Supernova Nucleosynthesis: Radioactive Nuclear Reactions and Neutrino-Mass Hierarchy

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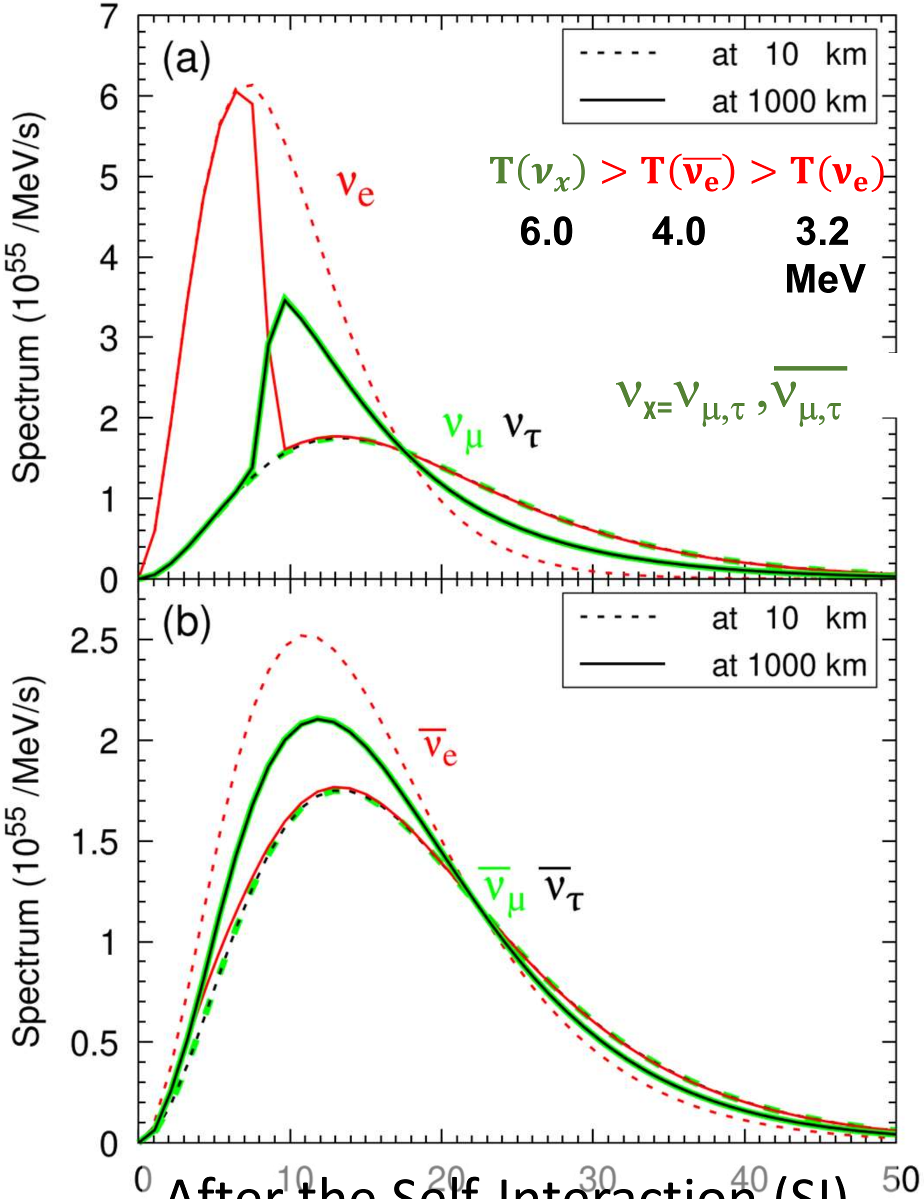
Introduction-1: Self-Interaction and MSW effect

