Ph 203 L18

Neutron Stars (NS)

Properties: $M_{NS} \simeq 1.4 - 2.4 \, M_\odot$

$R_{NS} \simeq 12 \text{ km} \quad (R_\odot \simeq 7 \cdot 10^5 \text{ km})$

$\rho_{core} \equiv \rho_c \doteq 5 - 10 \, \rho_N \, , \; \rho_N \simeq \frac{0.16}{\text{fm}^3}$ core of Nucleus

$\simeq 6.3 \cdot 10^{39} \frac{\text{nucl.}}{\text{cm}^3}$

$\langle \rho_{NS} \rangle \doteq \rho_N \simeq 1\text{-}2 \cdot 10^{14} \, \text{g/cm}^3$

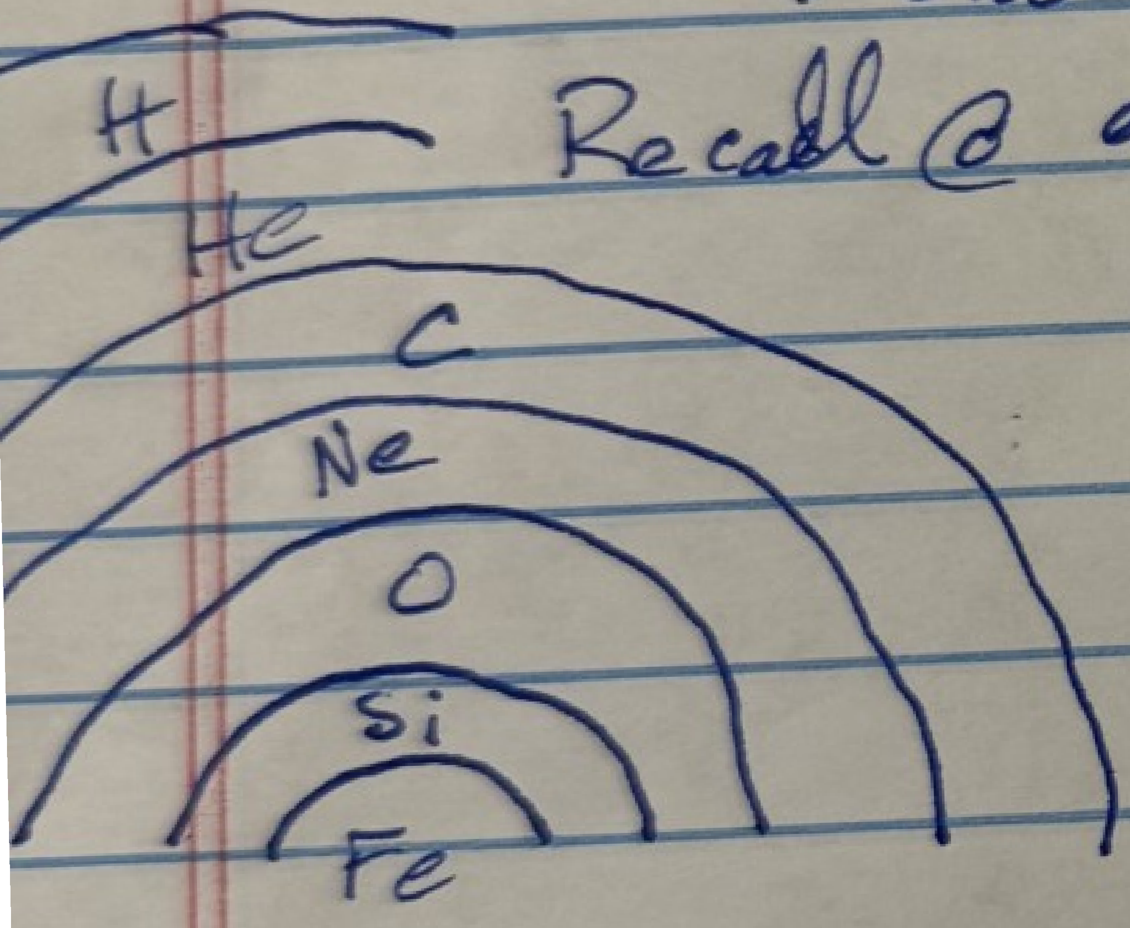
$|\vec{B}_{NS}| \gtrsim 10^4 - 10^{10} \, \text{T}$

