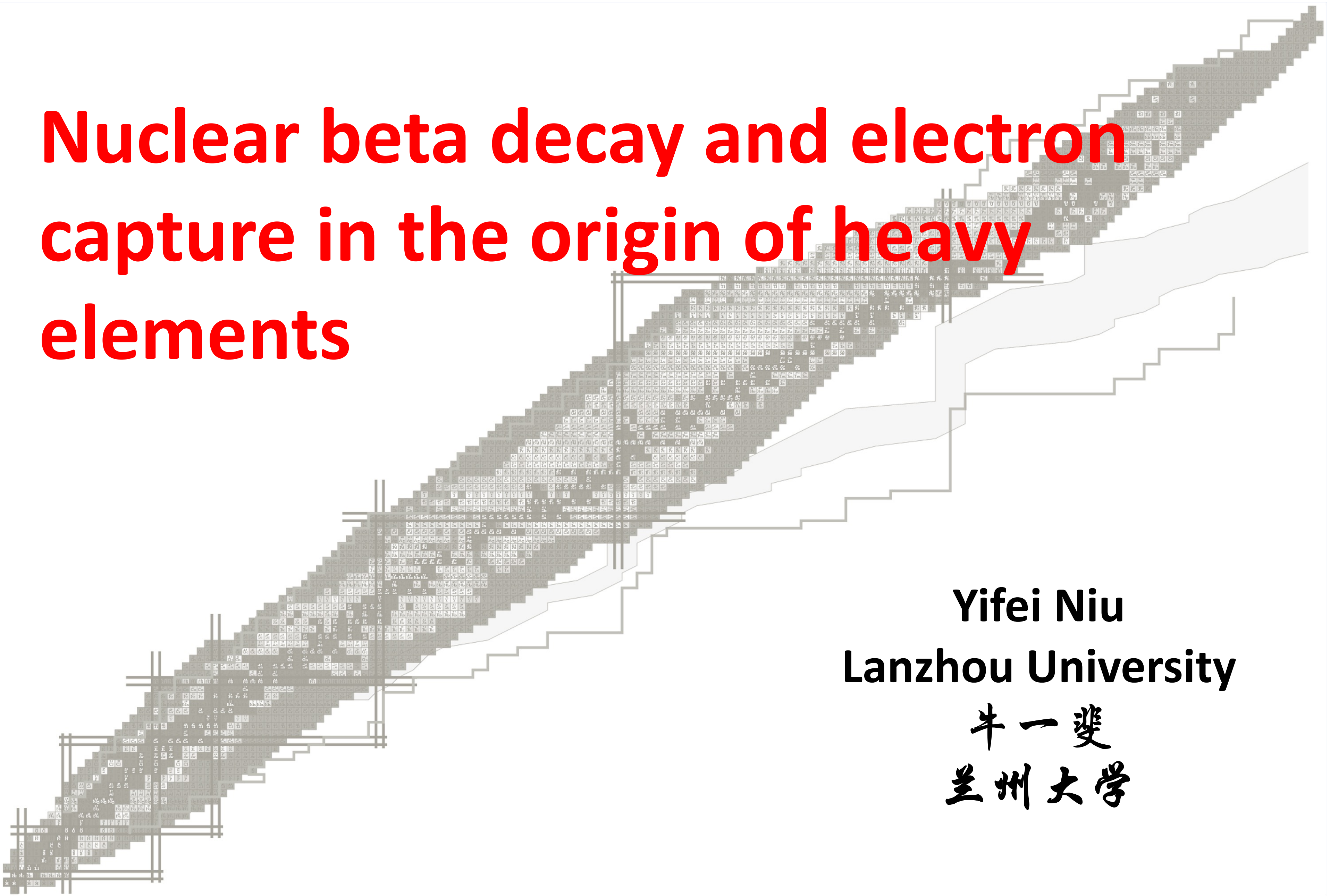
Nuclear beta decay and electron capture in the origin of heavy elements



