Stellar Weak-interaction Rates for rp-process by Angular-momentum Projection Theory

Long-Jun Wang

School of Physical Science and Technology, Southwest University (Chongqing)

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(for the 17th OMEG, @ Chengdu)

Outline

1. Introduction
2. Urca Neutrino Cooling for Accreting Neutron Star
3. Half-lives for rp-process waiting points
4. Summary

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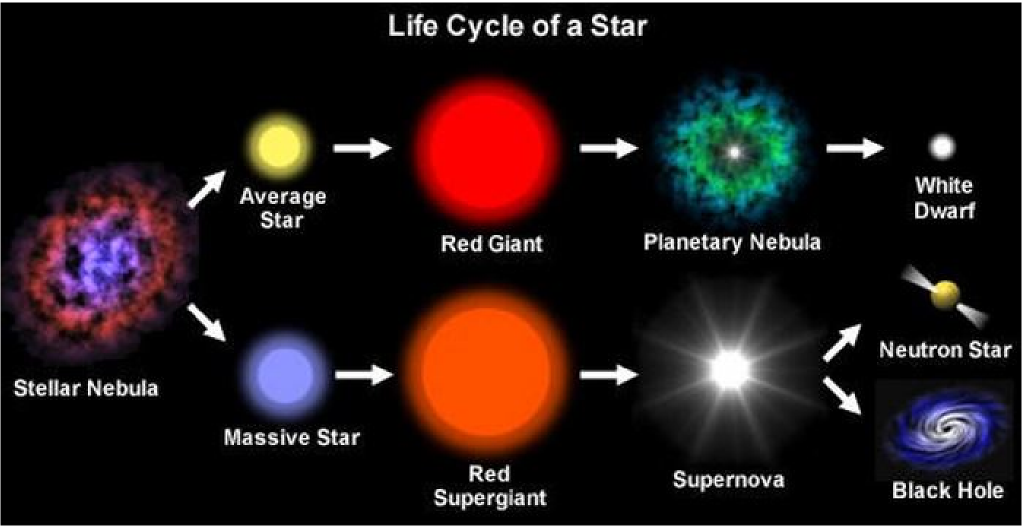
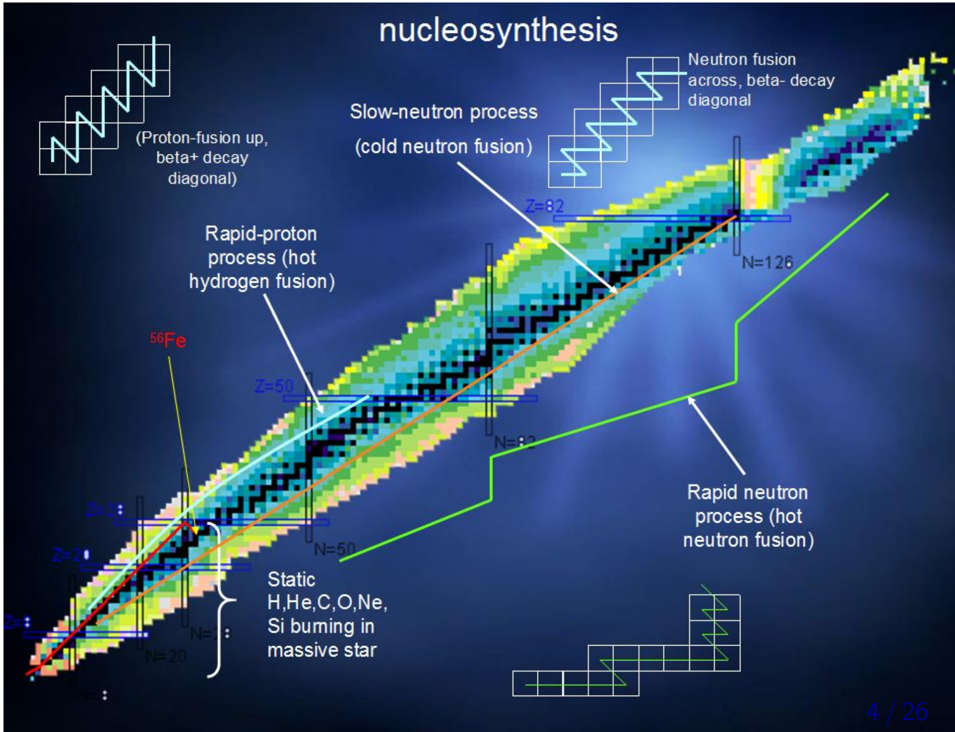
Nuclear weak process for nucleosynthesis

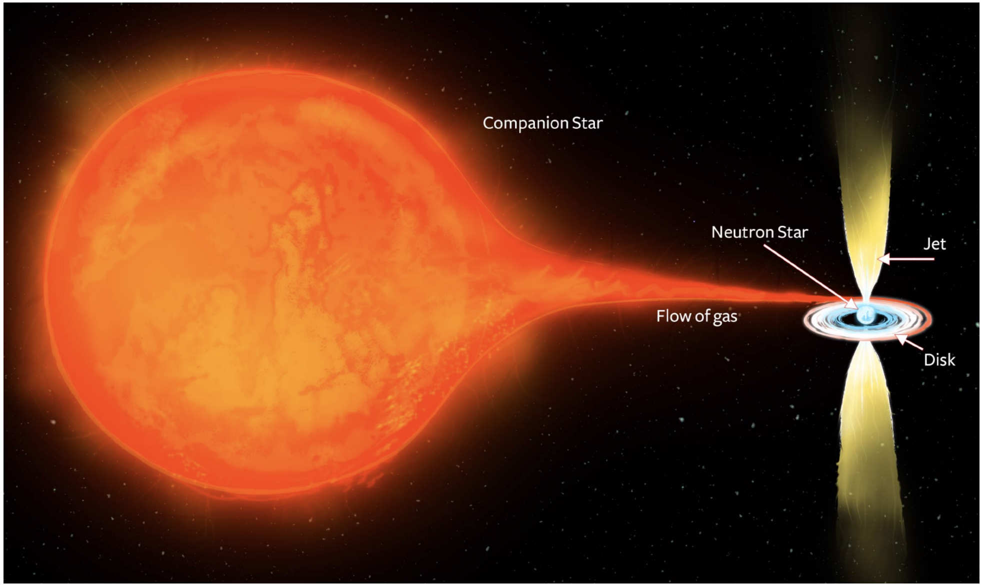


- neutron/proton capture rates

- Electron capture in supernova
- β-decay for nucleosynthesis
- neutrino cooling (Urca)



rp process: accreting neutron star



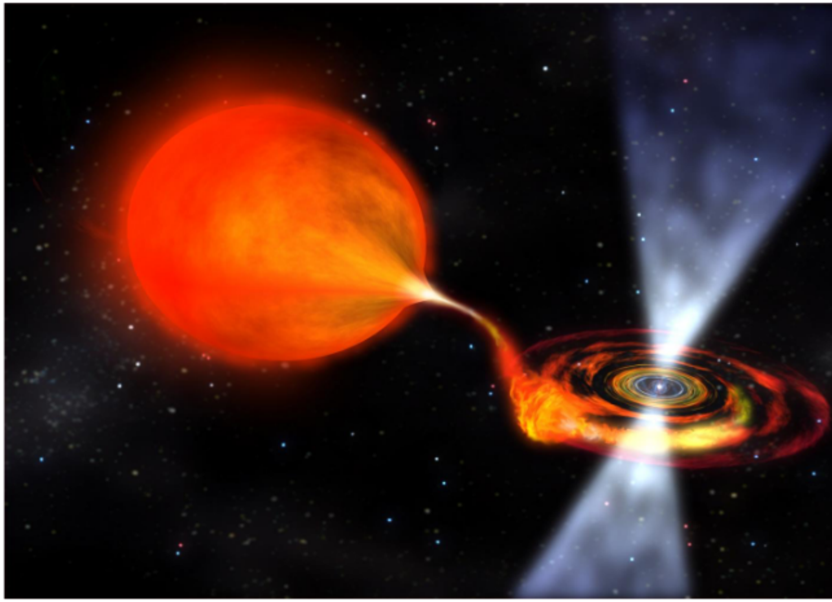
- X-ray bursts

- Urca cooling

$$\begin{aligned} \text{EC}: &\quad {}^{A}_{Z}\text{X} + e^- \;\rightarrow\; {}^{\;\;A}_{Z-1}\text{Y} + \nu_e \\ \beta^-: &\quad {}^{\;\;A}_{Z-1}\text{Y} \;\rightarrow\; {}^{A}_{Z}\text{X} + e^- + \bar{\nu}_e \end{aligned}$$

