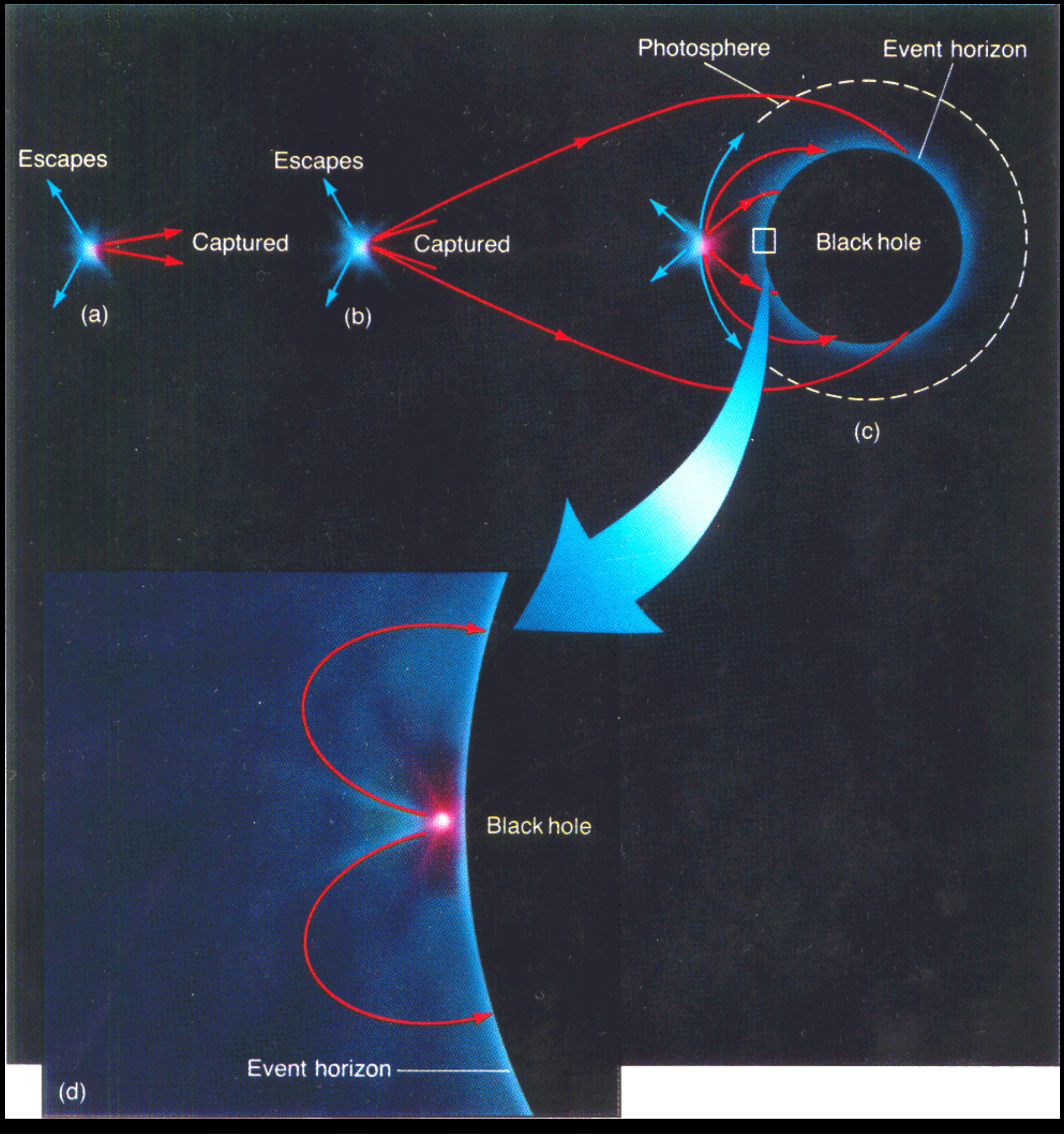
- The Sch. Radius (R_S) is the distance at which $v_{esc}=c$ for a BH:

$$c^2 = \frac{2GM}{R_S}$$

$$\text{so, } R_S = \frac{2GM}{c^2}$$

- Nothing travels faster than light, so anything passing closer than R_S will not re-emerge!