Yifei Niu
Lanzhou University
牛一斐
兰州大学

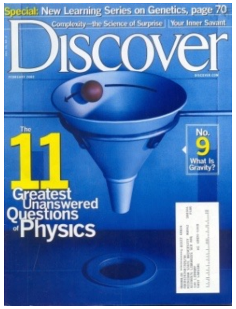
Outline

- **How were heavy elements from iron to uranium made?**
- **Accurate Nuclear Physics Inputs for r-process**
  - **β-decay half-lives**
- **Where does r-process happen?**
  - **Electron capture rates in core-collapse supernova**
- **Summary and Perspectives**

How Were the Heavy Elements Made?

How were the heavy elements from iron to uranium made?

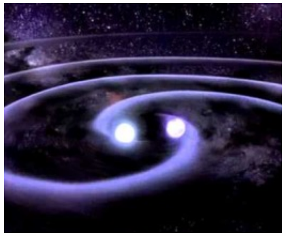
The 11 greatest unanswered questions of physics



- **r-process**

➢ **Where does r-process happen?**

Supernova Neutron star merger (NSM)

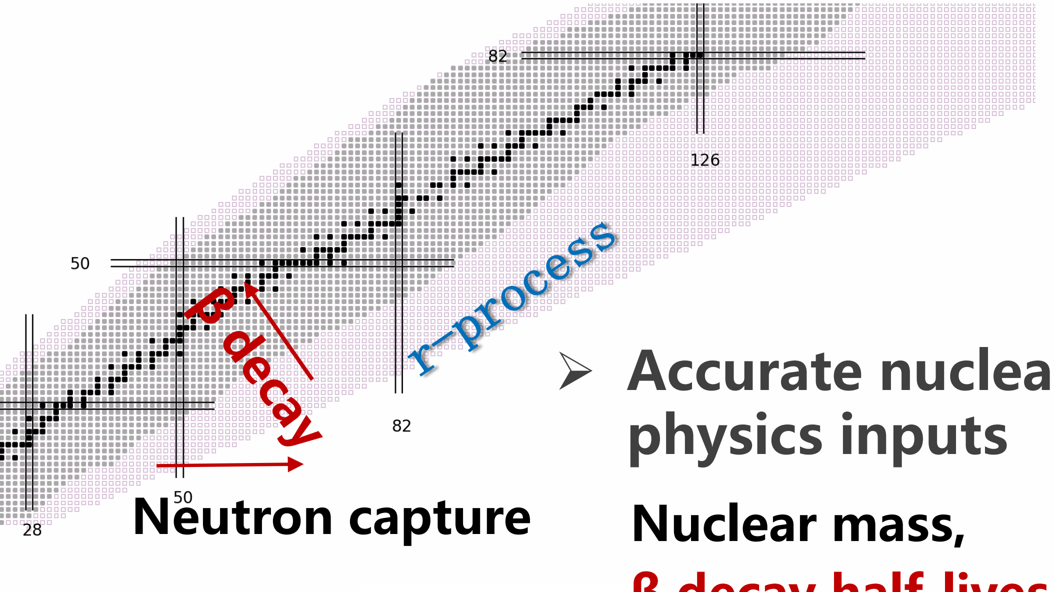


GW170817 NSM：
One of the main r-process sites

Nature **551**,64; 67; 75; 80 (2017)
Science **358**, 1559 (2017)
ApJL **848**, L17; L19 (2017)

NSM:
minimal contribution?

Nature **574**, 497; **569**,241 (2019)
arXiv:2102.05891v1



R-process path: far from stability, relies on theory!

➢ **Accurate nuclear physics inputs**

Nuclear mass,

β decay half-lives,

Neutron-capture cross section,

…

Outline

- How were heavy elements from iron to uranium made?

