PHYSICS OF SUPERNOVA (SN) NEUTRINOS (ν)

1] ν as particles and overview

2] SN ν emission

3] SN ν propagation (flavor oscillations)

4] SN ν detection & physics potential

5] Bonus material : 1) diffuse SN ν flux

2) testing physics beyond the Standard Model

1 ν as particles and overview

1. Intro: ν in the Standard Model (SM)

2. ν masses and mixing

3. ν in astrophysics

① Intro: ν in the Standard Model (SM)

- elementary, fermions ($S = 1/2$),
  neutral ($q_\nu = 0$)

LEPTONS

$$\underbrace{\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}}_{3 \text{ flavors}}$$

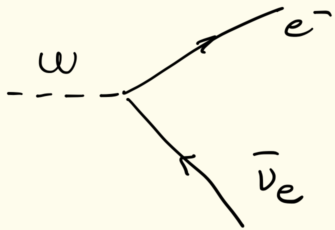
WEAK INT.
GAUGE BOSONS

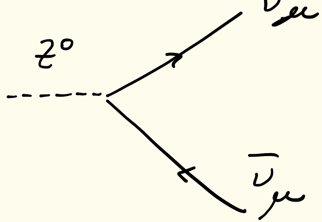
$W^\pm$

Z^0

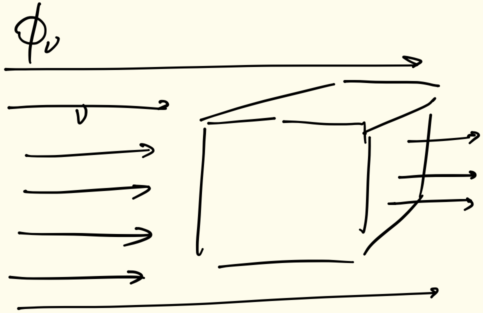
- No coupling to E.M. (γ)

- Couple to <u>Weak</u> Interaction
  - nuclear processes





Weak interaction



- cross section :

$$\sigma = \frac{N_{scatt}}{N_T \, \phi_\nu \, \Delta t} \sim G_F^2 \, E_\nu^2 \sim O(10^{-42}) \, cm^2$$

[comparison : E.M. cross section : $\sigma_T \sim 6 \cdot 10^{-25} \, cm^2$]

- mean free path : $\lambda \sim (\sigma N_A)^{-1} \sim \left(10^{-42} \, cm^2 \; 6 \cdot 10^{23} \, cm^{-3}\right)^{-1}$

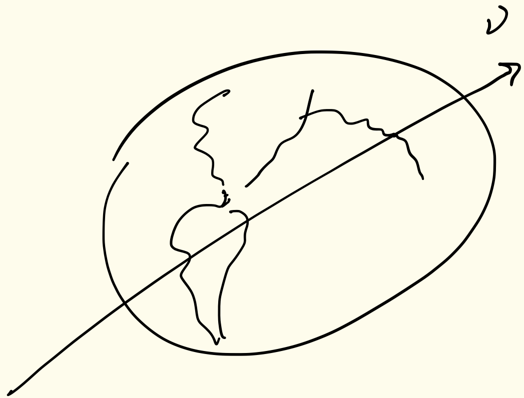
$$\sim 10^{19} \, cm \quad !!$$

$\rightarrow$ ν Ghost particles!

ν as "Ghost particles"

- $\lambda_{mfp} \gg R_\oplus$

($\text{for}\ E \lesssim \text{TeV}$)



2 ν masses and mixing

- in the SM, $m_\nu = 0$

- $m_\nu \neq 0$ was discovered (early 2000's)
  - ν oscillate : $P(\nu_e \longrightarrow \nu_\mu) \neq 0$

- Flavor basis : $\{\nu_e, \nu_\mu, \nu_\tau\}$

  Mass (vacuum H) basis : $\{\nu_1, \nu_2, \nu_3\}$

- Mixing matrix :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\, \nu_i \qquad \nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$$

large small

$$U = \begin{pmatrix} \sim 0.8 & \sim 0.5 & \sim 0.1 \\ \sim 0.3 & \sim 0.5 & \sim 0.7 \\ \sim 0.3 & \sim 0.6 & \sim 0.7 \end{pmatrix}.$$

(different from CKM matrix for quarks!)

