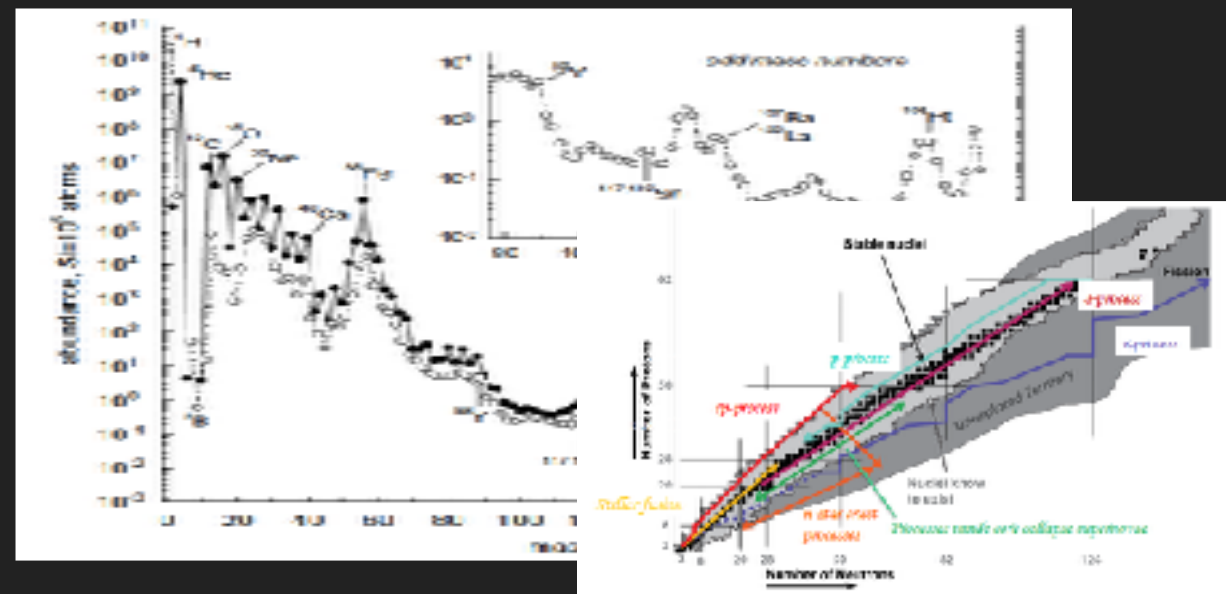
NUCLEAR INPUTS FOR R-PROCESS NUCLEOSYNTHESIS FROM DFT

DONG-LIANG FANG (IMP, CAS)

IN COLLABORATION WITH CHUN-LIN BAI(SCU), JIAN LI(JLU)

- Input for r-process
- Results for beta decay
- Results for neutron capture
- Conclusions and perspective

R-PROCESS



- Origin of elements in solar system

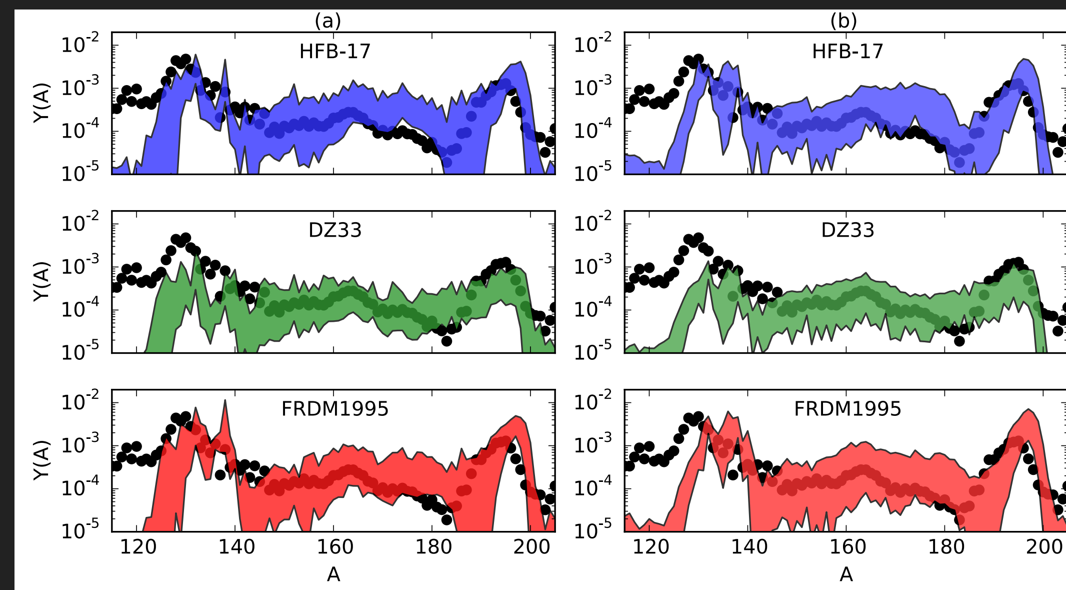
R-PROCESS

- The possible sites of r-process
  - Neutrino driven wind in supernova
  - Magneto-hydrodynamic jets from supernova and collapsars
  - Ejecta from binary neutron star merger
  - …

