Neutron Stars

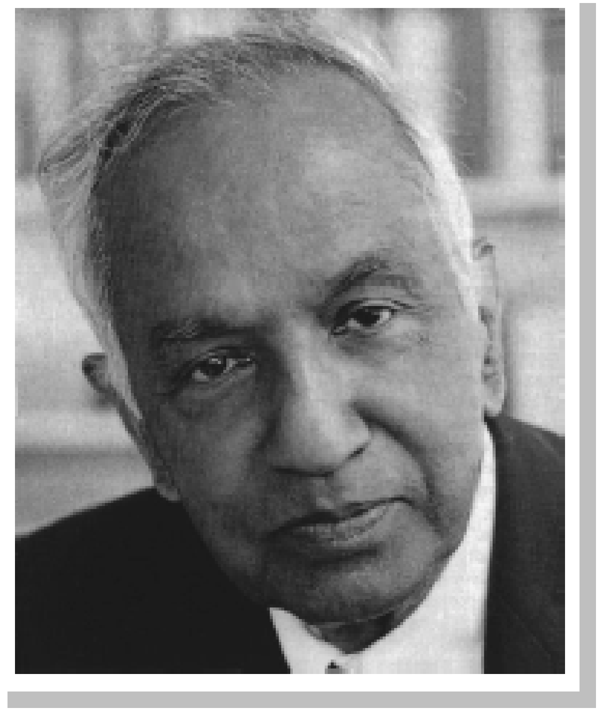
- Chandrasekhar limit on white dwarf mass
- Supernova explosions
  - Formation of elements (R, S process)
- Neutron stars
- Pulsars
- Formation of X-Ray binaries
  - High-mass
  - Low-mass

Maximum white dwarf mass

Electron degeneracy cannot support a white dwarf heavier than 1.4 solar masses

This is the "Chandrasekhar limit"