Fermi-Dirac Energy spectra→ change



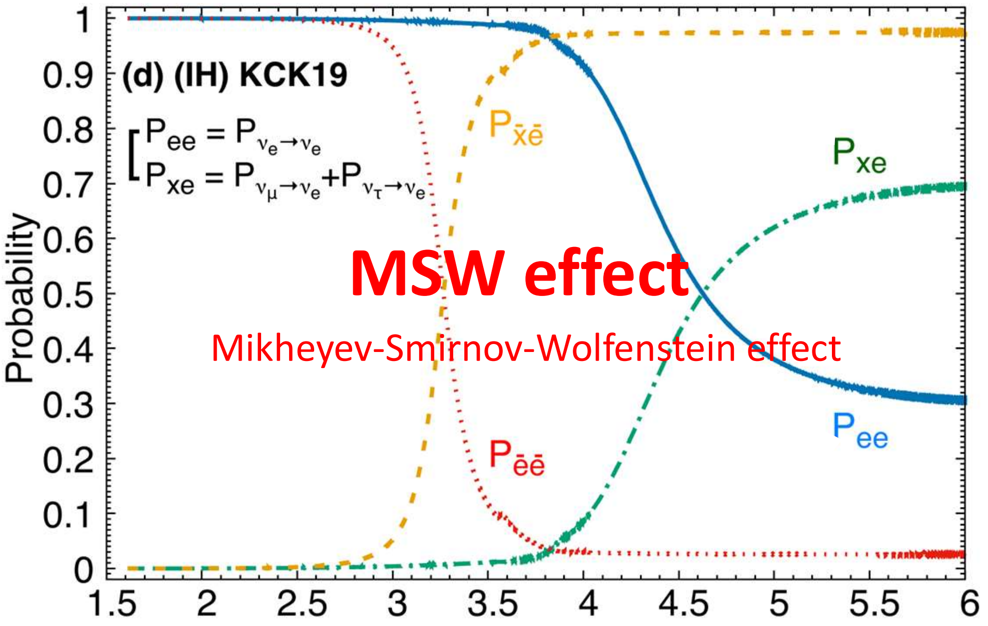
$\mathrm{T}(\nu_x) > \mathrm{T}(\overline{\nu_e}) > \mathrm{T}(\nu_e)$

6.0 4.0 3.2 MeV

$\nu_x = \nu_{\mu,\tau}, \overline{\nu_{\mu,\tau}}$

After the Self-Interaction (SI)

Neutrino Flavor change probability (**inverted** hierarchy)



MSW effect

Mikheyev-Smirnov-Wolfenstein effect

Two figures from (Ko et al. 2022ApJ 937:116) Fig.9 &4

$\mathrm{M_r}$ is the Lagrangian mass coordinate :

$$\mathrm{M_r} = \int_0^r 4\pi x^2 \rho(x) dx.$$

We show it in unit of solar mass

Model : **Supernova (SN) nucleosynthesis model and ν -process**

- Initial mass: $\mathbf{20}\boldsymbol{M}_{\odot}$ evolves to a **helium core of $\mathbf{6}\boldsymbol{M}_{\odot}$** before collapse (*Kikuchi et al., 2015*).
- Nuclear reactions :**JINA REACLIB** (Cyburt et al. 2011)
- Hydrodynamics & reaction network (*Kusakabe et al. 2019)*
- Neutrino flavor change:
  - MSW(Yoshida et al. 2006 ApJ)
  - Collective effect (Ko et al.2022 ApJ)

Neutrino Reaction rate:

- ^{12}C+ν &^{4}He+ν : (Yoshida et al. 2008)
- **^{16}O+ν** : (T. Suzuki et al. Phys. Rev. C. 2018) **(new)**
  (R.D. Hoffman & S.E. Woosley (1992) **(old)**
  ^{11}B abundance, ~ 3 larger!
- **^{20}Ne**+ν : (Satoshi Chiba, Suzuki's **new**)

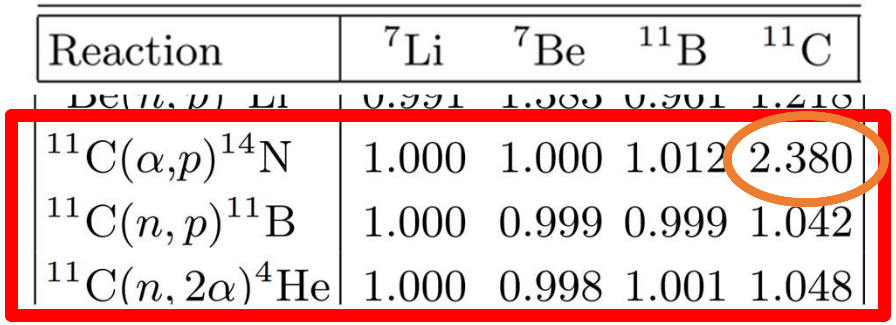
ν-A reaction rate uncertainties:

