Neutrino Reaction in Nuclear-Astro Physics

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Contents

0. Single and Double Beta Decay

1. Motivation for ν-processes in Nucleosynthesis

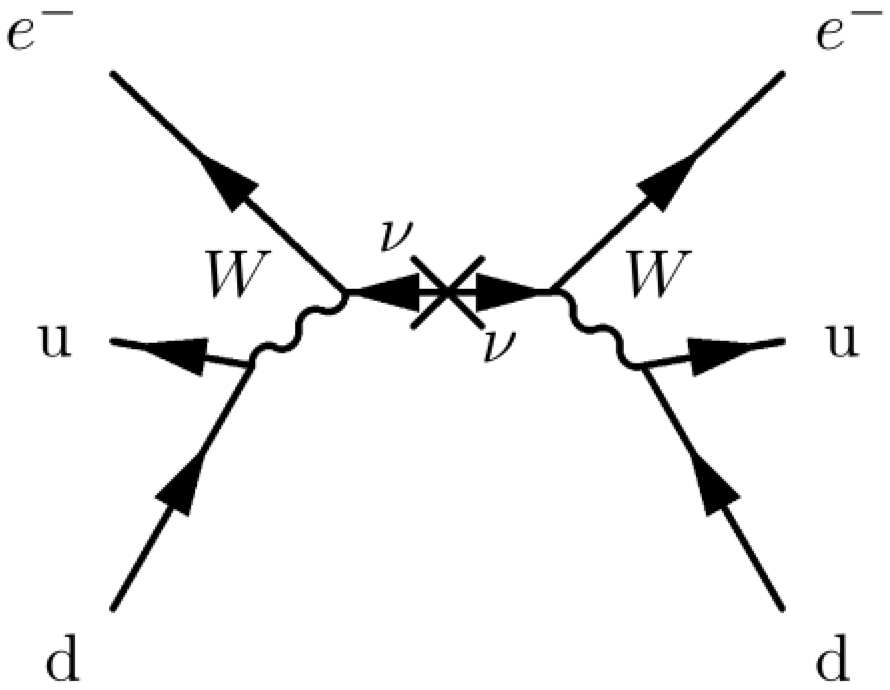
2. Indirect (Multi-step or Compound nuclei)
   and
   Direct (One-step or Knock-out) Processes
   for ν-^{12}C

3. Results and Summary

Beta Beam

- Zuccheli has first proposed the idea of producing electron (anti)neutrino beams using the beta-decay of boosted radioactive ions : the “beta-beam”.

- In the original scenario, the ions are produced, collected, accelerated up to several tens of GeV/nucleon….
- The neutrino beam is produced by the decaying ions, points to a water Cerenkov detector..



$$m_{\beta\beta}/\mathrm{eV} = 0.2 \implies T_{\frac{1}{2}}/\mathrm{y} = \begin{cases} 4.43 \times 10^{25} \; (^{76}\mathrm{Ge}) \, , \\ 1.34 \times 10^{25} \; (^{82}\mathrm{Se}) \, , \\ 1.20 \times 10^{25} \; (^{130}\mathrm{Te}) \, , \\ 3.43 \times 10^{25} \; (^{136}\mathrm{Xe}) \, , \end{cases}$$

$$\begin{aligned} m_\beta &\simeq m_\nu \, , \\ \Sigma &\simeq 3 m_\nu \, , \\ m_{\beta\beta} &\simeq m_\nu \, f \, , \end{aligned}$$

$$\Gamma = \quad G|M|^2 |m_{\beta\beta}|^2,$$

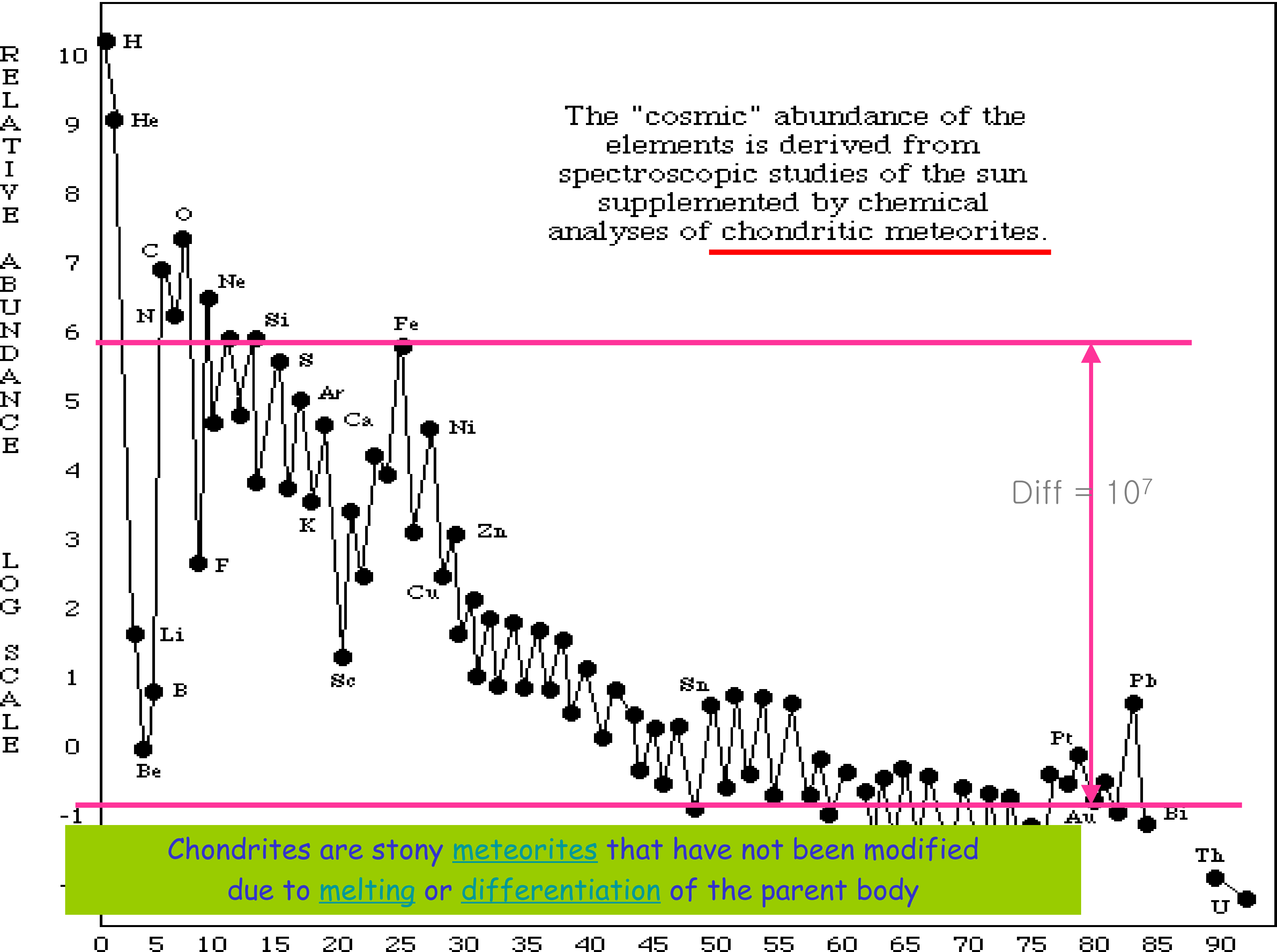
$$f \simeq |U_{e1}^2 + U_{e2}^2| \in [0.38, 1] \, ,$$

nge is obtained for the CP-conserving case
mock data, having the following central va

$$m_{\beta\beta} = \sum_{i=1}^{3} m_i U_{ei}^2.$$

$$\begin{aligned} m_\beta &\simeq 0.2(1 \pm 0.5) \text{ eV} \, , \\ \Sigma &\simeq 0.6(1 \pm 0.3) \text{ eV} \, , \\ m_{\beta\beta} &\simeq 0.2(1 \pm 0.3) \text{ eV} \, . \end{aligned}$$

Nucleosynthesis of Solar System



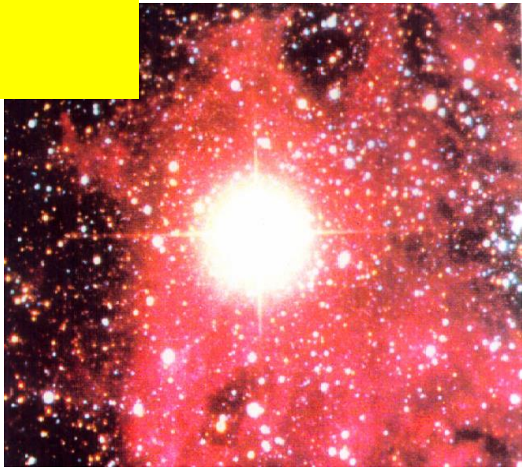
The "cosmic" abundance of the elements is derived from spectroscopic studies of the sun supplemented by chemical analyses of chondritic meteorites.