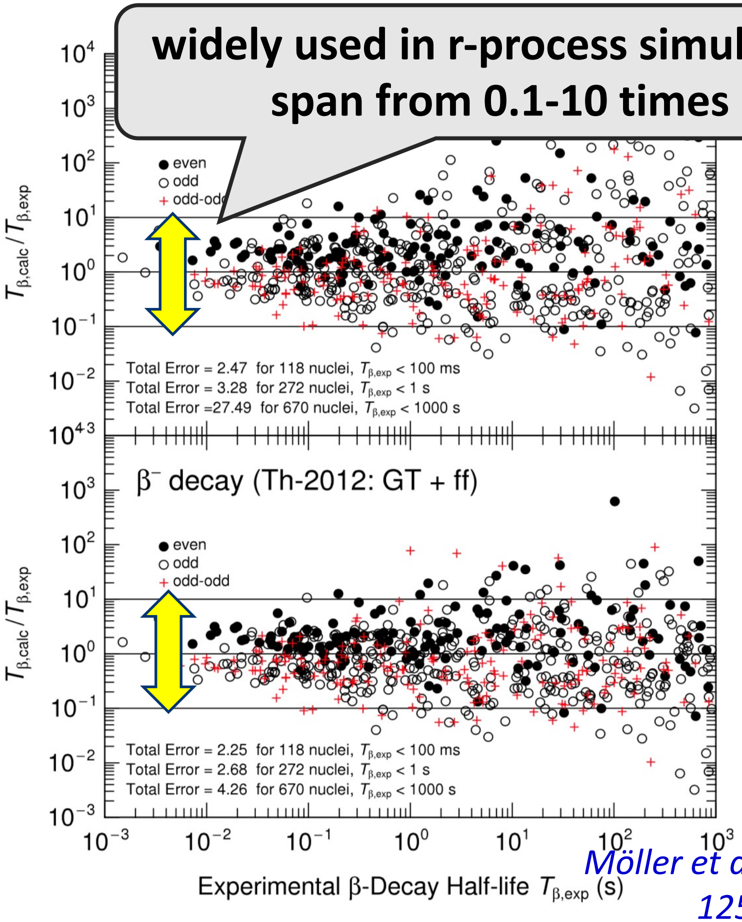
- **Accurate Nuclear Physics Inputs for r-process**
  - **β-decay half-lives**

- Where does r-process happen?
  - Electron capture rates in core-collapse supernova

- Summary and Perspectives

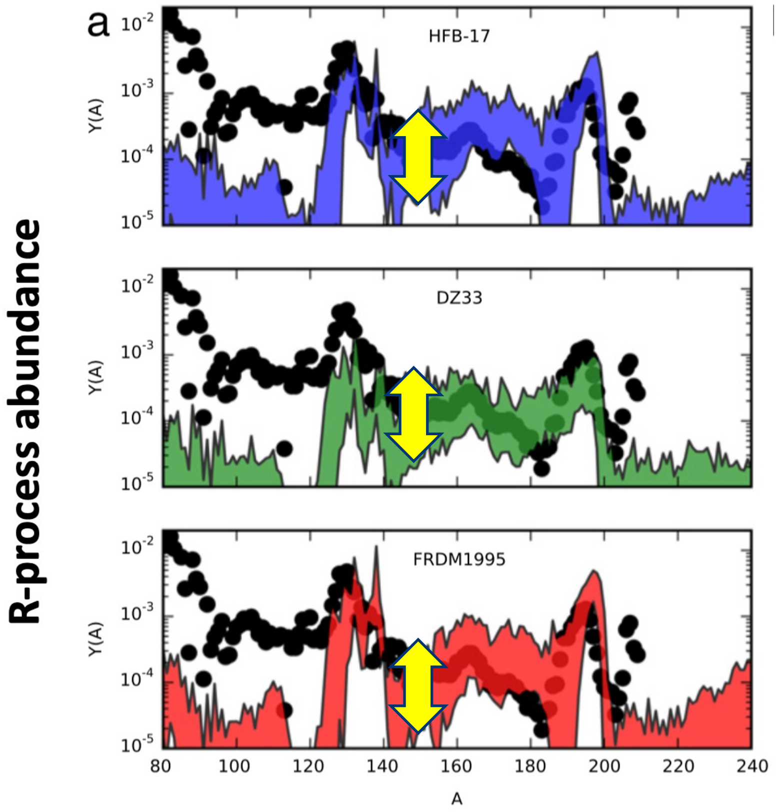
Consequences of uncertainties in β-decay half-lives