H. Schatz et al., Nature (2014)

L.-J. Wang et al., Phys. Rev. Lett. (2021)



rp process: waiting-point nuclei

X-ray bursts:
H and He are fused eplosively up to Te
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Energy production through rp-process
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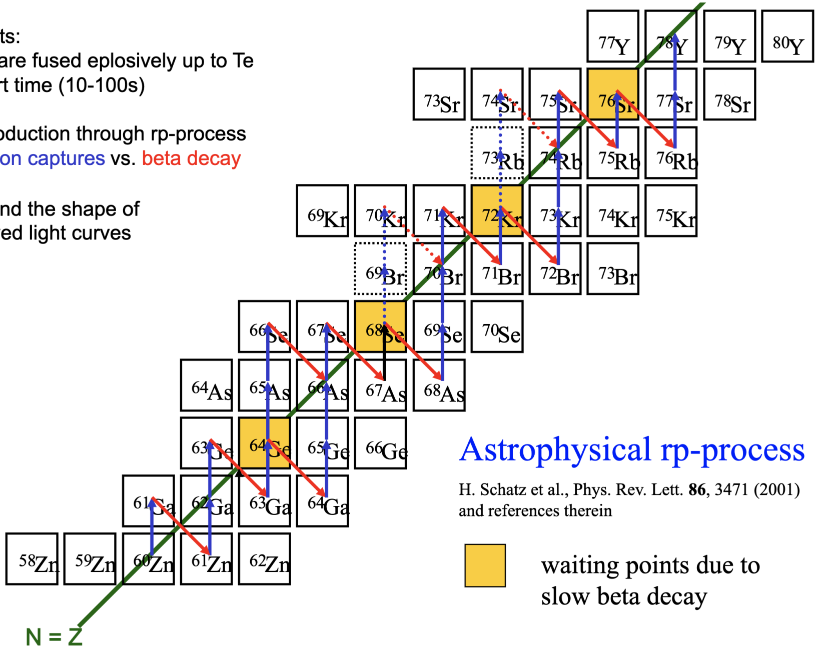


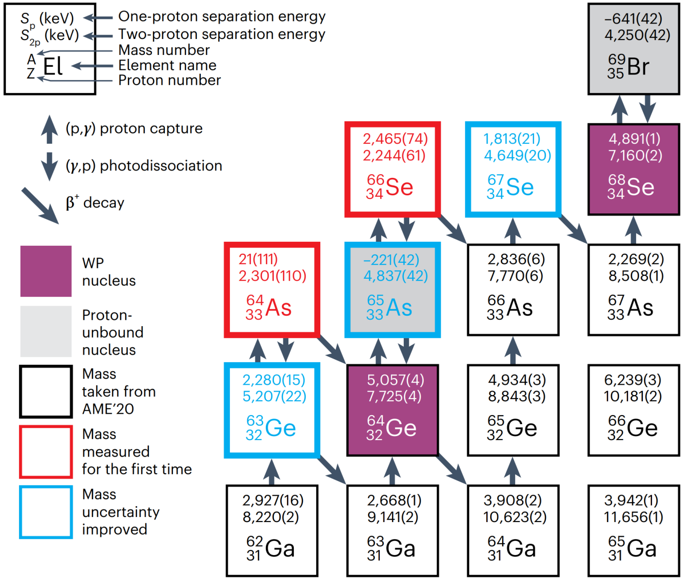
Astrophysical rp-process

H. Schatz et al., Phys. Rev. Lett. **86**, 3471 (2001)
and references therein

🟨 waiting points due to
slow beta decay

from Jokinen's slides

X. Zhou et al., Nat. Phys. (2023)



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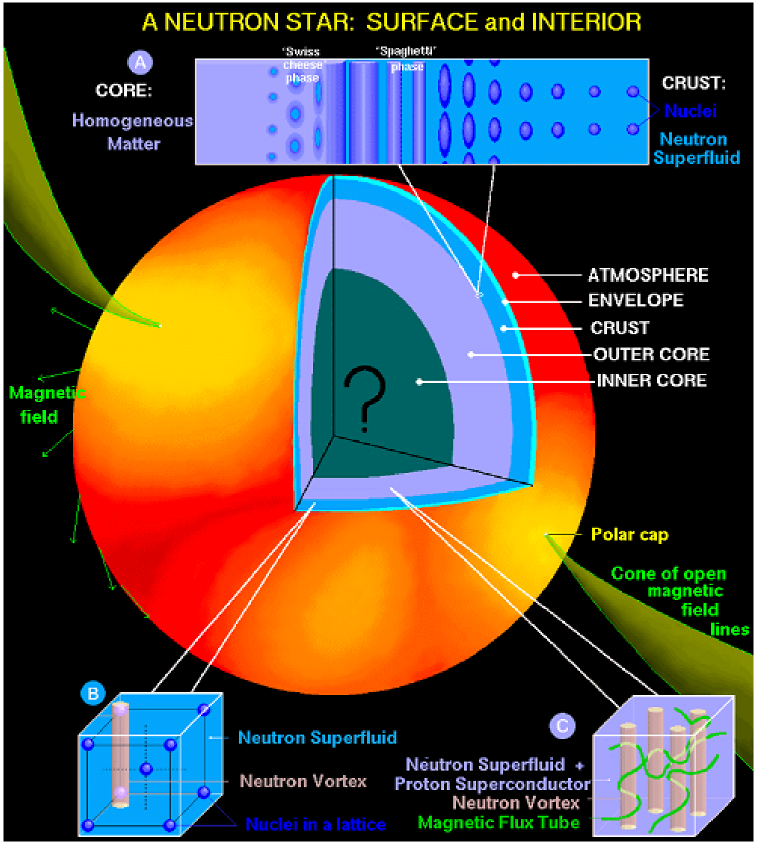
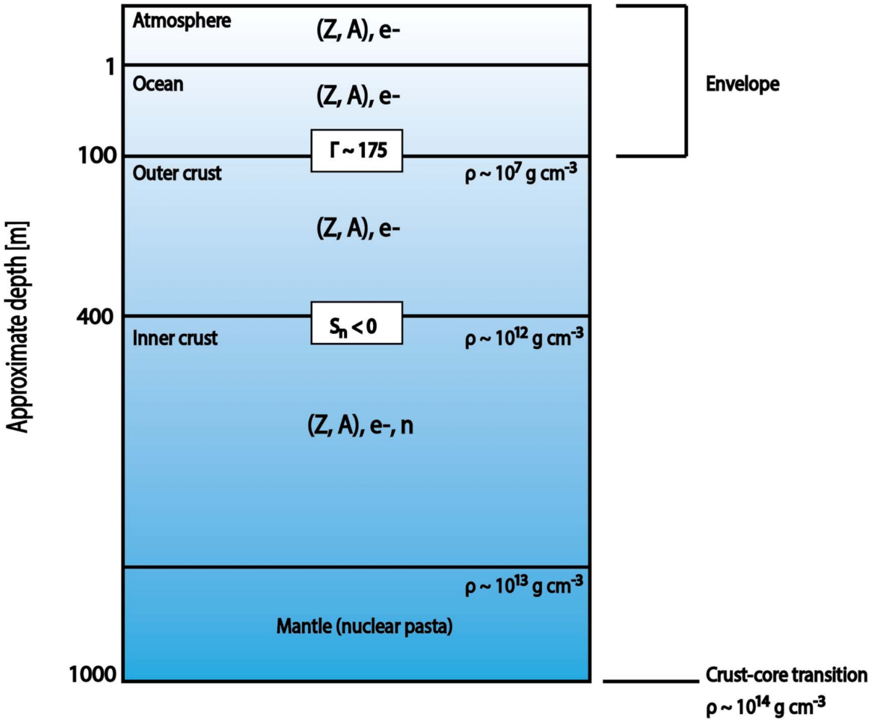
Neutron-star structure

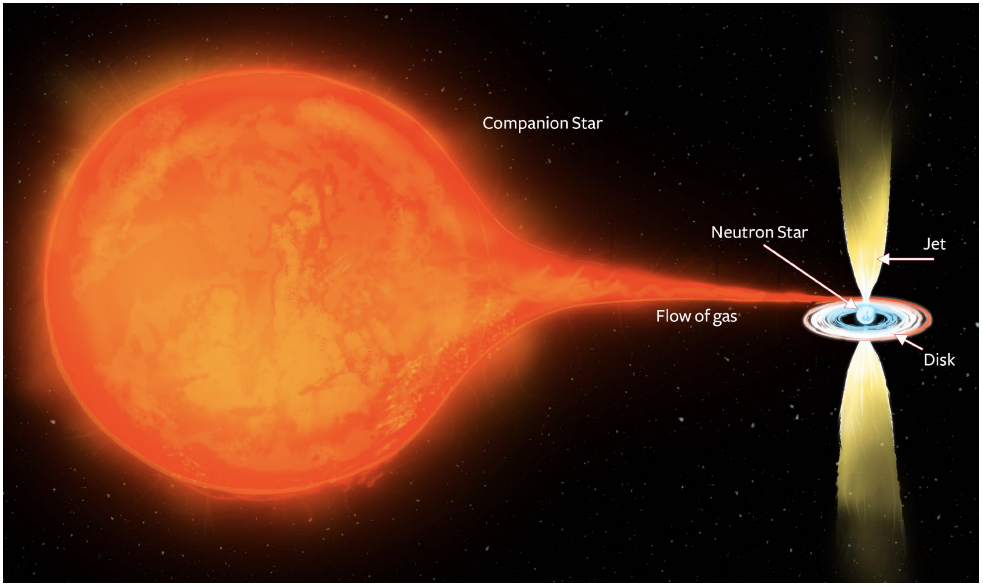


Lattimer and Prakash: Science (2004)