SENSITIVITY

Mumpower 15'

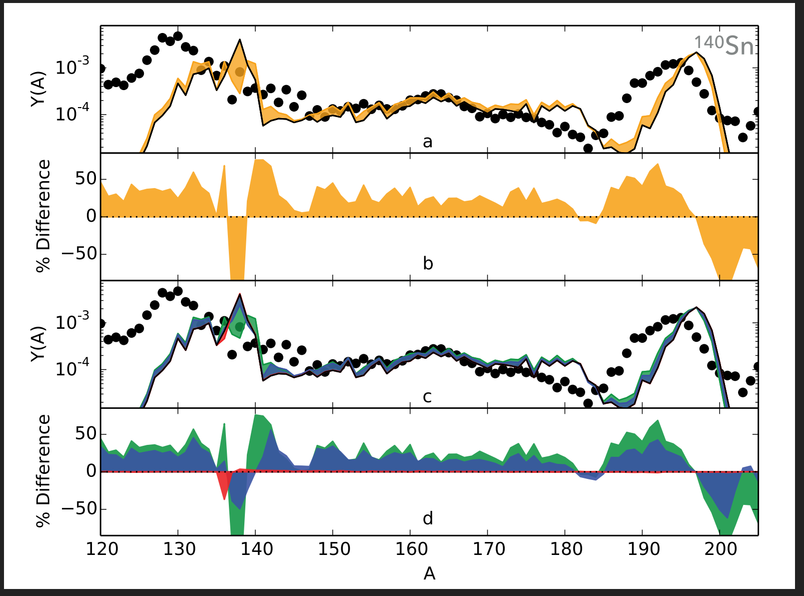
- Individual properties on nucleosynthesis



SENSITIVITY

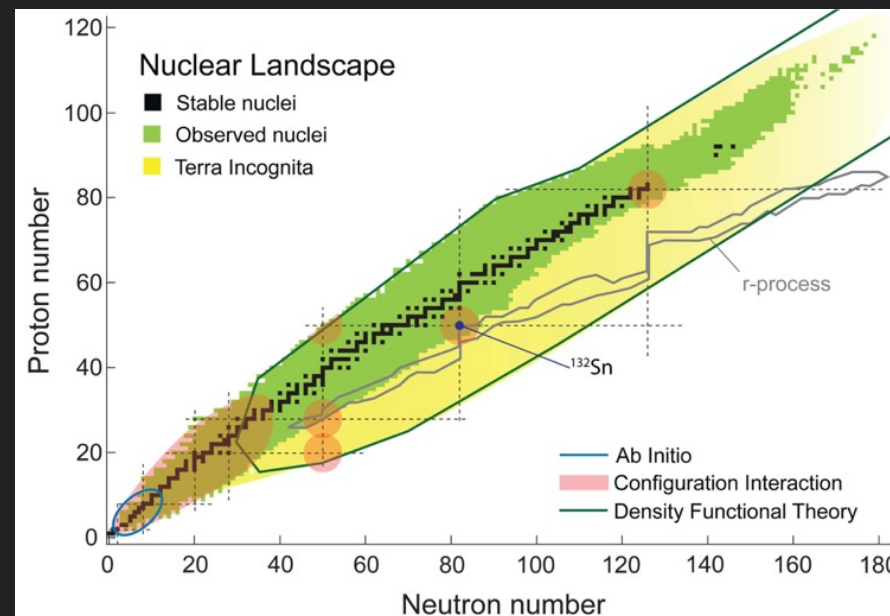
Mumpower 15'