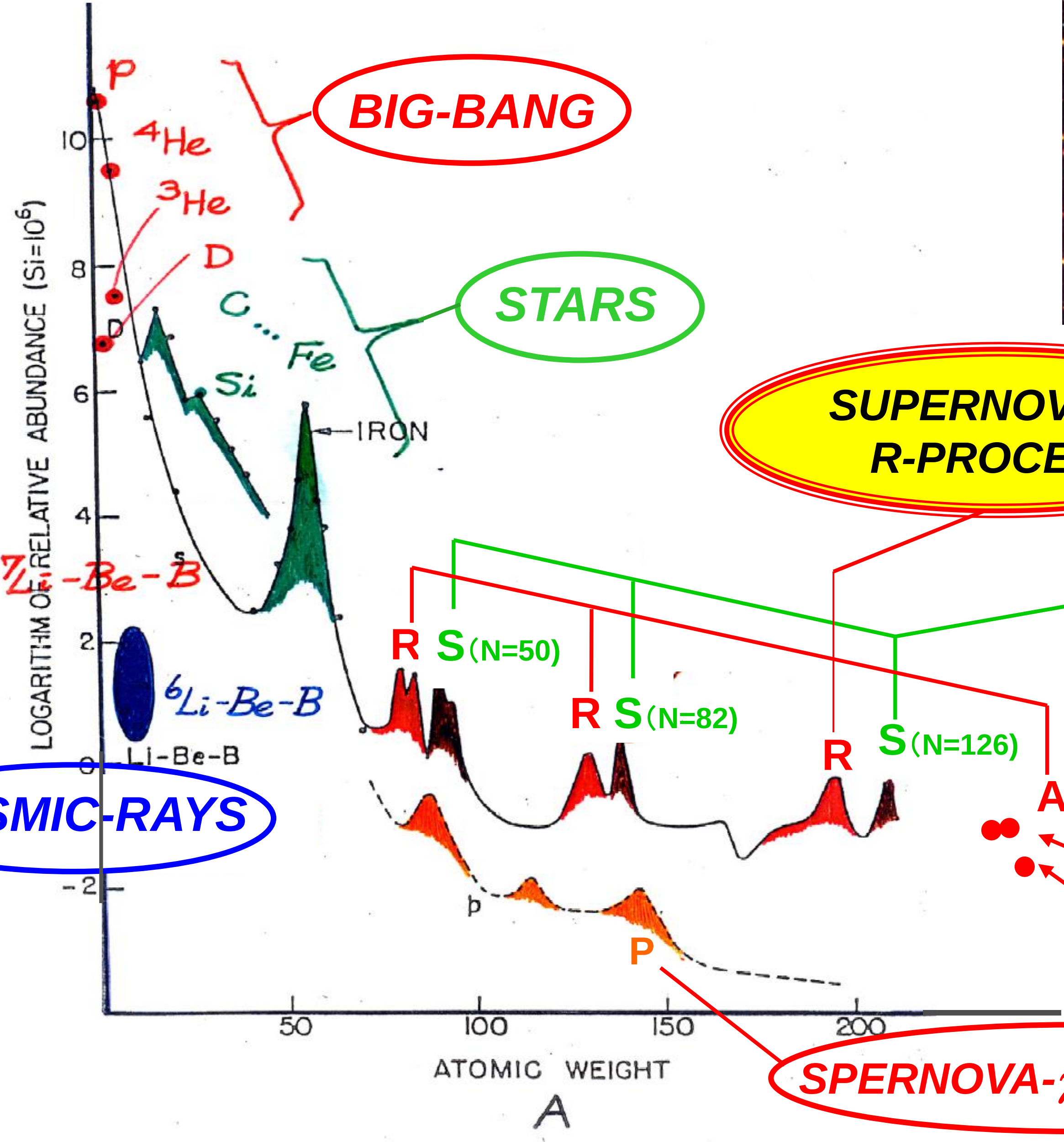
Diff = 10^7

Chondrites are stony meteorites that have not been modified due to melting or differentiation of the parent body

Solar system

Supernovae Model





BIG-BANG

STARS

SUPERNOVAE ?
R-PROCESS

AGB STARS
S-PROCESS

COSMIC-RAYS

R **S** (N=50)

R **S** (N=82)

R **S** (N=126)

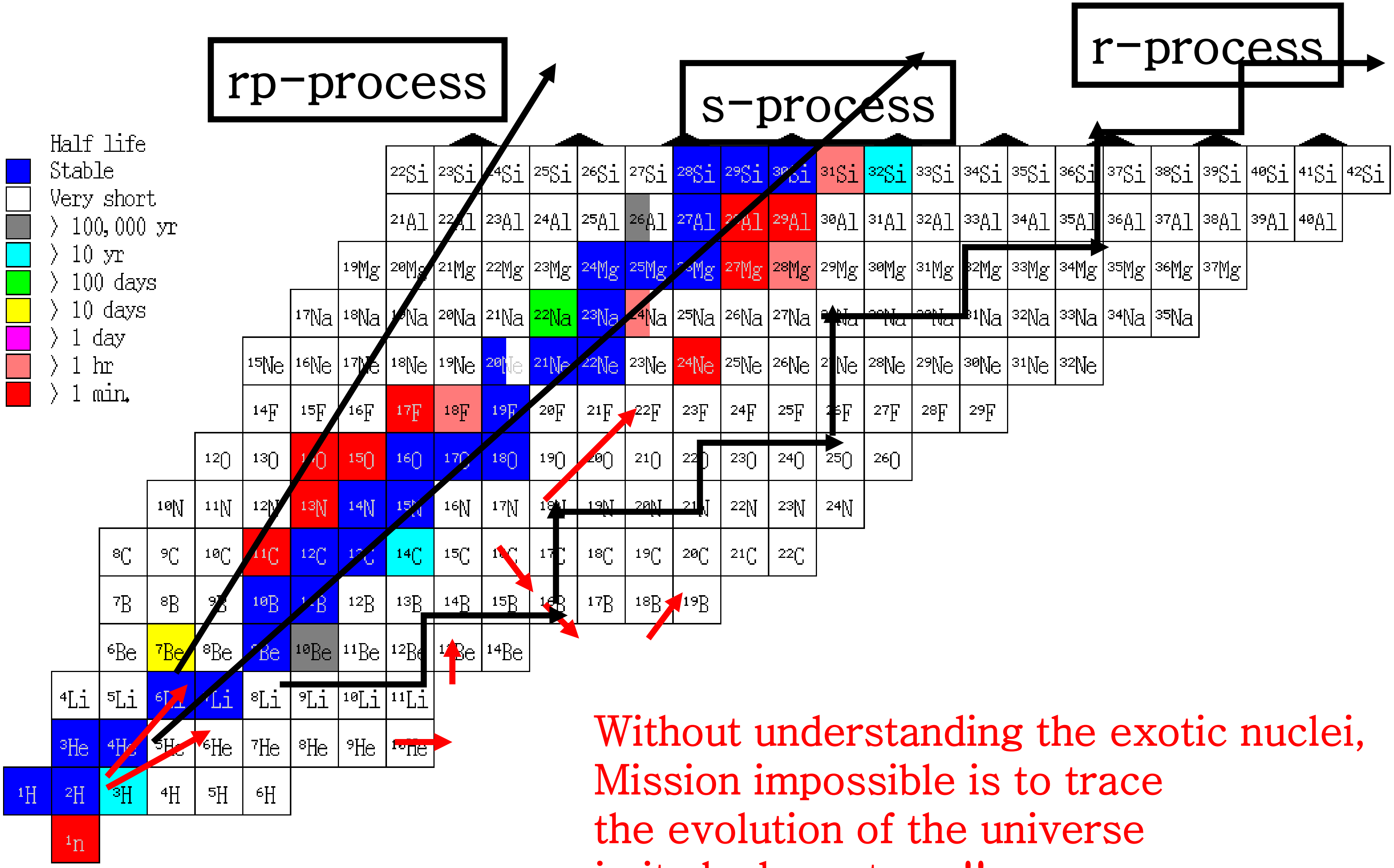
P

Actinide

●● ^{232}Th (14.05Gy)

● ^{238}U (4.47 Gy)

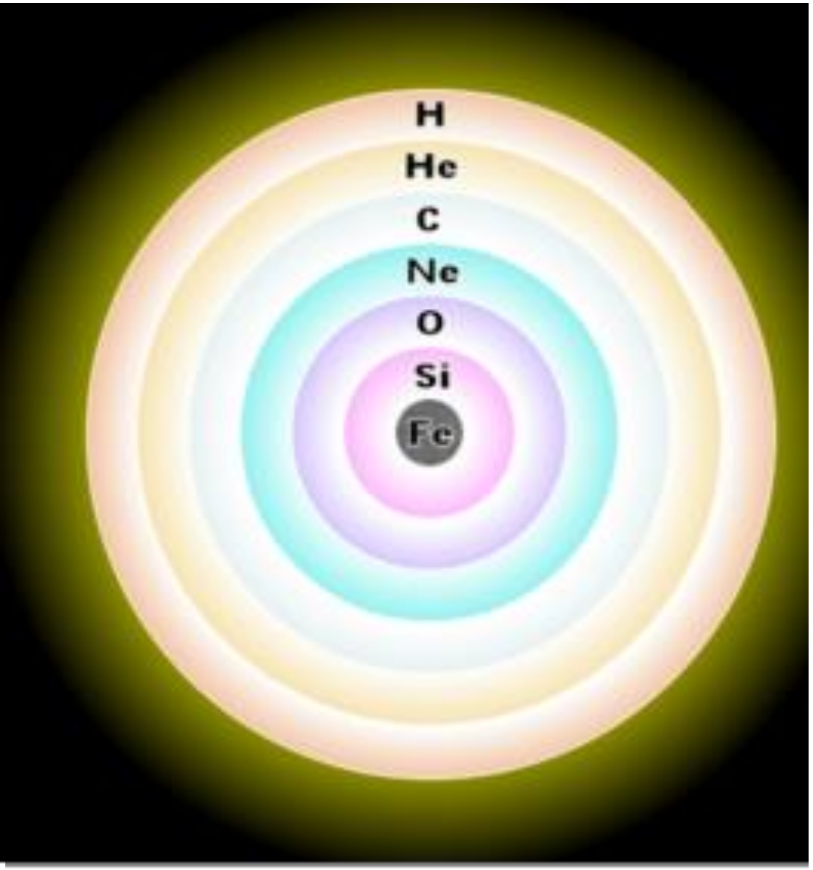
SPERNOVA-γ PROCESS ?