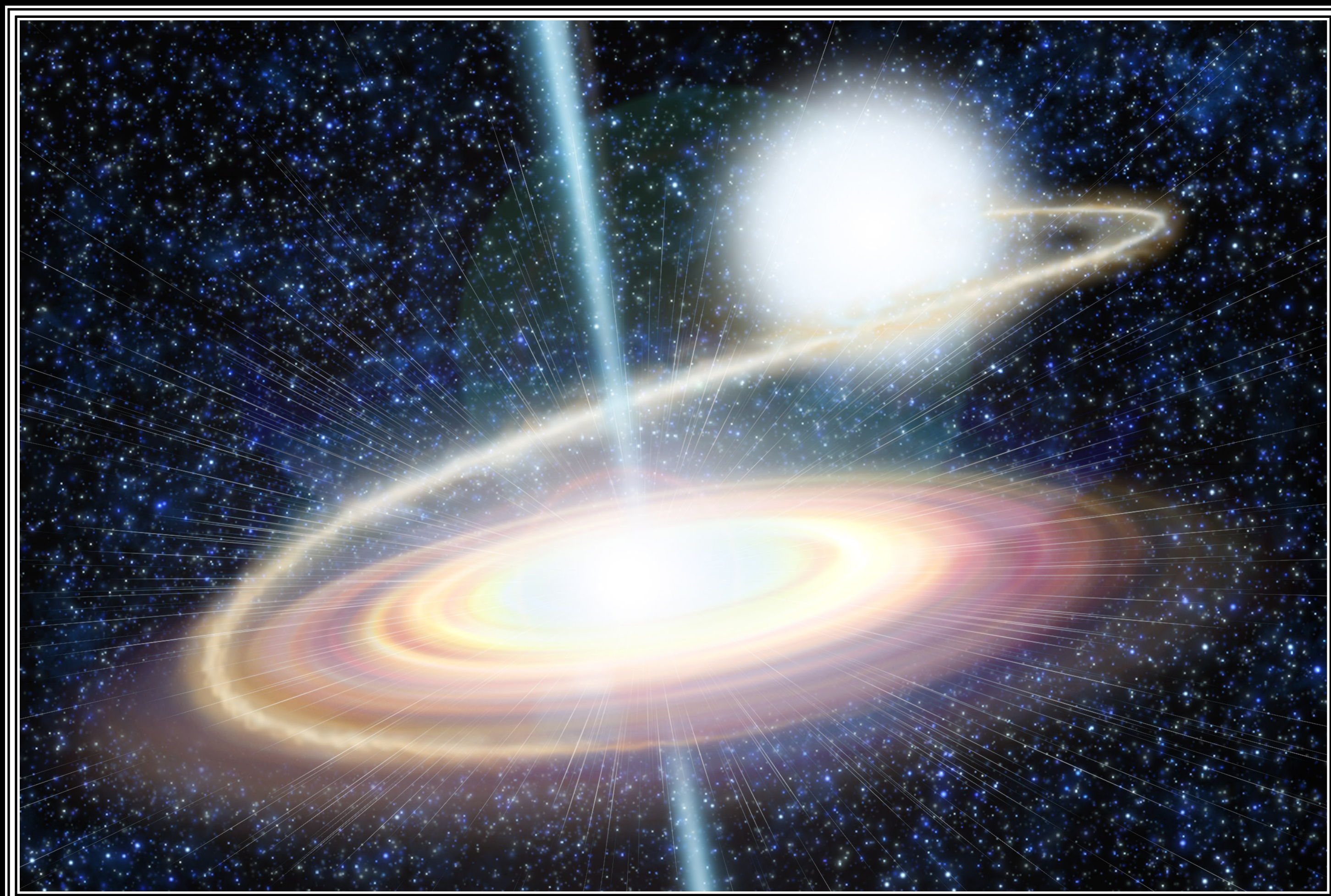
The Event Horizon