- Effects of single nucleus properties



NUCLEAR INPUTS

- R-process nucleosynthesis happens far away from stability valley

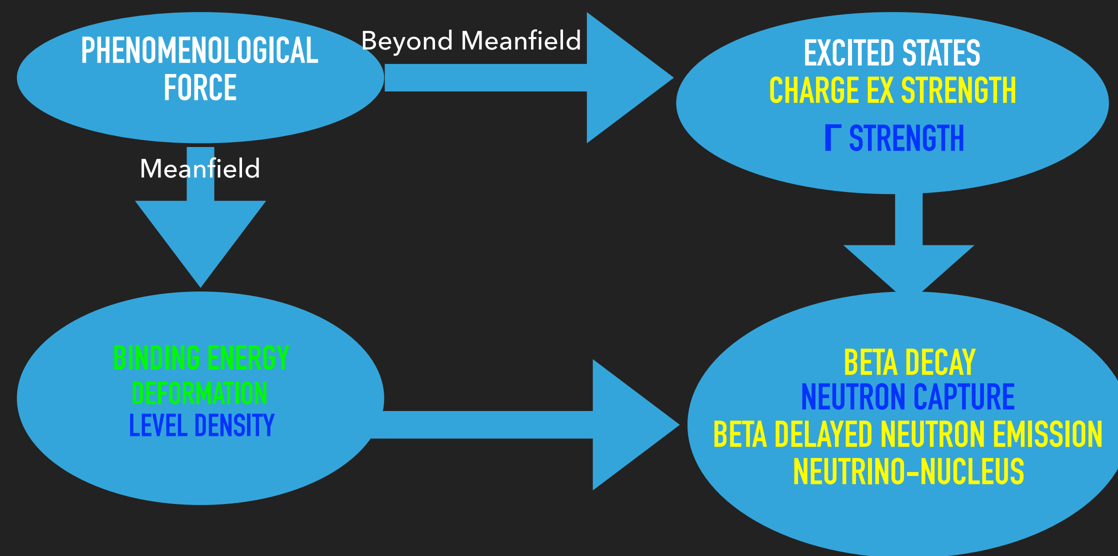


NUCLEAR DFT

- Widely used DFT versions:
- Skyrme DFT
  - Zero-range force
- Gogny
  - Finite range force
- Covariant DFT
  - Mediated by mesons

ROADMAP

- Starting from DFT theory, almost all the nuclear properties for finite nuclei can be obtained



QRPA CALCULATIONS BASED ON DFT

- Beta decay calculations based on DFT
  - Nuclear interactions
    - Isoscalar pairing Engel 99′, Nisik 05′
    - Tensor force Bai 09′, Bai 13′
  - Many-body correlations beyond 1 phonon excitation
    - PVC Niu 24′

TENSOR FORCE

- Tensor force with Triplet-Even and Triplet-Odd components

$$V^T = \frac{T}{2}\left\{[(\sigma_1 \cdot \boldsymbol{k}')(\sigma_2 \cdot \boldsymbol{k}') - \frac{1}{3}(\sigma_1 \cdot \sigma_2)\boldsymbol{k}'^2]\sigma(\boldsymbol{r}) + \delta(\boldsymbol{r})[(\sigma_1 \cdot \boldsymbol{k})(\sigma_2 \cdot \boldsymbol{k}) - \frac{1}{3}(\sigma_1 \cdot \sigma_2)\boldsymbol{k}^2]\right\}$$

$$+ \frac{U}{2}\left\{(\sigma_1 \cdot \boldsymbol{k}')\delta(\boldsymbol{r})(\sigma_2 \cdot \boldsymbol{k}) + (\sigma_2 \cdot \boldsymbol{k}')\delta(\boldsymbol{r})(\sigma_1 \cdot \boldsymbol{k}) - \frac{2}{3}[(\sigma_1 \cdot \sigma_2)\boldsymbol{k}' \cdot \delta(\boldsymbol{r})\boldsymbol{k}]\right\}.$$

- Iso-scalar pairing force

$$V_{\rm IV}(\boldsymbol{r}_1, \boldsymbol{r}_2) = V_0 \frac{1 - P_\sigma}{2}\left(1 - \frac{\rho(\boldsymbol{r})}{\rho_o}\right)\delta(\boldsymbol{r}_1 - \boldsymbol{r}_2),$$

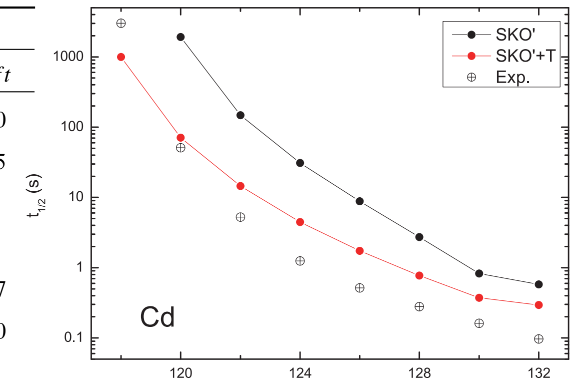
$$V_{\rm IS}(\boldsymbol{r}_1, \boldsymbol{r}_2) = f V_0 \frac{1 + P_\sigma}{2}\left(1 - \frac{\rho(\boldsymbol{r})}{\rho_o}\right)\delta(\boldsymbol{r}_1, \boldsymbol{r}_2),$$