Won Chandrasekhar the 1983 Nobel prize in Physics

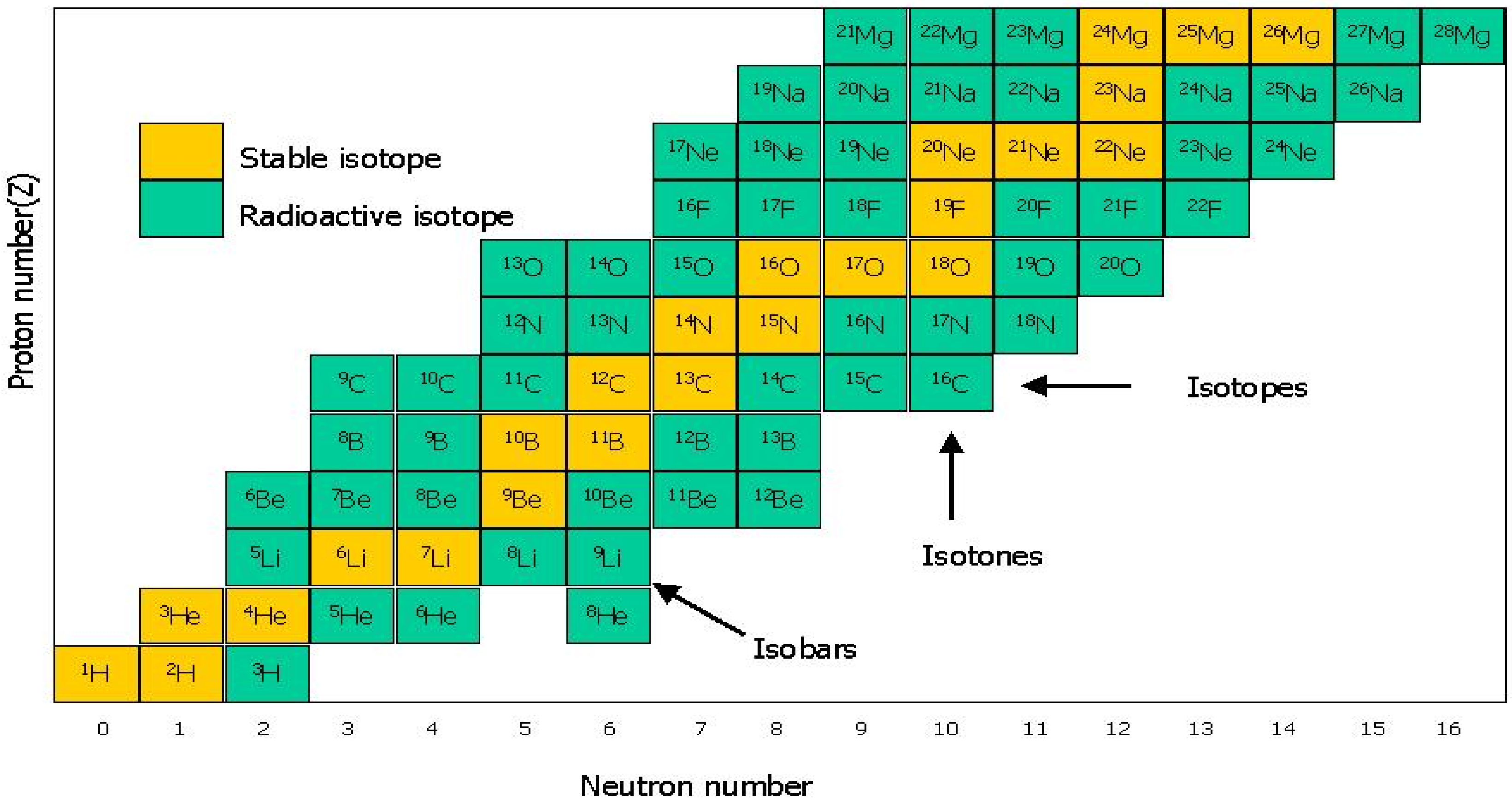


Supernova explosion

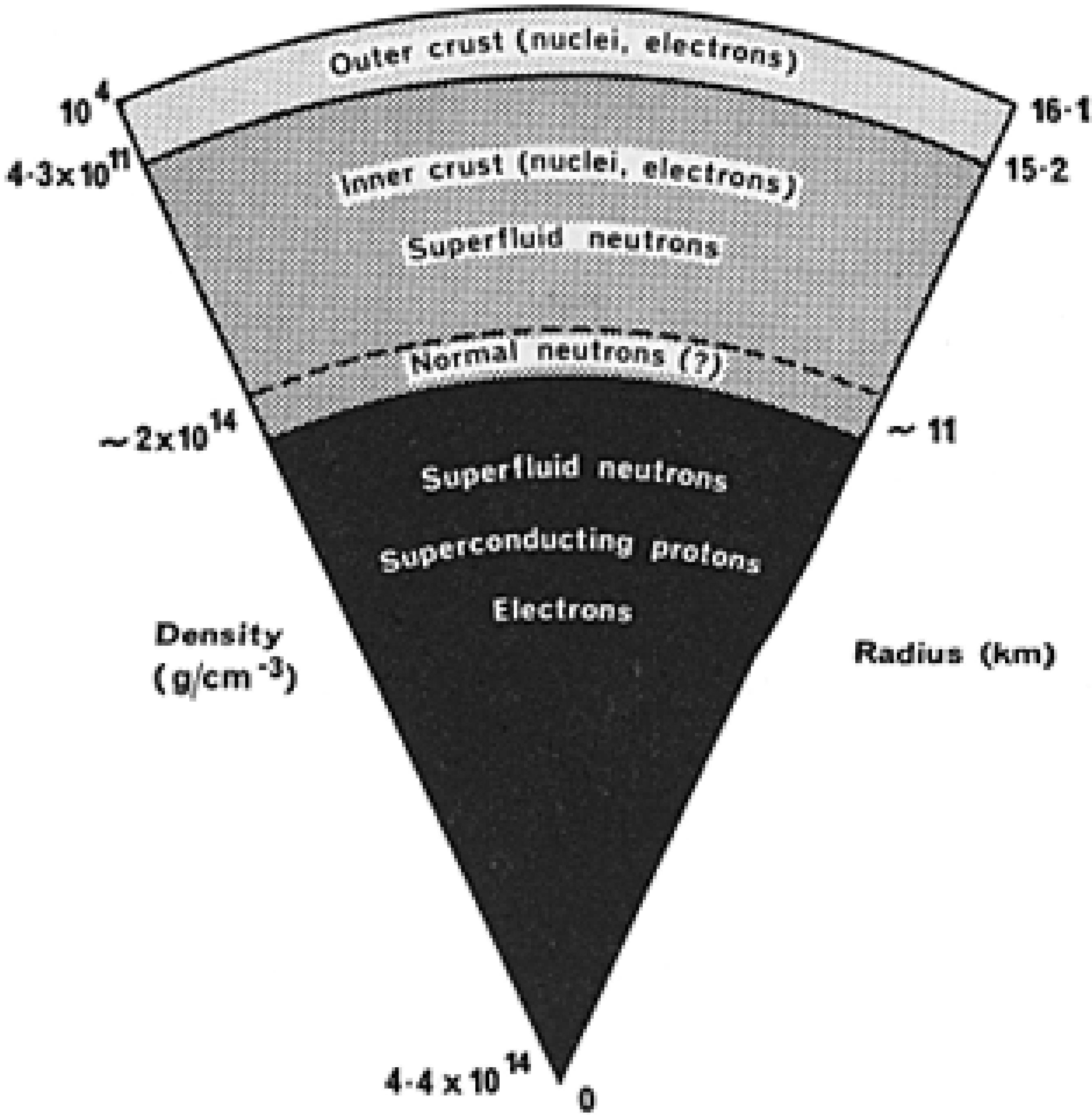
S-process (slow) - Rate of neutron capture by nuclei is slower than beta decay rate. Produces stable isotopes by moving along the valley of stability. Occurs in massive stars, particular AGB stars.

R-process (Rapid) – Rate of neutron capture fast compared to beta decay. Forms unstable neutron rich nuclei which decay to stable nuclei.

Table of Isotopes



Neutron Stars



Spinning Neutron Stars?

For a rotating object to remain bound, the gravitational force at the surface must exceed the centripetal acceleration:

$$\frac{GMm}{r^2} > m\omega^2 r \Rightarrow \frac{GM}{r^3} > \frac{4\pi^2}{P^2} \Rightarrow \rho > \frac{3\pi}{P^2 G}$$

For the Crab pulsar, P = 33 ms so the density must be greater than 1.3×10^{11} g cm^{-3}.

This exceeds the maximum possible density for a white dwarf, requires a neutron star.

Spin up of neutron star

If the Sun (spin rate 1/25 days, radius 7× 10[8] m) were to collapse to a neutron star with a radius of 12 km, how fast would it be spinning?

Angular momentum of sphere where M is mass, R is radius, ν is spin rate:

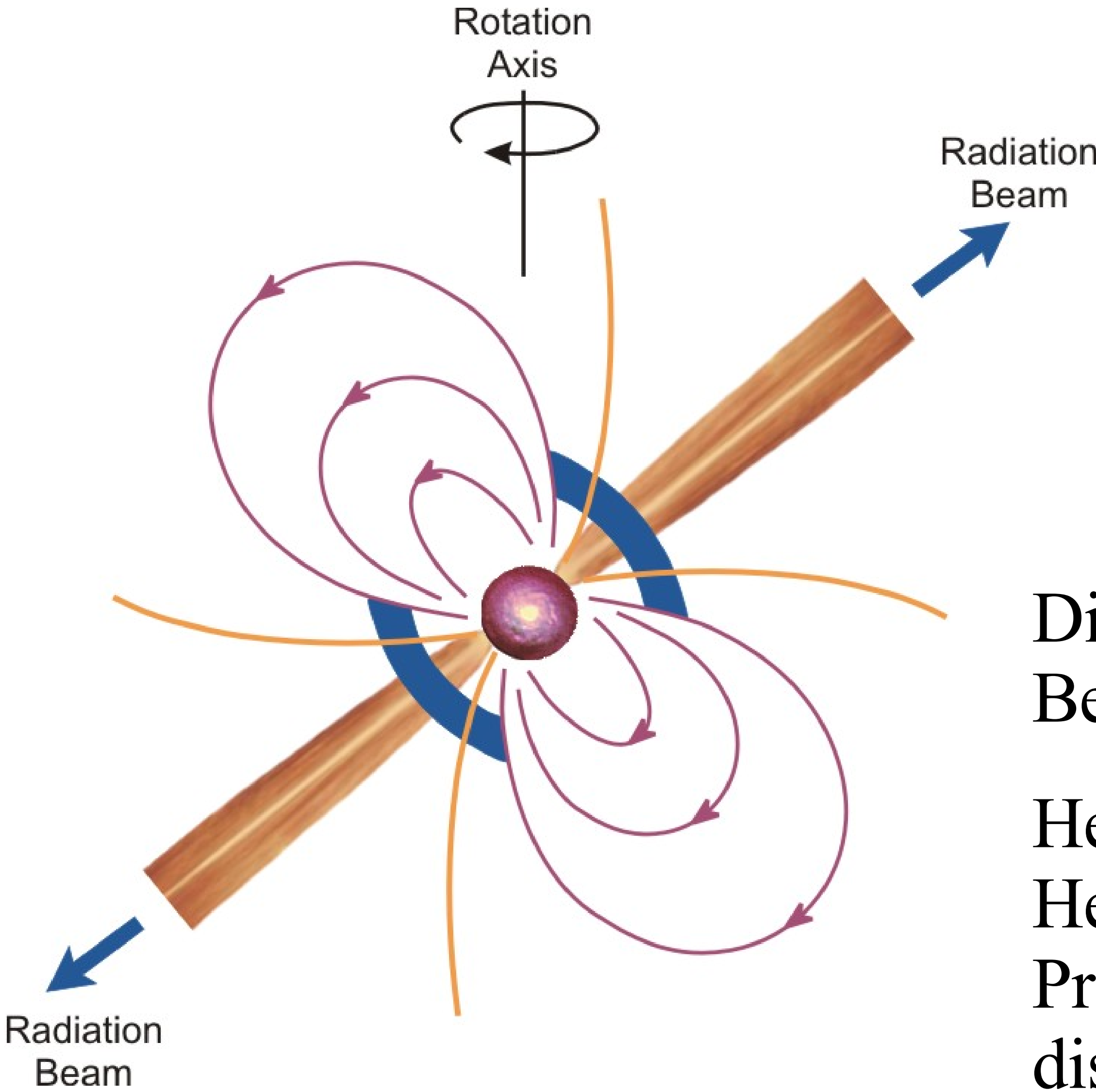
$$L = I \cdot 2\pi\nu = \frac{4}{5}\pi M R^2 \nu$$

$$\nu_f = \nu_i \left(\frac{R_i}{R_f}\right)^2 = 4.6\times10^{-7}\,s^{-1}\left(\frac{7\times10^8\,m}{1.2\times10^3\,m}\right)^2 = 1.6\times10^5\,s^{-1}$$

Very high rotation rates can be reached simply via conservation of angular momentum.

This is faster than any known (or possible) neutron star. Mass and angular momentum are lost during the collapse.

Pulsars



Discovered by Jocelyn Bell in 1967.

Her advisor, Anthony Hewish, won the Nobel Prize in Physics for the discovery in 1974.

Crab Pulsar

Spin down of a pulsar

Energy $E = \frac{1}{2} I (2\pi\nu)^2$

Power $P = -\frac{dE}{dt} = 4\pi^2 I \nu \frac{d\nu}{dt}$

For Crab pulsar: ν = 30/s, M = 1.4 solar masses, R = 12 km, and $d\nu/dt = -3.9\times 10^{-10}\ s^{-2}$.

Therefore, $P = 5 \times 10^{38}$ erg/s.

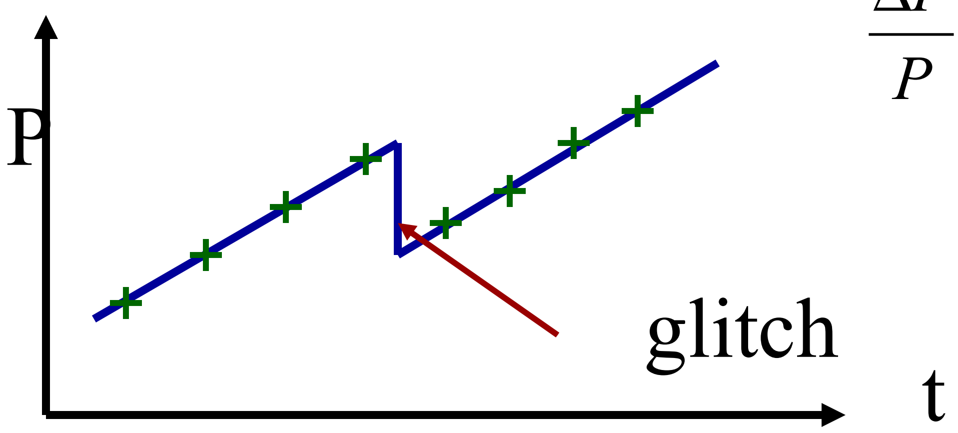
Over a year, the spin rate changes by 0.04%.

Pulsar Glitches

A glitch is a discontinuous change of period.