Rotation $\nu \doteq 1 - 700 \text{ Hz}$

$\hookrightarrow V_{surf} \gtrsim 0.1c$

Formation of NS:

$\hookrightarrow$ End of Stellar Evolution for $M_* \simeq 10 - 20 \, M_\odot$



Recall @ end of burning (to Fe)

for $M_* \simeq 10 M_\odot \quad M^{Fe}_{core} \simeq 1 - 2 \, M_\odot$

Once burning stops @ Fe in core $R \downarrow$, but e^- degeneracy pressure can't stop contraction (like in White Dwarf)

∴

1. As $T \uparrow \quad e^- + A_Z \rightarrow A_{Z-1} + \nu_e$ energetically OK & e^- pressure $\downarrow_{\phi}$ & Core Collapses

$@ \; T_6 = 10{,}000 \, , \; \rho_c \doteq 10^{-6} \rho_N$

2. Core Collapse: from $R_i \simeq 10^4 - 10^5 \text{ km}$ to $R_f \simeq 20 \text{ km}$ in $\sim 0.5 \text{ s}$ releasing

$\frac{3}{5} \frac{G M_*}{R_F} \simeq 10^{46} \text{ J}$; lotta Watts!

3. As $\rho \to \rho_N$, since $\sigma_{\nu x} \sim 10^{-40}\,\text{cm}^2$

$$\ell^{\nu}_{mfp} \sim \frac{1}{n\sigma} \simeq 30\,\text{cm} \ll R_c$$

$\therefore$ ν are trapped

4. When $\rho \gtrsim \rho_N$ collapse suddenly stops due to degenerate nucleon pressure

$\therefore$ Outer part of star "bounces" as hot shock wave propagates outward lead to "explosion"

$\simeq 10^{44}$ j in Kinetic Energy $\Delta t \simeq 50$s

$\simeq 10^{42}$ j in γ's $\Delta t \sim$ hrs → yrs

$\simeq 10^{46}$ j in ν's $\Delta t \sim 50$s

5. This is Type II SN ⟹ Core Collapse SN

"Recent" visable: SN 1987a

2/23/87

→ 20 $M_\odot$ Blue Giant

few hrs!

→ after visible observation, look-back ν in several ν detectors gave 25 10-50 MeV ν's over ~ 20 s