- Neutral current: $\pm 20\%$
- Charged current: $\pm 10\%$

Neutrino & SN model parameters (Yoshida et al., 2004, 2006):

- neutrino energy in SN:
  $E_{\nu} = 3 \times 10^{53}$erg
- decay time of neutrino luminosity:
  $\tau_{\nu} = 3$s
- Neutrino temperatures:
  $$T_{\nu_e} = 3.2; \quad T_{\overline{\nu}_e} = 5.0;$$
  $$\mathrm{T}_{\nu_x} = 6.0 \text{ MeV } (x = \mu, \tau, \bar{\mu}, \bar{\tau}).$$

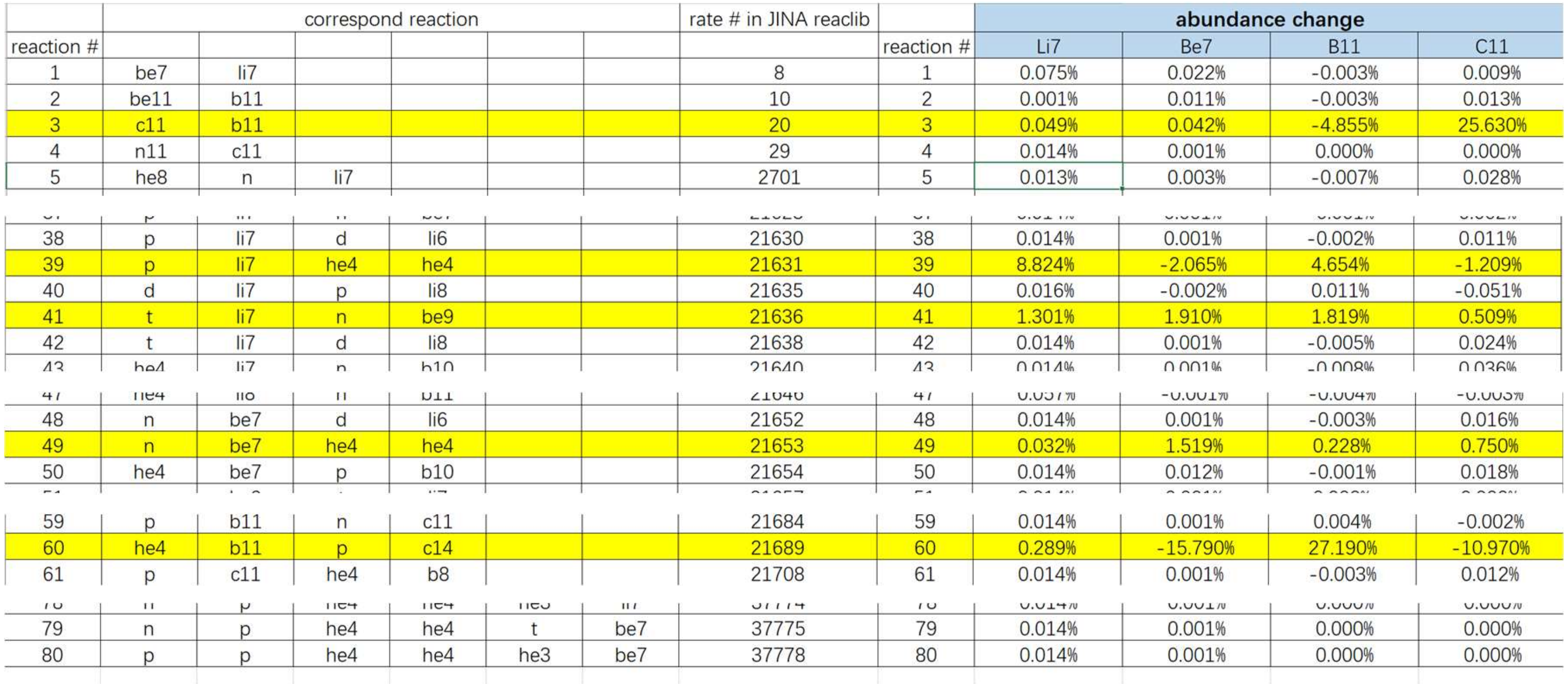
method: radioactive nuclear reaction effects, $^{11}C(\alpha,p)^{14}N$ and others



Reaction	^{7}Li	^{7}Be	^{11}B	^{11}C
$^{11}C(\alpha,p)^{14}N$	1.000	1.000	1.012	2.380
$^{11}C(n,p)^{11}B$	1.000	0.999	0.999	1.042
$^{11}C(n,2\alpha)^4He$	1.000	0.998	1.001	1.048

Table of without/with ratio. Without the left reaction, the relative change to nuclei result in nucleosynthesis.
$^{11}C(\alpha,p)^{14}N$ → significant to ^{11}C

91 reactions related to Li7 Be7 C11 B11 been studied.