DETAILED COMPARISON

Bai 24'

- In QRPA calculations, two parameters - isoscalar pairing and gA quenching are adjustable

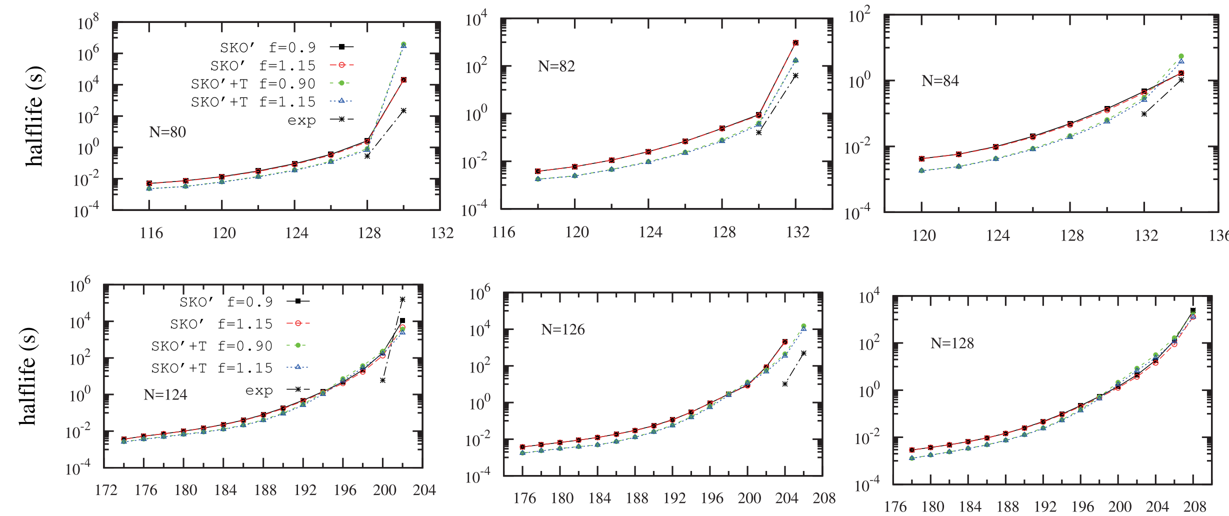
	SKO′		SKO′+T		Exp. [51]	
	Q_i	log ft	Q_i	log ft	Q_i	log ft
^{120}Cd	1.211	4.17	2.171	4.03	2.281	4.10
^{122}Cd	1.922	4.21	2.973	4.05	3.431	3.95
^{124}Cd	2.579	4.25	3.761	4.06		
^{126}Cd	3.191	4.29	4.538	4.08		
^{128}Cd	3.769	4.33	5.312	4.09	6.241	4.17
^{130}Cd	4.328	4.39	6.083	4.11	6.741	4.10
^{132}Cd	4.700	4.49	6.401	4.12		