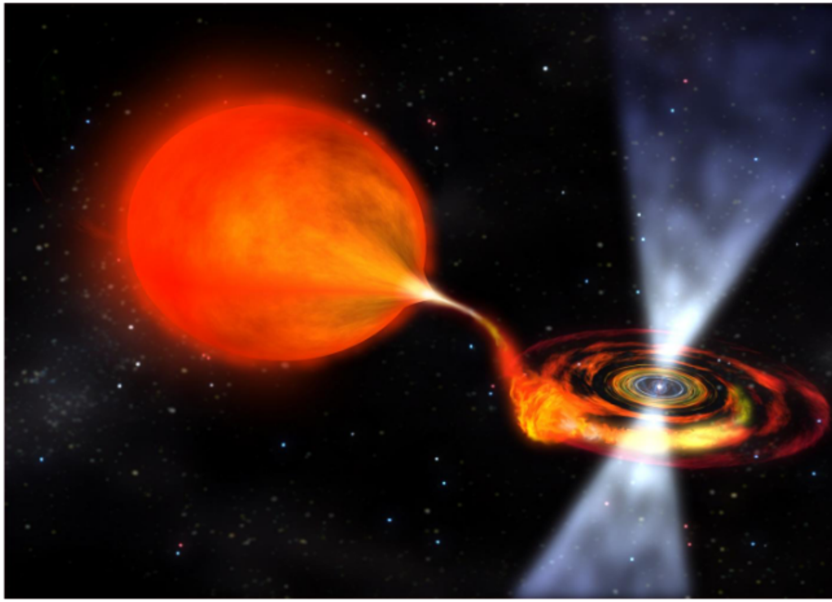


Meisel et al: JPG (2018)

Accreting neutron star



- X-ray bursts



- Urca cooling

$$\begin{array}{llcl} \text{EC}: & {}^{A}_{Z}\text{X} + e^- & \rightarrow & {}^{A}_{Z-1}\text{Y} + \nu_e \\ \beta^-: & {}^{A}_{Z-1}\text{Y} & \rightarrow & {}^{A}_{Z}\text{X} + e^- + \bar{\nu}_e \end{array}$$

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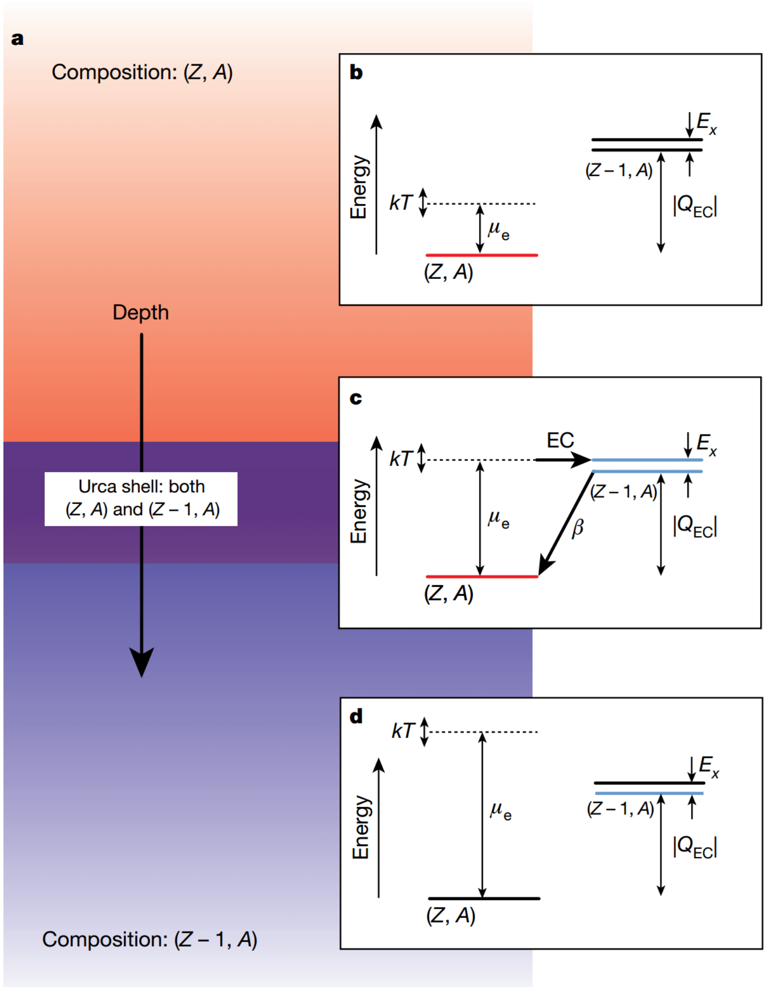
Urca cooling



H. Schatz: Nature (2014)

$$\text{EC}: \quad {}^{A}_{Z}\text{X} + e^- \rightarrow {}^{A}_{Z-1}\text{Y} + \nu_e$$

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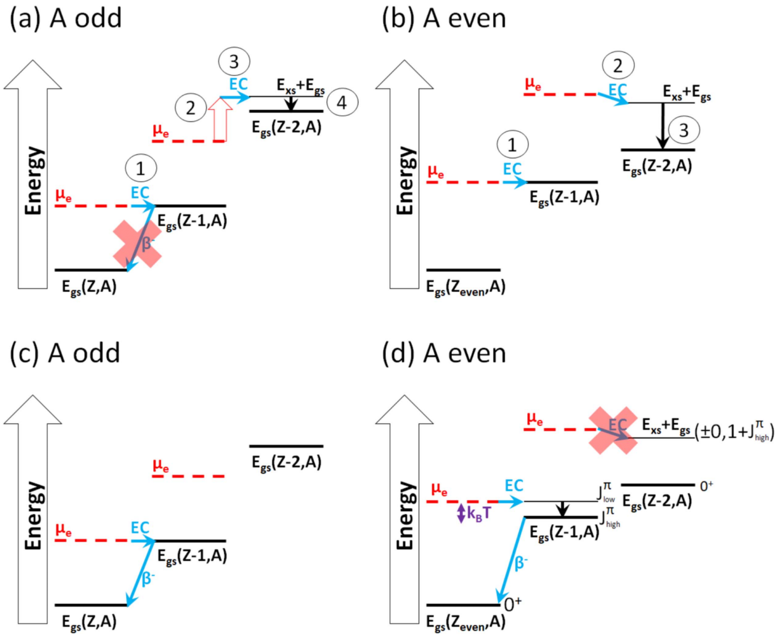


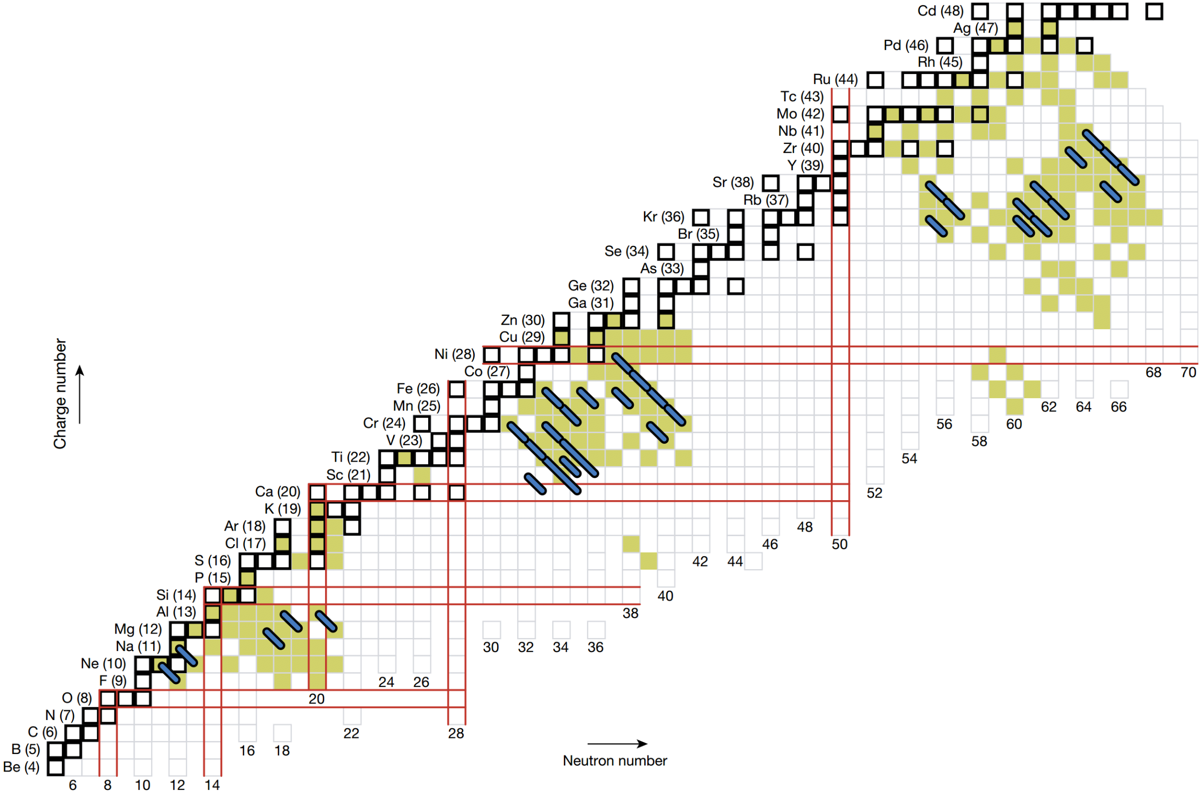
Meisel et al: JPG (2018)