Short timescales - pulsar slow-down rate is **remarkably uniform**

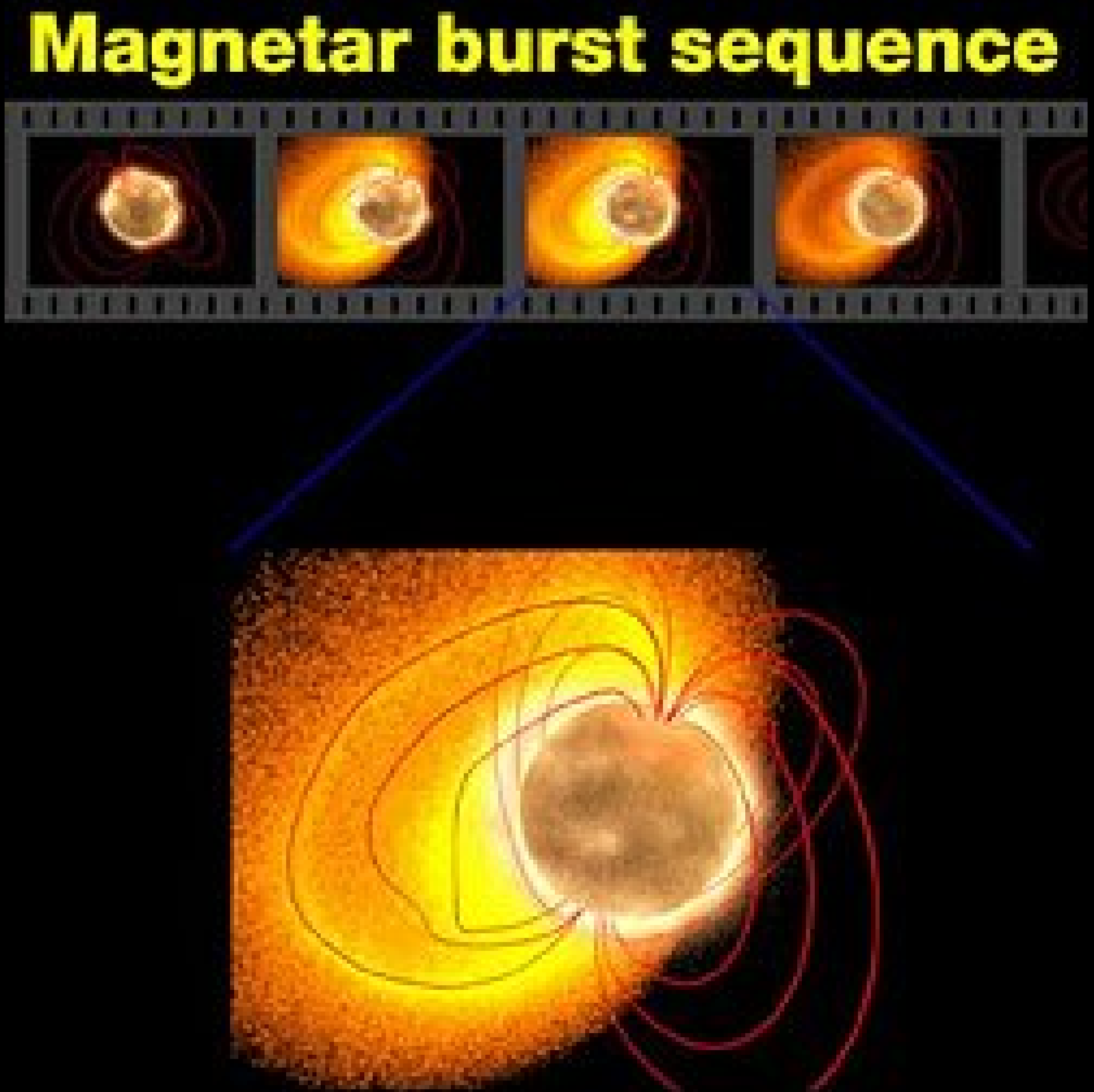
Longer timescales - irregularities apparent, in particular, 'glitches'



$$\frac{\Delta P}{P} \sim 10^{-10}$$ for Crab pulsar

Due to stresses and fractures in the crust?

Magnetars



Magnetic fields so strong that they produce starquakes on the neutron star surface.

These quakes produce huge flashes of X-rays and Gamma-rays.

Energy source is magnetic field.

Magnetic Field

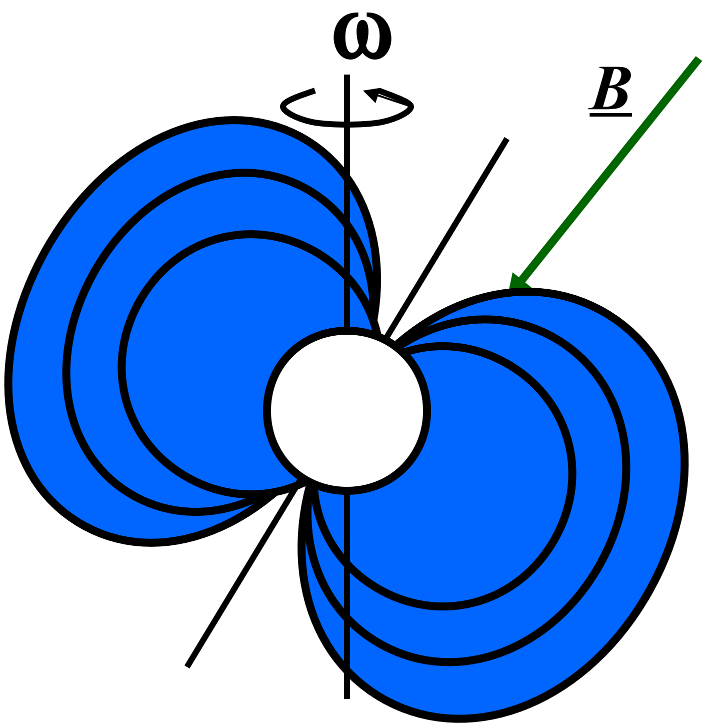
If a solar type star collapses to form a neutron star, while conserving magnetic flux, we would naively expect

$$R_{sun}^2 B_{sun} = R_{ns}^2 B_{ns} \Rightarrow \frac{B_{ns}}{B_{sun}} = \left(\frac{7\times10^{10}}{10^6}\right)^2 \approx 5\times10^9$$

For the sun, *B~100 G,* so the neutron star would have a field of magnitude *~10*^{12} *G.*

Magnetosphere

Neutron star rotating in vacuum:



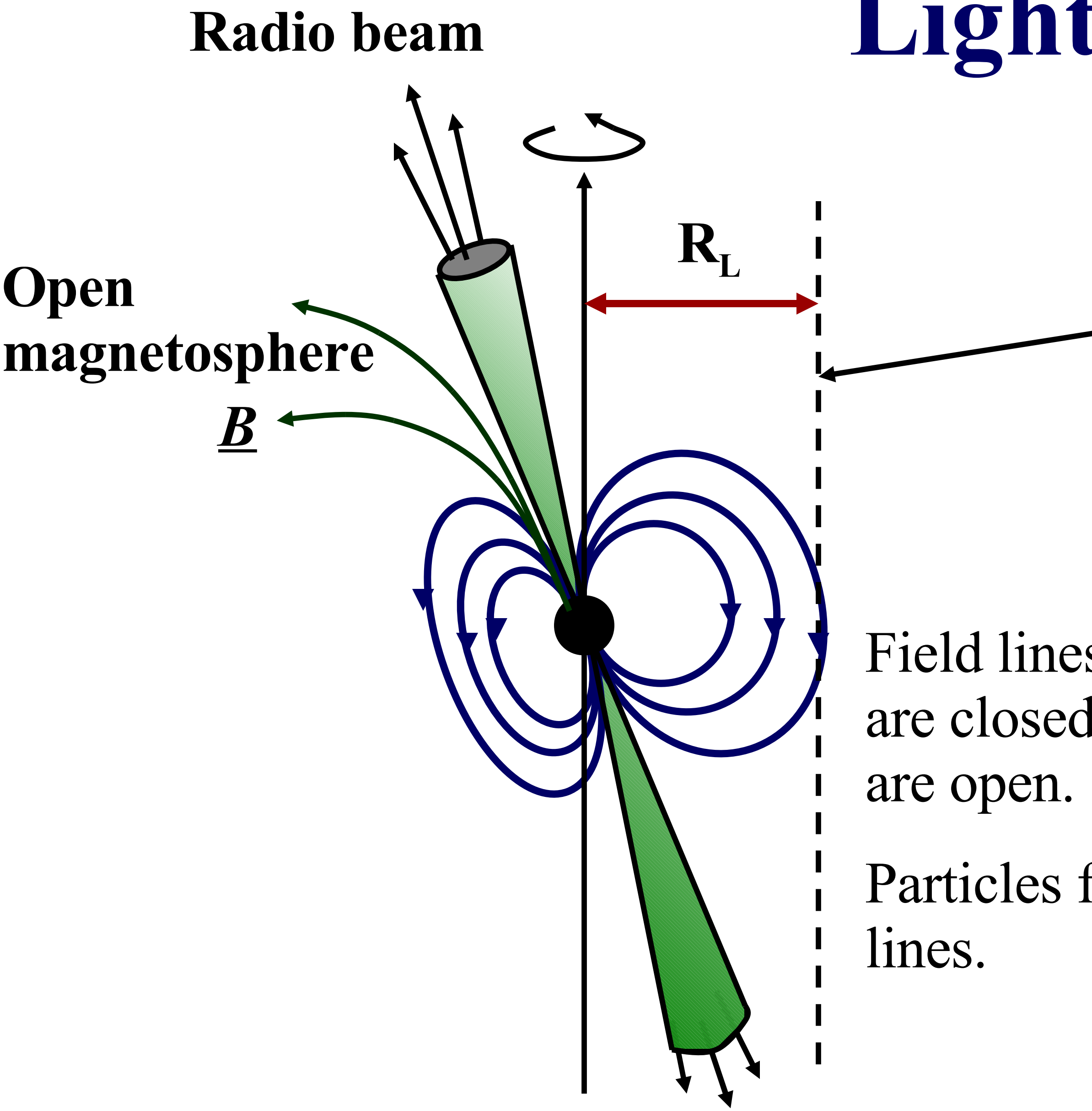
Electric field induced immediately outside NS surface.

$$E \simeq \frac{v}{c} B$$

The potential difference on the scale of the neutron star radius:

$$\Phi = ER \sim 10^{18} V$$

Light cylinder



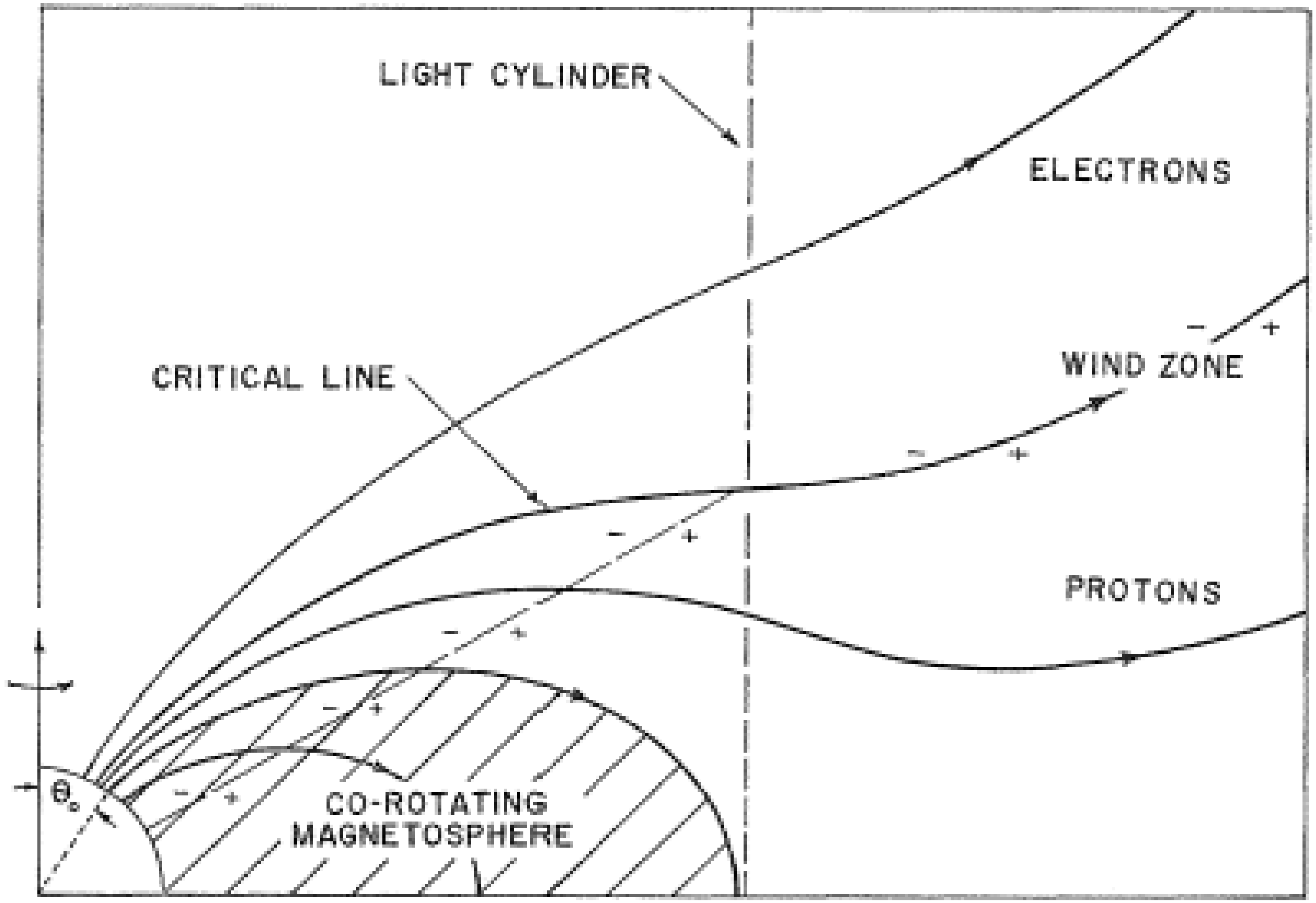
Light cylinder

$$\frac{2\pi R_L}{P} = c$$

Field lines inside light cylinder are closed, those passing outside are open.