Without understanding the exotic nuclei,
Mission impossible is to trace
the evolution of the universe
in its hadron stage !!

2023-01-10 APCTP, Pohang, Korea

Nucleosynthesis of Other Stars



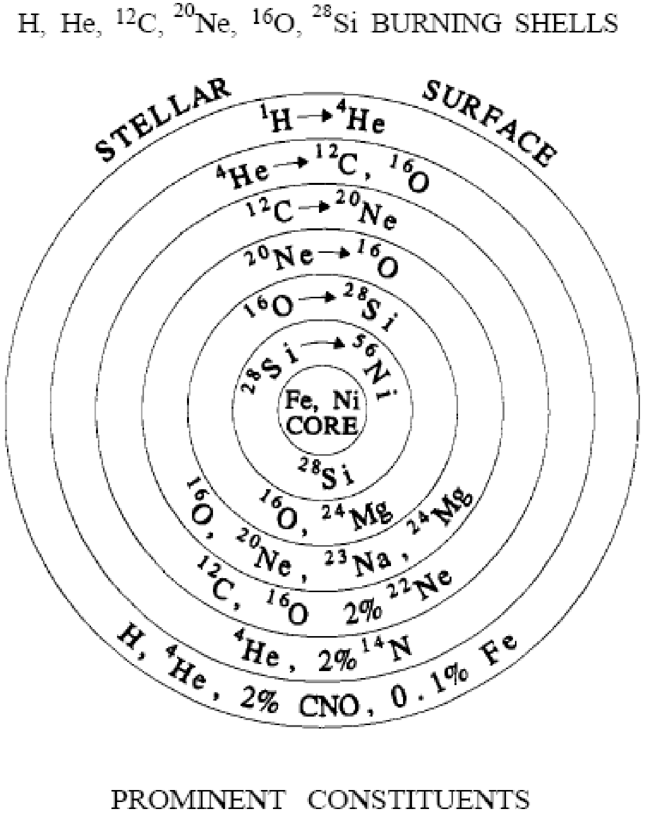


Fig. 5.6. Schematic onion-like structure of a pre-supernova star of 25 solar masses (not to scale).

The onion-like layers of a massive, evolved star just prior to core collapse.
(Not to scale.)

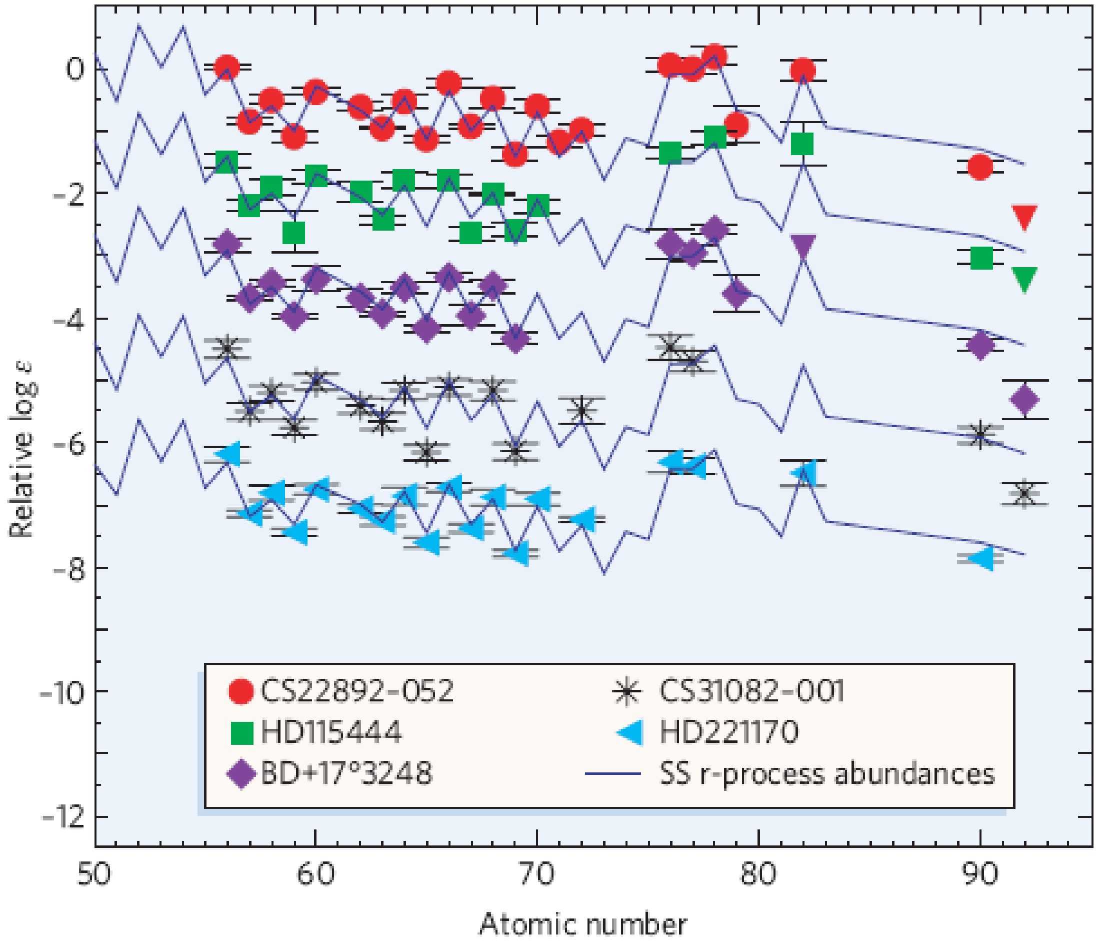


Figure 5 | Elemental abundance patterns in galactic halo stars. The plots show the neutron-capture elemental abundance pattern in the galactic halo stars CS22892–052, BD+17°3248, HD115444, CS31082–001 and HD221170 compared with the (scaled) Solar System (SS) r-process abundances (solid lines). The abundances (with sample deviation error bars) of all of the stars except CS22892–052 have been displaced downwards for display purposes.