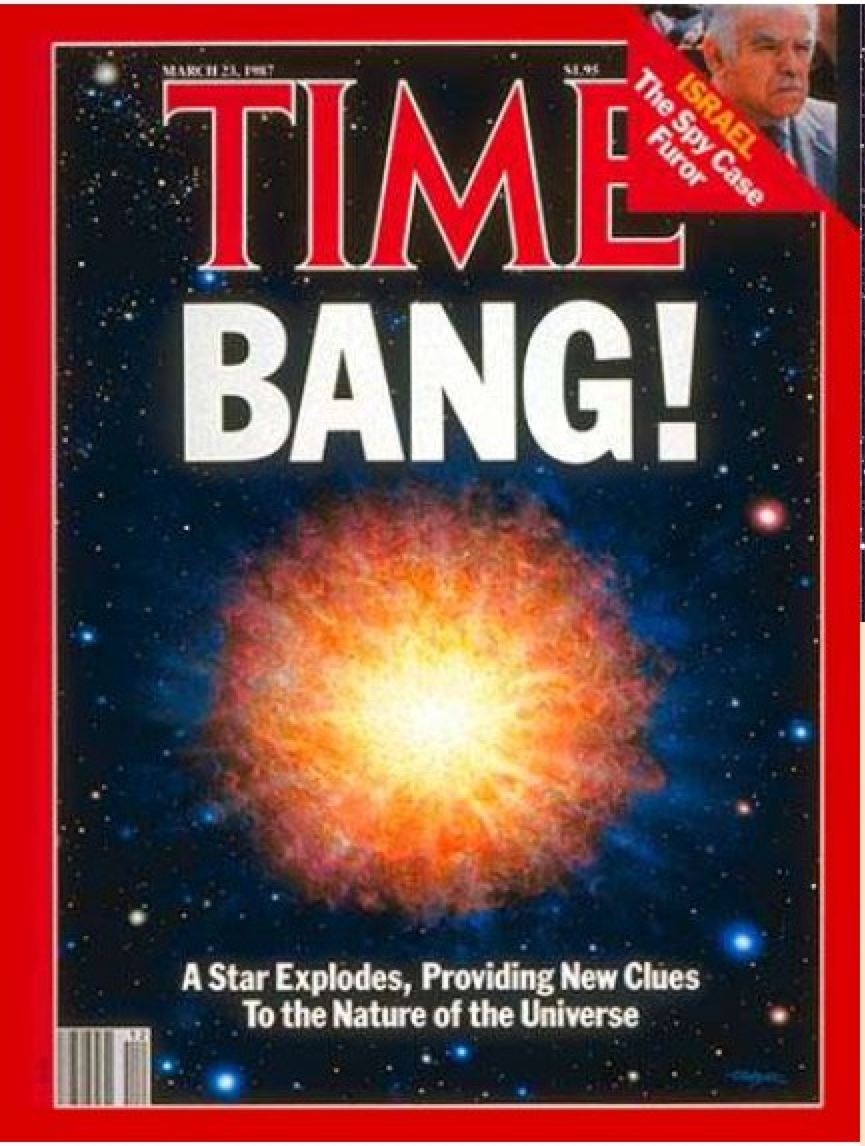
see Pics next 2 pages

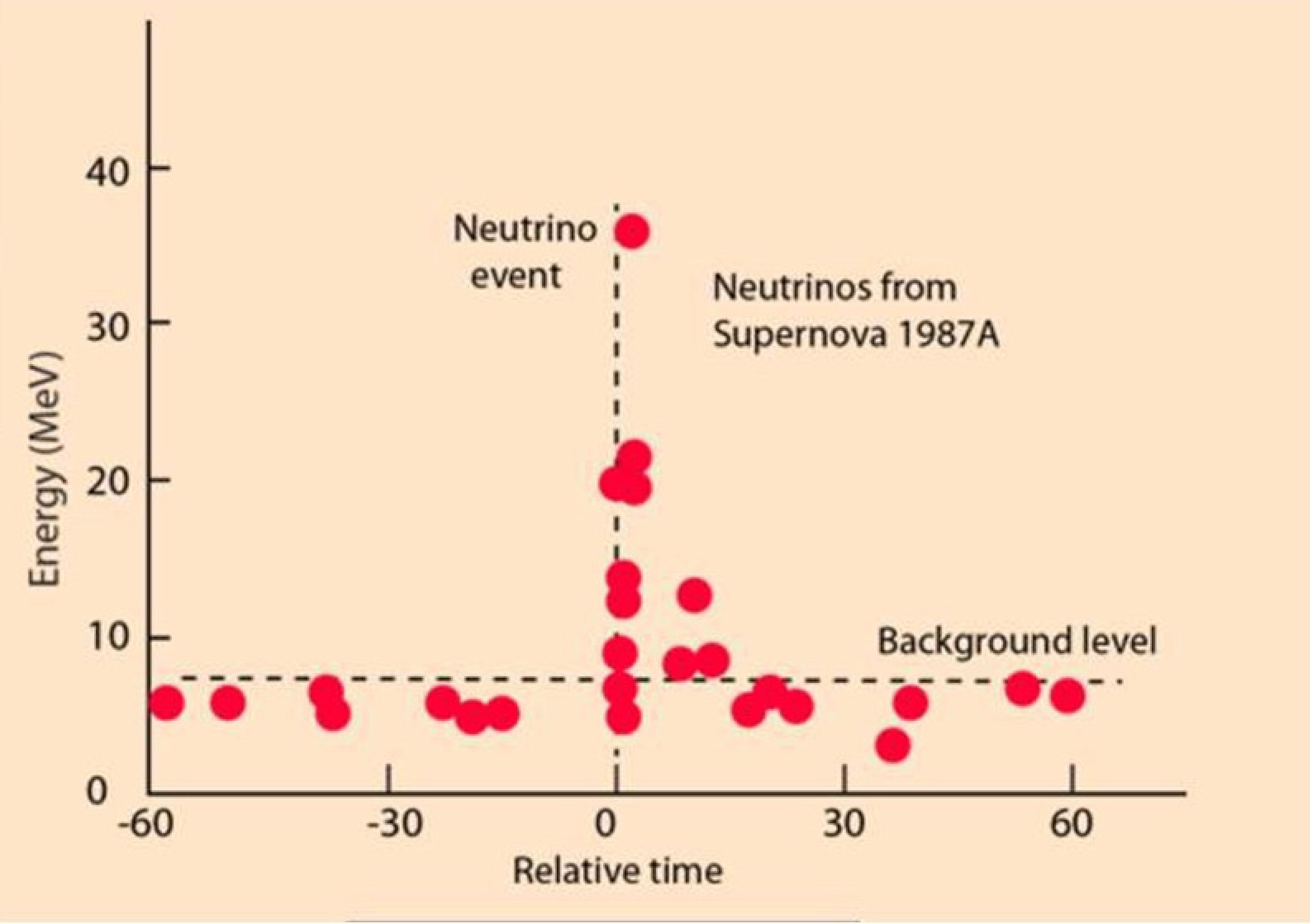
Note: After 50yrs trying to model explosion