Particles flow along open field lines.

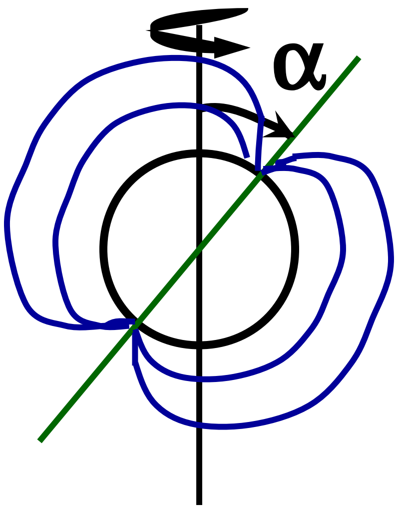
Particle Flow



Goldreich and Julian (1969)

Dipole Radiation

Even if a plasma is absent, a spinning neutron star will radiate if the magnetic and rotation axes do not coincide.



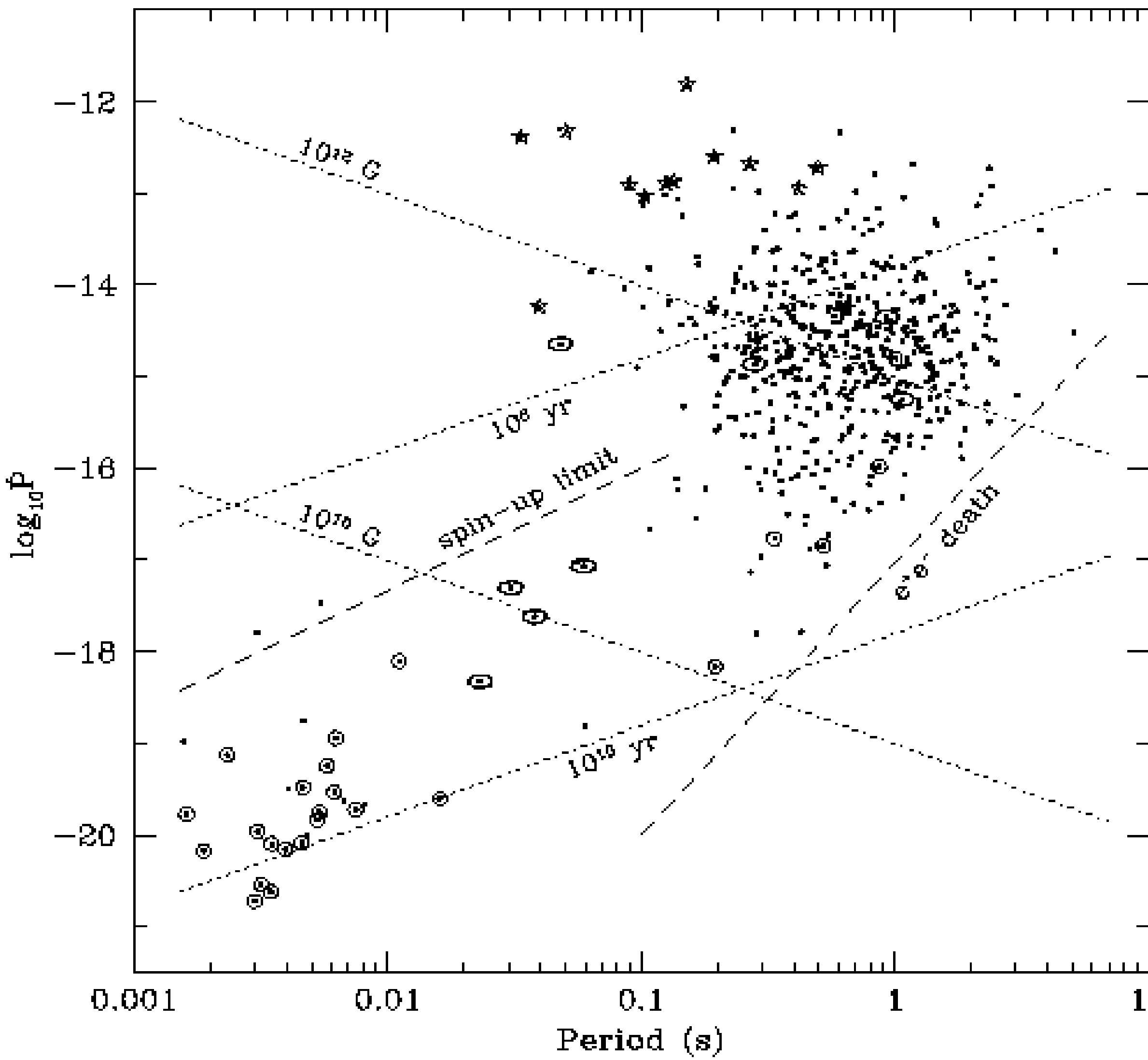
$$\frac{dE}{dt} \propto -\omega^4 R^6 B^2 \sin^2 \alpha$$

If this derives from the loss of rotational energy, we have

$$\frac{dE}{dt} \propto \omega \dot{\omega} \Rightarrow \dot{\omega} \propto B^2 \omega^3 \Rightarrow B \propto \sqrt{P \dot{P}}$$

Polar field at the surface: $B_0 = (3.3 \times 10^{19} G) \sqrt{P \dot{P}}$

Pulsar Period-Period Derivative



Braking Index

In general, the slow down may be expressed as

$\dot{\omega} = -k\omega^{n}$ where *n* is referred to as the *braking index*

The time that it takes for the pulsar to slow down is

$$t = -(n-1)^{-1}\omega\,\dot{\omega}^{-1}\left[1-(\omega/\omega_i)^{n-1}\right]$$