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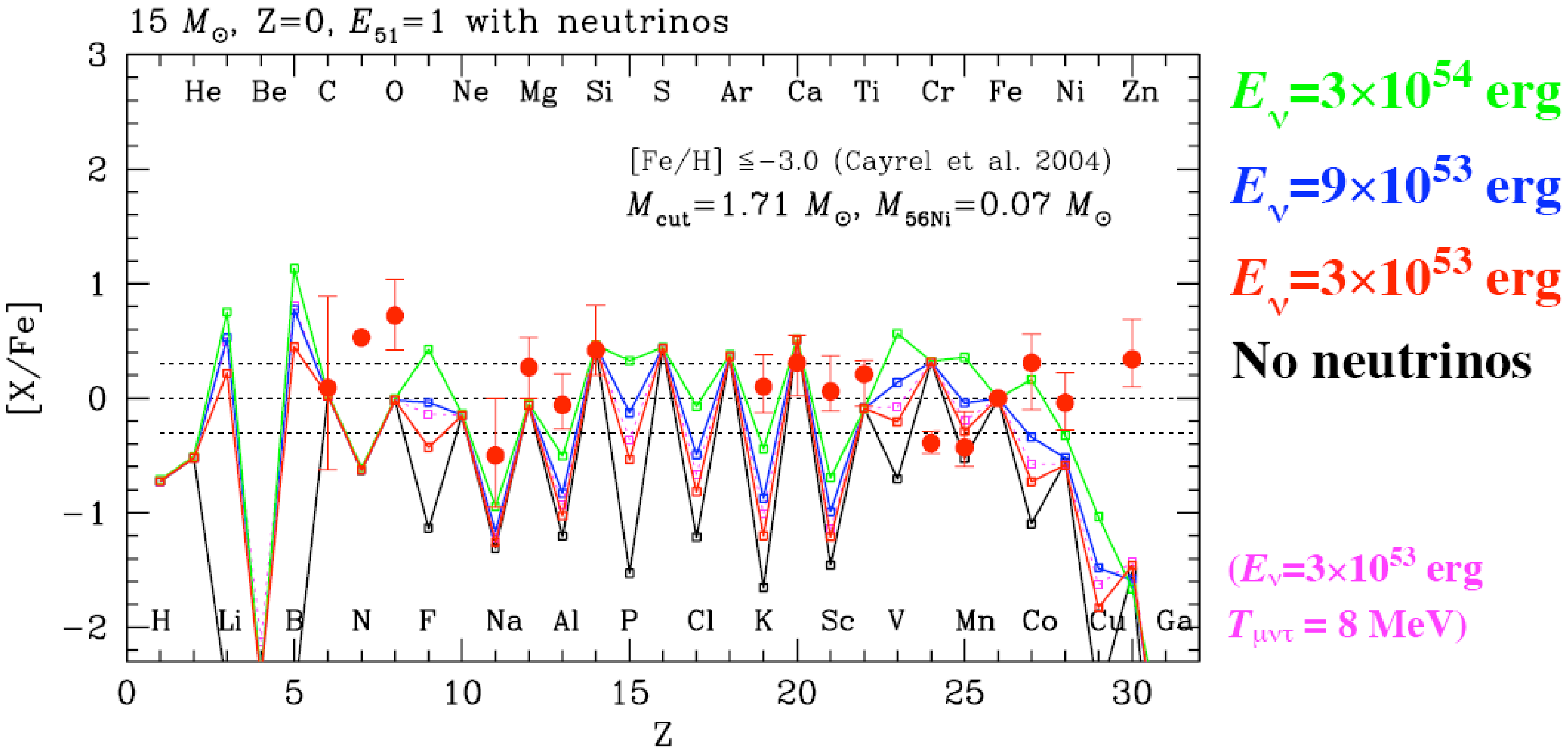
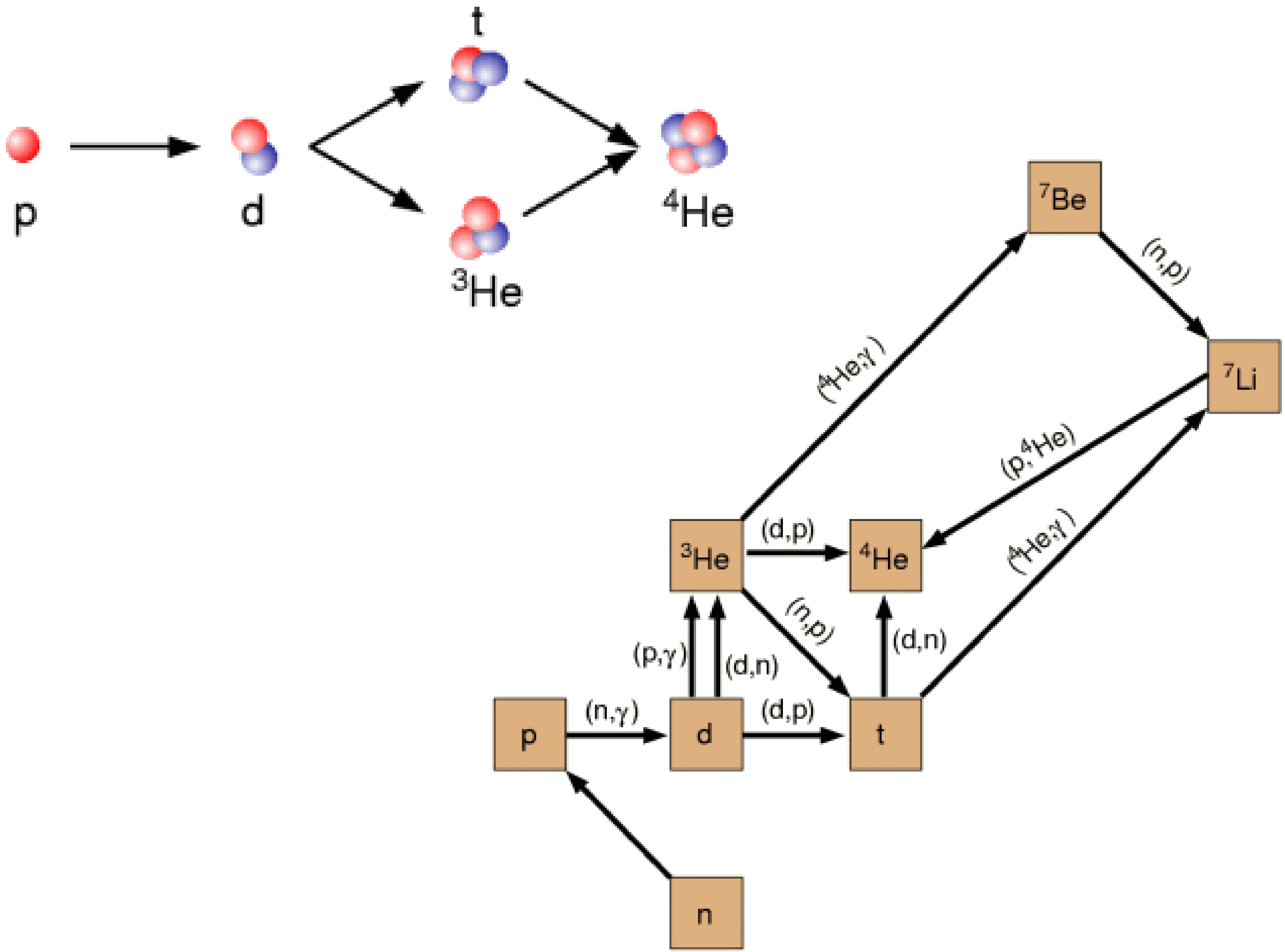
Abundances in a 15$M_\odot$ Supernova



- **Sc** → Abundance smaller than observed in EMP stars
- **Mn** → Observed abundance in $E_\nu < 9\times10^{53}$ ergs
- **Co** → Observed abundance in $E_\nu > 9\times10^{53}$ ergs

Big Bang Nucleosynthesis


t
p
d
^{3}He
^{4}He
^{7}Be
(n,p)
^{7}Li
(^{4}He,γ)
(p,^{4}He)
^{3}He
(d,p)
^{4}He
(^{4}He,γ)
(n,p)
(p,γ)
(d,n)
(d,n)
p
(n,γ)
d
(d,p)
t
n

Prediction and Observation by SBBN

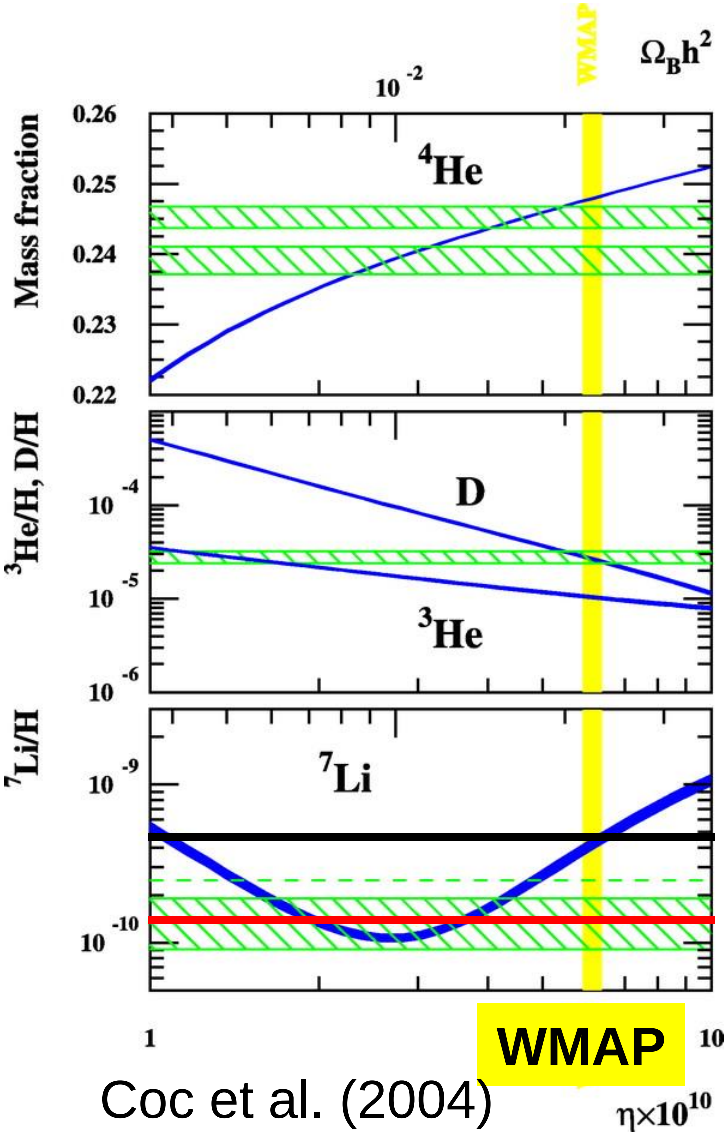
- SBBN: Parameter is baryon-to-photon ratio η

- WMAP Constraint of η

  $\eta=(6.14\pm0.25)\times10^{-10}$

  (Spergel et al. 2003)

Li problem! ←



Coc et al. (2004)