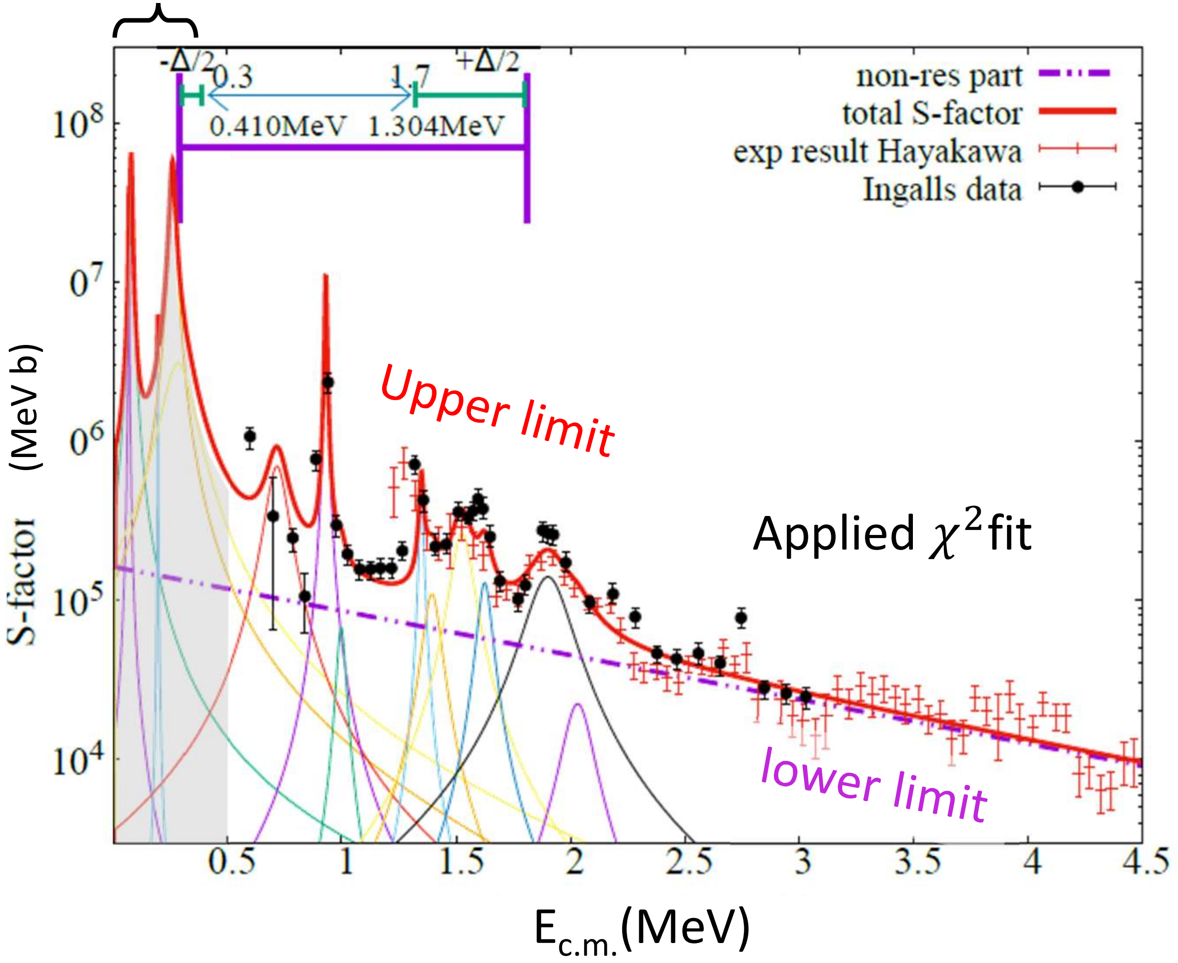
	correspond reaction						rate # in JINA reaclib		abundance change			
reaction #								reaction #	Li7	Be7	B11	C11
1	be7	li7					8	1	0.075%	0.022%	-0.003%	0.009%
2	be11	b11					10	2	0.001%	0.011%	-0.003%	0.013%
3	c11	b11					20	3	0.049%	0.042%	-4.855%	25.630%
4	n11	c11					29	4	0.014%	0.001%	0.000%	0.000%
5	he8	n	li7				2701	5	0.013%	0.003%	-0.007%	0.028%
38	p	li7	d	li6			21630	38	0.014%	0.001%	-0.002%	0.011%
39	p	li7	he4	he4			21631	39	8.824%	-2.065%	4.654%	-1.209%
40	d	li7	p	li8			21635	40	0.016%	-0.002%	0.011%	-0.051%
41	t	li7	n	be9			21636	41	1.301%	1.910%	1.819%	0.509%
42	t	li7	d	li8			21638	42	0.014%	0.001%	-0.005%	0.024%
43	he4	li7	n	b10			21640	43	0.014%	0.001%	-0.008%	0.036%
48	n	be7	d	li6			21652	48	0.014%	0.001%	-0.003%	0.016%
49	n	be7	he4	he4			21653	49	0.032%	1.519%	0.228%	0.750%
50	he4	be7	p	b10			21654	50	0.014%	0.012%	-0.001%	0.018%
59	p	b11	n	c11			21684	59	0.014%	0.001%	0.004%	-0.002%
60	he4	b11	p	c14			21689	60	0.289%	-15.790%	27.190%	-10.970%
61	p	c11	he4	b8			21708	61	0.014%	0.001%	-0.003%	0.012%
79	n	p	he4	he4	t	be7	37775	79	0.014%	0.001%	0.000%	0.000%
80	p	p	he4	he4	he3	be7	37778	80	0.014%	0.001%	0.000%	0.000%