- **β-decay half-lives by finite-range droplet model (FRDM) + quasiparticle random phase approximation (QRPA)**
- **Uncertainties caused by varying half-lives between 10^{-1} - 10 times randomly**



widely used in r-process simulation span from 0.1-10 times

*Möller et al., **ADNDT** 125, 1 (2019)*

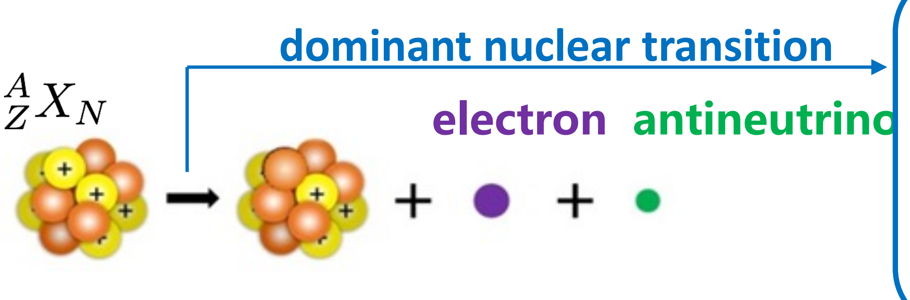


*Mumpower et al., **PPNP** 86, 86 (2016)*

Accurate description of nuclear β-decay half-lives is important for r-process study

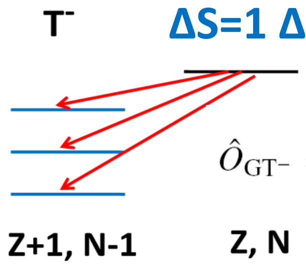
β-decay Half-life Is a Hard Problem

- **β-decay**



${}^{A}_{Z}X_{N}$

Gamow-Teller transition

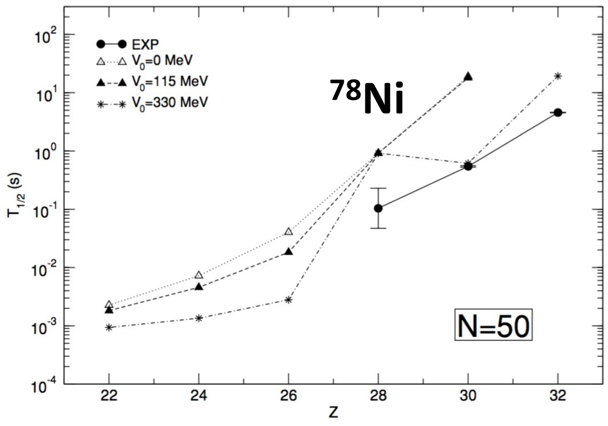


ΔS=1 ΔL=0 ΔT=1

$$\hat{O}_{\mathrm{GT}^-} = \sum_{i=1}^{A} \vec{\sigma}(i) \cdot \tau_-(i)$$

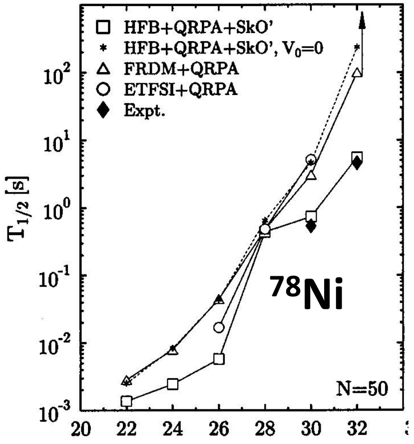
- **RHB+QRPA**

(quasiparticle random phase approximation)