$$|U_{e3}|^2 \approx 10^{-2}$$

$$
|V| = \begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{array}
\begin{array}{c}
\begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\
\begin{pmatrix}
0.798 \to 0.843 & 0.517 \to 0.584 & 0.137 \to 0.158 \\
0.231 \to 0.518 & 0.441 \to 0.693 & 0.617 \to 0.790 \\
0.251 \to 0.530 & 0.468 \to 0.711 & 0.595 \to 0.773
\end{pmatrix}
\end{array}
$$

$$
|V| = \begin{array}{c} \\ d' \\ s' \\ b' \end{array}
\begin{array}{c}
\begin{array}{ccc} d & s & b \end{array} \\
\begin{pmatrix}
0.975 & 0.224 & 0.0037 \\
0.224 & 0.974 & 0.042 \\
0.009 & 0.04 & 0.999
\end{pmatrix}
\end{array}
$$

Neutrino

Mixing Matrix

Quark

- $m_i = ?$

- Oscillations:

$$\left.\begin{aligned} m_3^2 - m_2^2 &\approx 2 \cdot 10^{-3}\ \mathrm{eV}^2 \\ m_2^2 - m_1^2 &\approx 7 \cdot 10^{-5}\ \mathrm{eV}^2 \end{aligned}\right\} \longrightarrow \mathrm{Max}\{m_i\} \geq 0.05\ \mathrm{eV}$$

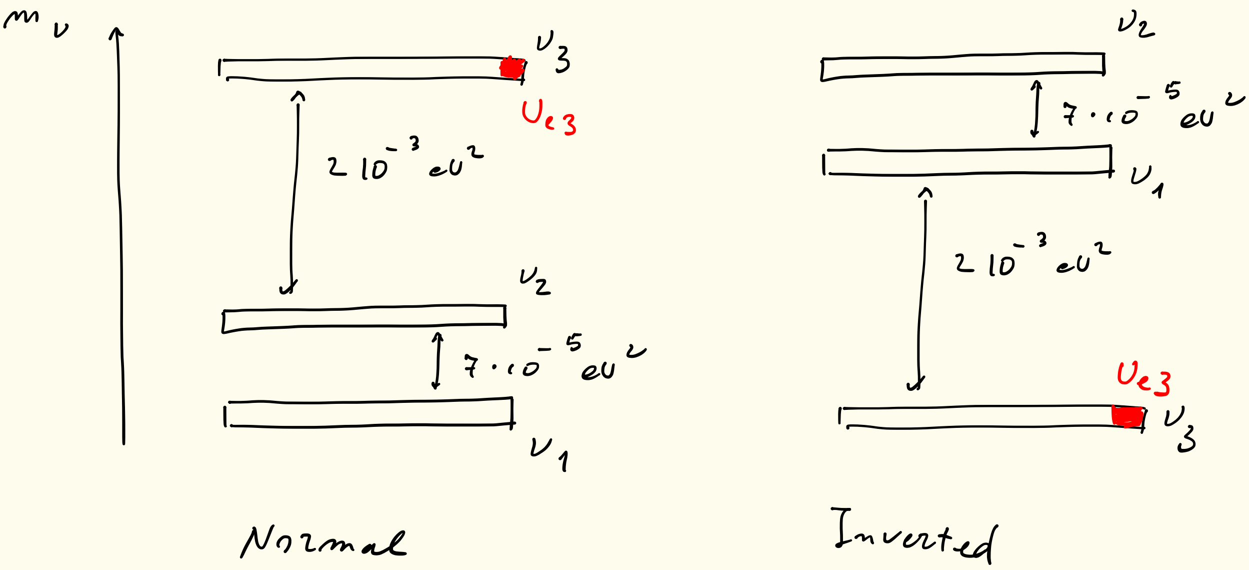
- Cosmology:

$$\sum_{i=1}^{3} m_i \lesssim O(0.1)\ \mathrm{eV}$$

- Lab limits

$$m_{\mathrm{eff}} \lesssim 2\ \mathrm{eV}$$

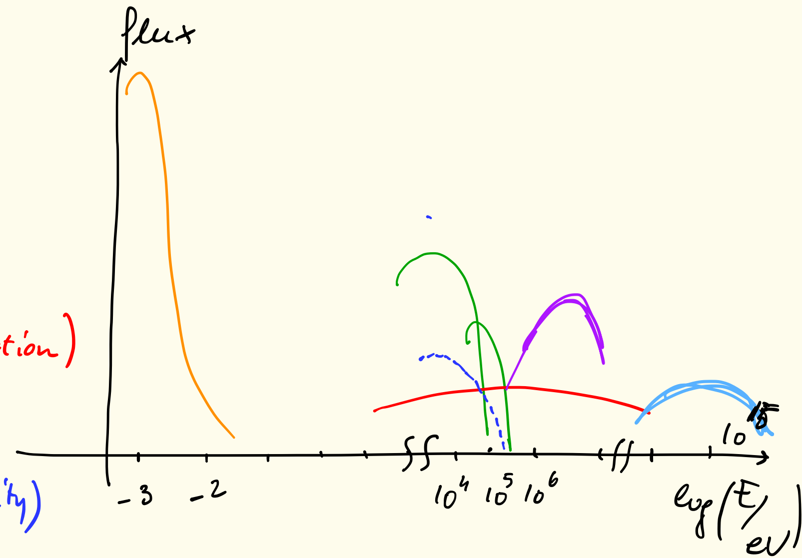
Mass ordering?