1D → 2D (didn't work)

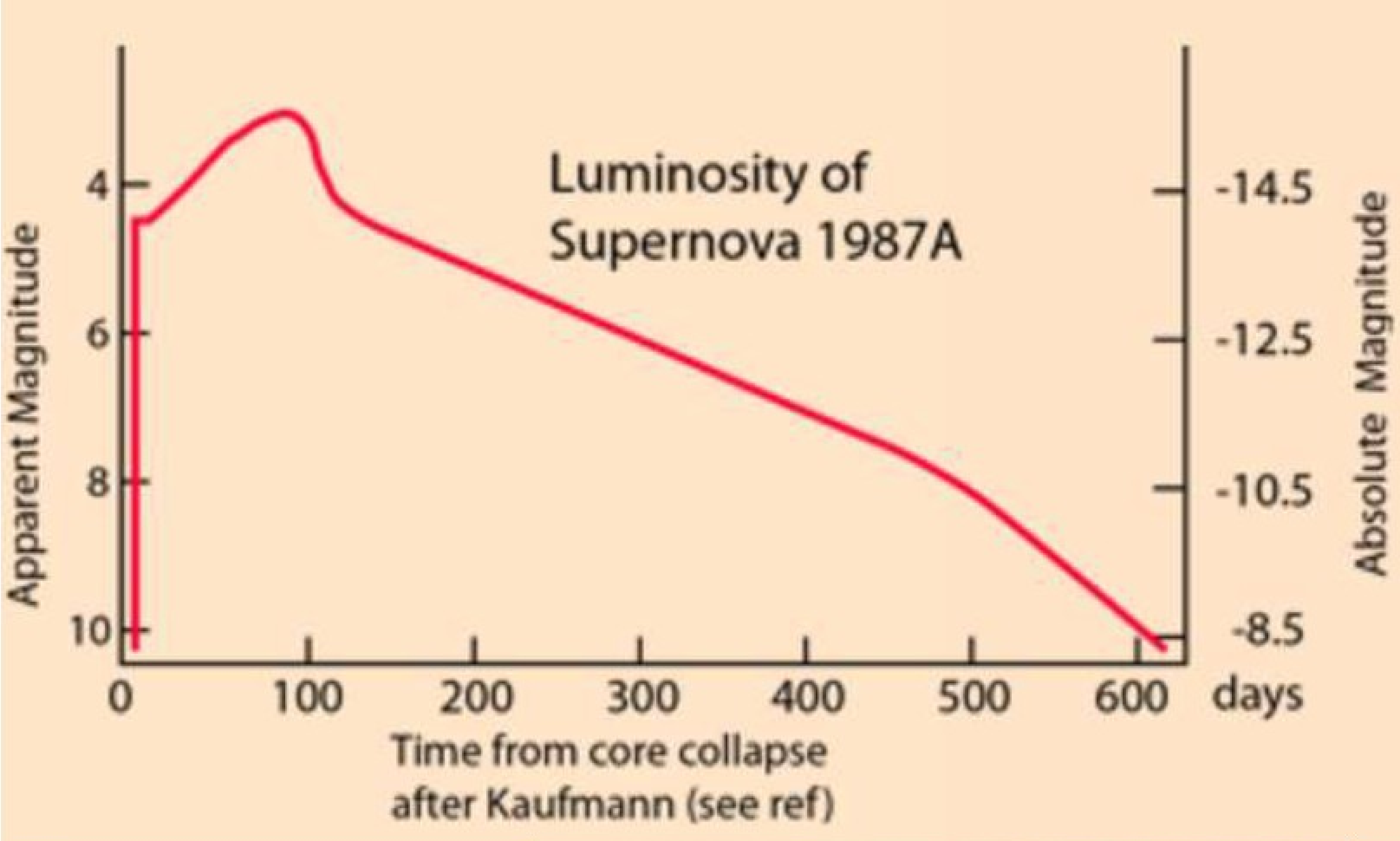
but 3D (turbulence) allowed Simulated explosion!