Niksic, et al., PRC 71, 014308 (2005)

- **Skyrme HFB+QRPA**



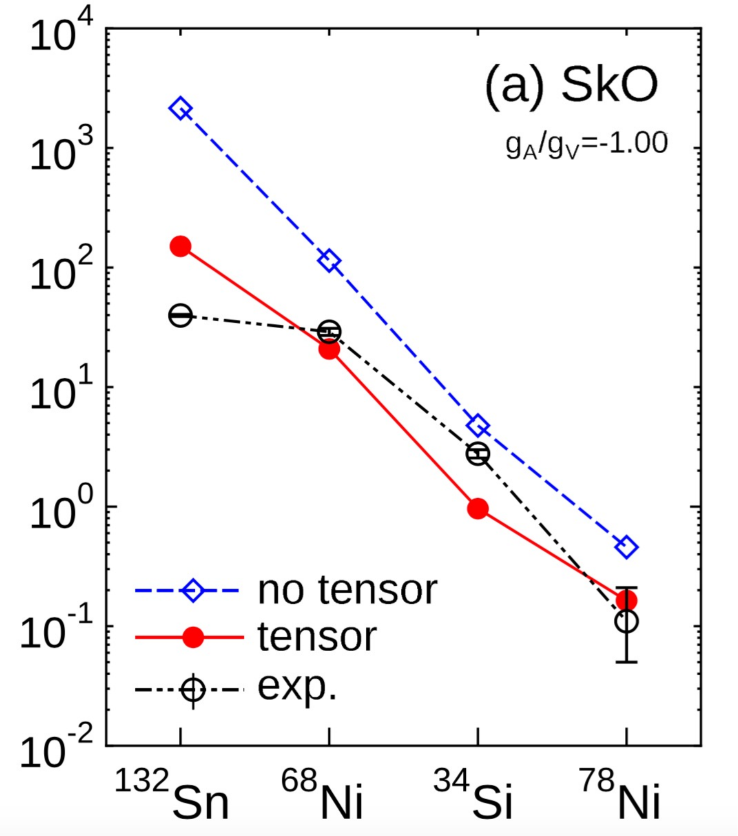
Engel, et al., PRC 60, 014302 (1999)

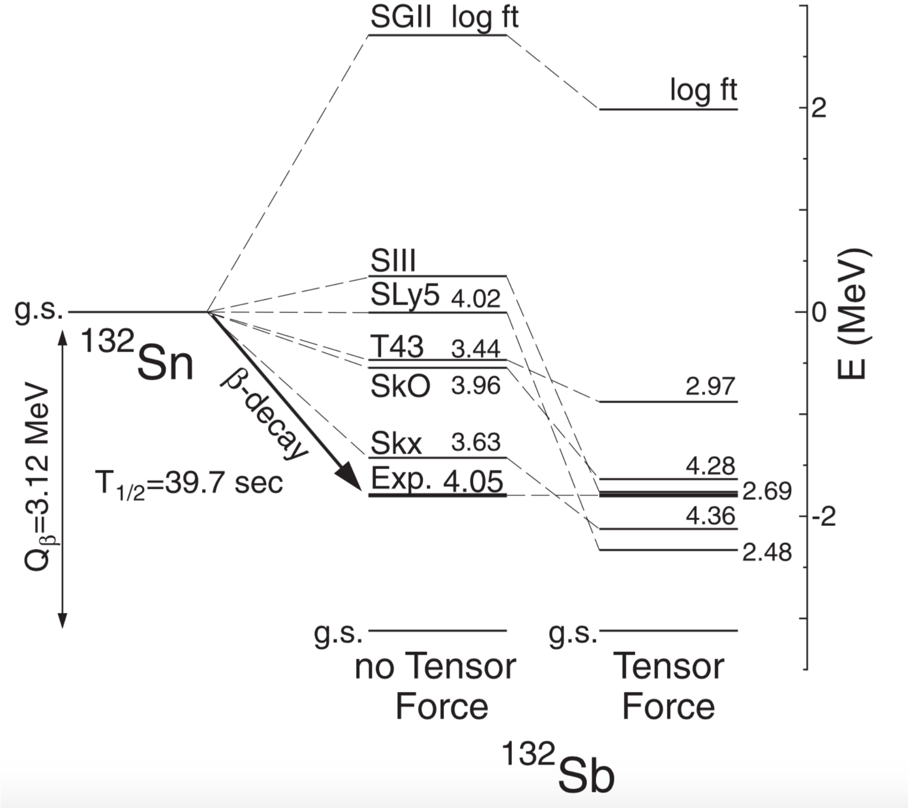
- **Half-lives are overestimated**
- **Due to the nuclear structure part – Gamow-Teller transition**

