Neutrinos and the Supernova Origin of the Elements

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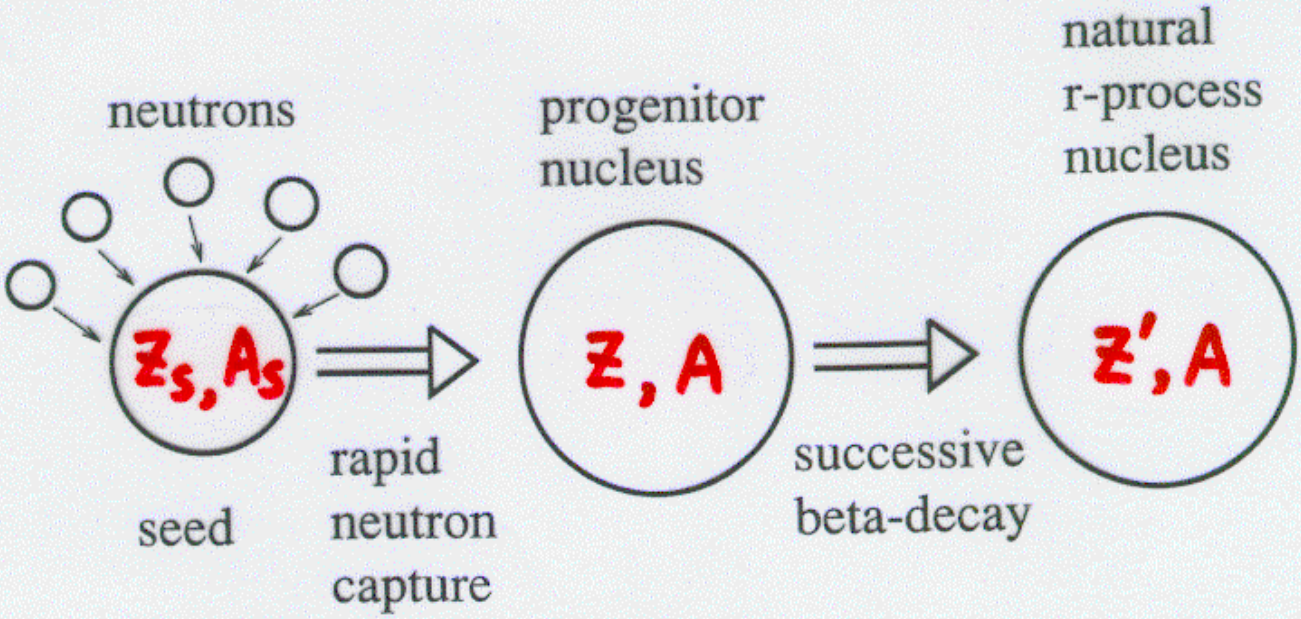
Various scenarios of nucleosynthesis

* Big Bang : ^{4}He

* Stars: H $\longrightarrow$ ^{4}He $\longrightarrow$ ..... $\longrightarrow$ ^{56}Fe

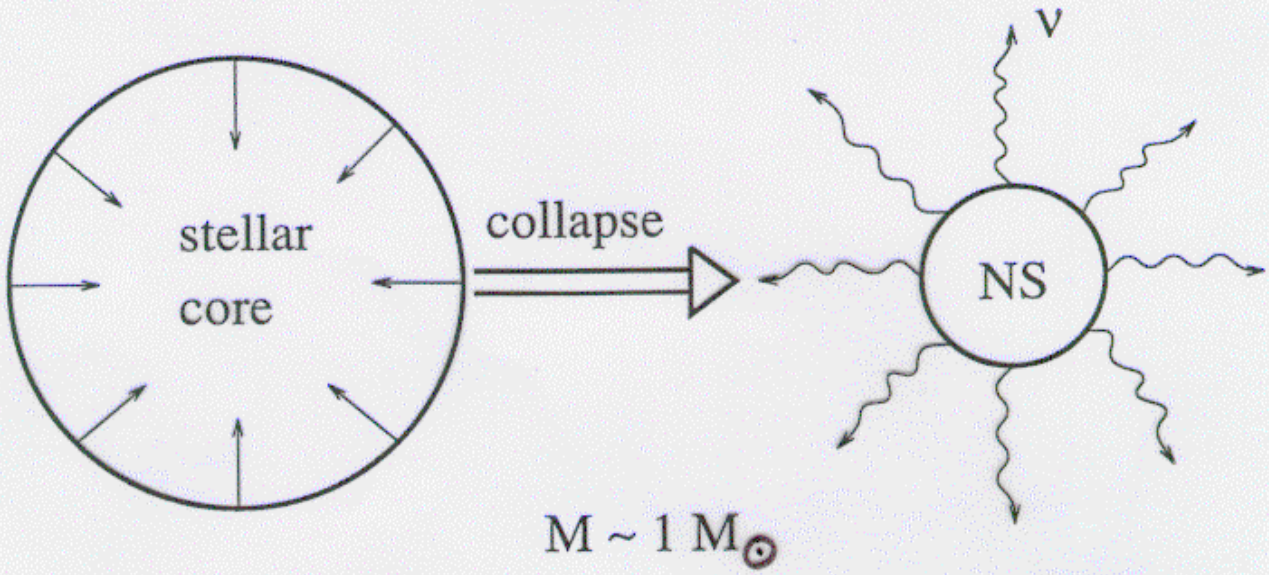
* Rapid neutron capture (r-process) : ~ 1/2 of A >100