③ ν in astrophysics (natural sources)

D E T E C T E D

- Big Bang ν
- Solar ν (fusion)
- atmospheric ν (CR interaction)
- geological ν (Radio activity)
- SN ν (thermal emission)
- HE extragalactic ν (jets UHECR)



- SN ν

  - observed in 1987 (SN198A)
    <u>once</u>

F
U
T
U
R
E

- still waiting for next nearby SN

- data on <u>diffuse</u> SN ν flux coming soon (~5-10 yrs)

2 SNV emission

1. Overview, emission stages

2. Basics - order of magnitude estimates

3. Advanced features:

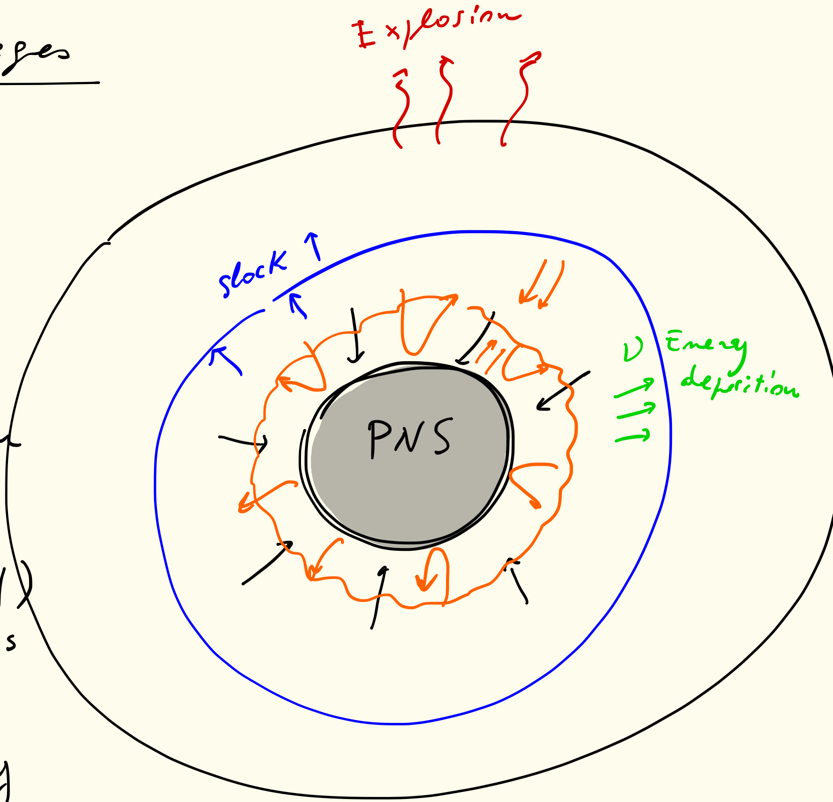
   - SASI

   - late time emission

1 Overview, emission stages

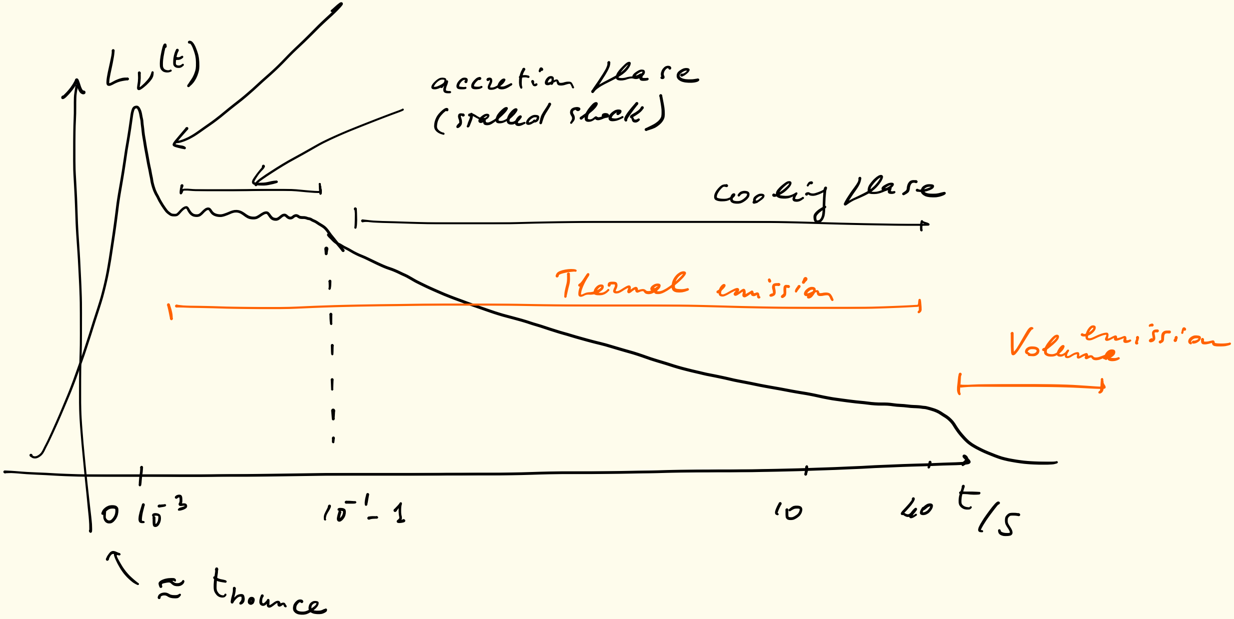
- End of core fusion
  - Fe core
- loss of pressure
  ↳ collapse → Proto-Neutron Star