What are missing in the calculation?

- **Nuclear Force: tensor force** **skyrme HF + RPA + tensor**

Minato and Bai, PRL 116, 089902 (2016)

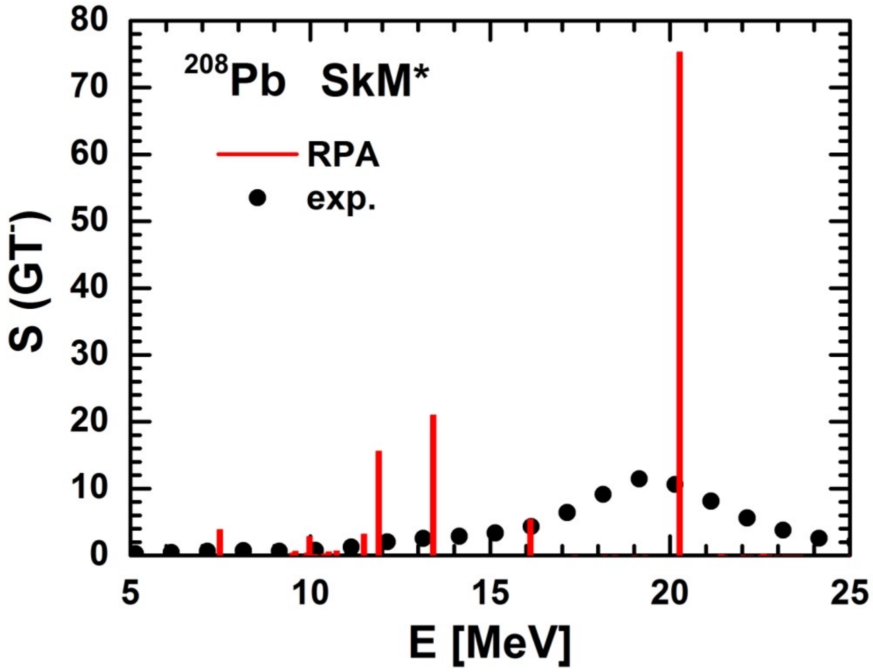




- **Nuclear Model: more correlations beyond RPA model**

Limits of (Q)RPA Description

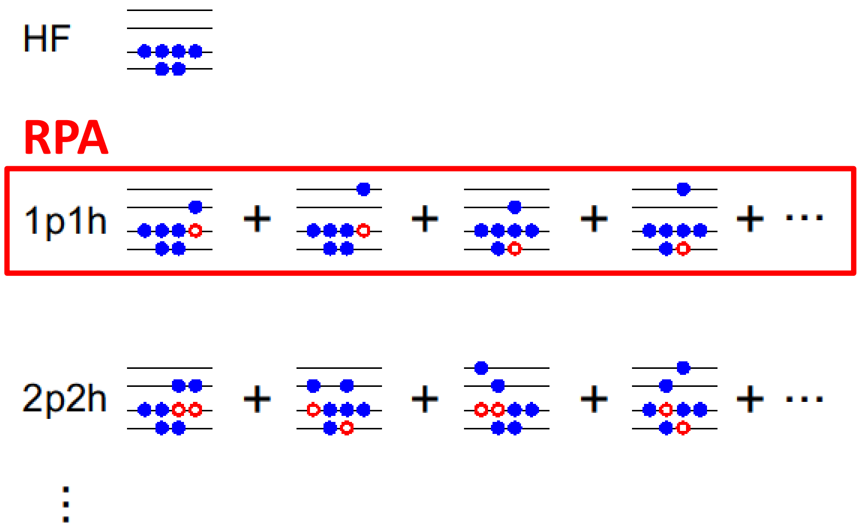
- **(Q)RPA cannot describe the spreading width**