  e.g., Eu, U, Th



$$A \approx A_s + \frac{n}{s}$$

Neutrino emission in supernovae



$M \sim 1\ M_\odot$

$R_C \sim 1000$ km $\qquad R_{NS} \sim 10$ km

$$E_B \sim \frac{GM^2}{R_{\rm NS}} \sim 10^{53}\ {\rm erg} \Rightarrow \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$$

$$\boxed{\nu + n \longrightarrow \nu + n, \quad \nu + p \longrightarrow \nu + p}$$

$$t_{\rm diff} \sim 10\ {\rm s\ (cf.\ SN1987a)}$$

$$\Rightarrow \boxed{L_{\nu_e} \approx L_{\bar{\nu}_e} \approx L_{\nu_\mu}} \approx \frac{1}{6}\frac{E_B}{t_{\rm diff}} \sim 10^{51}\ {\rm erg\ s^{-1}}$$

$$\boxed{L_{\nu_\mu} \approx L_{\bar{\nu}_\mu} \approx L_{\nu_\tau} \approx L_{\bar{\nu}_\tau}}$$

Energy-exchange processes and neutrino decoupling

$$\nu + e \longrightarrow \nu + e$$

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

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

$$\boxed{\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_\mu} \rangle}$$

$$\langle E_{\nu_\mu} \rangle \approx \langle E_{\bar{\nu}_\mu} \rangle \approx \langle E_{\nu_\tau} \rangle \approx \langle E_{\bar{\nu}_\tau} \rangle$$

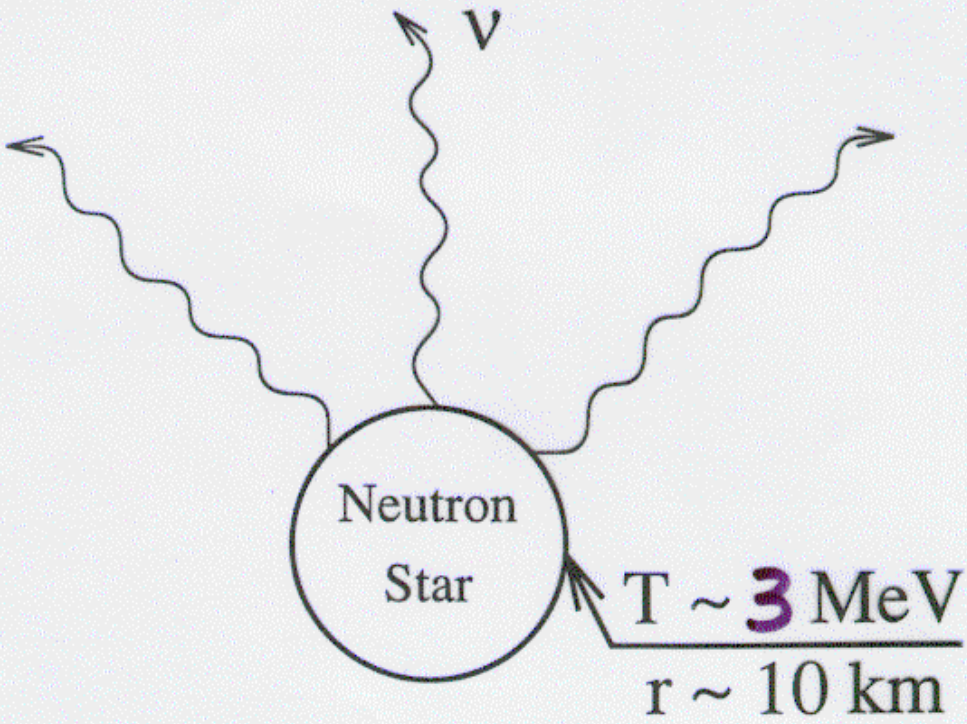
$$\langle E_{\nu_e} \rangle \approx 11 \text{ MeV}$$

$$\langle E_{\bar{\nu}_e} \rangle \approx 16 \text{ MeV}$$

$$\langle E_{\bar{\nu}_\mu} \rangle \approx 25 \text{ MeV}$$

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

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



Nucleosynthesis in the neutrino-driven wind

- at $T \gtrsim 1$ MeV

$$X_p + X_n \approx 1,\ X_p \approx Y_e < \frac{1}{2} \Rightarrow \text{neutron-rich}$$