ν EMISSION
- bounce & shock (stalled)
  ~100 ms
- shock launches → cooling phase
  ⋮
- star explodes → SN



ν narrative

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



Thermal emission:

- ν coupling:

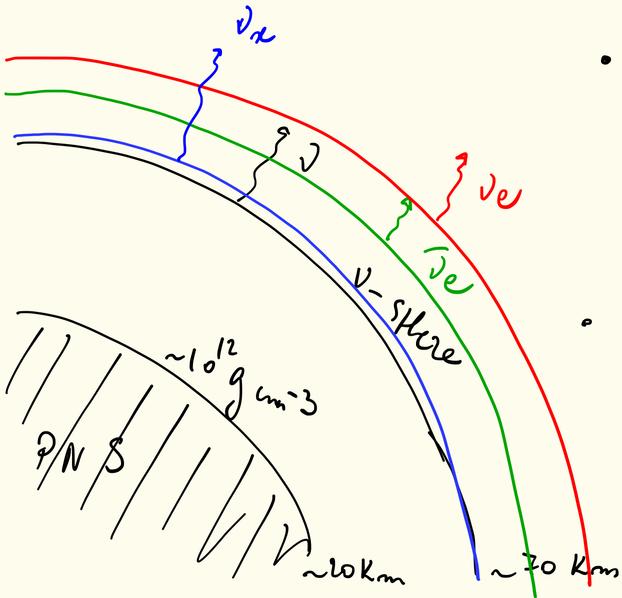
$$e^{\pm} + (A,Z) \longleftrightarrow \overset{(-)}{\nu}_e + (A, Z \mp 1)$$

$$e^{+} + e^{-} \longleftrightarrow \nu_\alpha + \bar{\nu}_\alpha$$

$$N + N \longrightarrow \nu_\alpha + \bar{\nu}_\alpha + N + N$$

$$\nu_\alpha + \genfrac{}{}{0pt}{}{N}{e^-} \longleftrightarrow \nu_\alpha + \genfrac{}{}{0pt}{}{N}{e^-}$$

- $\underbrace{\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau}_{\nu_x}$: same coupling