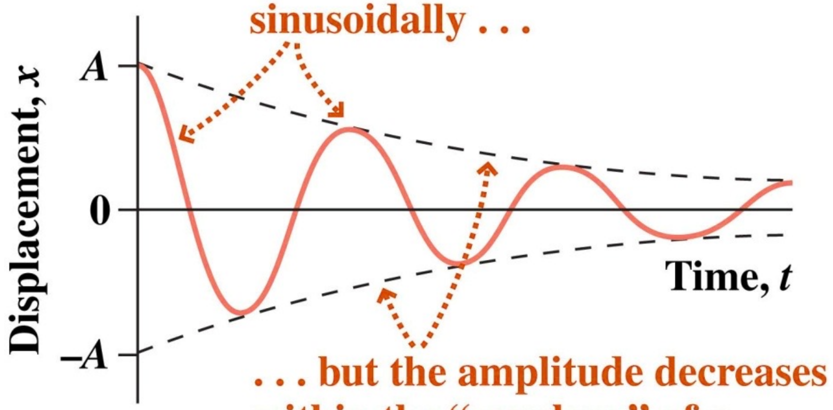


- **Spreading Width (Damping Width)**

  energy and angular momentum of coherent vibrations
  → more complicated states of 2p-2h, 3p-3h, … character

- **Correlations beyond RPA**





The object still oscillates sinusoidally . . .

. . . but the amplitude decreases within the "envelope" of a decaying exponential.

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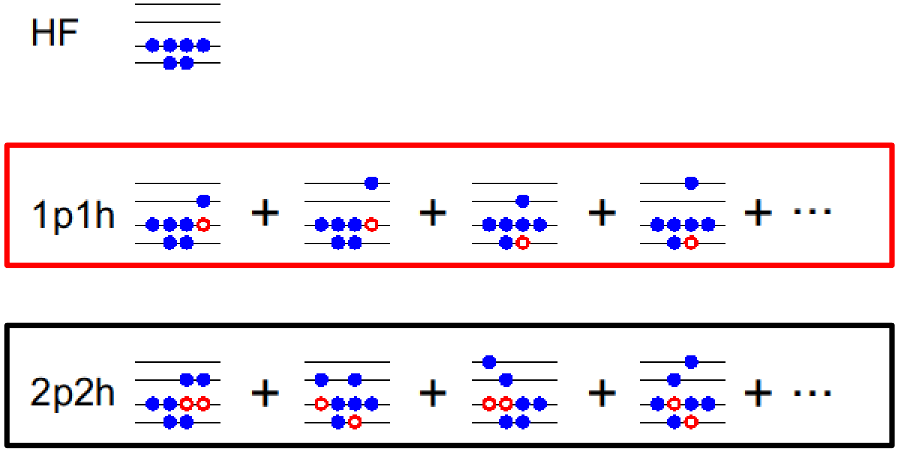
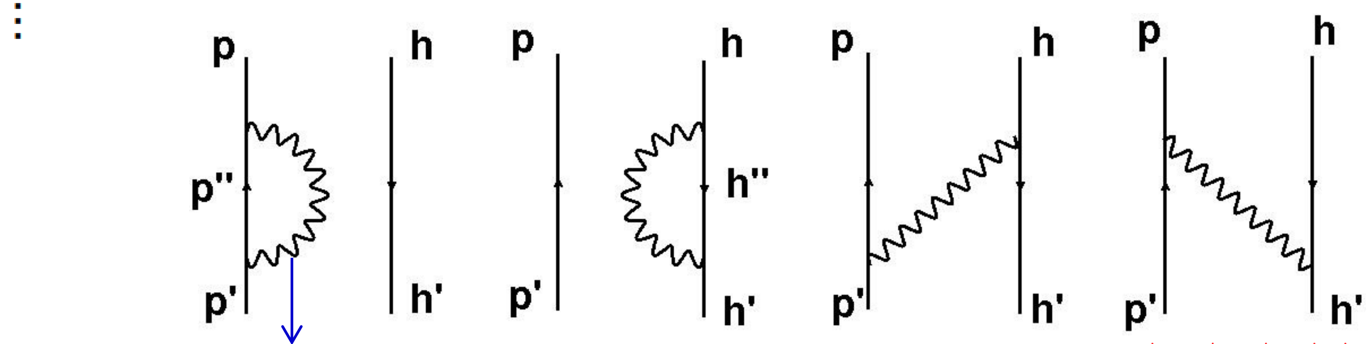
http://www.physics.louisville.edu/