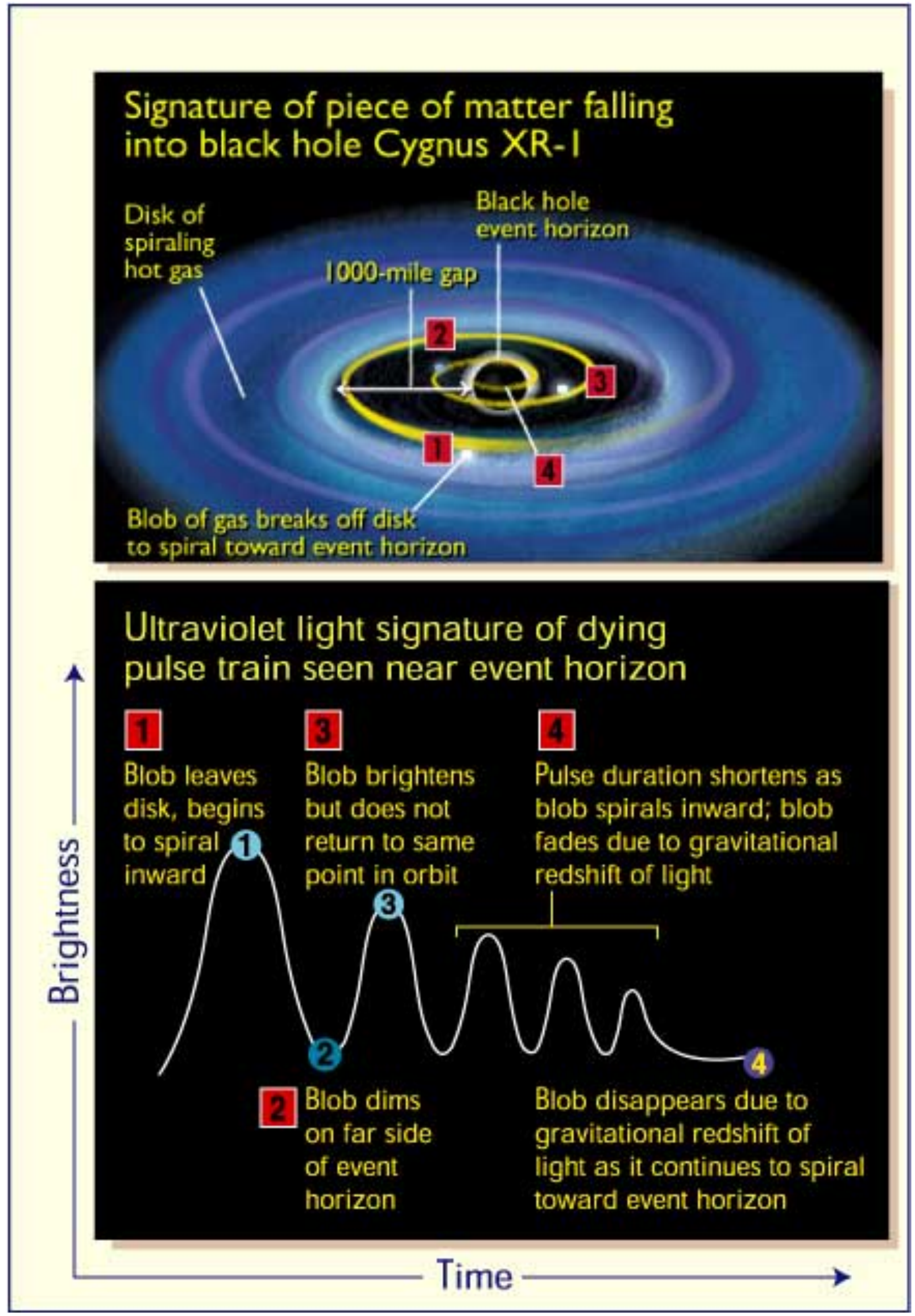
How to Detect?