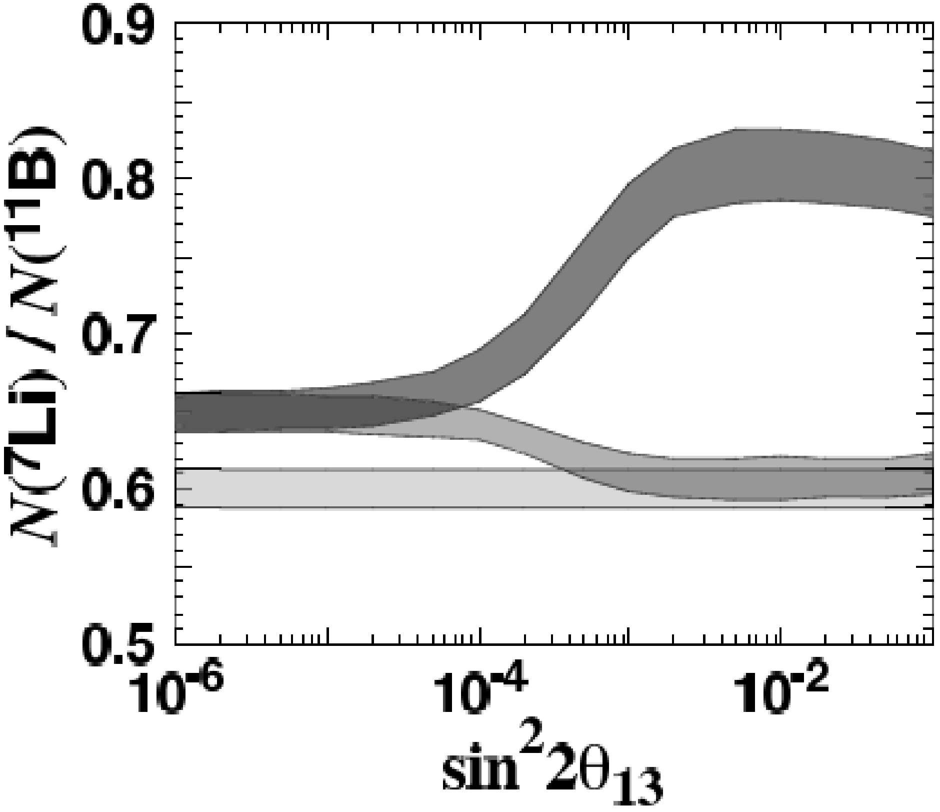
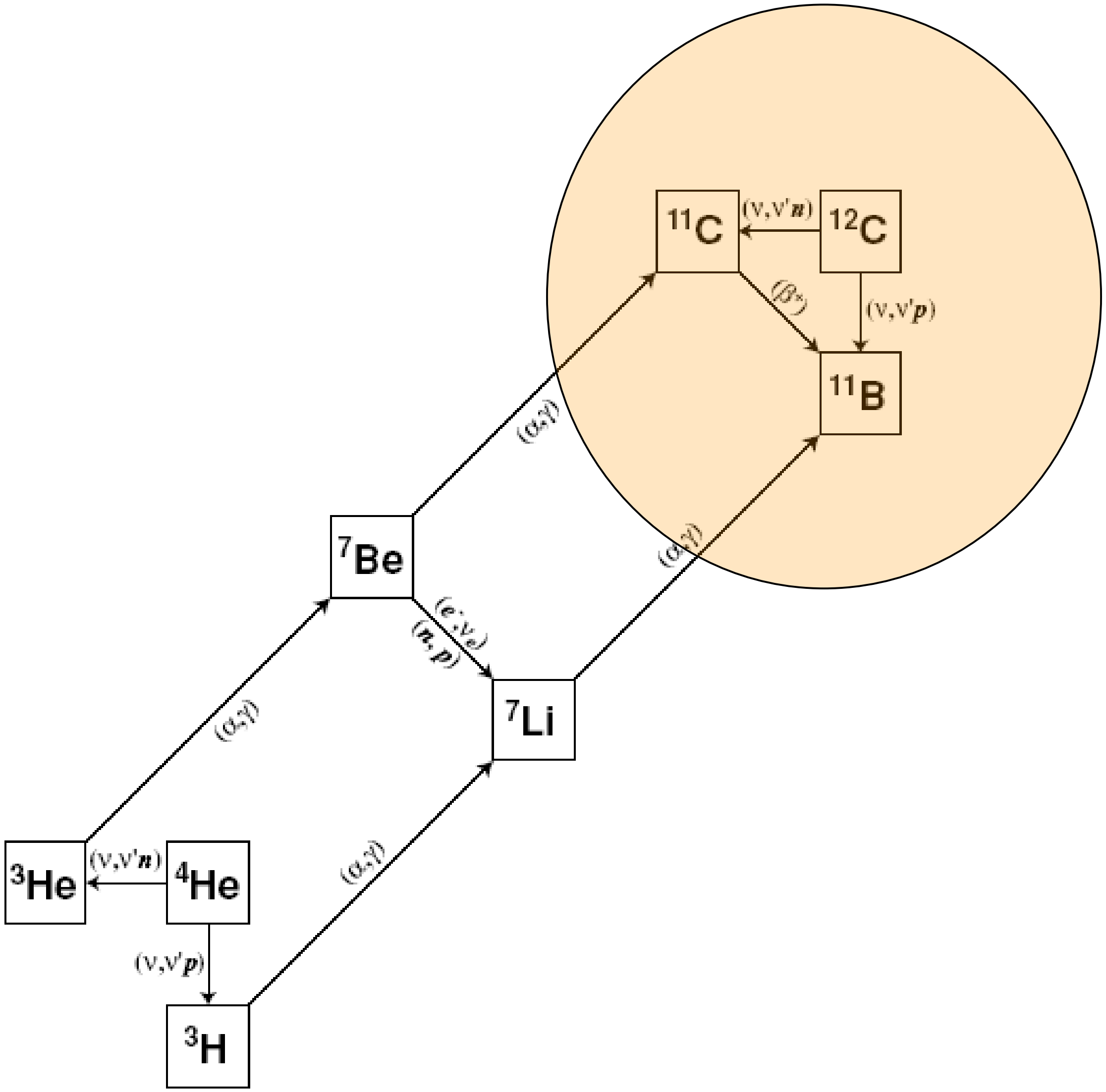


FIG. 10.— The ^{7}Li/^{11}B abundance ratio as a function of the mixing angle $\sin^2 2\theta_{13}$. Dark and medium shaded regions correspond to normal and inverted mass hierarchies, respectively. The lightly shaded region indicates the ratio obtained without neutrino oscillations. Each range is drawn using the results of Models 1, 2, LT, and ST.


^{11}C
(ν,ν'n)
^{12}C
(β+)
(ν,ν'p)
^{11}B
(α,γ)
(α,γ)
^{7}Be
(e⁻,ν$_e$)
(n, p)
^{7}Li
(α,γ)
^{3}He
(ν,ν'n)
^{4}He
(α,γ)
(ν,ν'p)
^{3}H

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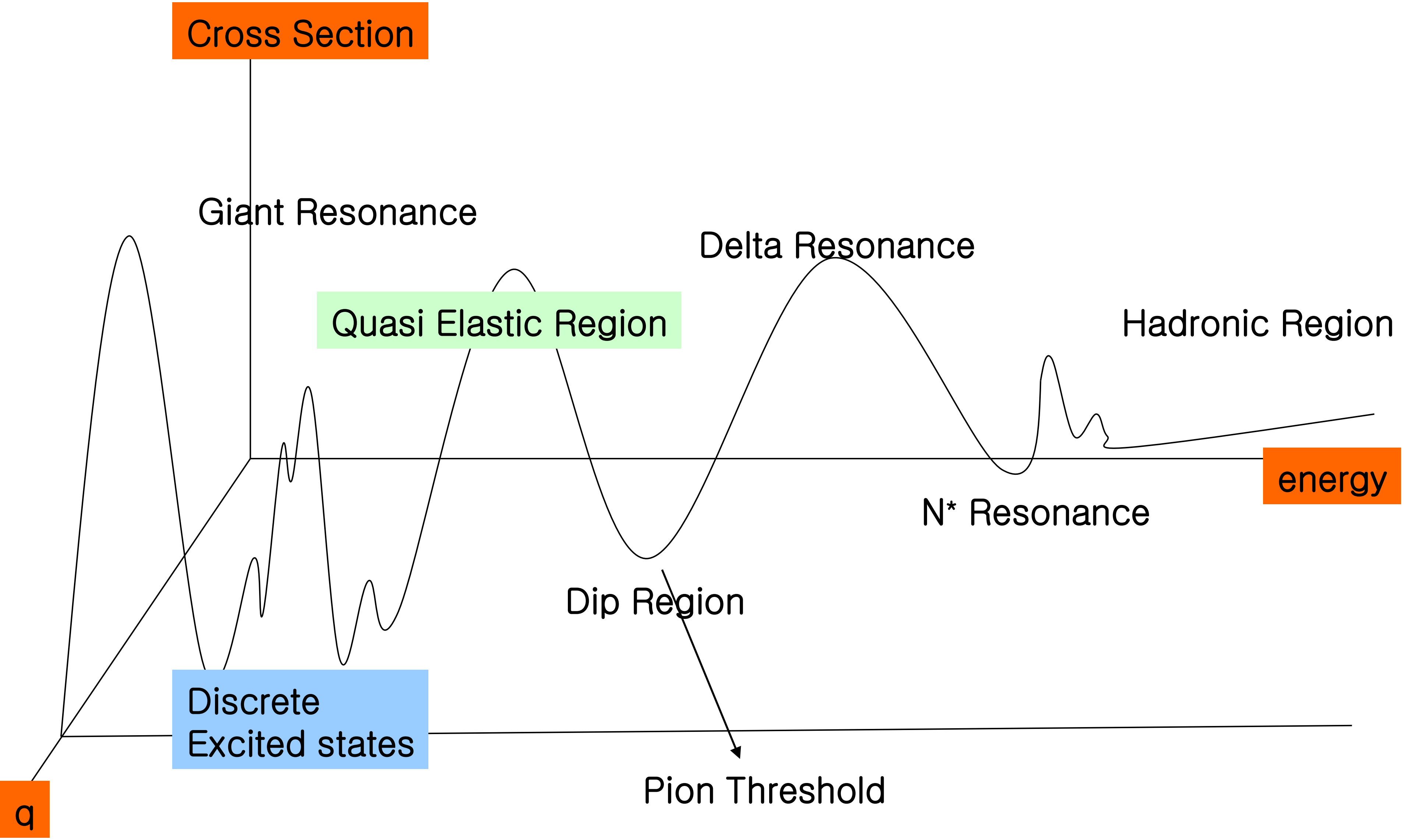