“Recent” Core-Collapse Supernova





170,000 ly away in Large Magellanic Cloud



Hubble view ~ 2012

James Webb
Space Telescope
2023

After SN explosion

The remaining 1.4–2.4 $M_\odot$ contracts to a neutron rich NS w

$\langle \frac{n_p}{n_n} \rangle \simeq 0.1$

compared to heavy nuclei

$\langle \frac{n_p}{n_n} \rangle_{Av} \simeq 0.7$

Over few sec to yrs NS cools via URCA process:

T 10GK t (1–10s)

$$\begin{cases} n \to p + e^- + \bar{\nu}_e & \& \; A_Z \to A_{Z+1} + e^- + \bar{\nu}_e \\ p + e^- \to n + \nu_e & \& \; e^- + A_Z \to A_{Z-1} + \nu_e \end{cases}$$

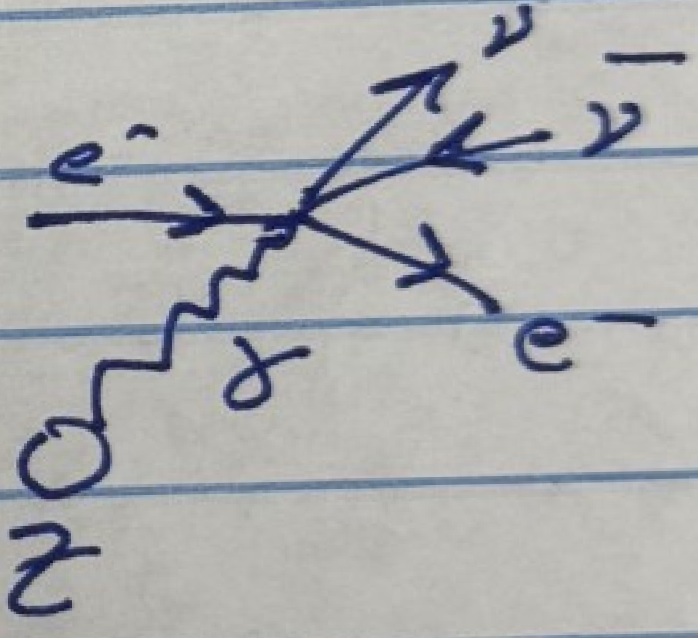
note A = nuclei & hypernuclei ↗ uds baryons since $T \gtrsim m_s$ (see later)

Later get modified URCA

T 1GK (min–hr) $n + n \to n + p + e^- + \bar{\nu}_e$

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

& also ν bremsstrahlung:



∴ early time get ~50 MeV $\nu_e, \bar{\nu}_e$
after 20 s ~ 10 MeV $\nu_e/\bar{\nu}_e$, $\nu_\mu/\bar{\nu}_\mu$ & $\nu_\tau/\bar{\nu}_\tau$

Stay tuned: next SN in galaxy
≃ 2037!