- Although small and faint/invisible, NS's and BHs **do** influence their surroundings
- Can infer their presence in binaries from the motion of a visible star
- Also, in binaries these compact objects can draw matter from the normal star to form an accretion disk, with associated X-ray emission
- Some good examples are Cyg X-1 and A0620-00

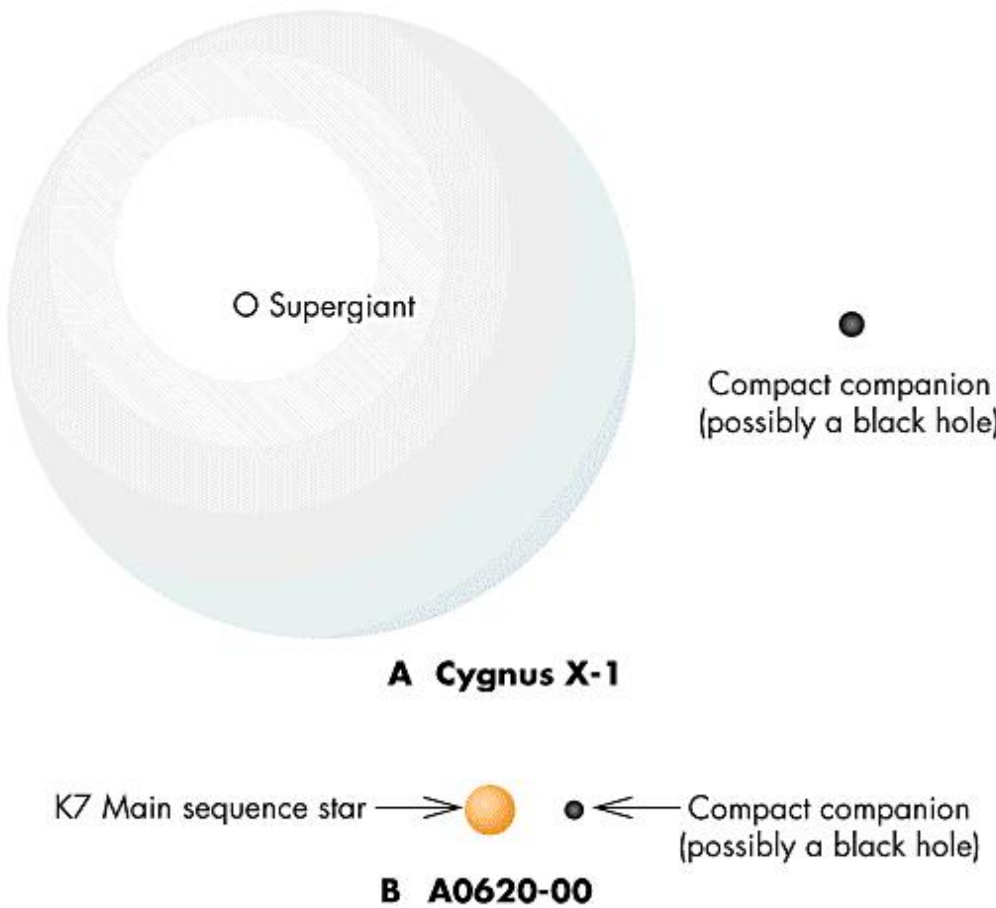
Cartoon of Cygnus X-1



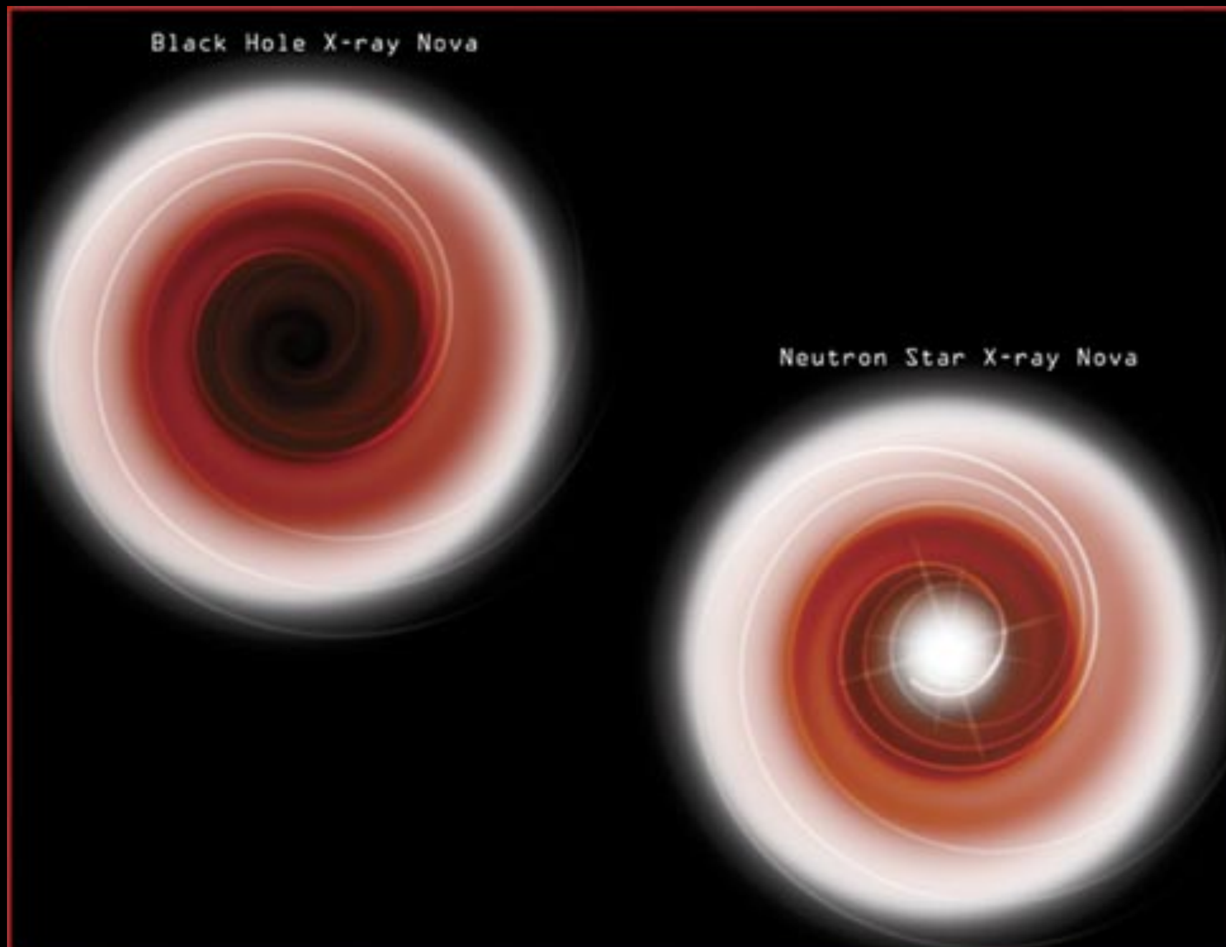
Signature for the presence of a black hole