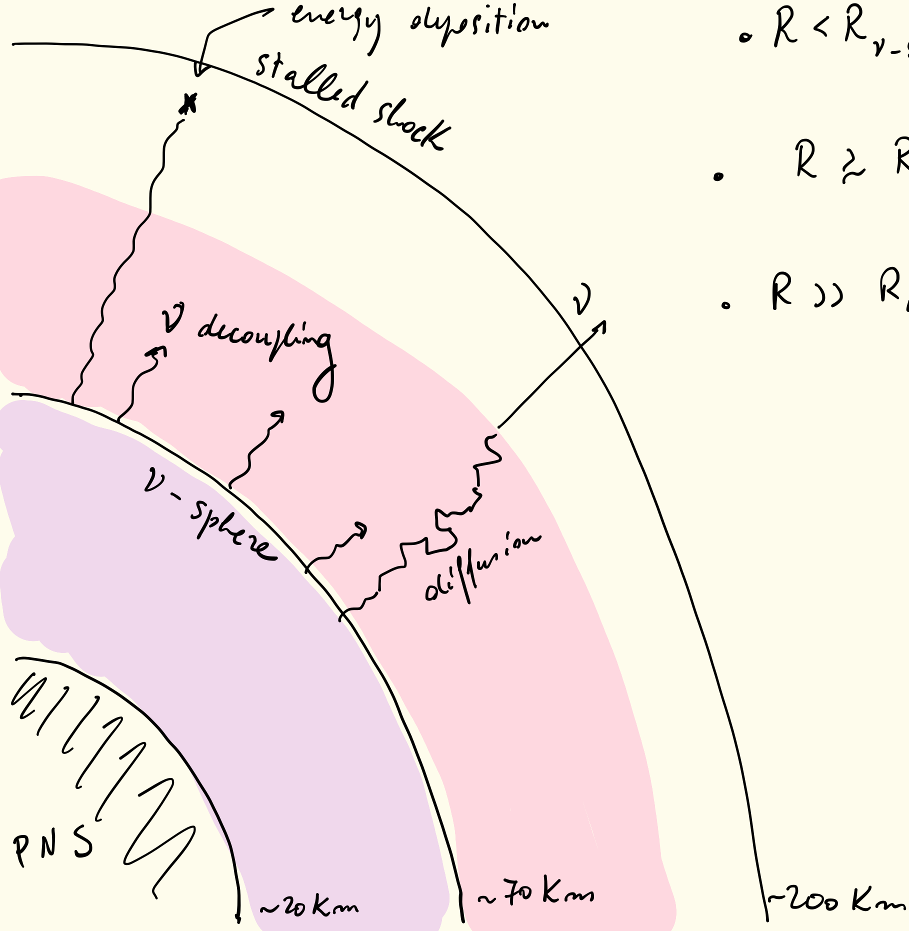


- $R^{(\nu_x)}_{\nu\text{-sph}} < R^{(\bar{\nu}_e)}_{\nu\text{-sph}} < R^{\nu_e}_{\nu\text{-sph}}$

$$\hookrightarrow \boxed{T_{\nu_e} < T_{\bar{\nu}_e} < T_{\nu_x}}$$

~ 3 MeV $\quad \sim 5$ MeV $\quad \sim 6$ MeV

Thermal emission



- $R < R_{\nu\text{-sph}}$: ν thermalized
- $R \gtrsim R_{\nu\text{-sph}}$: diffusion
- $R \gg R_{\nu\text{-sph}}$: free stream

(2) Basics : Order of magnitude

- $E_\nu^{TOT} \simeq \Delta U_{grav} \sim U_{\substack{pre-\\collapse}} - U_{PNS} \sim -U_{PNS} \sim \dfrac{G M_{PNS}^2}{R} \sim 3\,10^{53}$ ergs

- Diffusion time: $\tau \sim \dfrac{R^2}{\lambda_{mfp}} \sim O(10)\,s$ $\qquad$ $(\lambda_{mfp} \sim 10$ cm$)$

- $F(E)_{\text{Fermi-Dirac}} \propto \dfrac{E^2}{e^{E/T - \eta} + 1}$ $\qquad$ Blackbody

- $T \sim \left[\dfrac{1}{\sigma} \left(\dfrac{E_\nu^{TOT}}{\tau} \right) \dfrac{1}{4\pi R^2_{\nu\text{-sph}}} \right]^{1/4}$

$\simeq 3 - 5$ MeV

Check:

$$\frac{G M^2}{R} = \frac{6.7 \cdot 10^{-11}\, m^3 kg^{-1} s^{-2} \cdot \left(2 \cdot 10^{30}\, kg\right)^2}{(10^4\, m)}$$

$$\simeq 7.4 \cdot 10^{-11+60-4}\, m^2\, kg\, s^{-2} \sim 28 \cdot 10^{45}\, J$$

$$\sim 3 \cdot 10^{46}\, J \xrightarrow[\times 10^7\, erg/J]{} 3 \cdot 10^{53}\, ergs \checkmark.$$

$$\tau \sim \frac{(10\, Km)^2}{10\, cm} \cdot \frac{1}{c} = \frac{(10^4\, m)^2}{10^{-2}\, m} \frac{1}{3 \cdot 10^8\, m/s} = \frac{1}{3} \cdot 10^{8+2-8} \sim$$

$$\sim 30\, s$$

λ_{mfp}
(see Janka)

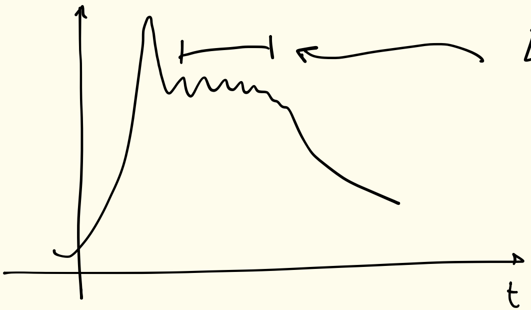
$$T \sim \left[\frac{1}{\underset{2}{\cancel{6}} \cdot 10^{-8}\ W\, m^{-2} K^{-4}} \cdot \frac{\cancel{3} \cdot 10^{46}\ J}{10\ s \cdot \underbrace{4\pi}_{\sim 10}} \ \frac{1}{(10^4 m)^2} \right]^{1/4}$$

$$\sim \left[0.5 \cdot 10^{\cancel{8}+46-2\cancel{-8}} \right]^{1/4} K =$$

$$\sim \mathcal{O}(10^{44/4}) K \sim \mathcal{O}(10^{11}) K \cdot 10^{-4} \frac{eV}{K} \sim \mathcal{O}(10^{7})\, eV$$

~ 10 MeV ✓.