Cross Section

Giant Resonance

Delta Resonance

Quasi Elastic Region

Hadronic Region

energy

N* Resonance

Dip Region

Discrete
Excited states

Pion Threshold

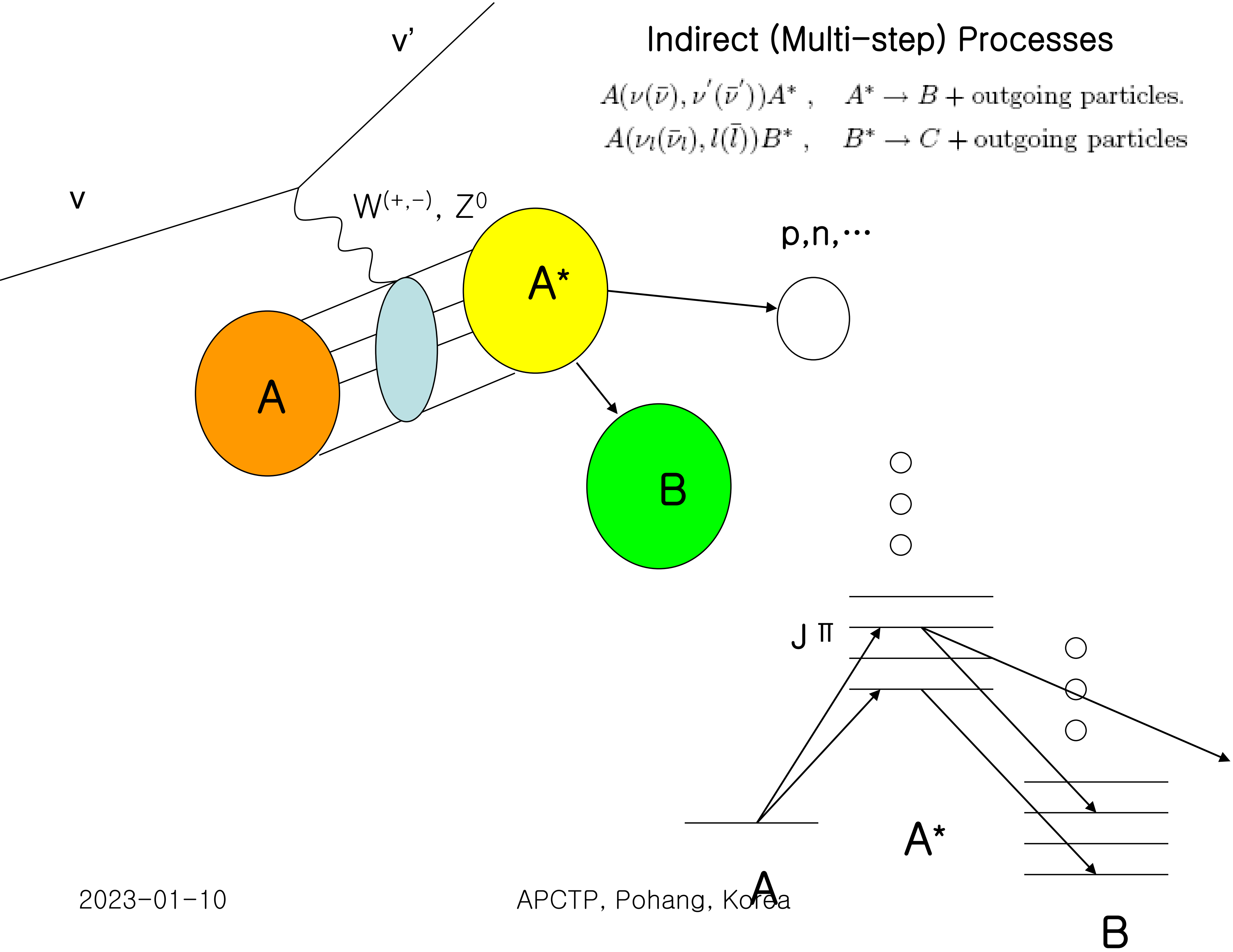
q

Typical cross section by incident electron

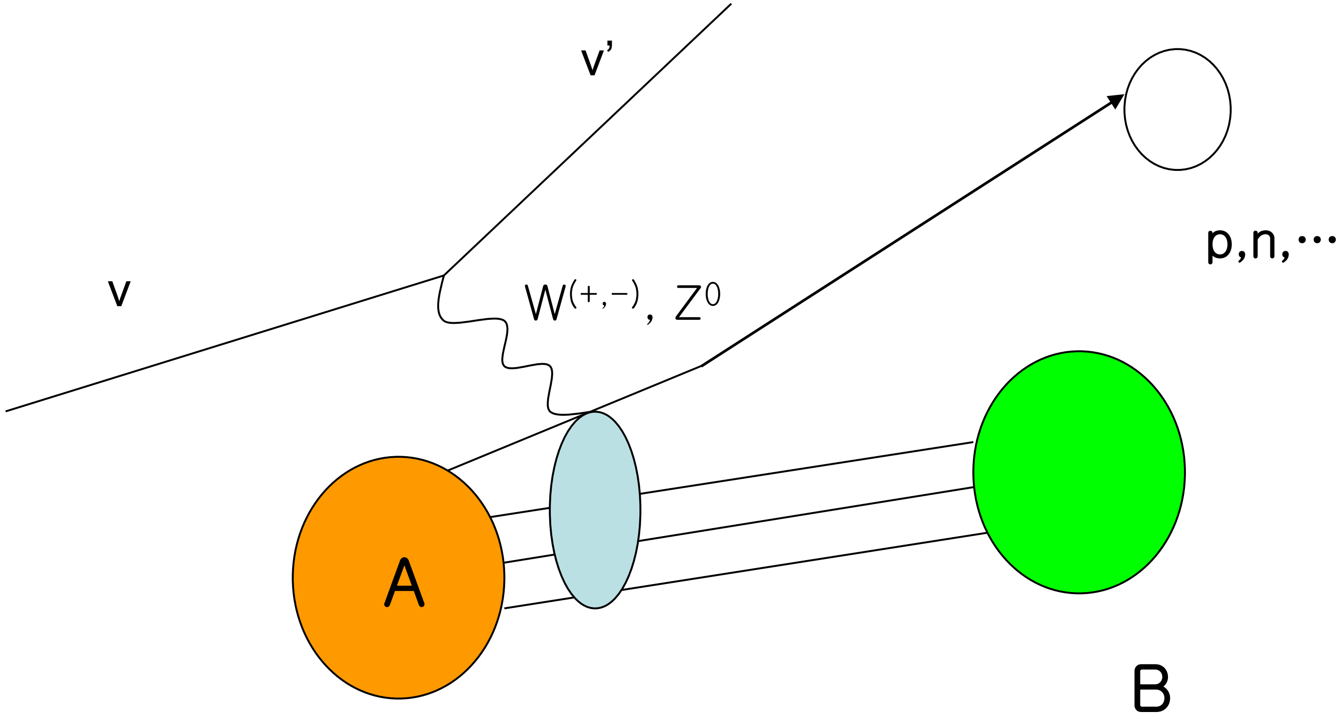
Indirect (Multi-step) Processes

$$A(\nu(\bar{\nu}),\nu'(\bar{\nu}'))A^*\,,\quad A^*\to B+\text{outgoing particles.}$$

$$A(\nu_l(\bar{\nu}_l),l(\bar{l}))B^*\,,\quad B^*\to C+\text{outgoing particles}$$



Direct (One-step) Processes



Indirect Processes by QRPA

QRPA

- The description of an operator, $\hat{O}_\lambda$, in the QRPA formalism

$$< \mathrm{QRPA} \| \hat{\mathrm{O}}_\lambda \| \omega; JM >= [\lambda]^{-1} \sum_{ab} < a \| \hat{\mathrm{O}}_\lambda \| b >< \mathrm{QRPA} \| [c_a^+ \tilde{c}_b]_\lambda \| \omega; JM >$$

nuclear model independent part

nuclear model dependent part

Quasi-Boson approximation (QBA)

- QRPA ground state =|QRPA>≈|BCS> : BCS vacuum

- QRPA excited state =|ω, *JM*> : 1 or 2 quasi-particle states to the BCS ground state

$$| \omega; JM >= \mathrm{Q}_{JM}^{+,\omega} | \mathrm{QRPA} >, \; \mathrm{Q}_{JM}^{\omega} | \mathrm{QRPA} >= 0$$

$$\mathrm{Q}_{JM}^{+,\omega} = \sum_{a \le b} [X_{ab}^{\omega} A_{ab}^{+}(JM) - Y_{ab}^{\omega} \tilde{A}_{ab}(JM)],$$

phonon operator

$$\mathrm{Q}_{JM}^{\omega} = \sum_{a \le b} [X_{ab}^{\omega *} A_{ab}(JM) - Y_{ab}^{\omega *} \tilde{A}_{ab}^{+}(JM)]$$

- |a> and |b> are the single particle state

Calculation and Method

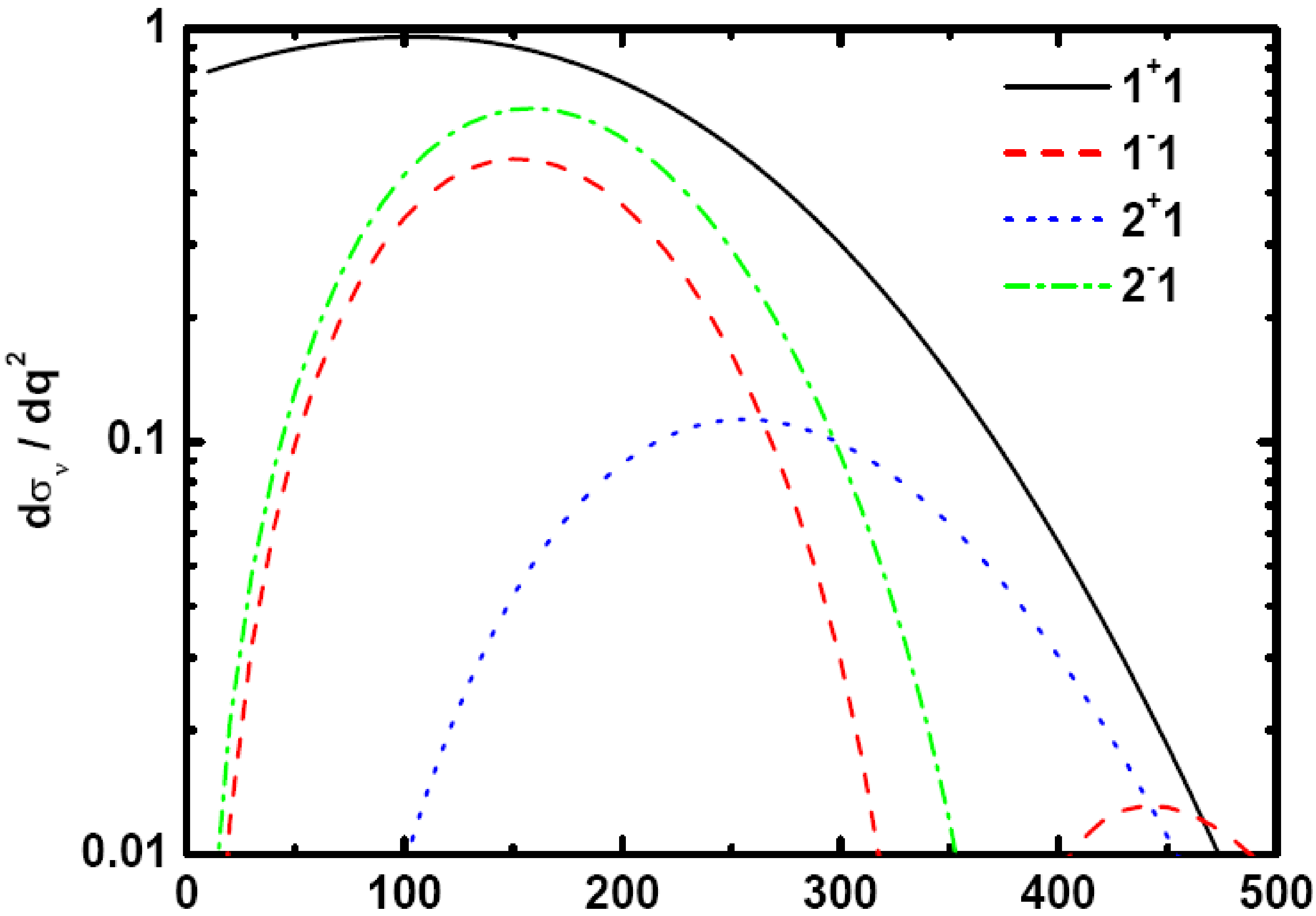
- The differential neutrino-nucleus cross section takes the form