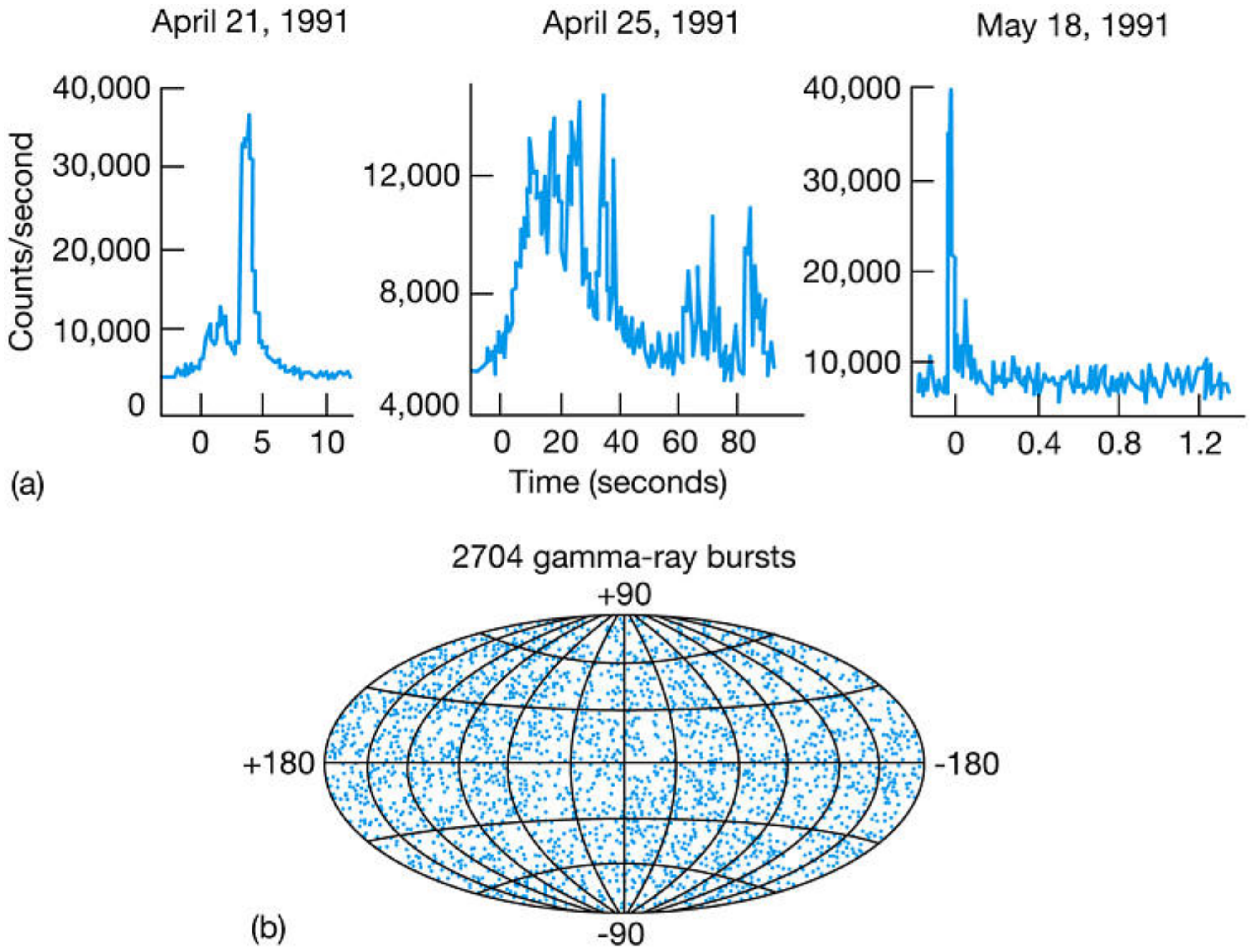
Black Hole Candidates

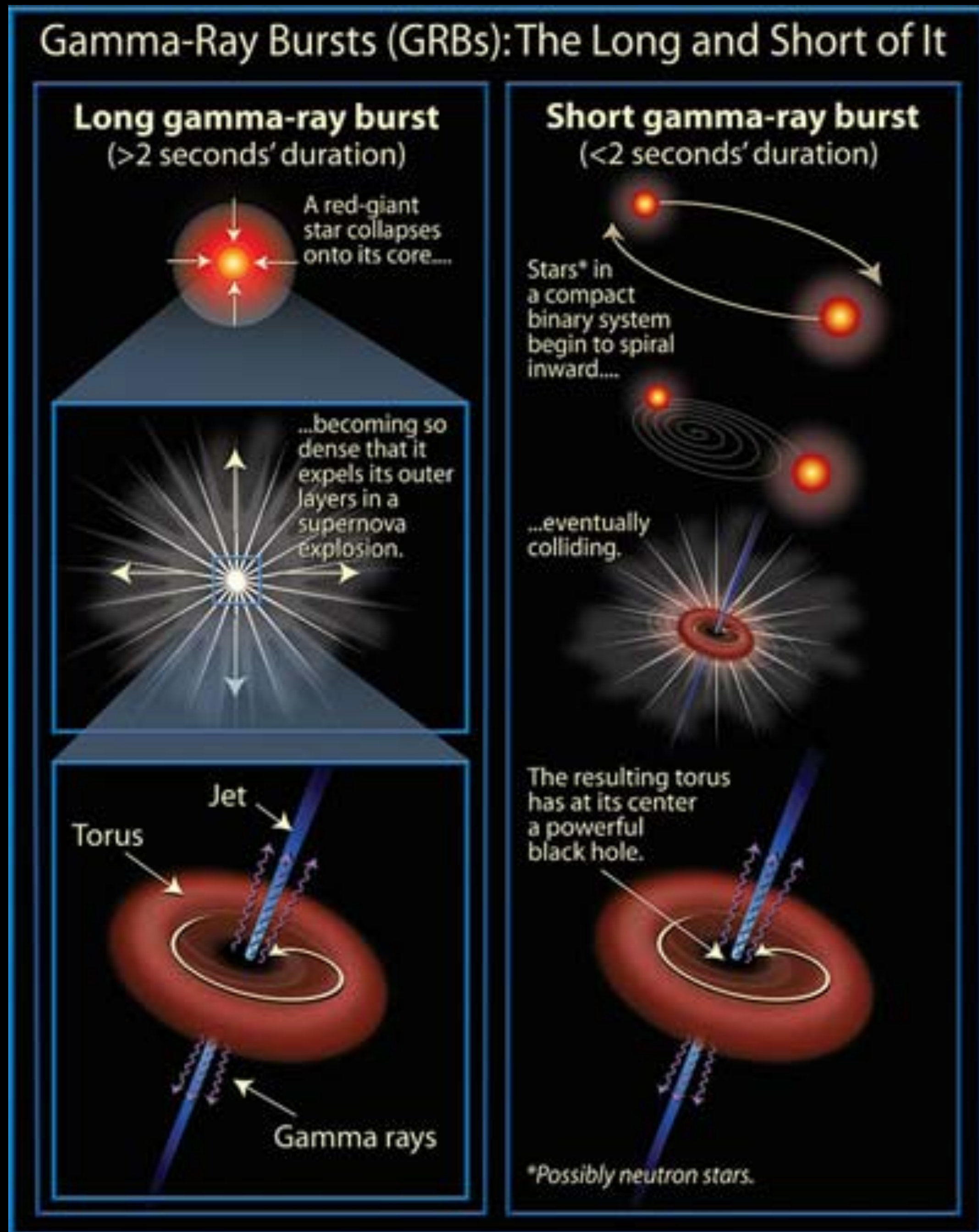


Black Holes vs Neutron Stars

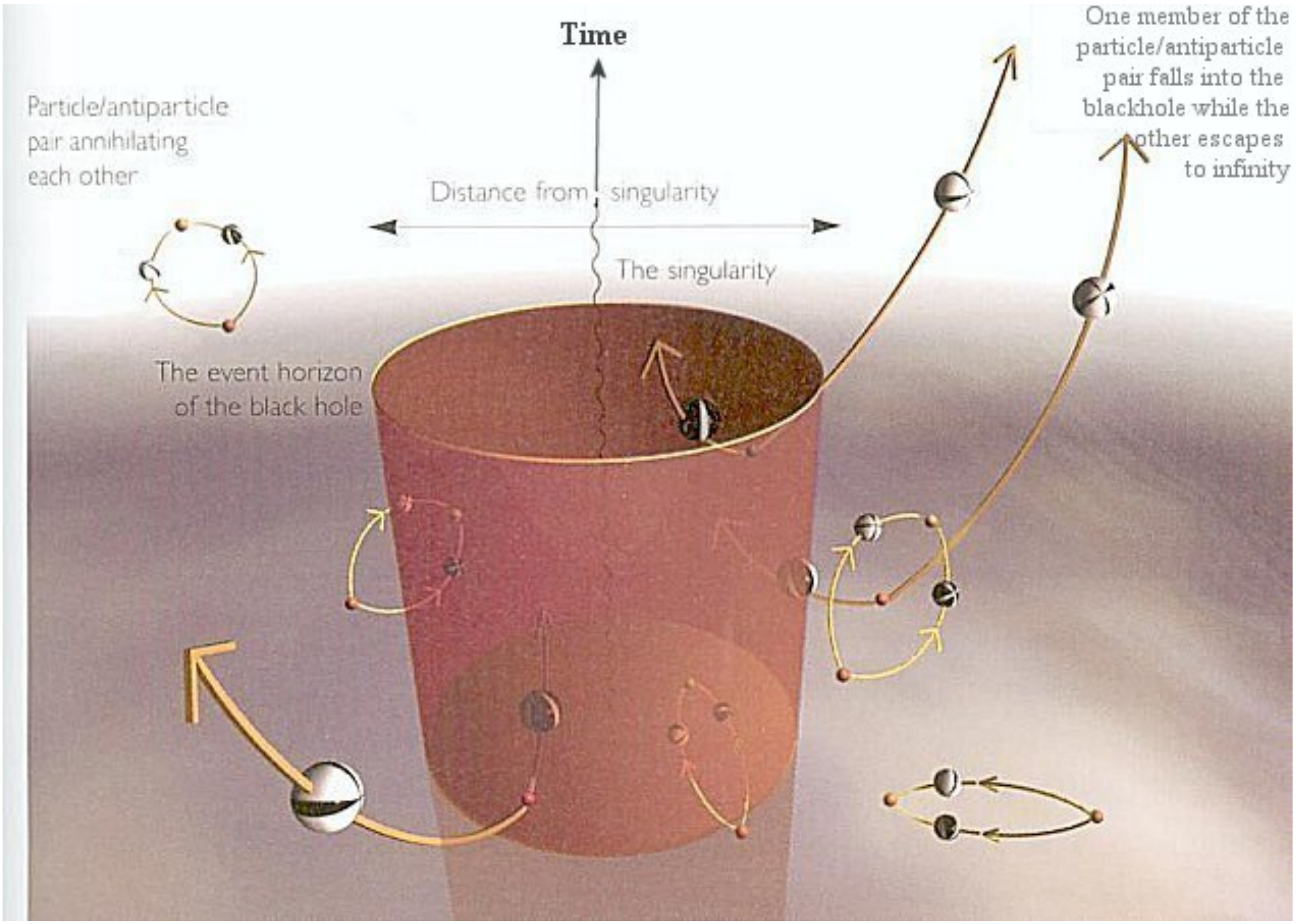


The Gamma-Ray Bursts




Gamma-Ray Bursts (GRBs): The Long and Short of It
Long gamma-ray burst
(>2 seconds' duration)
A red-giant star collapses onto its core....
...becoming so dense that it expels its outer layers in a supernova explosion.
Jet
Torus
Gamma rays
Short gamma-ray burst
(<2 seconds' duration)
Stars* in a compact binary system begin to spiral inward....
...eventually colliding.
The resulting torus has at its center a powerful black hole.
*Possibly neutron stars.

Hawking Radiation: Can Black Holes Glow?



Luminosity of Hawking Radiation