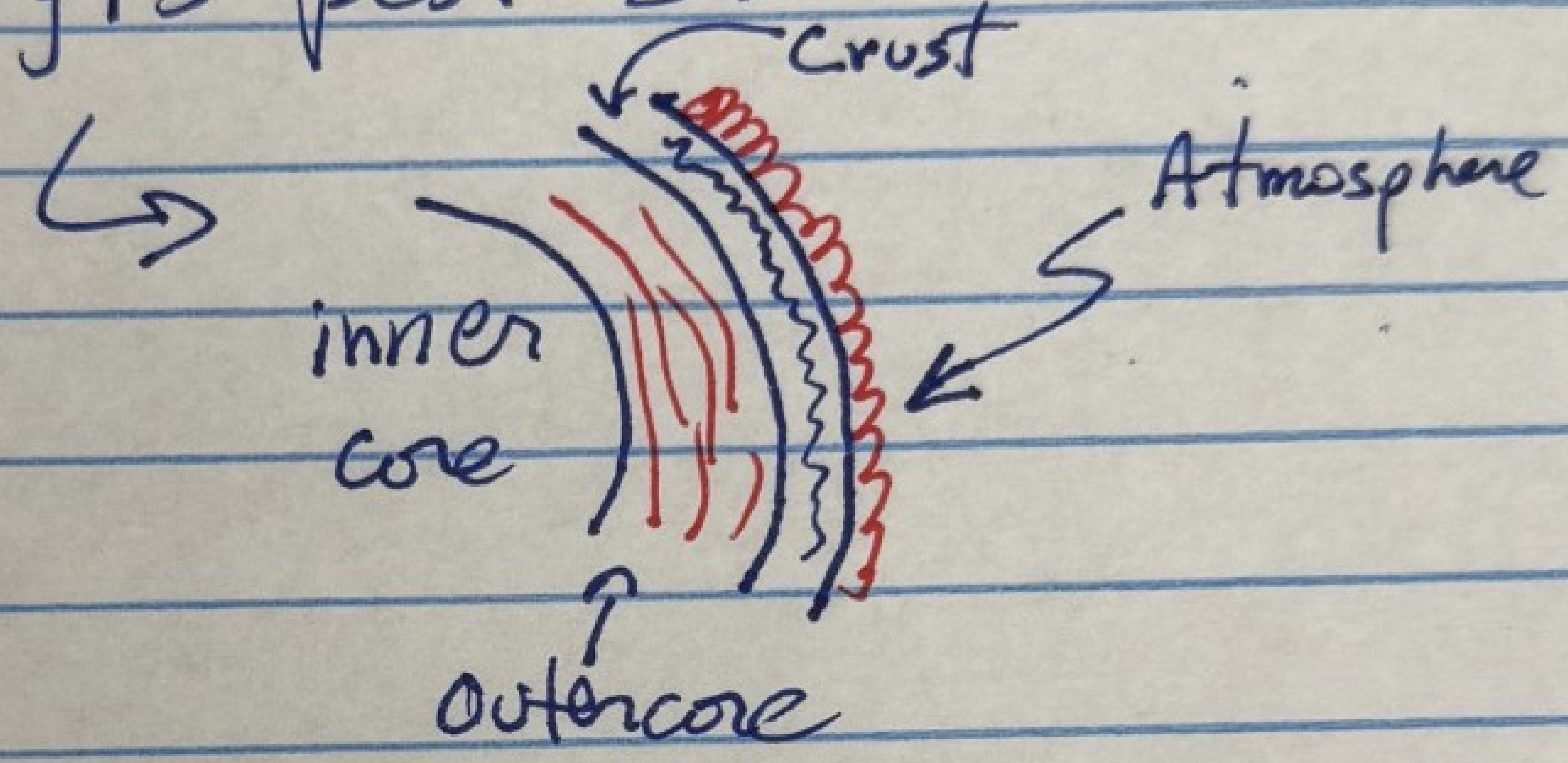
(should see $>10^3$ ν's)

SN Summary: ① for $M_* \sim 8-20 M_\odot$
CCSN gives NS
② for $M_* \gtrsim 25 M_\odot$
CCSN gives BH
③ Full 3D needed to reproduce CCSN
(simulate)
④ Lots of NP in SN

NS Structure & Why Imp.