- Simultaneous agreement of transition strength and excitation energies

RESULTS

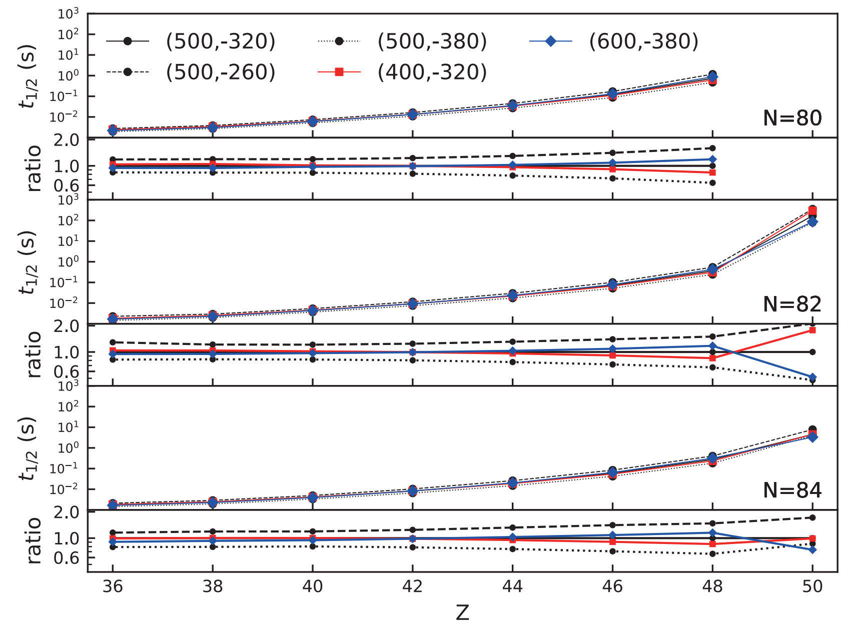
Bai 24′



- Predicted beta decay rates N~82 and N~126

RESULTS

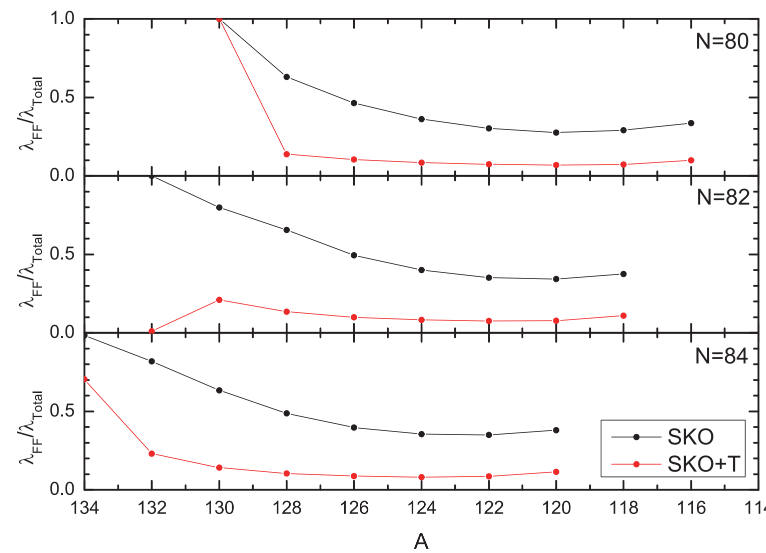
Bai 24'



- Uncertainties from tensor force

RESULTS

Bai 24′



- Impact of tensor force on different decay types

LEVEL DENSITY

Hilaire 01′

- Unlike weak rates, neutron capture calculations are rougher, less structure issues
- The density can be obtained from single particle levels

$$\mathcal{Z}(x_1, x_2, x_3, x_4) = \prod_{k=1}^{4} \prod_{i=1}^{I_k} (1 + x_k p_i^k y^{\varepsilon_i^k} t^{m_i^k}) = \sum_{\mathcal{N}} \mathcal{F}_{\mathcal{N}}(y, t) \prod_{k=1}^{4} x_k^{N_k}$$

$$\mathcal{F}_{\mathcal{N}}(y, t) = \sum_{U} \sum_{M} \sum_{P=-1,+1} C_{\mathcal{N}}(U, M, P) y^U t^M$$

- The level density can hence be obtained

$$\rho_i(U, M, P) = \frac{1}{\varepsilon_0} C_{\mathcal{N}}(U, M, P)$$

LEVEL DENSITY

Hilaire 01'

- General expression

$$\rho(U,M,P) = [1 - f_{\text{dam}}(U)]K_{\text{vib}}\rho_{\text{sph}}(U,M,P) + f_{\text{dam}}(U)K_{\text{vib}}\rho_{\text{def}}(U,M,P)$$

- Spherical density

$$\rho_{\text{sph}}(U,M,P) = \rho_i(U,M=J,P) - \rho_i(U,M=J+1,P)$$

- Deformed density

$$\rho_{\text{def}}(U,M,P) = \frac{1}{2}\left[\sum_{K=-J,K\neq 0}^{J} \rho_i(U - E_{\text{rot}}^{J,K}, K, P)\right] \quad E_{\text{rot}}^{J,K} = \frac{J(J+1) - K^2}{2\mathcal{J}_\perp}$$