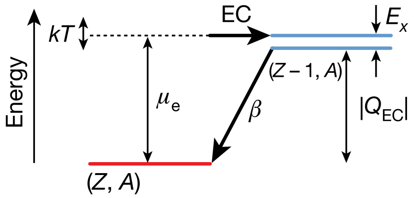
Neutrino luminosity: Previous expression

$$L_\nu(Z,A,T) \approx L_{34}(Z,A,T)\times 10^{34}\,\mathrm{erg\ s^{-1}}\,X(A)\,T_9^5\left(\frac{g_{14}}{2}\right)^{-1}R_{10}^2,$$

$$L_{34}(Z,A) = 0.87\left(\frac{10^6\ \mathrm{s}}{ft}\right)\left(\frac{56}{A}\right)\left(\frac{|Q_{\mathrm{EC}}|}{4\ \mathrm{MeV}}\right)^5\left(\frac{\langle F\rangle^*}{0.5}\right).$$

Deibel, Meisel, Schatz, Brown & Cumming: ApJ (2016)

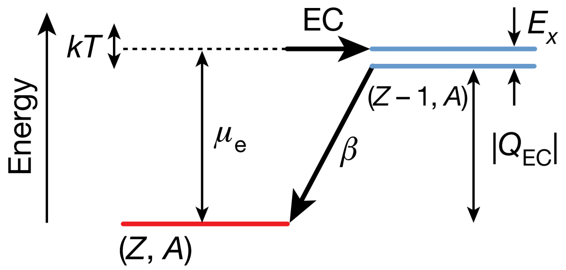


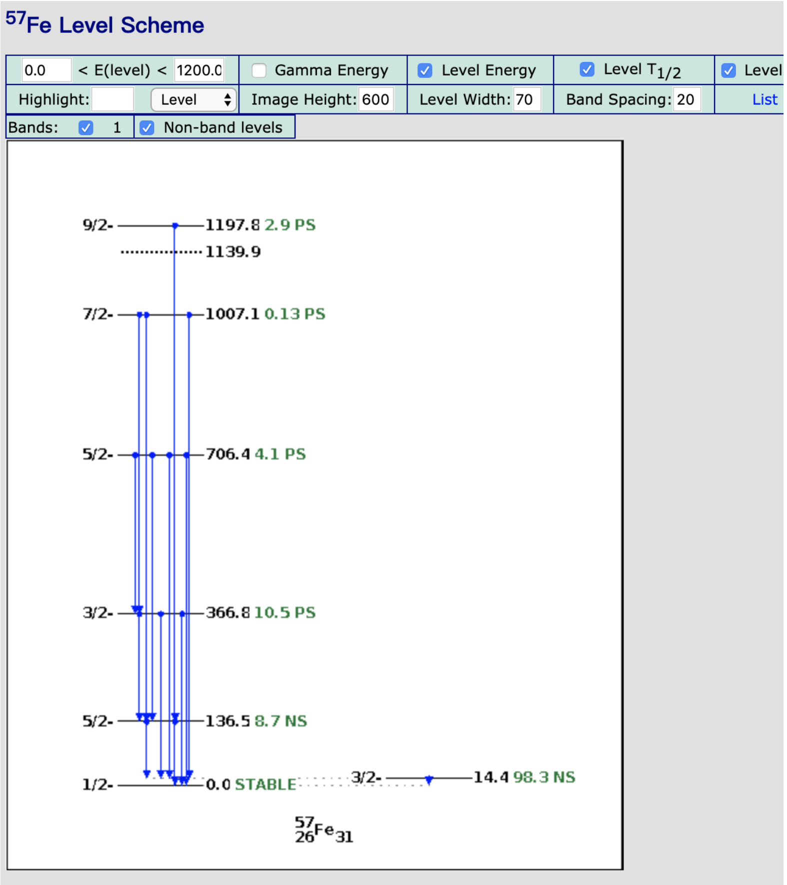


Schatz et al: Nature (2014)

Meisel et al: ApJ (2017)

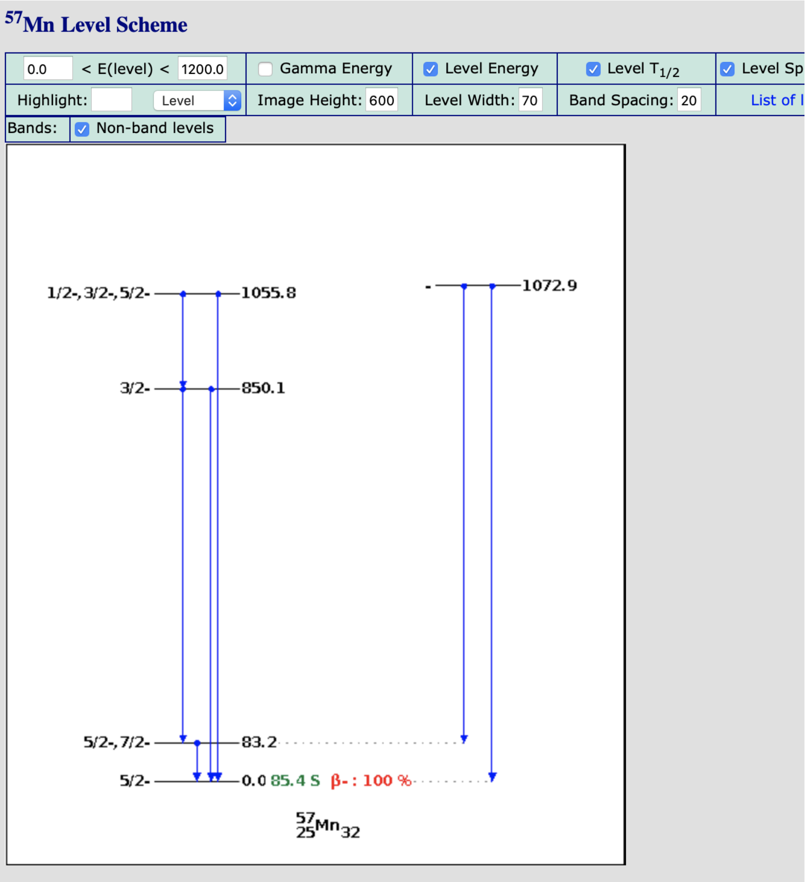
Nuclear excitations: odd-A





^{57}Fe Level Scheme

0.0 < E(level) < 1200.0
☐ Gamma Energy
☑ Level Energy
☑ Level $T_{1/2}$
☑ Level
Highlight: Level
Image Height: 600
Level Width: 70
Band Spacing: 20
List
Bands: ☑ 1
☑ Non-band levels



^{57}Mn Level Scheme

0.0 < E(level) < 1200.0
☐ Gamma Energy
☑ Level Energy
☑ Level $T_{1/2}$
☑ Level Sp
Highlight: Level
Image Height: 600
Level Width: 70
Band Spacing: 20
List of l
Bands: ☑ Non-band levels

Neutrino luminosity: modified expression

$$L_\nu(Z,A,T) \approx L_{34}(Z,A,T) \times 10^{34}\mathrm{erg\ s}^{-1} X(A)\ T_9^5 \left(\frac{g_{14}}{2}\right)^{-1} R_{10}^2 \tag{1}$$