If the initial spin frequency is very large, then

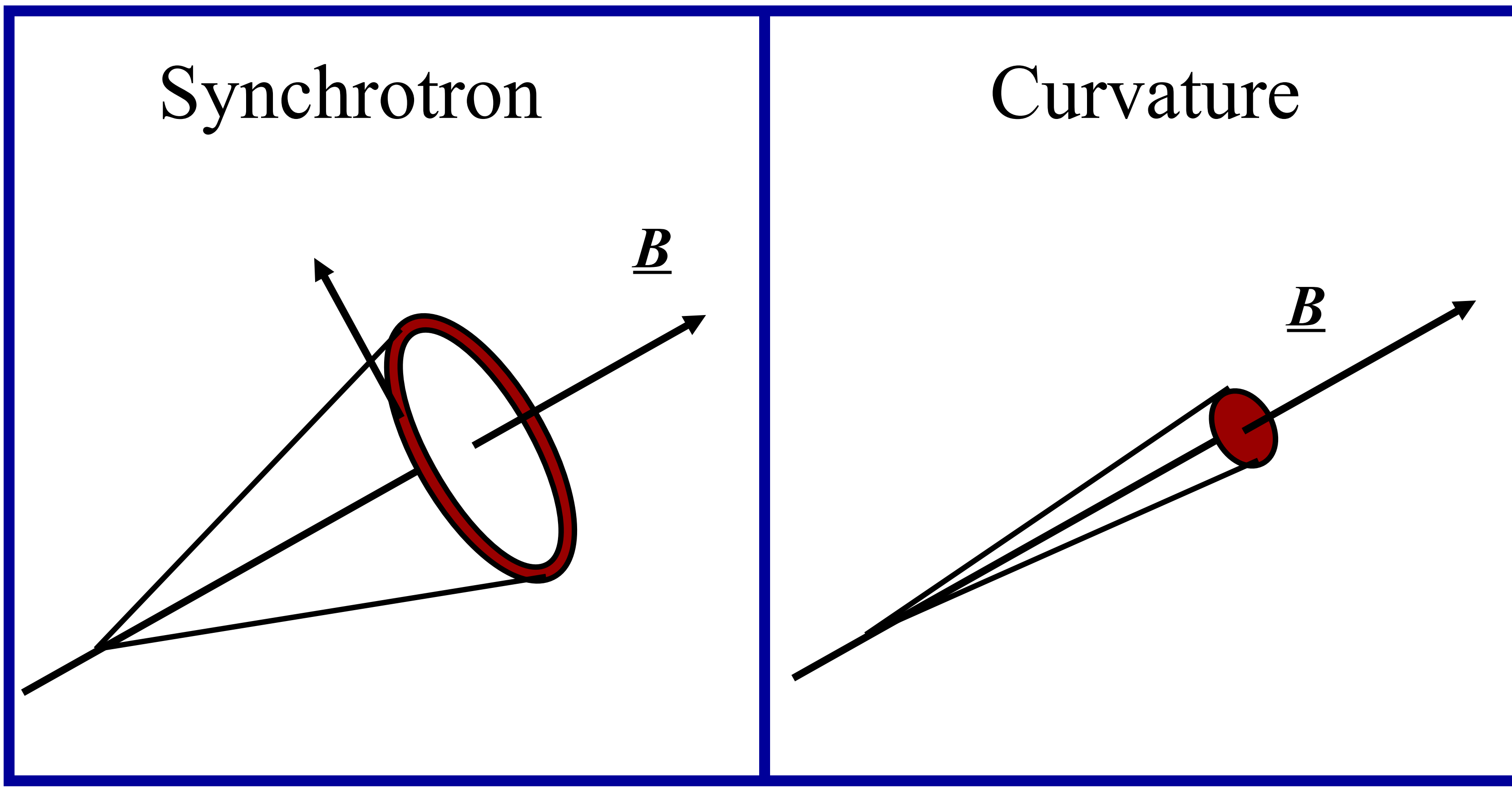
$$t = -(n-1)^{-1}\omega\,\dot{\omega}^{-1} = (n-1)^{-1}P\,\dot{P}^{-1}$$

For dipole radiation, *n=3,* we have

$$t = \frac{P}{2\dot{P}}$$

Characteristic age of the pulsar

Curvature vs Synchrotron



Curvature Radiation

If v ~ c and r = radius of curvature, the "effective frequency" of the emission is given by:

$$\nu = \frac{\gamma^3 v}{2\pi r_c}$$

γ = Lorentz factor

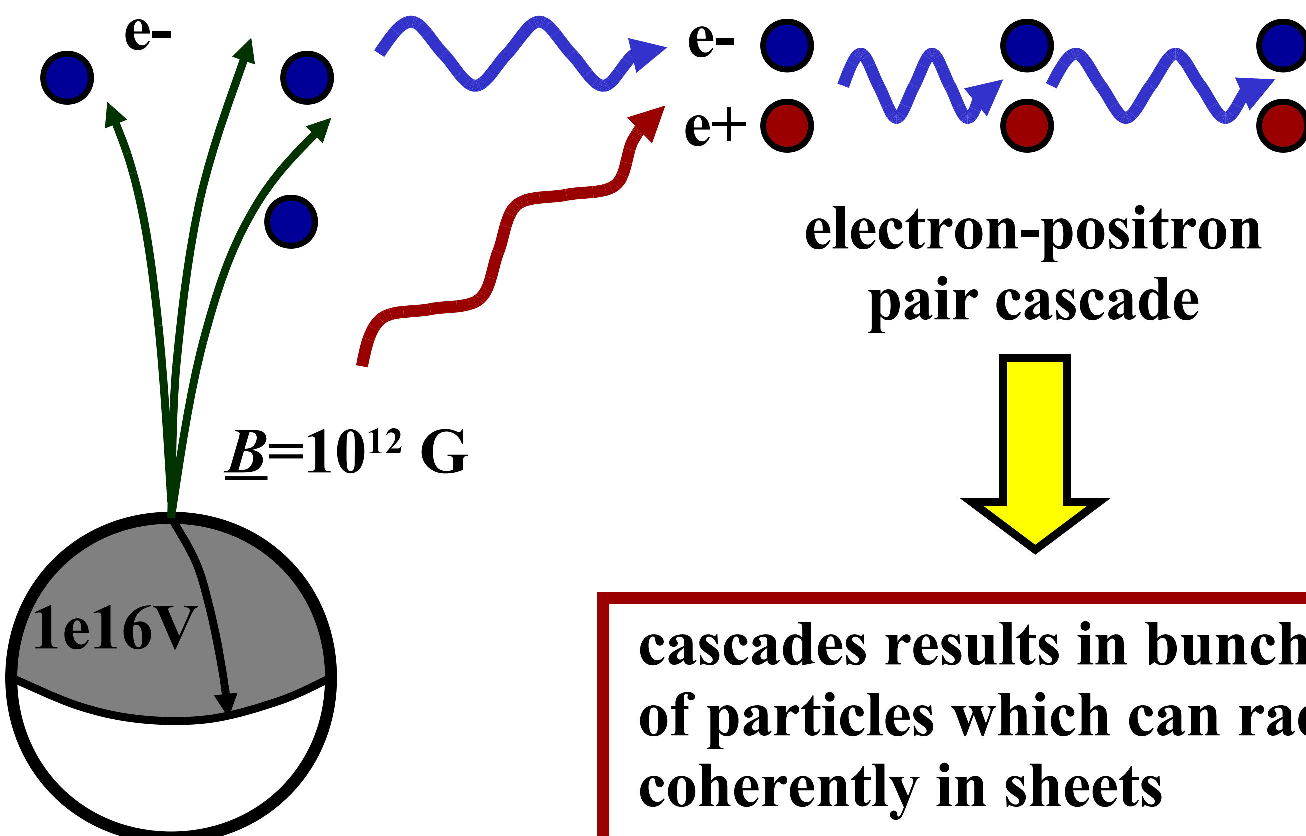
v = velocity

r_c = radius of curvature

Lorentz factor can reach 10^6 or 10^7, so $\nu \sim 10^{22}\ s^{-1}$ = gamma-ray

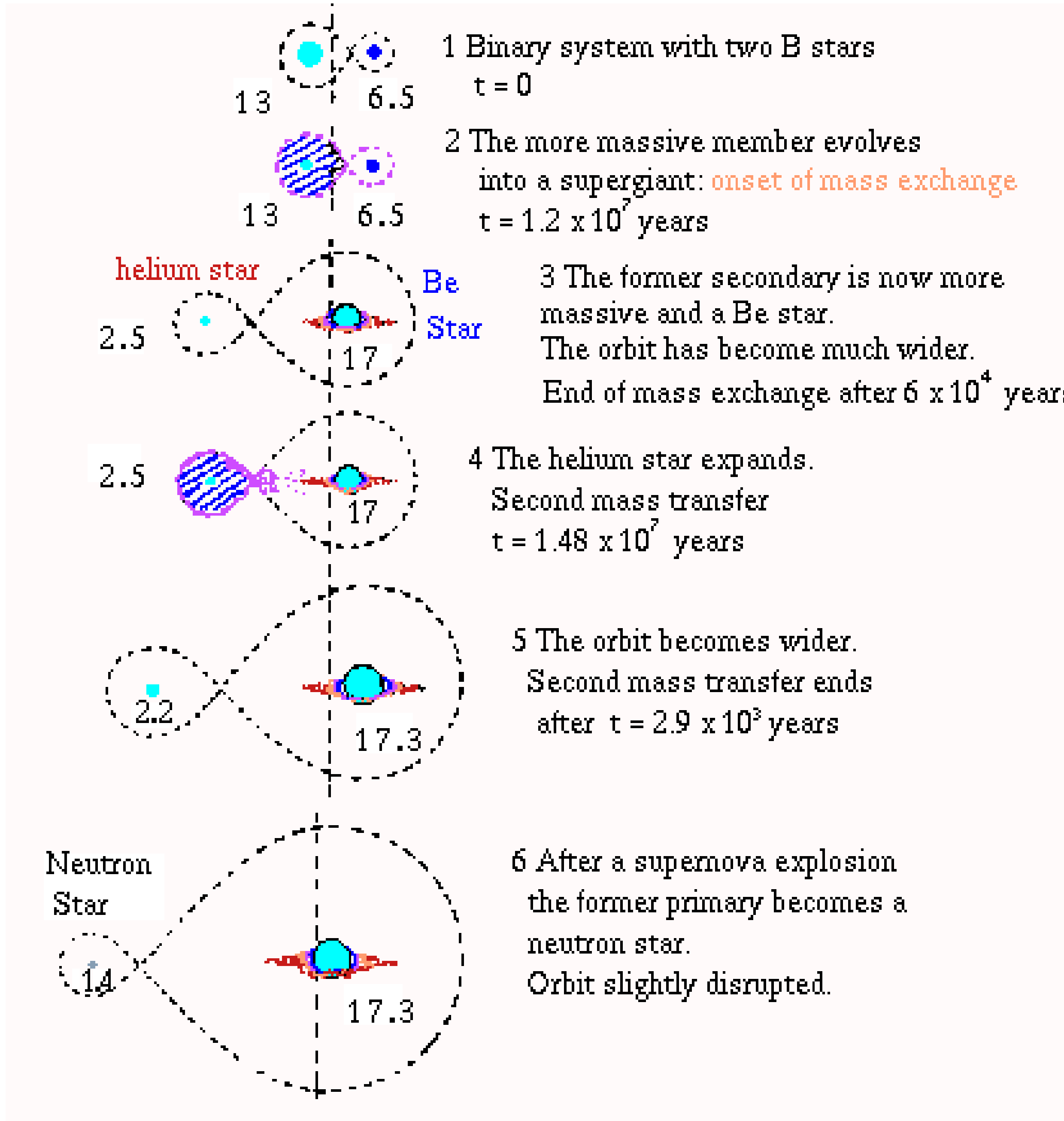
Radio is Coherent Emission

high-***B*** sets up large potential => high-E particles



cascades results in bunches of particles which can radiate coherently in sheets

HMXB Formation



LMXB Formation

There are 100x as many LMXBs per unit mass in globular clusters as outside

Dynamical capture of companions is important in forming LMXBs

Whether or not LMXBs form in the field (outside of globulars) is an open question

Keeping a binary bound after SN is a problem, may suggest NS forms via accretion induced collapse