After ~ 10yrs post SN

↳



1. Thin Atmosphere

(Fe → Au + n)

thickness given by Scale height: $H \equiv \frac{kT}{mg}$

w/ $\rho(z) = \rho_0 e^{-z/H}$

e.g. for Earth ⊕

$T_s = 300\,K,\ m_{Atom} \doteq N_2;\ g_\oplus = \frac{GM_\oplus}{R_\oplus^2}$

$H_\oplus \simeq 8\,km$ $= 9.8\,m/s^2$

for NS

$T_s \sim 10^6\,K,\ m \doteq Fe,\ g \doteq 10^{10} g_\oplus$

↳ $H \simeq 10\,cm$

2. Crust $\simeq$ 1 km thick

w/ n, Fe $\rightarrow A \simeq 200$ & $\frac{n_p}{n_n} \sim 0.1$

$\rho \simeq 10^6$ g/cm^3 @ top of crust

$\simeq 10^{12}$ g/cm^3 @ bottom "

note: $\rho_N \simeq 2 \cdot 10^{14}$ g/cm^3

then near bottom of crust: n binding energy $\ll \frac{8\,\text{MeV}}{\text{Nucleon}}$

↳ nucleon Fluid

3. Outer Core

$\rho \lesssim \rho_N$ & $kT \simeq$ keV $\Rightarrow$ no lab system to compare to

but theorists predict: ("Italian Dinner")

I. for $\rho \ll \rho_N \Rightarrow$ Nuclei (Meatballs)

II. for $\rho \sim 0.1 \rightarrow 1\,\rho_N$

Predict continuous change in "dimensionality":

a. nuclei merge to long strings (0D → 1D)

↳ spaghetti

b. 1D → 2D spaghetti merges into slabs

↳ lasagna

c. Slabs merge to thick tubes

↳ Ziti

d. 2D → 3D tubes merge to thick walled bubbles

↳ Ravioli

e. @ $\rho = \rho_N \Rightarrow$ Uniform nuclear Matter

↳ Sauce!

(FYI → it gets) weirder!

4. Inner Core

$\rho_c \sim 5-10\,\rho_N$, $T_c \simeq 10^7$K (after ~10 yrs)

$E_{Fermi} \simeq 90$ MeV ⇒ $T_F \simeq 10^{12}$K

∴ cold, degenerate matter

Many options for composition (what's lowest E state?)

a. Neutrons form cooper pairs ⇒ superfluid

b. Mixed phase of hadronic & deconfined quark-gluon soup

c. Various Bose Condensates

Pion Pion or Kaon

d. Hypernuclei (Λ = uds) is disting. from n = udd

∴ lower energy

e. Some QCD models suggest strange quark matter

↳ uds more bound than ud system

↳ becomes "color-flavor-locked" CFL

$u_r d_g$ but not $u_g d_r$

$u_r s_g$ " " $u_g s_r$

↳ superconducting

or $u_{c_1} d_{c_2} s_{c_3}$ superfluid

Each of above can have different $P(\rho, T)$

e.g. Eq. of State (EOS)

↳ Nuc. EOS = NEOS

NEOS affects:

1. Bounce in CCSN
2. NS: M vs R (see Pic)
3. GW signal from NS-NS merger

→ w more events (NS-NS mergers)
GW can teach us about NEOS

Neutron Star Mass vs Radius with different NEOS

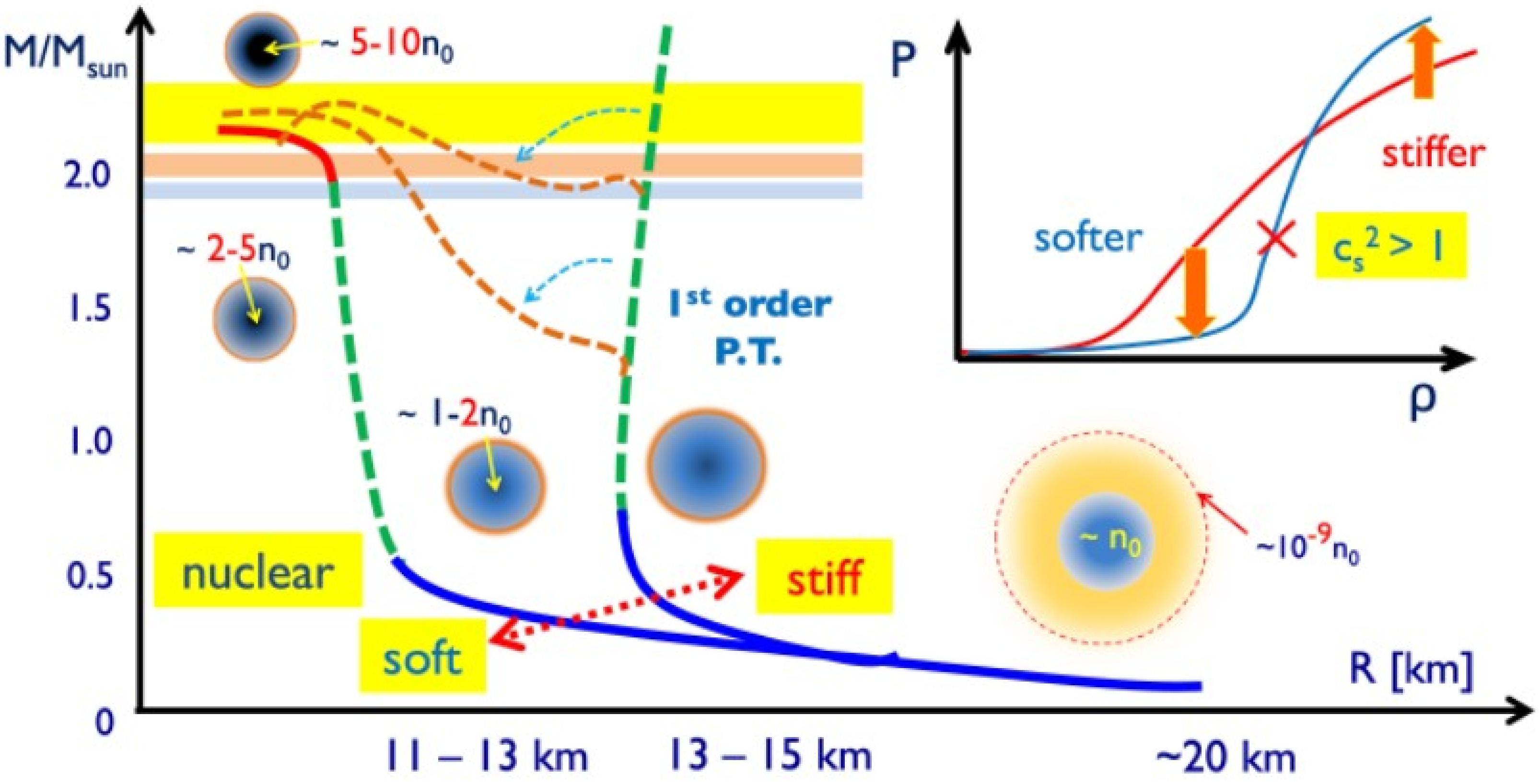


Fig. 3 *M*-*R* curves as functions of the central density n_c. For a small *M* neutron stars have large radii due to loosely bound crust. When the central density reaches $n_c = 1 \sim 2n_0$, the dilute matter is highly compressed and the size of a neutron star is characterized by a matter beyond the saturation point. The curves go up with small variation in the radii. The exception is equations of state with the first order transitions which lead to kinks in the *M*-*R* curves. The top right figure illustrates how the causality constrains the relation between low and high density behaviors of $P(\rho)$.

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