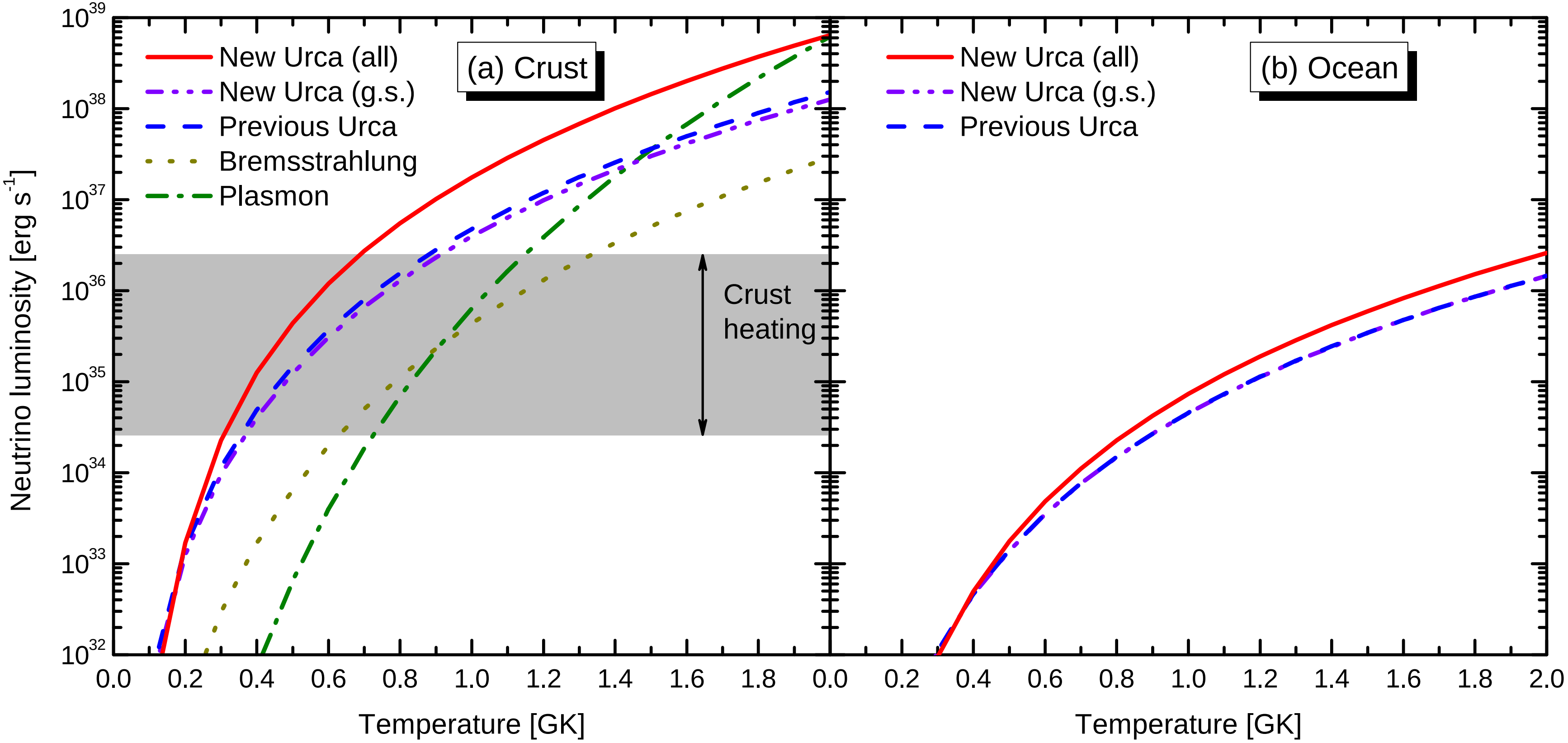
Previous:
$$L_{34}(Z,A) = 0.87 \left(\frac{10^6\ \mathrm{s}}{ft}\right)\left(\frac{56}{A}\right)\left(\frac{|Q_{\mathrm{EC}}|}{4\ \mathrm{MeV}}\right)^5 \left(\frac{\langle F\rangle^*}{0.5}\right) \tag{2}$$

Ours:
$$L_{34}(Z,A,T) = \sum_{if} 0.87 \left(\frac{10^6\ \mathrm{s}}{\langle ft\rangle_{if}}\right)\left(\frac{56}{A}\right)\left[\frac{|Q_{(if)}(Z,A)|}{4\ \mathrm{MeV}}\right]^5 \left(\frac{\langle F\rangle^*}{0.5}\right) \tag{3}$$

$$\begin{aligned}
\langle ft\rangle_{if} &\equiv \frac{\langle F\rangle^+ \widetilde{ft}_{if}^- + \langle F\rangle^- \widetilde{ft}_{if}^+}{\langle F\rangle^+ + \langle F\rangle^-} \\
\langle F\rangle^* &\equiv \frac{\langle F\rangle^+ \langle F\rangle^-}{\langle F\rangle^+ + \langle F\rangle^-} \\
\langle F\rangle^\pm &\approx \frac{2\pi\alpha Z}{\left|1 - e^{(\mp 2\pi\alpha Z)}\right|} \\
\widetilde{ft}_{if}^+ &\equiv \frac{G^+(Z,A,T)}{(2J_i+1)e^{-E_i/(kT)}} ft_{if}^+ \\
\widetilde{ft}_{if}^- &\equiv \frac{G^-(Z,A,T)}{(2J_f+1)e^{-E_f/(kT)}} ft_{if}^- \\
Q_{(if)}(Z,A) &= M_p c^2 - M_d c^2 + E_i - E_f
\end{aligned}$$

L.-J. Wang, L. Tan, Z. Li, G. W. Misch and Y. Sun*: Phys. Rev. Lett. (2021)*

Effects of nuclear excitations



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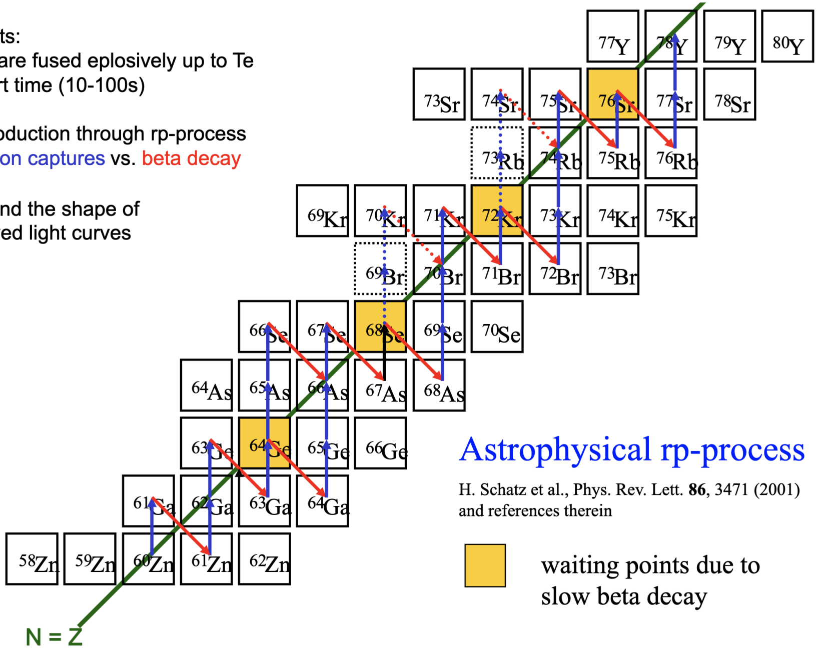

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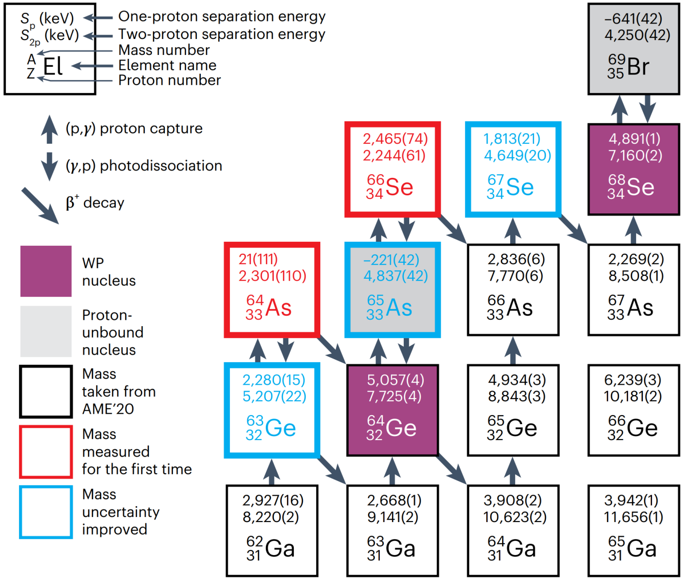


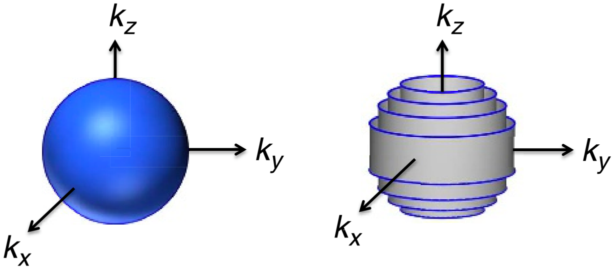
X. Zhou et al., Nat. Phys. (2023)

Stellar weak rates

$$\beta^- : {}^A_Z\mathrm{X} \to {}^{\;\;A}_{Z+1}\mathrm{Y} + e^- + \bar{\nu}_e, \qquad \mathrm{EC} : {}^A_Z\mathrm{X} + e^- \to {}^{\;\;A}_{Z-1}\mathrm{Y} + \nu_e,$$
$$\beta^+ : {}^A_Z\mathrm{X} \to {}^{\;\;A}_{Z-1}\mathrm{Y} + e^+ + \nu_e, \qquad \mathrm{PC} : {}^A_Z\mathrm{X} + e^+ \to {}^{\;\;A}_{Z+1}\mathrm{Y} + \bar{\nu}_e,$$