by increase them 10 times (based on JINA rate)

method: ^{11}C(α,p)^{14}N reaction rate estimation

Breit-Wigner formula: $$\sigma_R(E) = \pi\lambda^2\omega_R \frac{\Gamma_{\alpha_R}(E)\Gamma_{p_R}(E)}{(E-E_R)^2 + \frac{\Gamma^2_{tot_R}(E)}{4}}$$

Below the lowest experiment point: 5 resonances exist!



Upper limit

Applied χ^2fit

lower limit

Total cross section:

$$\boldsymbol{\sigma_{tot}} = \sigma_{non-res} + \Sigma_R \sigma_R$$

Non-resonance contribution:

$$\sigma_{non-r} = \exp(-A_1 E + A_0)$$

Resonant contribution depends on:

$$\Gamma_{\alpha_R}(E) = 2\gamma^2_{\alpha_R} P_\alpha(E)\theta^2_R, \theta^2_R \leq 1$$

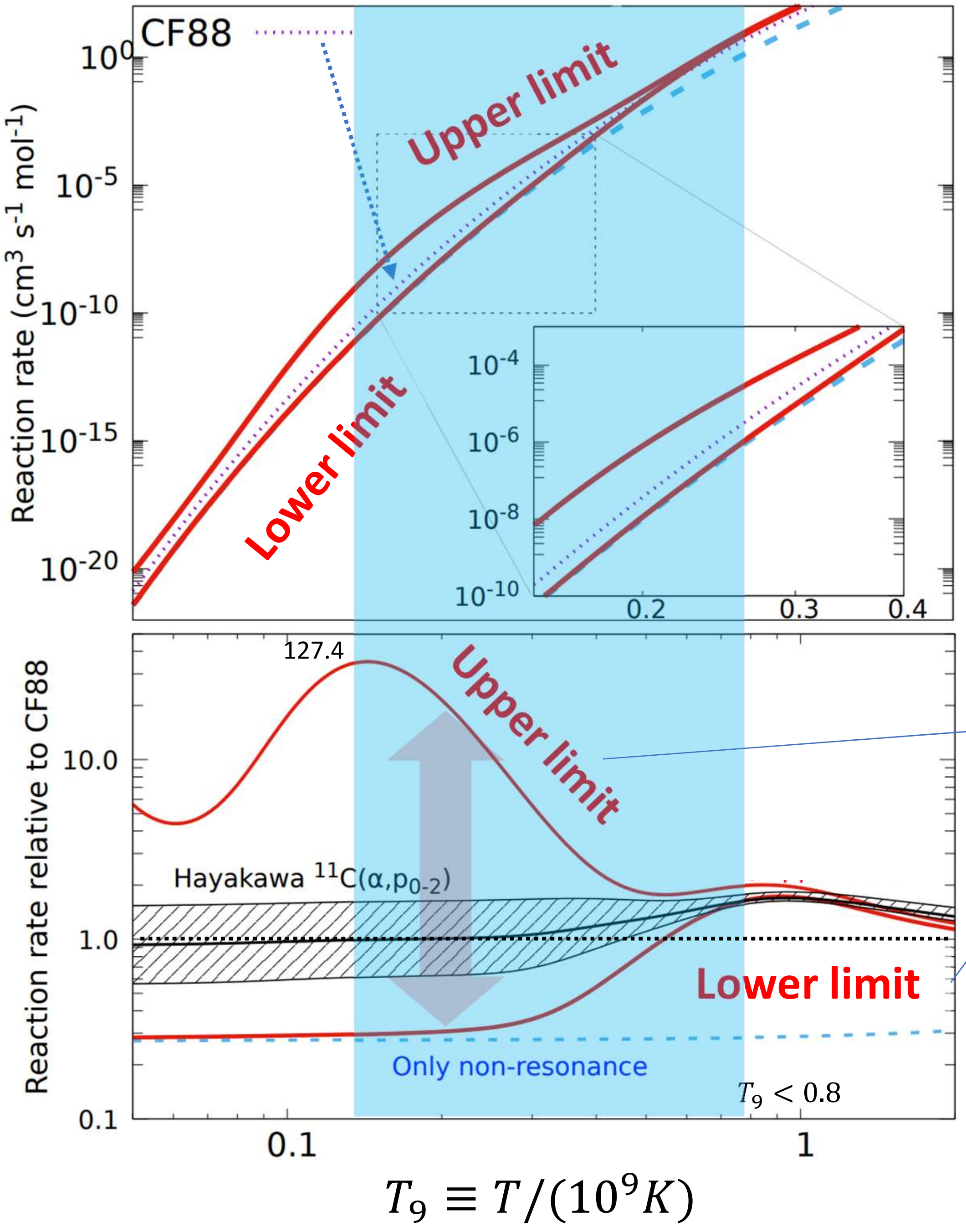
For the lowest 5 resonances,

→Upper limit : θ^2 = 1 (Wigner-limit)

→Lower limit : θ^2= 0

Data from S. Hayakawa et al. PRC **93**, 065802 (2016).