3 Advanced features: SASI



$$T(t) \sim T_0 (1 + \beta \cos(\omega t + \varphi))$$
$$L_\nu(t) \simeq L_0 (1 + \alpha \cos(\omega t + \varphi))$$

$$\omega \sim O(10^2)\ \mathrm{Hz}$$

- Standing Accretion Shock Instability

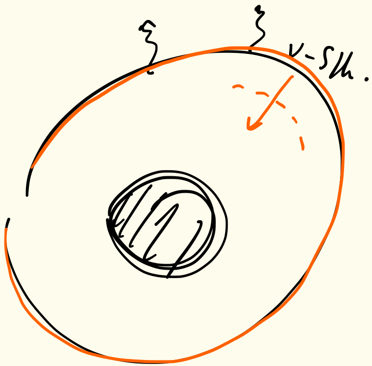
  - large scale shock sloshing mode

    ↳ varying mass accretion rate $\dot{M}(t) \propto L_\nu(t)$

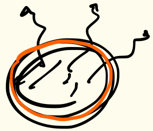
Late time: from thermal to volume emission:

T_ν decreases

$R_{\nu\text{-sph}} \to 0$

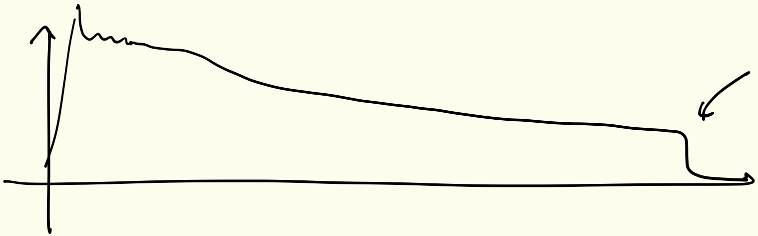


$t \ll 40$ s



ν from PNS volume

(<u>NO</u> ν-sphere)



3] SN ν propagation

① SN ν & Heavy element synthesis

② ν flavor conversion (oscillations)

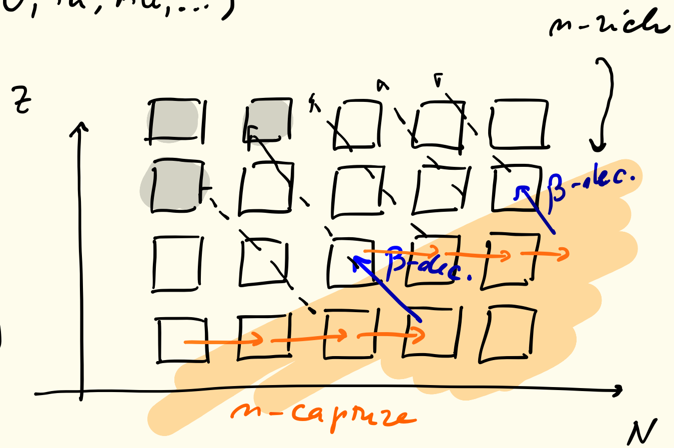
(③ Quantum decoherence)

1 SN ν & Heavy element synthesis

- formation of heavy nuclei (U, Th, Au, ...)

  r-process:

  $${}^{A}_{Z}X + n \longrightarrow {}^{A+1}_{Z}X^{*} \hookrightarrow \gamma + {}^{A+1}_{Z}X$$



  r = Rapid (faster than β-decay)

- ν effect on abundances:

  - change p/n ratio

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

  $$\bar{\nu}_e + p \to n + e^+$$

② ν flavor conversion (oscillations)