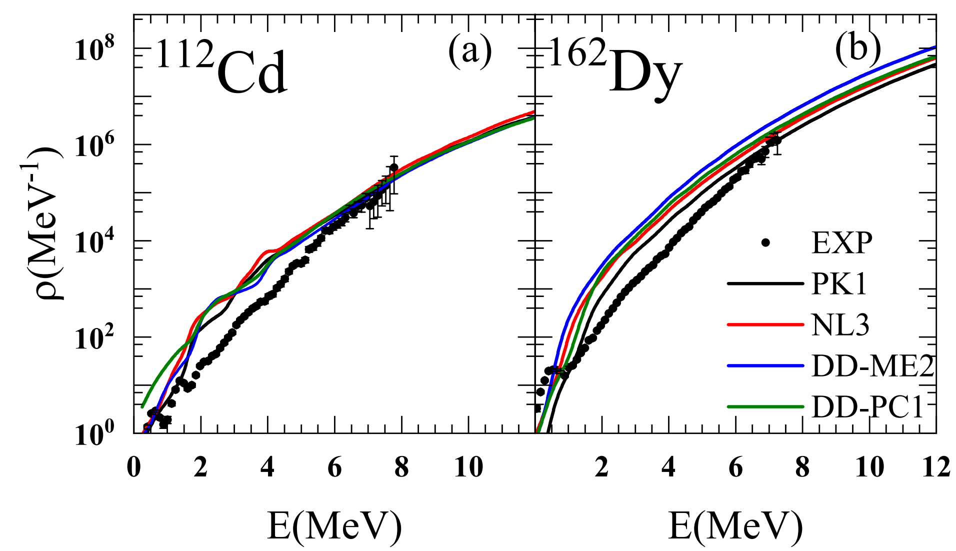
$$+ (\delta_{(J\text{even})}\delta_{(p=+)}\rho_i(U - E_{\text{rot}}^{J,K}, 0, P) + \delta_{(J\text{odd})}\delta_{(p=-)}\rho_i(U - E_{\text{rot}}^{J,K}, 0, P$$

- Vibration enhancement and the damping function

$$K_{\text{vib}} = \exp[\delta S - (\delta U/T)] \quad f_{\text{dam}} = 1 - \frac{1}{1 + \exp(\beta - 0.18)/0.038}$$

LEVEL DENSITY

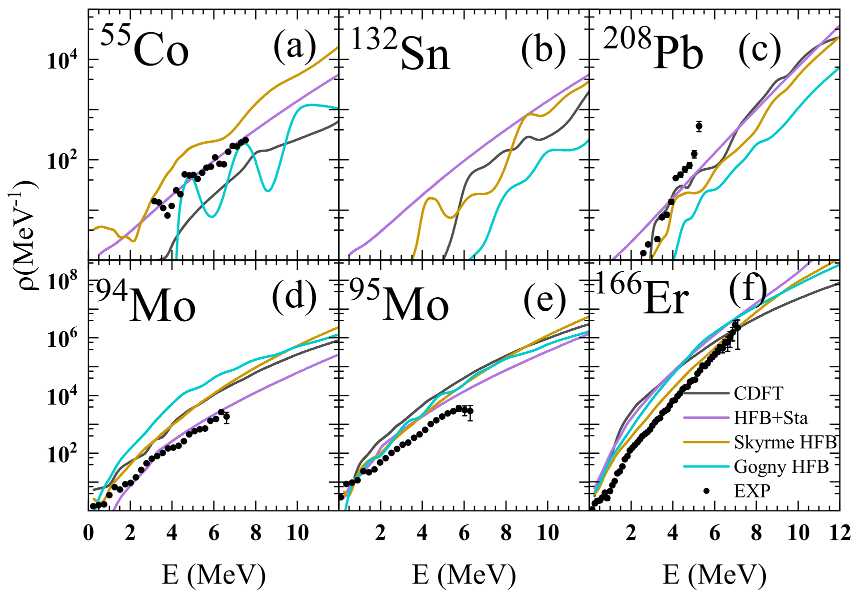
Geng 23'



- Effect of nuclear Hamiltonians on NLD

LEVEL DENSITY

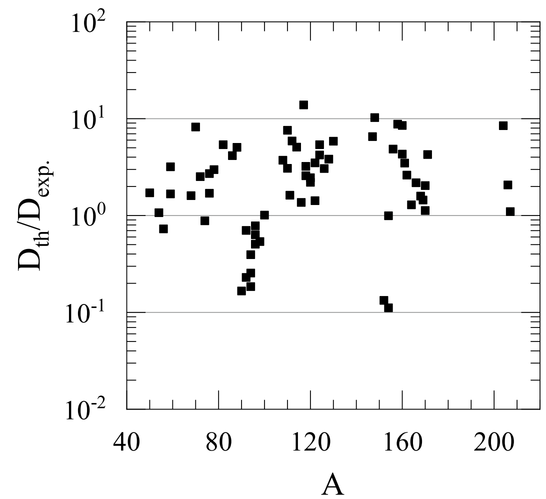
Geng 23'