- at $T \sim 0.5$ MeV

$$X_n + X_\alpha \approx 1,\ \frac{1}{2} X_\alpha \approx Y_e \Rightarrow \boxed{X_n \approx 1 - 2Y_e}$$

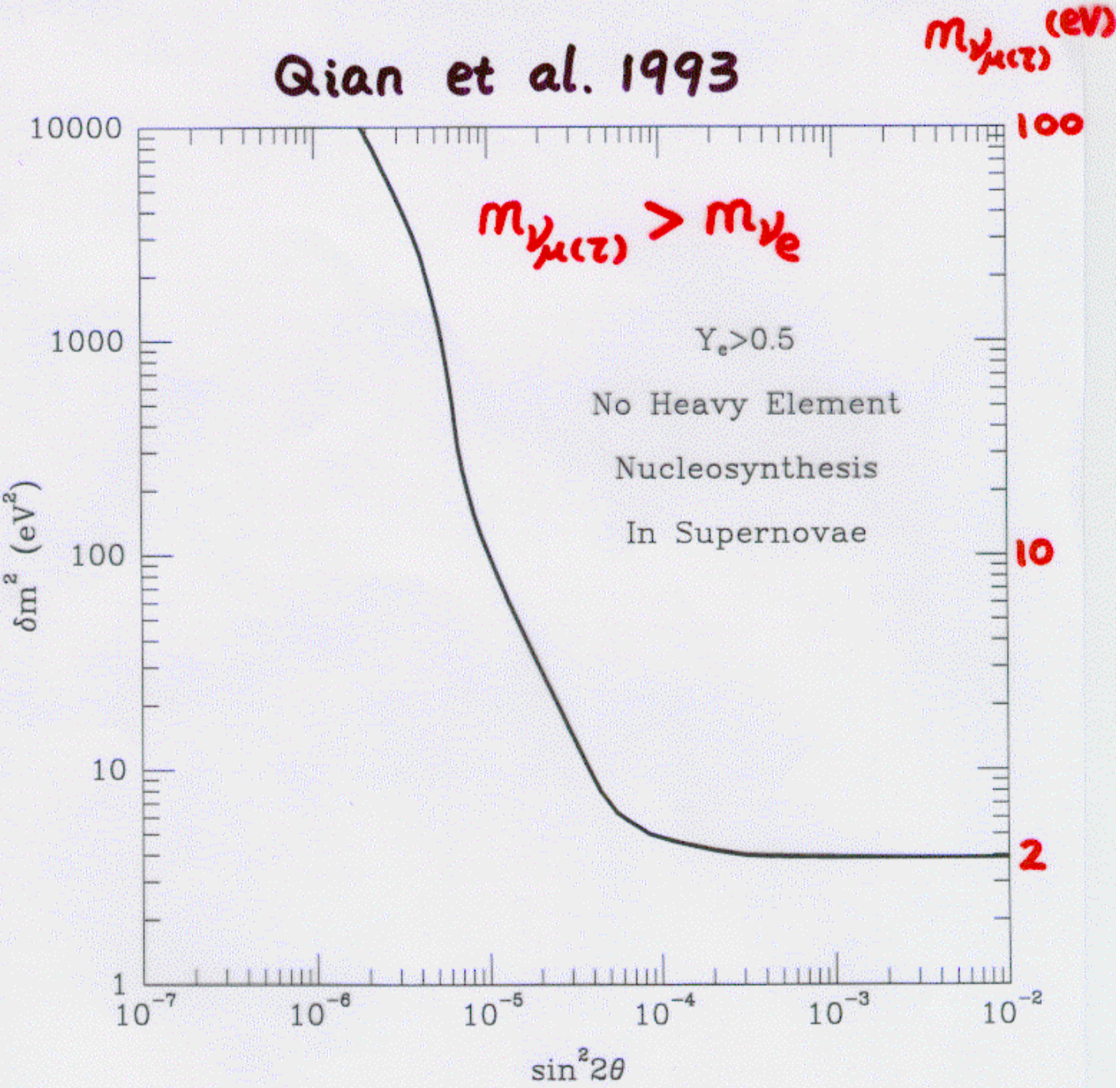
- $0.5 \gtrsim T \gtrsim 0.25$ MeV (α-process)

$$\left.\begin{aligned} \alpha + \alpha + \alpha &\rightarrow {}^{12}\mathrm{C} + \gamma \\ \alpha + \alpha + n &\rightarrow {}^{9}\mathrm{Be} + \gamma \\ {}^{9}\mathrm{Be} + \alpha &\rightarrow {}^{12}\mathrm{C} + n \\ &\cdots\cdots \end{aligned}\right\} \Rightarrow \left\{\begin{aligned} &\text{seed nuclei} \\ &Z_s \sim 35 \\ &\boxed{A_s \sim 100} \end{aligned}\right.$$

