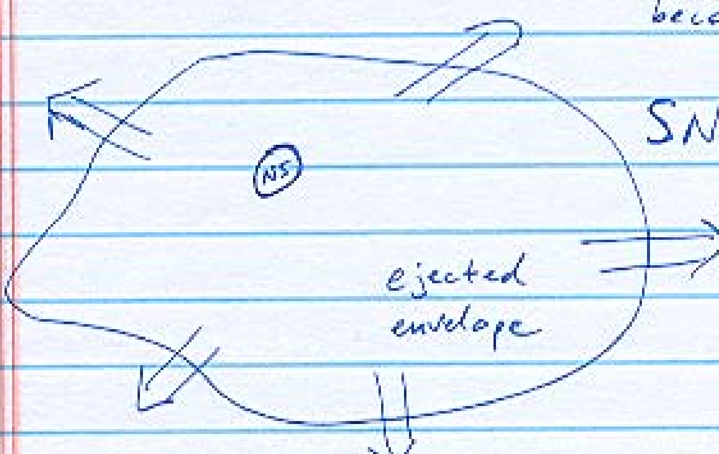
Neutron Stars

Feb. 26, 2008

- **Discovery** → first postulated by theory
  (Baade & Zwicky 1934)
  also (Landau 1938)

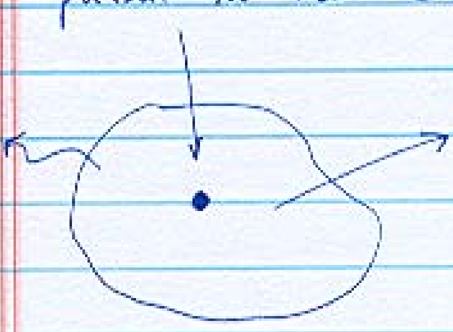
- Idea (now known to be correct):
  Neutron stars (NSs) born when massive stars ($\gtrsim 8\ M_\odot$) die as supernovae (SN)
  → below $8 M_\odot$ stars will become WDs (this is the initial mass of the star!)

SN



- observed serendipitously by radio astronomers
  (Bell & Hewish 1967)

- "pulsar" in the Crab Nebula – a rotating NS



synchrotron radiation (indirectly powered by pulsar)

period = 33 ms

→ <u>Cannot be a WD</u>

- WD oscillation/pulsation:

  $\Rightarrow \tau_{ff,WD} \sim 1$ second

- WD rotation: rotating at 33 ms per rotation would tear a WD apart!

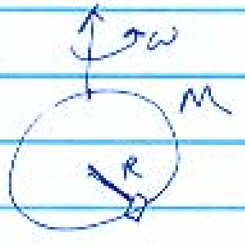
- Pulsars are rotating NSs!

• <u>Basic Properties</u>

- from pulsar observations → can infer NS properties!

→ $M_{NS} \sim 2 M_\odot$ (from binary pulsars)

→ Estimate radius from observed period, $P_{NS} = 30$ ms



→ rotation speed at surface, $V_{rot} = \frac{2\pi R_{NS}}{P_{NS}}$

centrifugal force < gravity

$$\frac{V_{rot}^2}{R_{NS}} < \frac{GM}{R_{NS}^2}$$

$$\Rightarrow R_{NS} < \left(\frac{G M_{NS} P_{NS}^2}{4\pi^2} \right)^{1/3} \simeq 100 \text{ km}$$

→ Now known that $R_{NS} \sim 10$ km

⇒ average density:

$$\langle \rho \rangle_{NS} = \frac{M_{NS}}{\frac{4\pi}{3} R_{NS}^3} \sim 10^{17} \text{ kg m}^{-3}$$

(compare to $\langle \rho \rangle_{\odot} \sim 1{,}000 \text{ kg m}^{-3}$; $\langle \rho \rangle_{WD} \sim 10^9 \frac{\text{kg}}{\text{m}^3}$)

→ Notice: this is EXTREME

→ nuclear density $\sim \frac{\text{proton}}{\frac{4\pi}{3} r_0^3} \sim \frac{m_H}{\frac{4\pi}{3} r_0^3}$

$\sim 4 \times 10^{17} \text{ kg m}^{-3}$

→ nuclear radius $R = r_0 A^{1/3}$ ← nucleon number (n+p)

$r_0 \hat{=}$ radius of proton $\sim 10^{-15}$ m (= 1 Fermi)

→ NSs are like giant atomic nuclei, but not quite:

- NS held together by gravity
- nucleus held together by strong force

• Neutronization

Basic Q: Why are NSs mostly composed of neutrons?

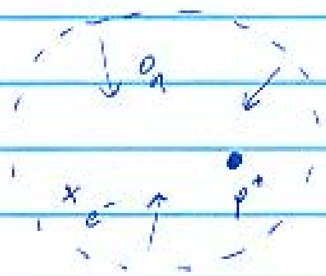
→ recall: $n \rightarrow p^+ + e^- + \bar{\nu}_e$ (β decay)

($\tau_{1/2} \sim 10$ mins) $\qquad 1.3\ \text{MeV} = (m_n - m_p)c^2$

→ Q: Why don't we see this decay in NSs?

A: Because this is energetically disfavored!

→ Consider collapse of the core of a massive star (en route to NS)



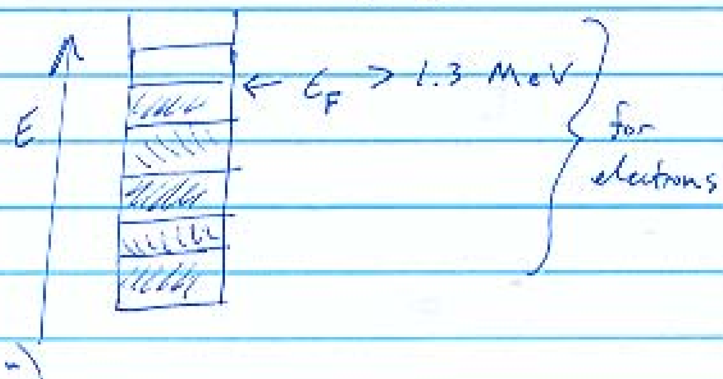
- mixture of (n, p^+, e^-)

- recall: Fermi momentum for deg. e^-:

$$p_F = h\left(\frac{3}{8\pi}\right)^{1/3} n_e^{1/3}$$

→ Define: Fermi energy

$$\epsilon_F = p_F c$$



→ n-decay prohibited ("no space in Fermi sea")

Furthermore: energetically favored to have

$$p^+ + e^- \longrightarrow n + \nu_e$$

(inverse β-decay)

→ Matter becomes increasingly neutron-rich