- Without magnetic field:

$$\lambda^\alpha = \sum_{if} \frac{(2J_i+1)e^{-E_i/k_BT}}{G(Z,A,T)} \lambda^\alpha_{if}$$



$$\lambda^{\beta^-}_{if} = \frac{\ln 2}{K}\int_1^{Q_{if}} \boldsymbol{C(W)} F_0(Z+1,W)pW(Q_{if}-W)^2[1-S_e(W)]dW, \qquad (4)$$

$$\lambda^{\mathrm{EC}}_{if} = \frac{\ln 2}{K}\int_{\omega_l}^{\infty} \boldsymbol{C(W)} F_0(Z,W)pW(Q_{if}+W)^2 S_e(W)dW, \qquad (5)$$

$$\lambda^{\beta^+}_{if} = \frac{\ln 2}{K}\int_1^{Q_{if}} \boldsymbol{C(W)} F_0(-Z+1,W)pW(Q_{if}-W)^2[1-S_p(W)]dW, \qquad (6)$$

$$\lambda^{\mathrm{PC}}_{if} = \frac{\ln 2}{K}\int_{\omega_l}^{\infty} \boldsymbol{C(W)} F_0(-Z,W)pW(Q_{if}+W)^2 S_p(W)dW, \qquad (7)$$

$$\rho Y_e = \frac{1}{\pi^2 N_A}\left(\frac{m_e c}{\hbar}\right)^3 \int_0^\infty (S_e - S_p)p^2 dp, \qquad (8)$$

Stellar weak rates

$$\beta^- : {}^A_Z\mathrm{X} \to {}^{\;\;A}_{Z+1}\mathrm{Y} + e^- + \bar{\nu}_e, \qquad \mathrm{EC} : {}^A_Z\mathrm{X} + e^- \to {}^{\;\;A}_{Z-1}\mathrm{Y} + \nu_e,$$

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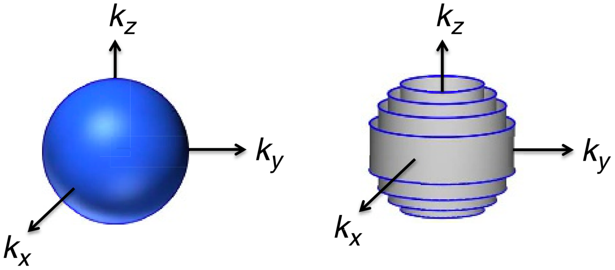
- With strong magnetic field:



$$\lambda^\alpha = \sum_{if} \frac{(2J_i+1)e^{-E_i/k_BT}}{G(Z,A,T)} \lambda^\alpha_{if}$$

$$\lambda^{\beta^-}_{if} = \frac{\ln 2}{K}\frac{B^*}{2}\sum_{n=0}^{N_{\max}}(2-\delta_{n0})\int_0^{\sqrt{Q_{if}^2-1-2nB^*}} \boldsymbol{C(W)} F_0(Z+1,W)(Q_{if}-W)^2[1-S_e(W)]dp_z, \tag{9}$$

$$\lambda^{\mathrm{EC}}_{if} = \frac{\ln 2}{K}\frac{B^*}{2}\sum_{n=0}^{N_{\max}}(2-\delta_{n0})\int_{p_{znl}}^{\infty} \boldsymbol{C(W)} F_0(Z,W)(Q_{if}+W)^2 S_e(W)dp_z, \tag{10}$$

$$\lambda^{\beta^+}_{if} = \frac{\ln 2}{K}\frac{B^*}{2}\sum_{n=0}^{N_{\max}}(2-\delta_{n0})\int_0^{\sqrt{Q_{if}^2-1-2nB^*}} \boldsymbol{C(W)} F_0(-Z+1,W)(Q_{if}-W)^2[1-S_p(W)]dp_z, \tag{11}$$

$$\lambda^{\mathrm{PC}}_{if} = \frac{\ln 2}{K}\frac{B^*}{2}\sum_{n=0}^{N_{\max}}(2-\delta_{n0})\int_{p_{znl}}^{\infty} \boldsymbol{C(W)} F_0(-Z,W)(Q_{if}+W)^2 S_p(W)dp_z, \tag{12}$$

$$\rho Y_e = \frac{B^*}{2\pi^2\lambda_e^3}\sum_{n=0}^{\infty}(2-\delta_{n0})\int_0^{\infty}(S_e-S_p)dp_z, \tag{13}$$

Allowed transition

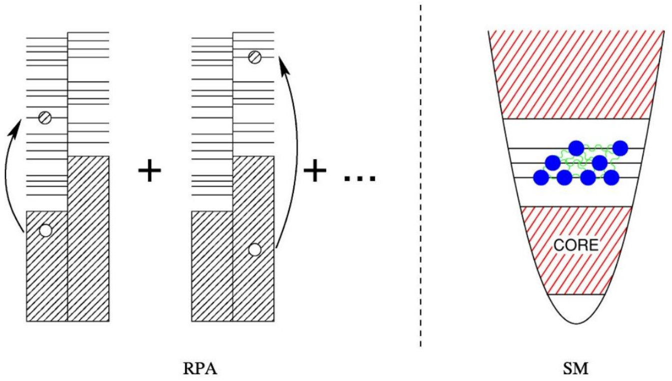
- Reduced nuclear transition M.E.

$$C(W) = B_{if}(\mathrm{GT}^{+}) = \left(\frac{g_A}{g_V}\right)^2_{\text{eff}} \frac{\left\langle \Psi^{n_f}_{J_f} \middle\| \sum_k \hat{\sigma}^k \hat{\tau}^k_+ \middle\| \Psi^{n_i}_{J_i} \right\rangle^2}{2J_i + 1} \tag{14}$$

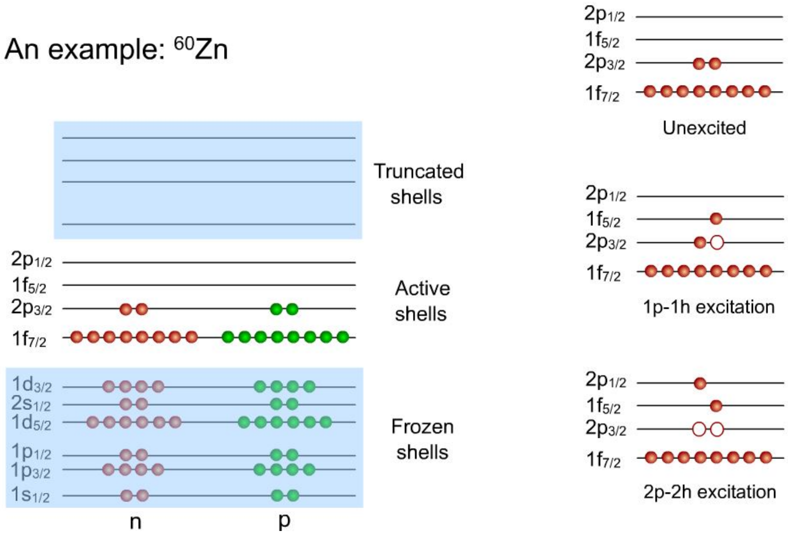
- Transition operator:

$$\left(\frac{g_A}{g_V}\right)_{\text{eff}} = f_{\text{quench}} \left(\frac{g_A}{g_V}\right)_{\text{bare}} \tag{15}$$

- Nuclear wave functions:



Langanke & Martínez-Pinedo: RMP (2003)



https://www.physics.sjtu.edu.cn/ ysun/

Stellar rates: PSM

- Description in intrinsic system

$$\Big\{\hat{a}^\dagger_{\nu_i}|\Phi\rangle(\varepsilon),\ \hat{a}^\dagger_{\nu_i}\hat{a}^\dagger_{\nu_j}\hat{a}^\dagger_{\nu_k}|\Phi(\varepsilon)\rangle,\ \hat{a}^\dagger_{\nu_i}\hat{a}^\dagger_{\pi_j}\hat{a}^\dagger_{\pi_k}|\Phi\rangle(\varepsilon),$$
$$\hat{a}^\dagger_{\nu_i}\hat{a}^\dagger_{\nu_j}\hat{a}^\dagger_{\nu_k}\hat{a}^\dagger_{\pi_l}\hat{a}^\dagger_{\pi_m}|\Phi(\varepsilon)\rangle,\ \hat{a}^\dagger_{\nu_i}\hat{a}^\dagger_{\nu_j}\hat{a}^\dagger_{\nu_k}\hat{a}^\dagger_{\nu_l}\hat{a}^\dagger_{\nu_m}\hat{a}^\dagger_{\pi_n}\hat{a}^\dagger_{\pi_o}|\Phi(\varepsilon)\rangle,$$
$$\hat{a}^\dagger_{\nu_i}\hat{a}^\dagger_{\nu_j}\hat{a}^\dagger_{\nu_k}\hat{a}^\dagger_{\pi_l}\hat{a}^\dagger_{\pi_m}\hat{a}^\dagger_{\pi_n}\hat{a}^\dagger_{\pi_o}|\Phi(\varepsilon)\rangle.\Big\} \tag{16}$$

$$\Big\{\hat{a}^\dagger_{\pi_i}|\Phi\rangle(\varepsilon),\ \hat{a}^\dagger_{\pi_i}\hat{a}^\dagger_{\pi_j}\hat{a}^\dagger_{\pi_k}|\Phi(\varepsilon)\rangle,\ \hat{a}^\dagger_{\pi_i}\hat{a}^\dagger_{\nu_j}\hat{a}^\dagger_{\nu_k}|\Phi(\varepsilon)\rangle,$$
$$\hat{a}^\dagger_{\pi_i}\hat{a}^\dagger_{\pi_j}\hat{a}^\dagger_{\pi_k}\hat{a}^\dagger_{\nu_l}\hat{a}^\dagger_{\nu_m}|\Phi(\varepsilon)\rangle,\ \hat{a}^\dagger_{\pi_i}\hat{a}^\dagger_{\pi_j}\hat{a}^\dagger_{\pi_k}\hat{a}^\dagger_{\pi_l}\hat{a}^\dagger_{\pi_m}\hat{a}^\dagger_{\nu_n}\hat{a}^\dagger_{\nu_o}|\Phi(\varepsilon)\rangle,$$
$$\hat{a}^\dagger_{\pi_i}\hat{a}^\dagger_{\pi_j}\hat{a}^\dagger_{\pi_k}\hat{a}^\dagger_{\nu_l}\hat{a}^\dagger_{\nu_m}\hat{a}^\dagger_{\nu_n}\hat{a}^\dagger_{\nu_o}|\Phi(\varepsilon)\rangle.\Big\} \tag{17}$$