- $0.25 \gtrsim T \gtrsim 0.1$ MeV (r-process)

$$\boxed{A_s + \frac{n}{s} \approx \langle A \rangle}$$

Qian et al. 1993



hot dark matter $m_\nu \sim 2-5$ eV

(Ma & Bertschinger 1994, Ma 1996)

Sterile neutrinos & supernova nucleosynthesis

(Caldwell, Fuller, & Qian 1999)

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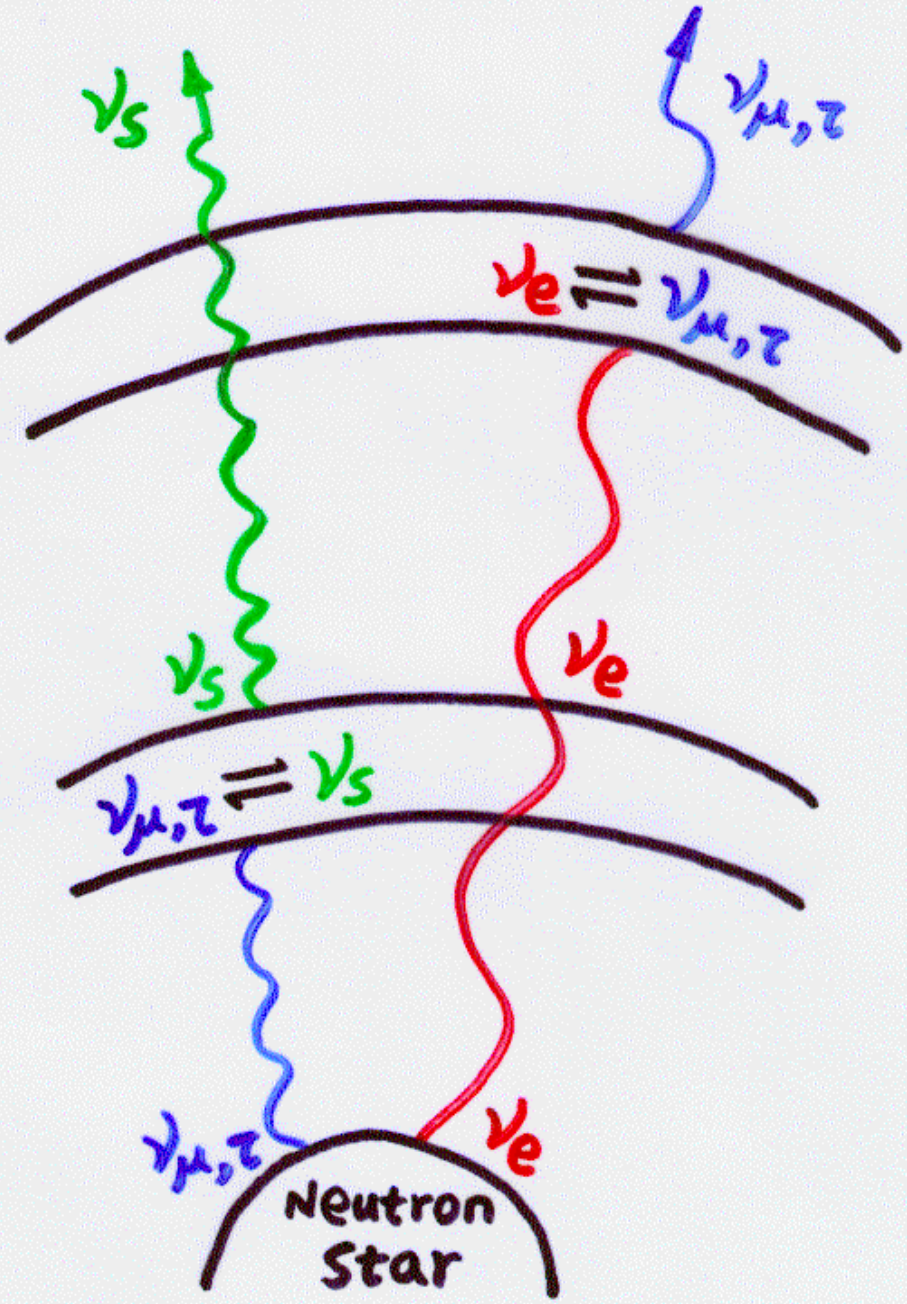
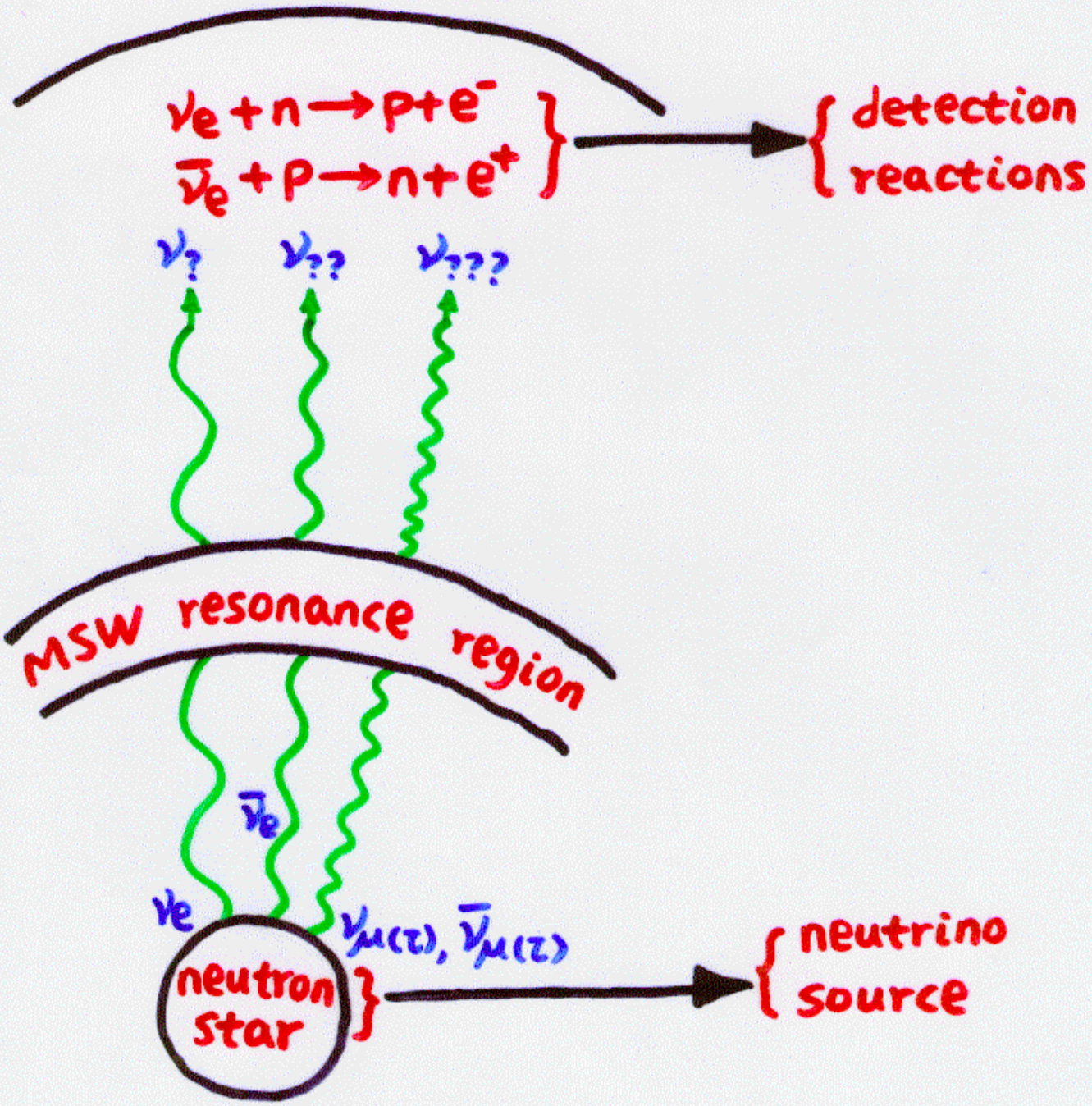