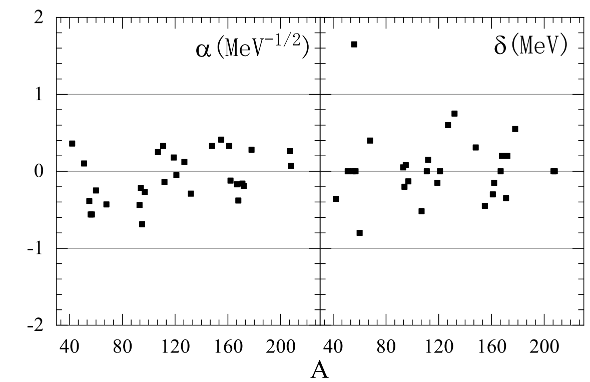
- Comparison with other calculations

LEVEL DENSITY

Geng 23'



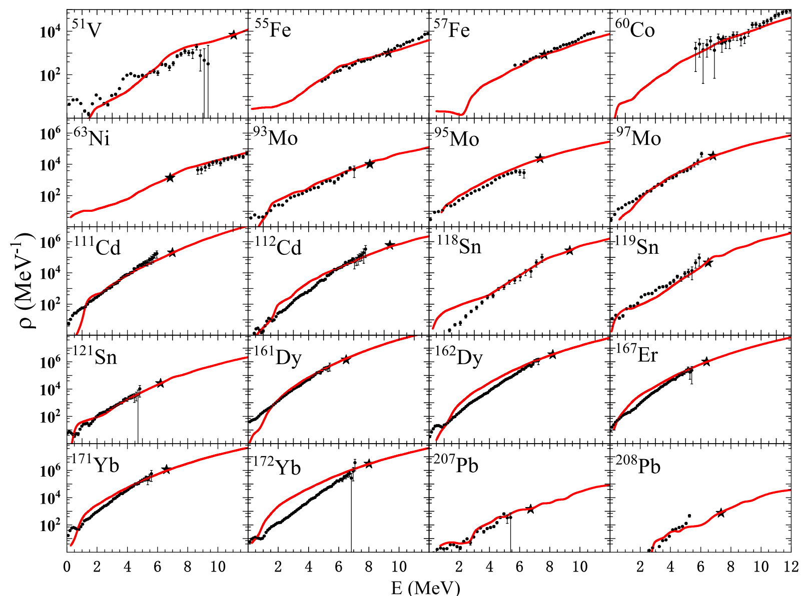
$$\rho(U,J,P) = e^{\alpha\sqrt{U-\delta}} \times \rho(U-\delta,J,P)$$



- the rms of s-wave resonance spacing and renormalizations

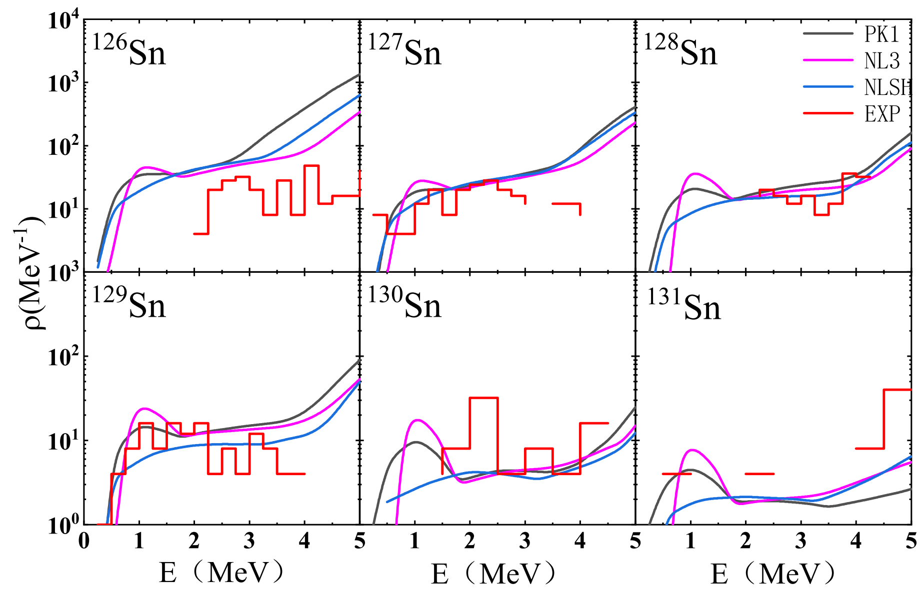
LEVEL DENSITY

Geng 23'