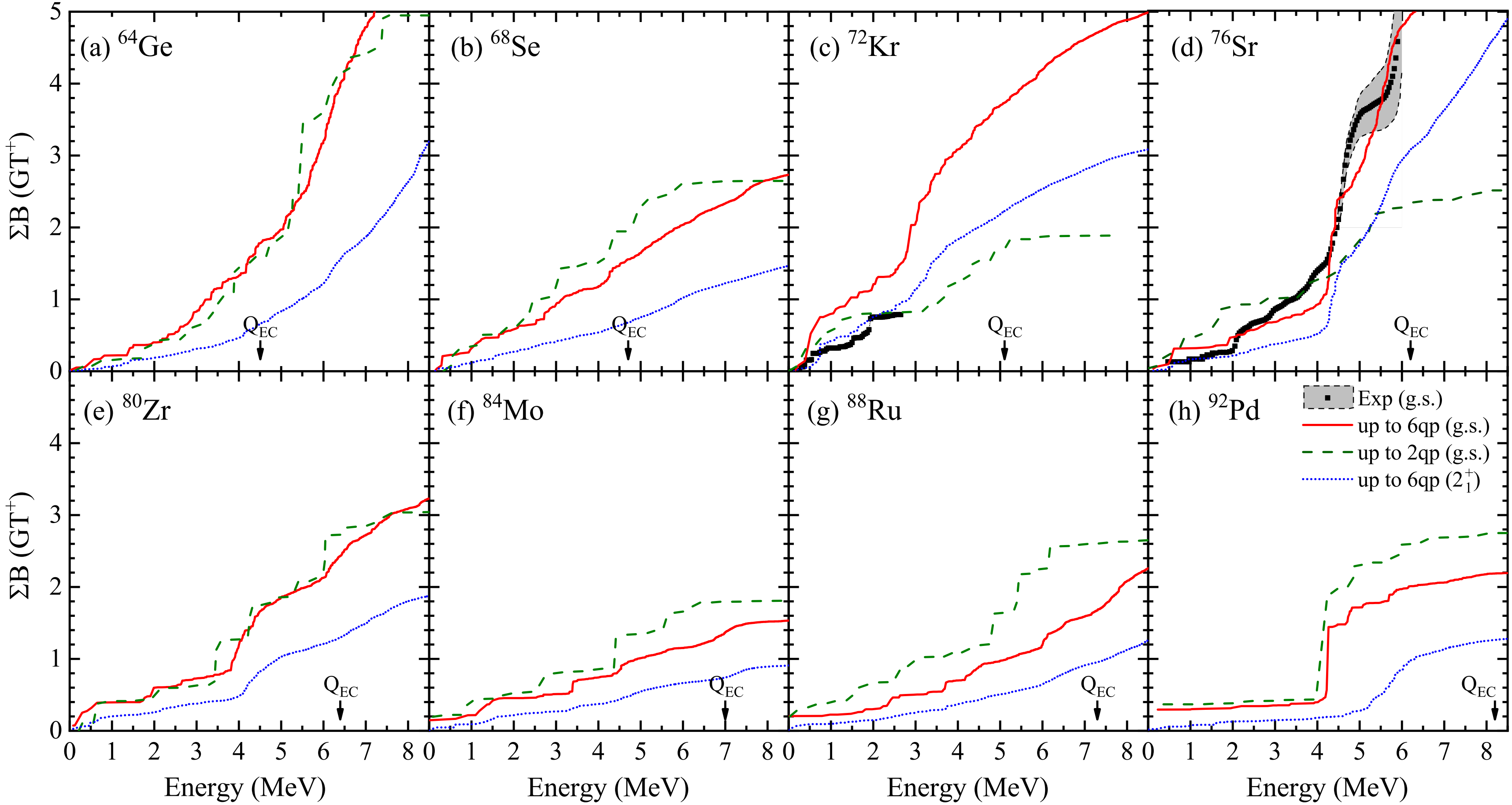
- Transform to laboratory frame

$$|\Psi^n_{JM}\rangle = \sum_{K\kappa} F^n_{JK\kappa}\hat{P}^J_{MK}|\Phi_\kappa\rangle, \tag{18}$$

$$\hat{P}^J_{MK} = \frac{2J+1}{8\pi^2}\int d\Omega D^J_{MK}(\Omega)\hat{R}(\Omega), \tag{19}$$

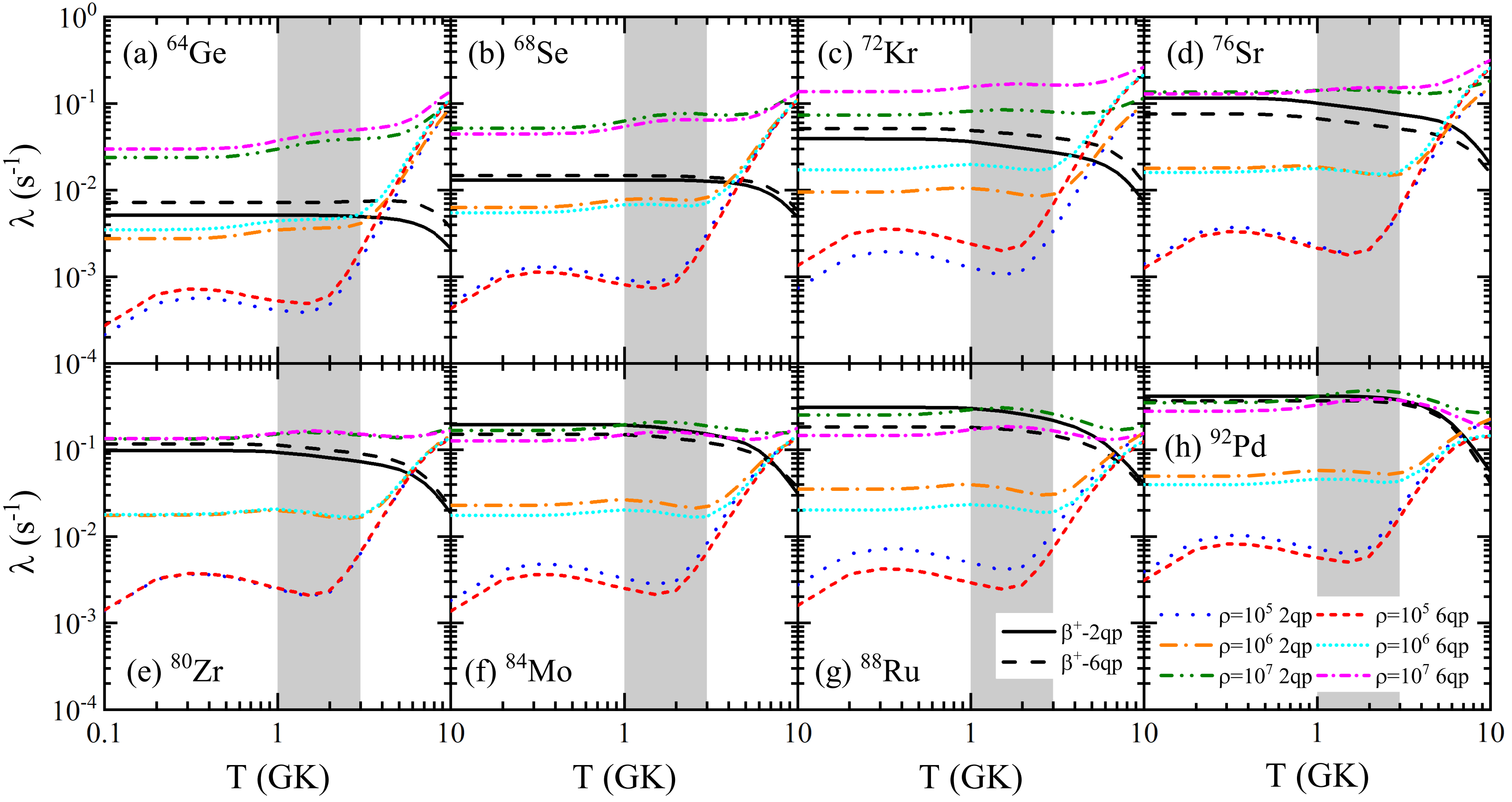
L.-J. Wang, Y. Sun & S.K. Ghorui: PRC (2018)*; *L. Tan, Y.X. Liu, L.-J. Wang* et al.,: PLB (2020)*