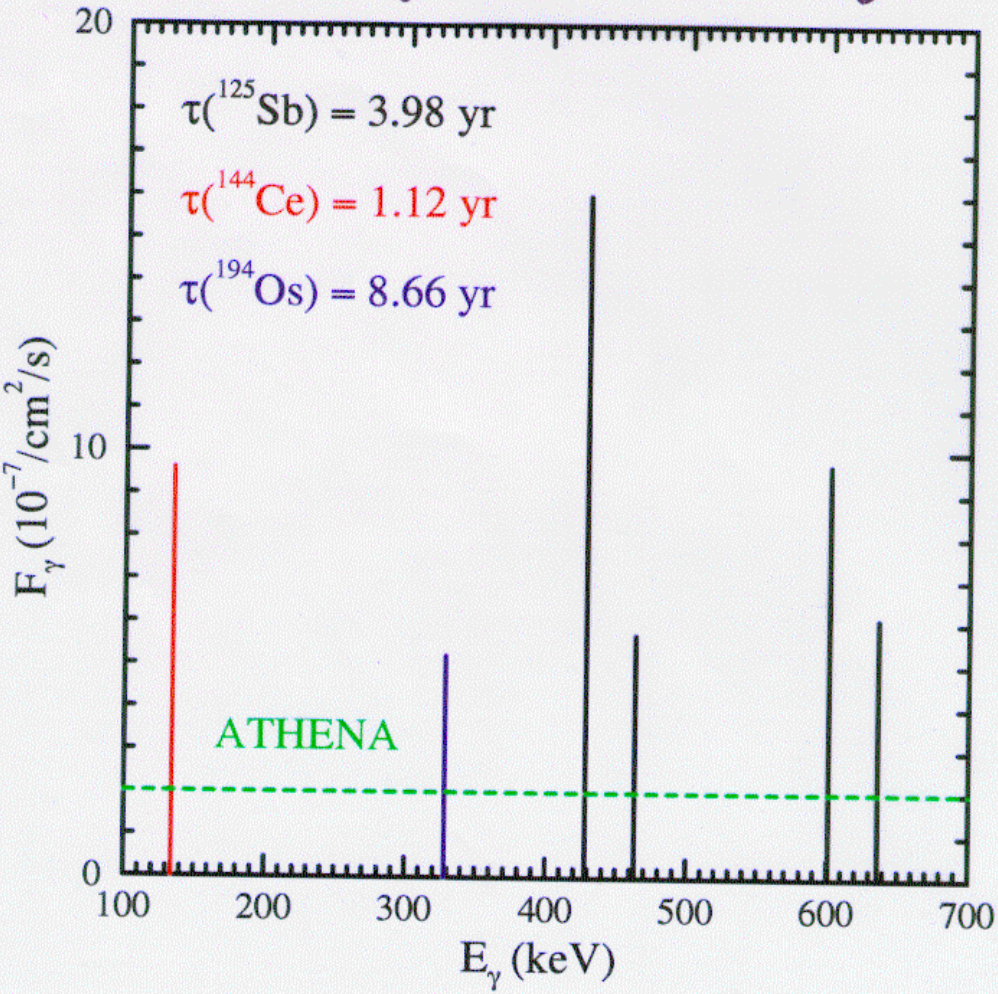
neutrino oscillation experiments in supernovae