method: $^{11}C(\alpha,p)^{14}N$ reaction rate estimation



- New $< \sigma v > / < \sigma v >_{CF88}$

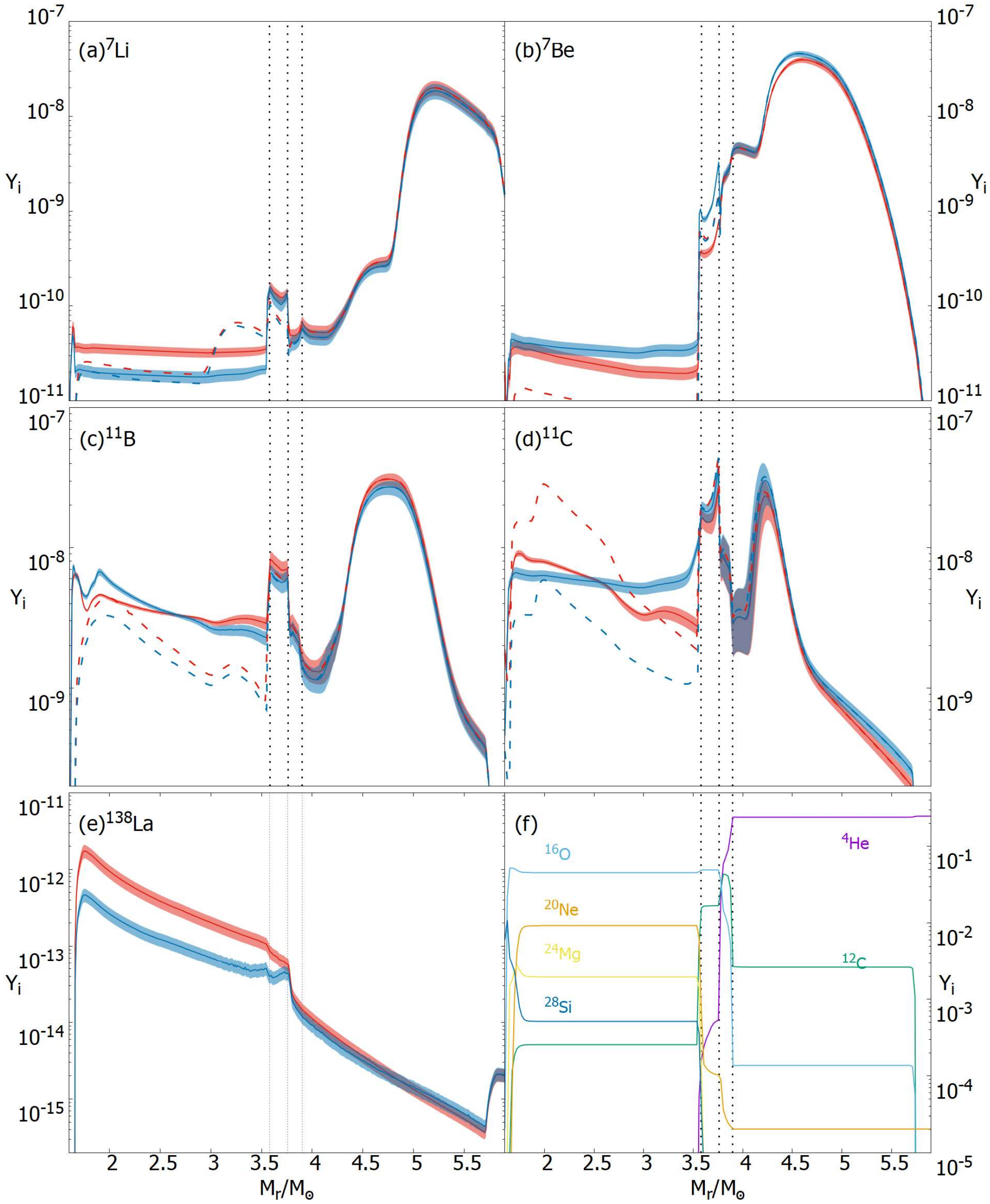
Caughlan and Fowler 1988 (CF88)

For the lowest 5 resonances,

→Upper limit : $\theta^2 = 1$ (Wigner-limit)

→Lower limit : $\theta^2 = 0$

Result: abundance of 4 nuclei



*M_r is the Lagrangian mass coordinate :

$M_r = \int_0^r 4\pi x^2 \rho(x) dx.$

Abundance of ^{7}Li, ^{7}Be, ^{11}B, ^{11}C, ^{138}La and abundant nuclei

🟥 invert 🟦 normal : uncertainty bands.

Neutrino induced reaction :