Waiting points: BGT



Z.-R. Chen and L.-J. Wang, Phys. Lett. B 848, 138338 (2024)*

Waiting points: stellar rates



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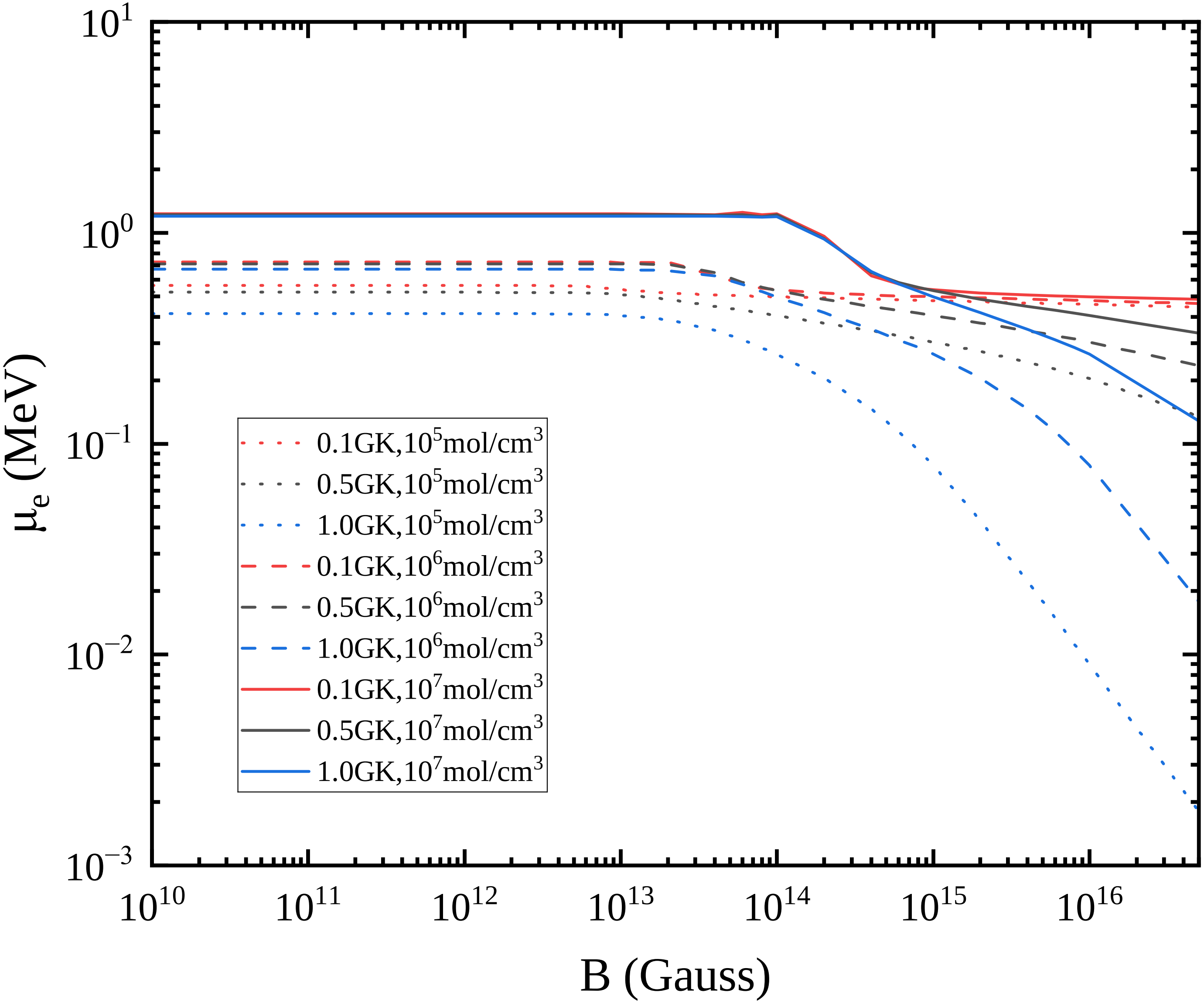
With strong magnetic field: Preliminary



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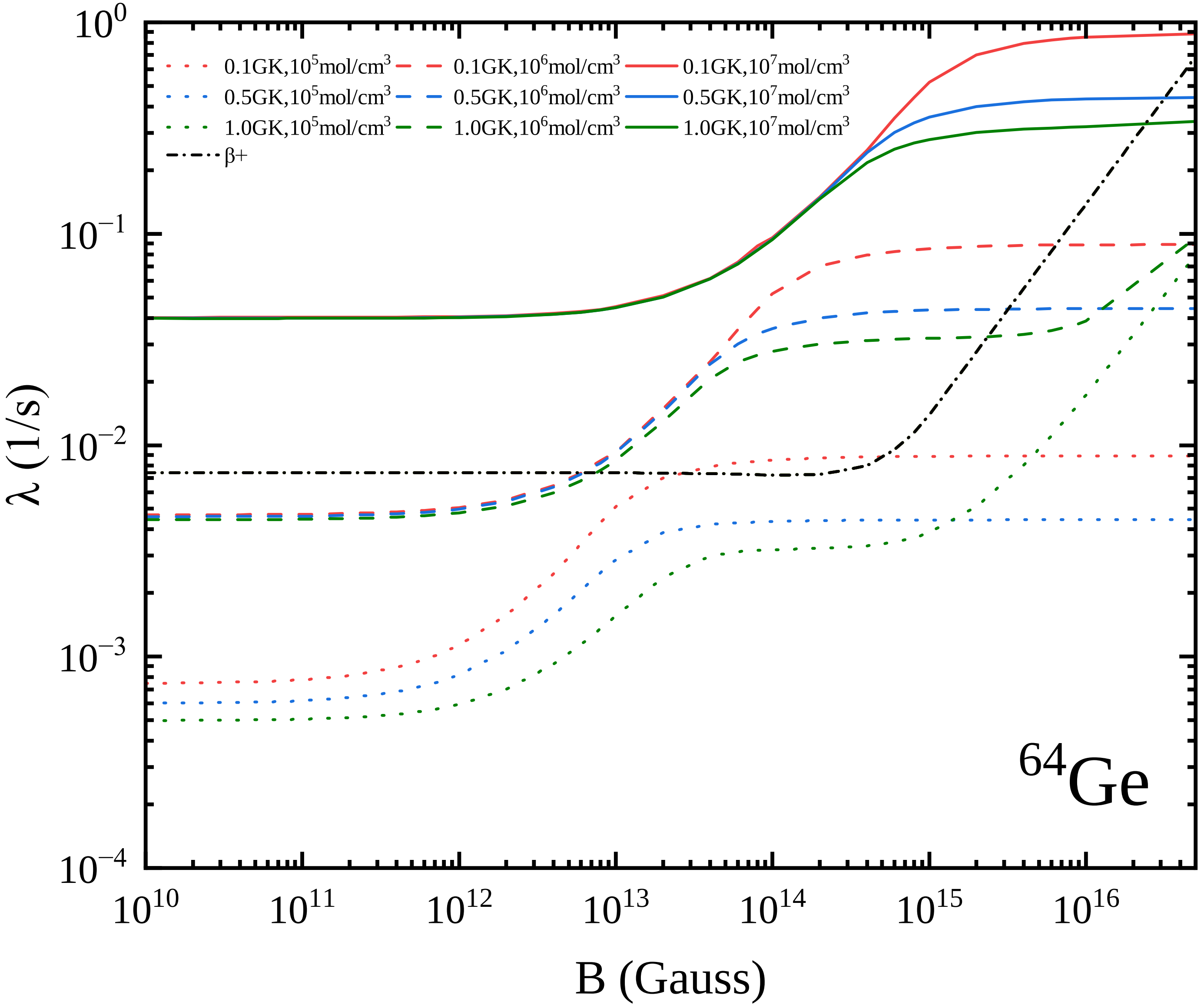

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Summary

- Effect of excited nuclear states for Urca neutrino cooling in accreting neutron star.
- Stellar weak-interaction rates for rp-process waiting-point nuclei by projected shell model.

Outlook

- Calculate β (neutrino) spectrum for experimentalists,
- First-forbidden transition of β decay for astrophysics,
- New updated data tables of stellar weak-process rates for s-, rp-, r-processes ...
- Two-body currents for β and $0\nu\beta\beta$ decay with qp excitation,
- $\dots\ \dots$

Acknowledgement

Recent Collaborators:

Yang Sun	SJTU
G. Wendell Misch	Los Alamos National Lab
Zhipan Li	SWU
Liang Tan	SWU & SJTU
Zi-Rui Chen	SWU & NKU
Bin-Lei Wang	SWU & BNU
Fan Gao	SWU & XJTU
Yang Xiao	SWU

Thank you for your attention!