$$\left(\frac{d\sigma_\nu}{dq^2}\right)_{\nu/\bar{\nu}} = \frac{2G_F^2\varepsilon\,\cos^2(\theta/2)}{\nu\,2\,(J_i+1)}\Big[R_{CL}(q,\omega)+\left[\frac{1}{2}\frac{q^2}{\vec{q}^{\,2}}+\tan(\theta/2)\right]R_T(q,\omega)$$

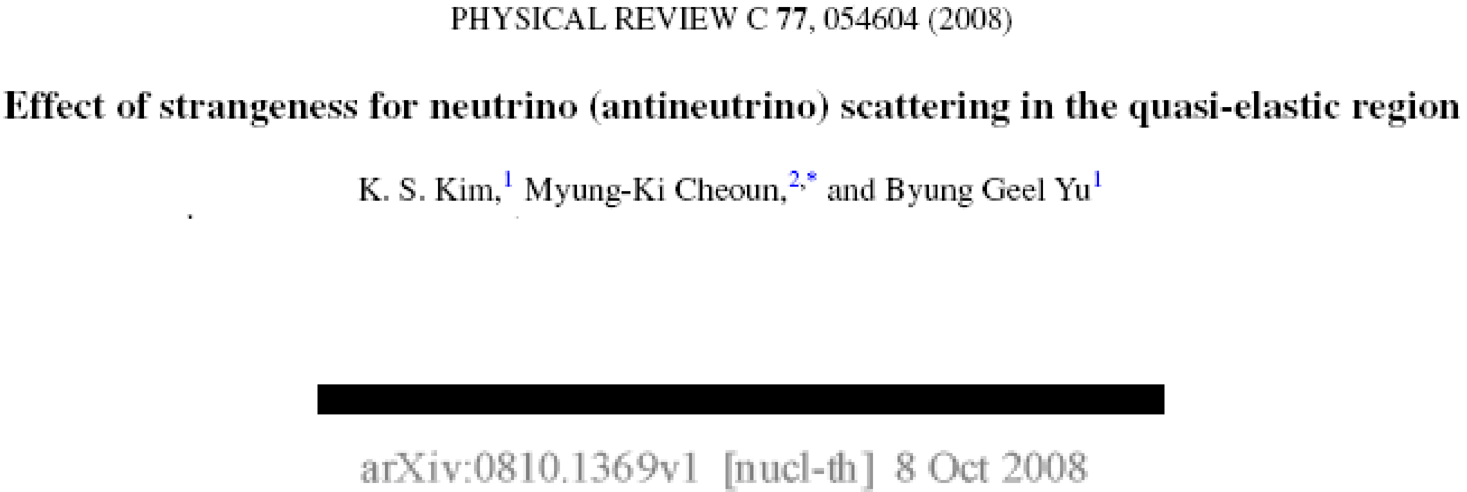
$$\mp\tan(\theta/2)\left[\frac{q^2}{\vec{q}^{\,2}}+\tan(\theta/2)\right]R_I(q,\omega)\Big]$$

where, $q \equiv (\vec{q}\,,\,\omega)$

Structure functions


1
0.1
0.01
$d\sigma_\nu$ / dq^2
0
100
200
300
400
500
1^+1
1^-1
2^+1
2^-1

Direct Processes by Distorted Wave Born Approximation



PHYSICAL REVIEW C **77**, 054604 (2008)

Effect of strangeness for neutrino (antineutrino) scattering in the quasi-elastic region

K. S. Kim,[1] Myung-Ki Cheoun,[2,*] and Byung Geel Yu[1]

[redacted]

arXiv:0810.1369v1 [nucl-th] 8 Oct 2008

Neutrino-nucleus (^{12}C) scattering

The differential cross section is given by

$$\frac{d\sigma}{dT_p} = 4\pi^2 \frac{M_N M_{A-1}}{(2\pi)^3 M_A} \int \sin\theta_l d\theta_l \int \sin\theta_p d\theta_p$$
$$p f_{rec}^{-1} \sigma_M^{Z,W^\pm} [v_L R_L + v_T R_T + h v_T' R_T']$$

M_N : mass of nucleon

M_{A-1} : mass of residual nucleus

M_A : mass of target nucleus

h : helicity for neutrino (antineutrino)

The recoil factor is given by

$$f_{rec} = \frac{E_{A-1}}{M_A} \left| 1 + \frac{E}{E_{A-1}} \left[1 - \frac{\mathbf{q}\cdot\mathbf{p}}{p^2} \right] \right|$$

and corresponding structure functions are given by

$$R_L^0 = |J^0|^2 \qquad R_L^z = |J^z|^2 \qquad R_L^{0z} = -2\mathrm{Re}(J^0 J^{z*})$$

$$R_T = |J^x|^2 + |J^y|^2 \qquad R_T' = 2\mathrm{Im}(J^x J^{y*})$$

with

$$v_L R_L = v_L^0 R_L^0 + v_L^z R_L^z + v_L^{0z} R_L^{0z}$$

The total cross section

$$\sigma = \int \frac{d\sigma}{dT_p}\, dT_p$$

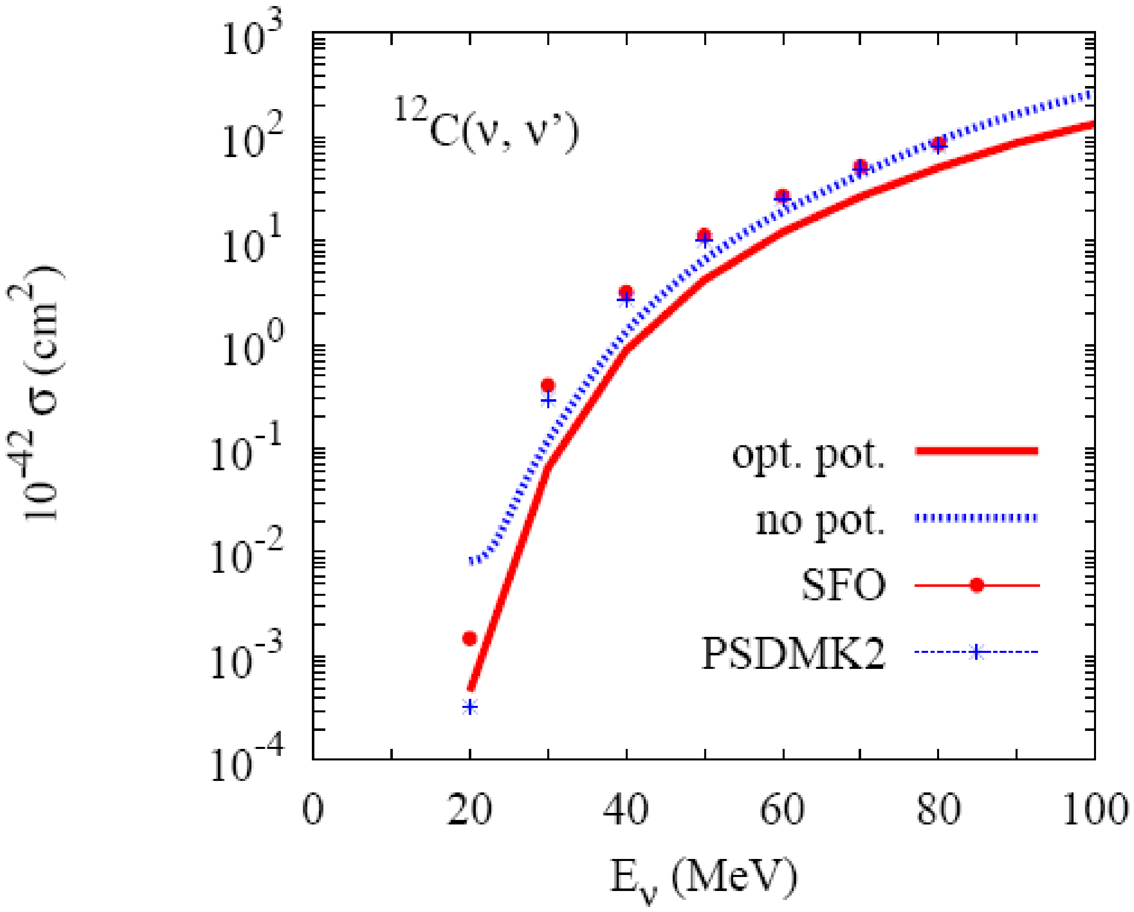


FIG. 1: (Color online) NC reaction for ν by direct process, $^{12}\mathrm{C}(\nu,\nu')$, obtained by integrating the kinetic energy and summing all possible knocked-out nucleon states for $^{12}\mathrm{C}(\nu,\nu' N)$ reaction [11]. Data points for indirect processes, which is a sum of two cross sections, $^{12}\mathrm{C}(\nu,\nu')^{12}\mathrm{C}^* \rightarrow {}^{11}\mathrm{B} + \mathrm{p}$ and $^{11}\mathrm{C} + \mathrm{n}$, come from the SM calculation [2]. SFO and PSDMK2 mean two different Hamiltonian exploited in the calculation.