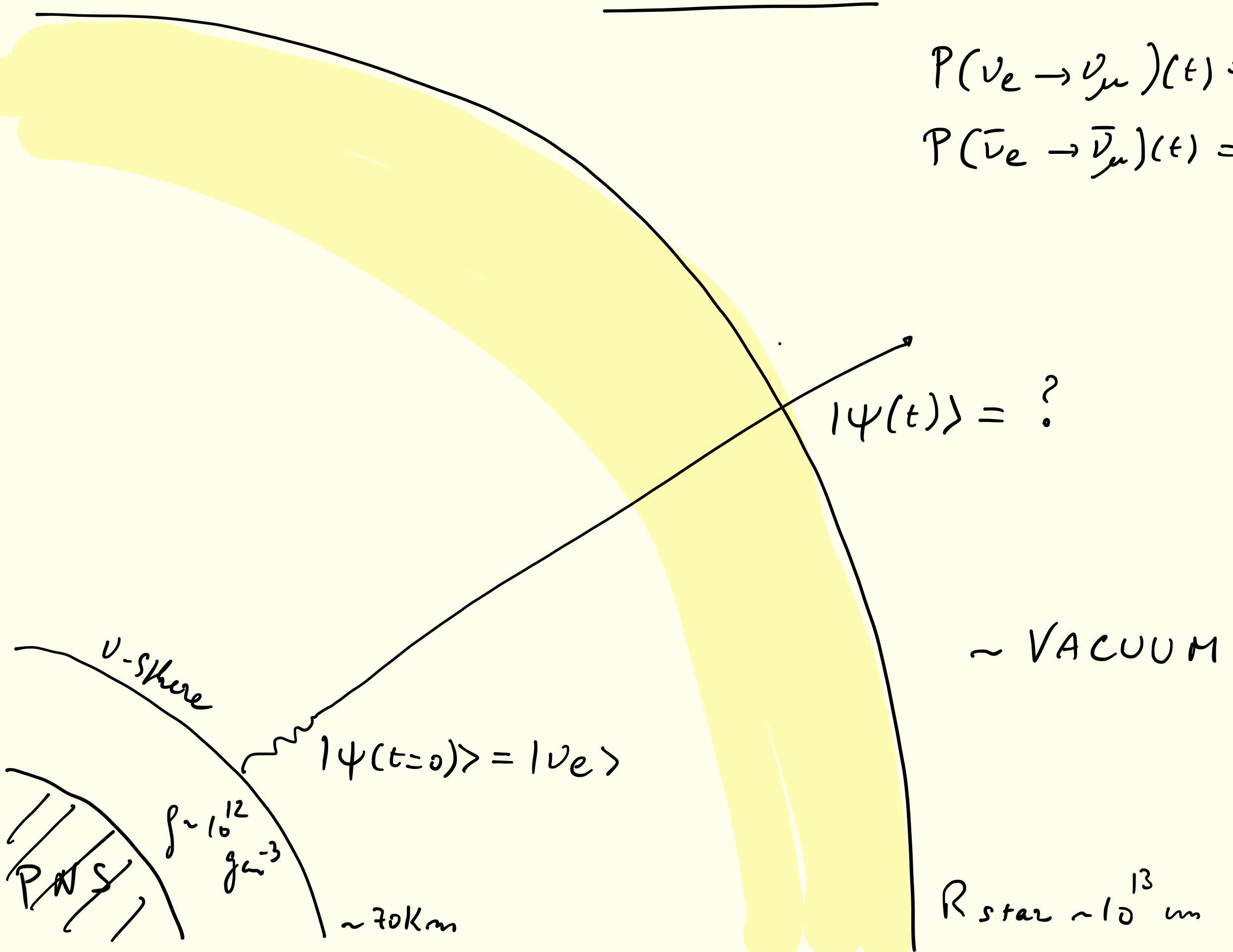
- adiabatic conversion in star
- (possible) adiabaticity violations in star
- oscillations in Earth

(• ν-ν scattering effects)

- Conversion in star: <u>adiabatic</u>

$$P(\nu_e \to \nu_\mu)(t) = ?$$

$$P(\bar{\nu}_e \to \bar{\nu}_\mu)(t) = ?$$



2-flavor toy model : $(m_2 < m_3)$

- Mixing: $\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = U \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$

- Hamiltonian in t-varying medium:

Flavor basis:

$$H = \underbrace{U \begin{pmatrix} E_2 & 0 \\ 0 & E_3 \end{pmatrix} U^\dagger}_{\text{Kinetic}} + \underbrace{\begin{pmatrix} V_e & 0 \\ 0 & V_\mu \end{pmatrix}}_{\text{Refraction (coherent)}}$$

$$E_i = \sqrt{p^2 + m_i^2} \approx p\left(1 + \frac{m_i^2}{2E}\right)$$

$V_\alpha \propto G_F$ (not G_F^2)

- subtract Identity term : $-\mathrm{Tr}(H)\,I$:

$$U\begin{pmatrix} -\frac{\Delta m^2}{4E} & 0 \\ 0 & \frac{\Delta m^2}{4E} \end{pmatrix}U^\dagger + \underbrace{\begin{pmatrix} V_{cc}/2 & 0 \\ 0 & -\frac{V_{cc}}{2} \end{pmatrix}}$$