1. ^{4}He+ν; 2. ^{12}C+ν; 3. ^{16}O+ν; 4. ^{20}Ne+ν

-------- :without ^{16}O+ν & ^{20}Ne+ν

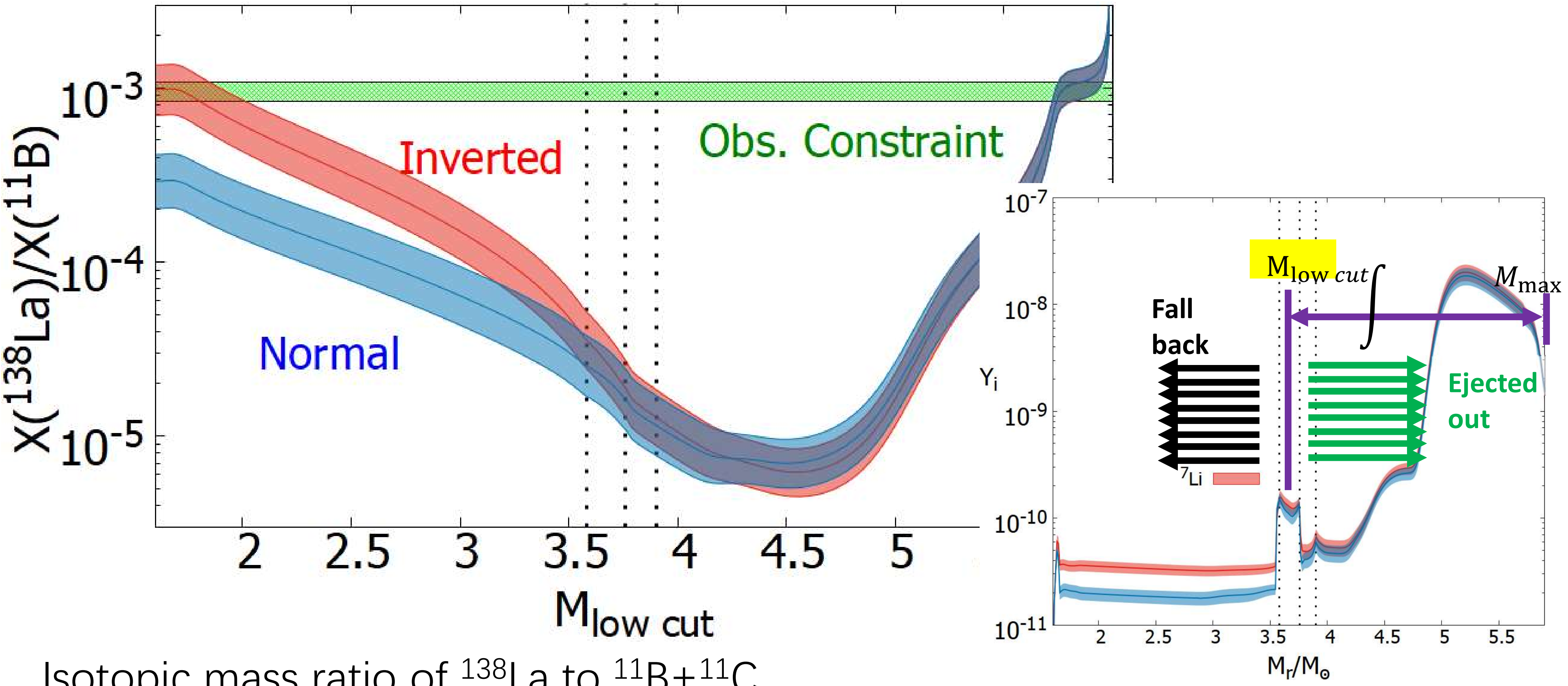
Uncertainty:

- 1. ^{11}C (α,p)^{14}N
- 2. Neutrino reactions: CC$\pm$20% NC$\pm$10%

Neutrino Flavor change:

- MSW effect
- Self Interaction (collective oscillation)

Result: mass ratio of ^{138}La/^{11}B & Observation Constraint



Isotopic mass ratio of ^{138}La to ^{11}B+^{11}C.

Invert & **Normal** hierarchy cases; 🟥🟦 : uncertainty

🟩 : SN mass ratio in solar system $X(^{138}La)/X(^{11}B)_{SN} = 9.3497^{+1.4355}_{-0.9965} \times 10^{-4} (\pm 1\sigma)$

Note: the La138 has been multiplied by 4 to fit the metallicity difference between SN1987A ($Z_\odot/4$) and solar system.

Summary

Thank you for your attention

Motivation and Purpose:

- Neutrino oscillation effect (MSW+SI) in the SN
- Important nuclear reaction (^{11}C(α,p)^{14}N)
- Comparing with astronomical observation

→ distinguish the neutrino hierarchy.

Results

1. Final abundances of ^{7}Li, ^{11}B & ^{138}La depend strongly on the neutrino mass hierarchy.
2. The new ^{16}O & ^{20}Ne+ν reaction rates are included in the nucleosynthesis program.
3. The uncertainties in $^{11}\mathrm{C}(\alpha, \mathrm{p})^{14}\mathrm{N}$ and its effect are estimated.
4. To predict mass-hierarchy dependent yields more accurately → to remove nuclear reaction rate uncertainties (both $\nu - A$ and radioactive reactions).
5. ^{138}La/^{11}B mass ratio with mass cut is compared with solar system abundance → Inverted hierarchy more preferred.