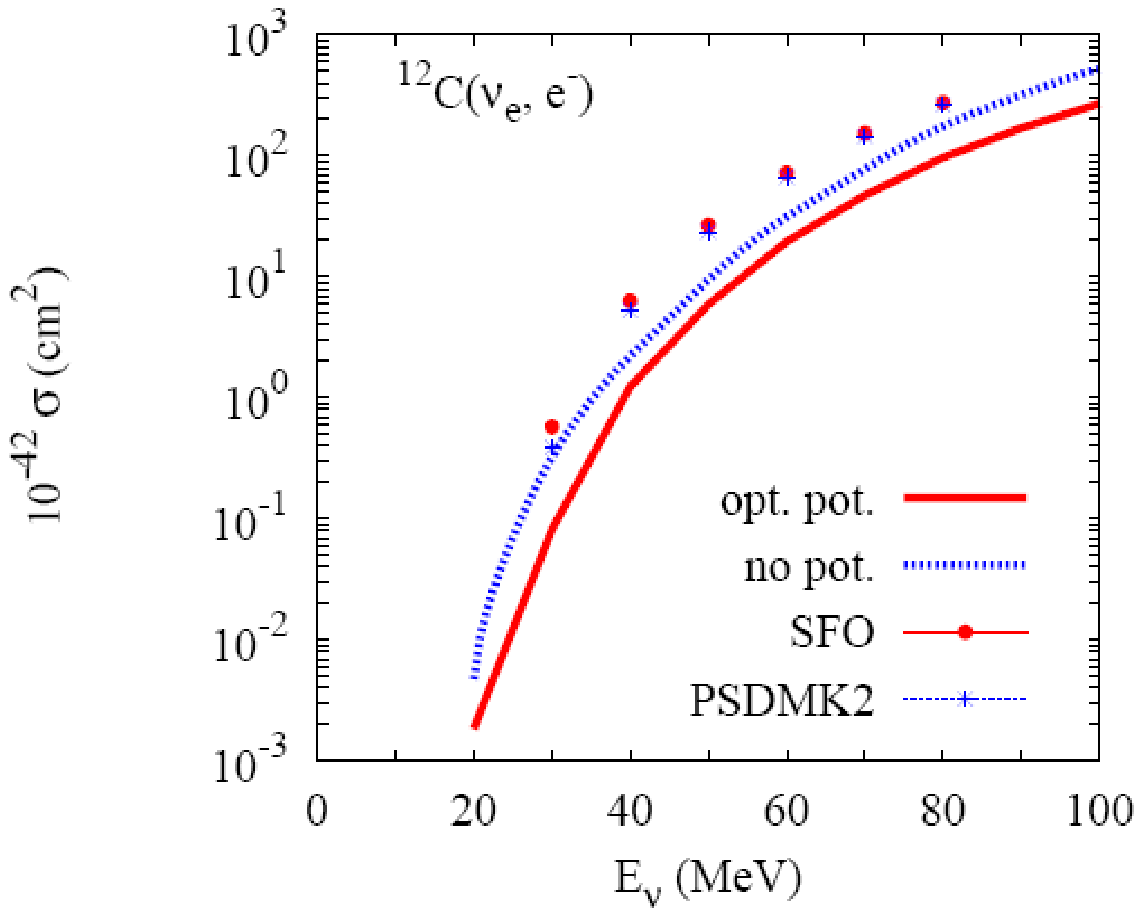
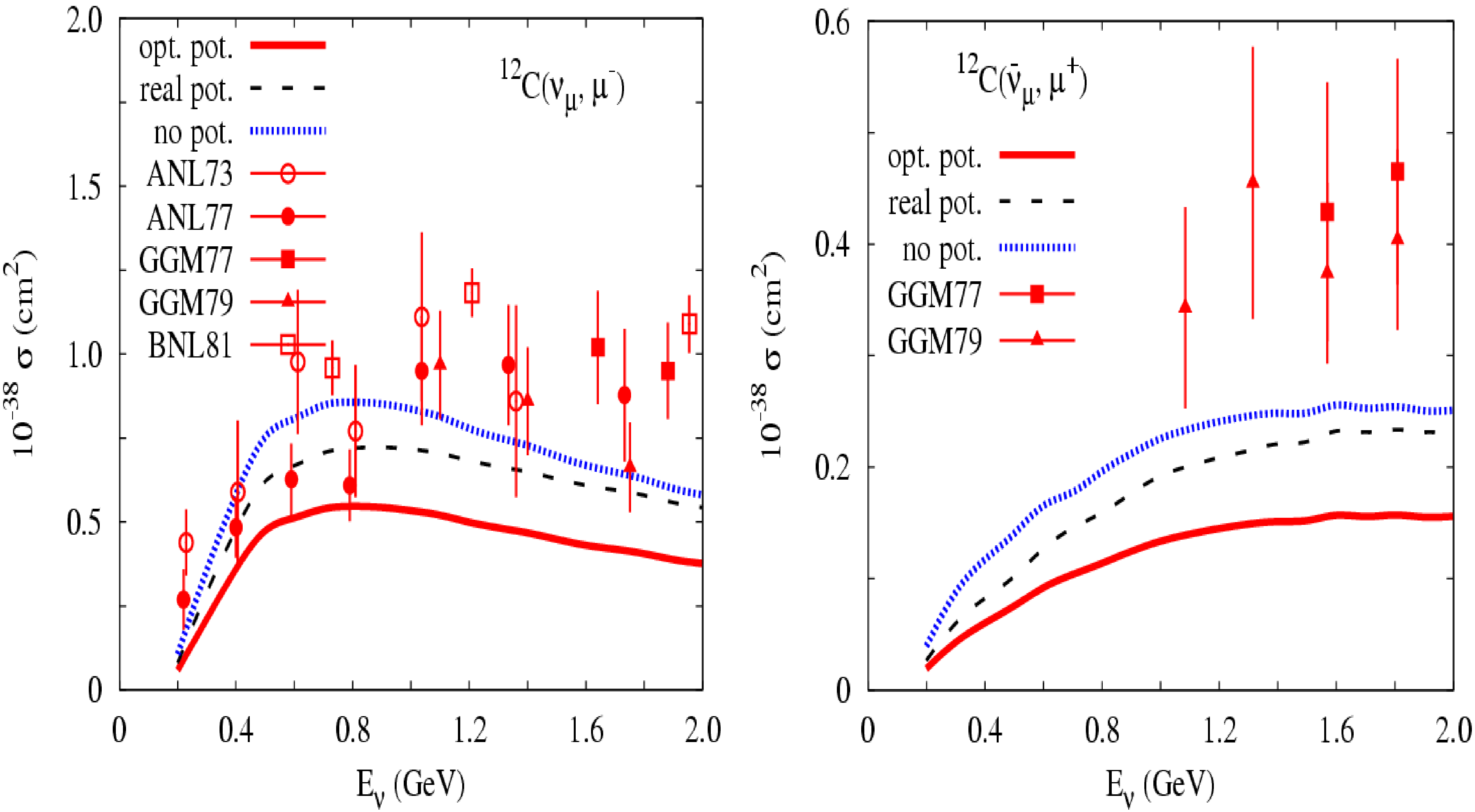


FIG. 2: (Color online) CC reaction for ν_e by direct process, ^{12}C(ν_e, e^-), obtained by integrating the kinetic energy and summing all possible knocked-out proton states in the reaction, ^{12}C($\nu_e, e^- p$). Data points for indirect processes come from the SM calculation for $^{12}\mathrm{C}(\nu_e, e^-) \rightarrow {}^{12}\mathrm{N}^* \rightarrow {}^{11}\mathrm{C} + p$ [2]. Others are same as Fig.1.

Total cross section (CC reaction)



Summary 1

- In this work, we present how to include multipole transitions between ground and excited states in our QRPA code by using Donnelly's multipole operator method for nuclear interactions. We showed a preliminary result obtained by this method, and applied to the ν reaction with ^{12}C nuclei.

- We are going to apply our method to another nuclei, Mg and Al series, and also for medium and heavy nuclei, i.e. Fe, Co and Ni series, and La and Ta series, which are known to play very important roles in the ν and rapid proton processes for nucleosynthesis.

Summary 2

- Contribution by Direct processes for BBN nucleosynthesis are smaller 2-4 times than those by Indirect Processes with Final state interactions.

- But, Indirect Processes need to be checked carefully in the aspect of final state interaction between outgoing particles and residual nuclei. Direct reaction could be comparable to those by Indirect Processes.

- Abundances of ^{7}Li might be changed by the contribution of Direct Processes. It may lead to different results for the information of neutrino deduced from the BBN, such as neutrino masses and oscillation parameters.

Thanks for your attention
and
for LOC !!