production of r-process elements in supernovae → signal

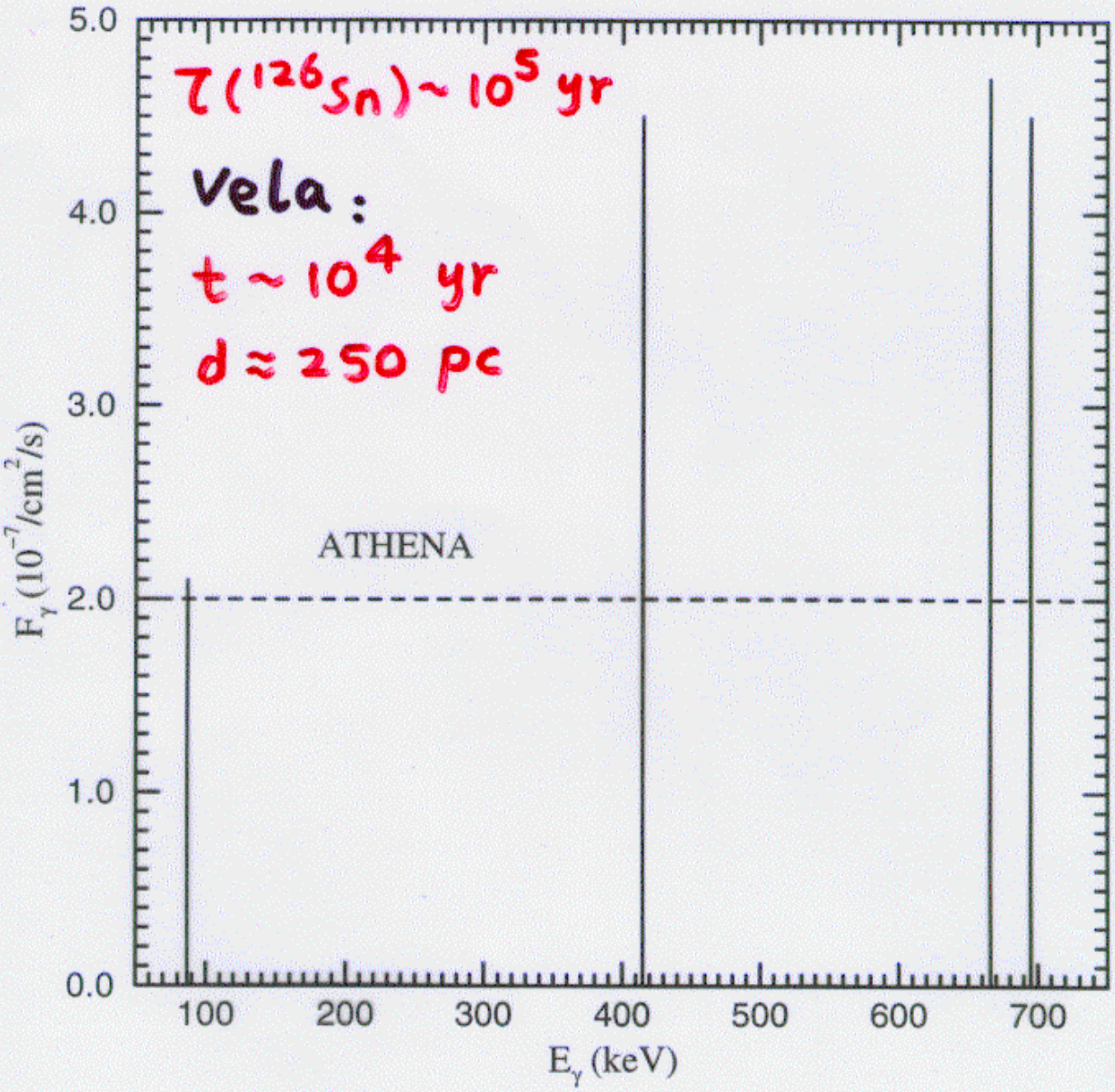


Meyer & Howard 1991

Qian, Vogel, & Wasserburg 1998

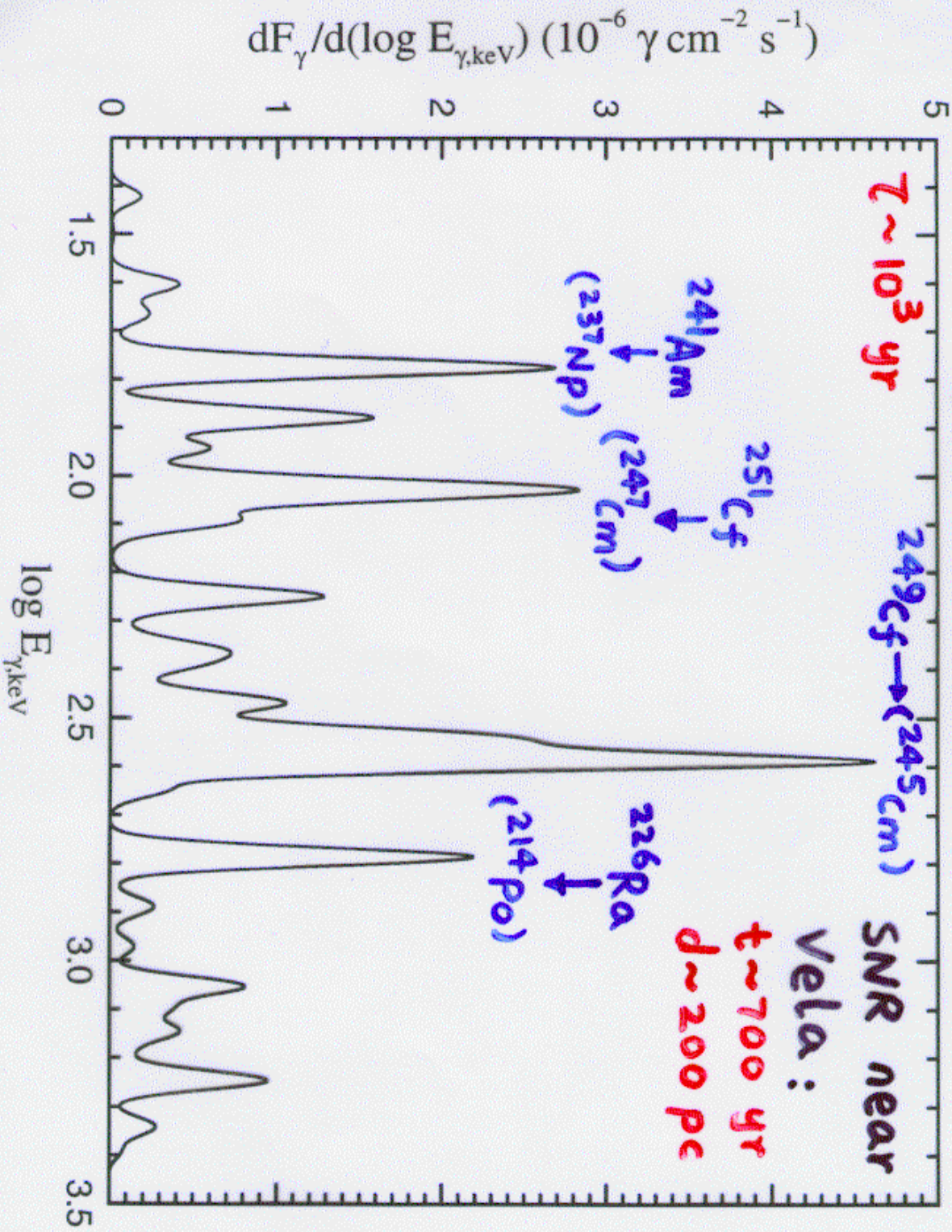


Qian, Vogel, & Wasserburg 1998



Clayton & Craddock 1965

Qian, Vogel, & Wasserburg 1999

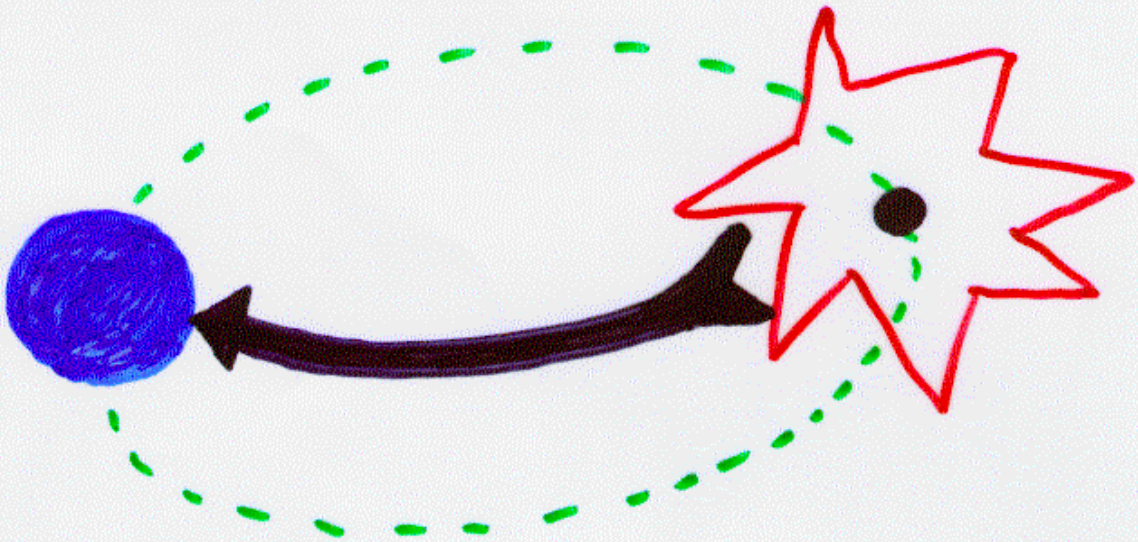


'Historic' development of γ-ray detection

time	sensitivity ($\gamma\ cm^{-2}\ s^{-1}$)	detection
~1980	$\sim 10^{-4}$	^{26}Al decay γ-rays from all sources in the Galaxy