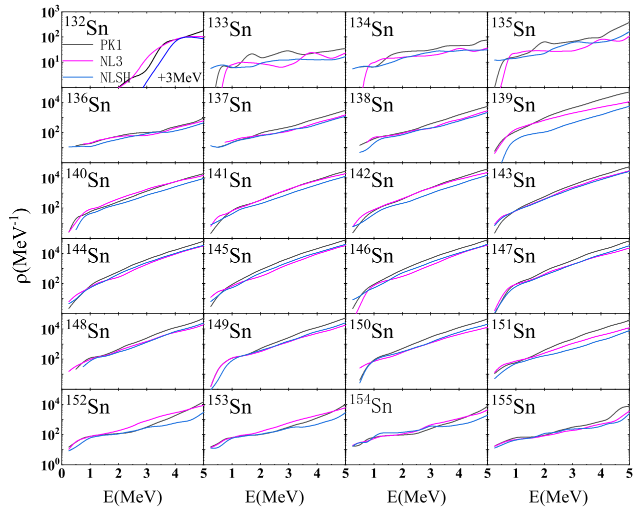
- Normalized NLDs

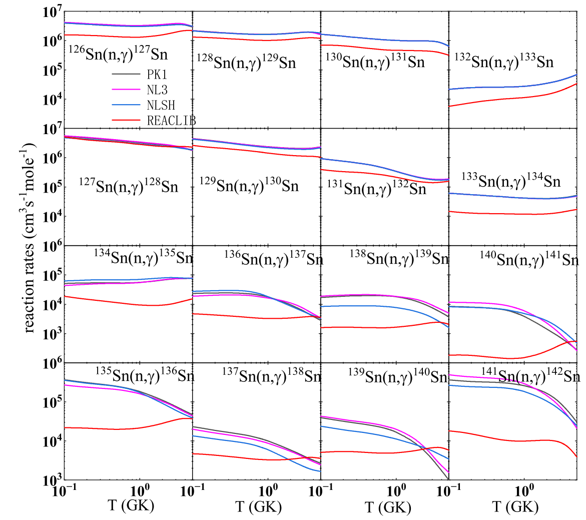
LEVEL DENSITY



- For tin isotopes

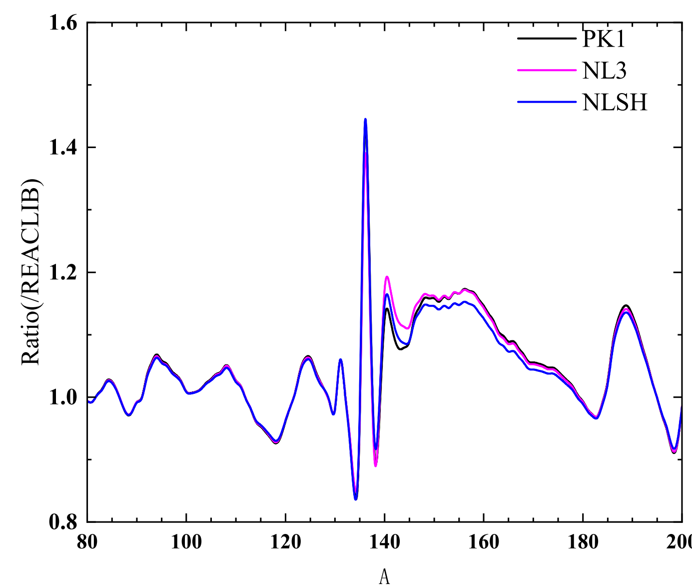
CAPTURE RATES





- Comparison to reaclib

EFFECTS ON NUCLEOSYNTHESIS



- New rates of tin isotope affects the abundance non-locally

- To construct a self-consistent nuclear database for r-process nucleosynthesis is a hard task
- We try to understand the roles of different components of nuclear forces on various nuclear properties
- Then we could understand how these different components affect the nucleosynthesis

BETA DECAY

- Deformed nuclei
  - Large computation burden
- Odd mass nuclei
- Odd-Odd nuclei
- Neutrino energy distribution
- Neutrino-nucleus scattering cross-section

NEUTRON CAPTURE

- Microscopic treatment of pairing correlations
- Gamma strength functions from QRPA or beyond based on DFT
- More microscopic treatment of neutron capture, e.g. self-consistent optical potential

NUCLEAR INPUT DATABASES

- Understand uncertainties of nuclear properties from the nuclear force side and the extrapolation to neutron-rich occasions
- Sensitivity studies based on self-consistent nuclear database
- Reverse engineering from r-process simulations

THANKS FOR ATTENTION