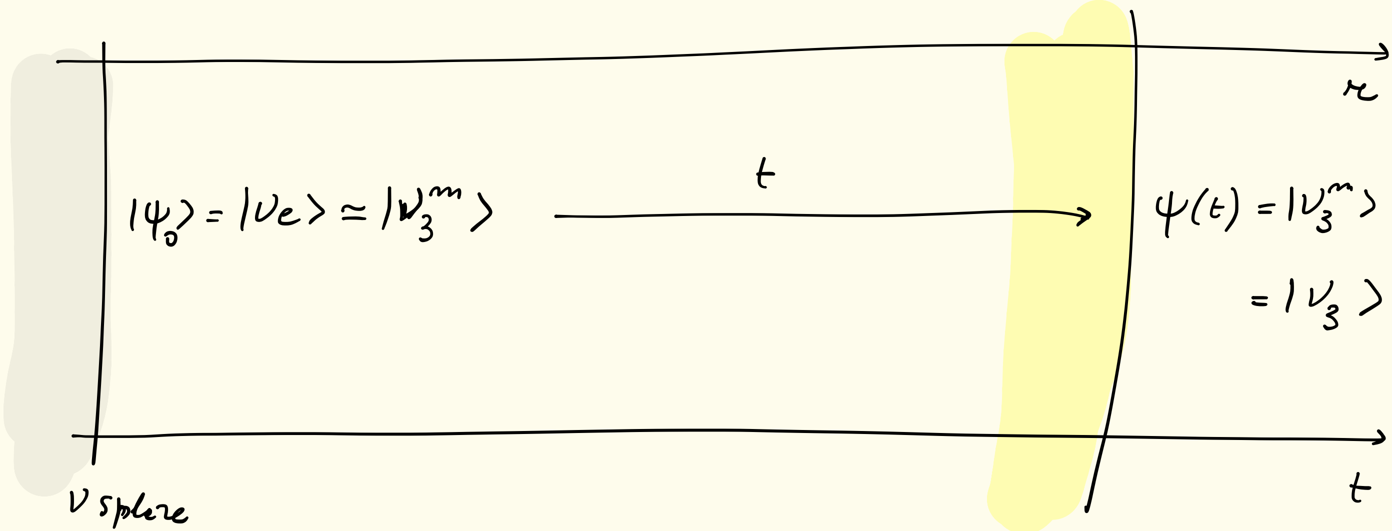
$$\Delta m^2 = m_3^2 - m_2^2$$

$$\sim 2\cdot 10^{-3}\ \mathrm{eV}^2$$

$$\begin{cases} V_{cc} = V_e - V_\mu = \sqrt{2}\,G_F\, n_e \\ n_e = \rho/2m_N \quad \text{(electron number density)} \end{cases}$$

- limits:

$$V_{cc} \quad \rho \begin{cases} \gg 10^3\ \mathrm{g\,cm^{-3}} \\ \gg \frac{\Delta m^2}{2E} \longrightarrow \quad H \simeq H_{\text{Refr}} : \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \\ \ll 10^3\ \mathrm{g\,cm^{-3}} \\ \ll \frac{\Delta m^2}{2E} \longrightarrow \quad H \simeq H_{\text{Kin}} : \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix} \end{cases}$$



$V_{CC}/2 \gg \frac{\Delta m^2}{4E}$

$V_{CC}/2 \ll \frac{\Delta m^2}{4E}$

- $\boxed{\nu_e \longrightarrow \nu_3} = -\sin\theta\ \nu_e + \cos\theta\ \nu_\mu$
- $P(\nu_e \rightarrow \nu_e) = \sin^2\theta$

Realistic 3-flavor case (normal mass ordering $m_1 < m_2 < m_3$)

- Adiabatic:

$$\nu_e \approx |\nu_3^m\rangle \longrightarrow |\nu_3\rangle \qquad P(\nu_e \to \nu_e) = |U_{e3}|^2 \approx 10^{-2}\,!$$

$$\bar{\nu}_e \approx |\bar{\nu}_1^m\rangle \longrightarrow |\bar{\nu}_1\rangle \qquad P(\bar{\nu}_e \to \bar{\nu}_e) = |U_{e1}|^2 \sim 0.7$$

- Effective flavor fluxes @ Earth:

$$F_{\oplus}^{\nu_e} = |U_{e3}|^2 F^0_{\nu_e} + \left(1 - |U_{e3}|^2\right) F^0_{\nu_x} \approx F^0_{\nu_x}$$

$$F_{\oplus}^{\bar{\nu}_e} = |U_{e1}|^2 F^0_{\bar{\nu}_e} + \left(1 - |U_{e1}|^2\right) F^0_{\nu_x}$$

- Observable: spectrum hardening