~1990	$\sim 10^{-5}$ (CGRO)	^{26}Al decay γ-rays from the Vela region
~2000	$\sim 10^{-6}$ (INTEGRAL)	?
~2010?	$\sim 10^{-7}$	^{126}Sn, ^{226}Ra decay γ-rays from the Vela region

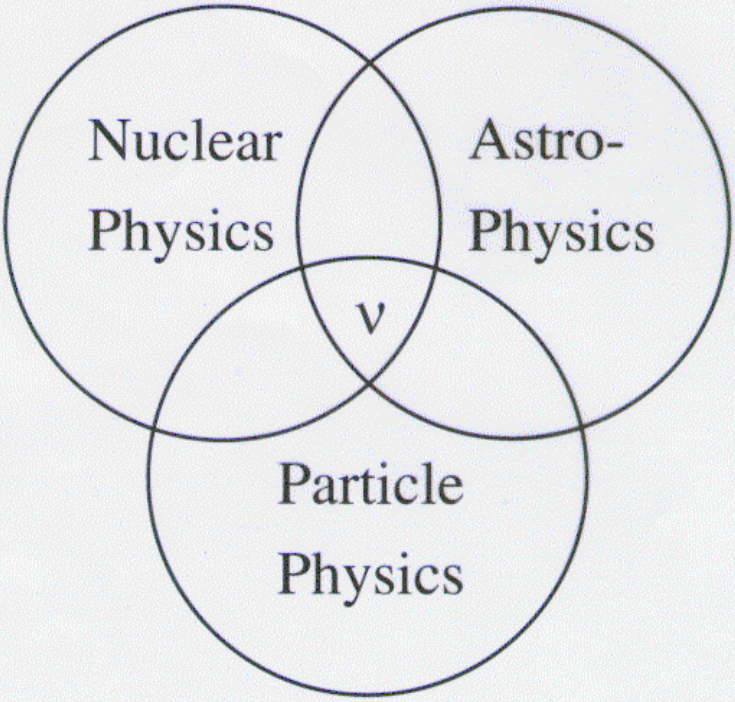
Surface contamination by supernova r-process ejecta in binaries

(Qian 2000)



large overabundances of O, Mg, Si, and S observed in the companion star of a black hole

(Israelian et al. 1999)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