Solution: RPA + PVC



RPA

- **Second RPA** drozdz et al., PR 197, 1 (1990)
  Gambacurta et al., PRL 125, 212501 (2020)
- **RPA + PVC (particle vibration coupling)**



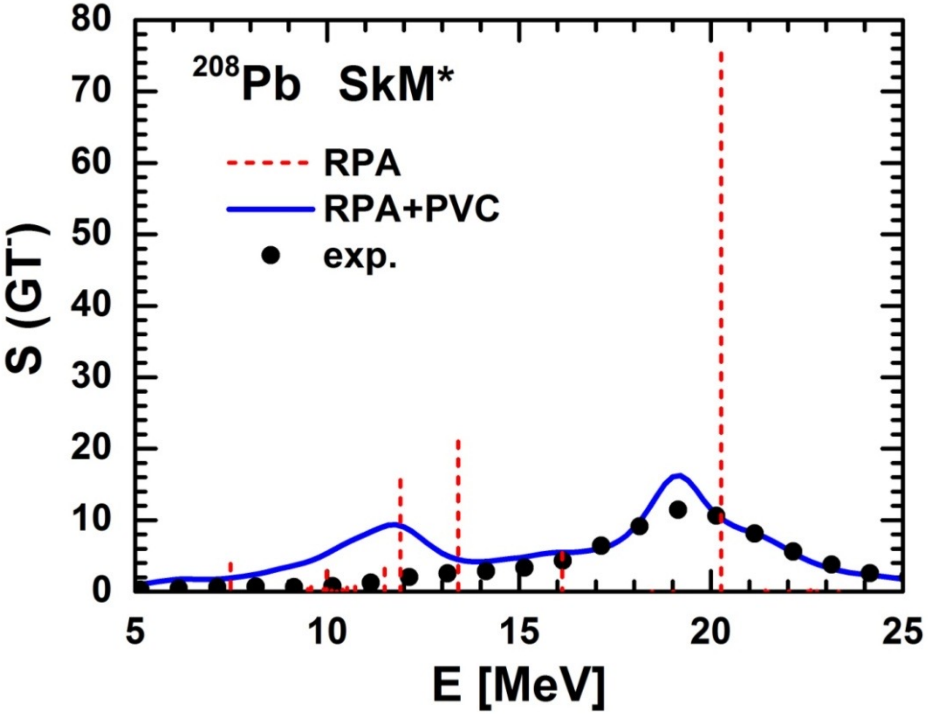
Low-lying vibration phonons |N>

$$W^{\downarrow}_{ph,p'h'}(\omega) = \sum_N \frac{\langle ph|V|N\rangle\langle N|V|p'h'\rangle}{\omega - \omega_N}$$

- RPA+PVC model based on Skyrme DFT
  Colo et al., PRC 50, 1496 (1994); Niu et al., PRC 85, 034314 (2012)
- RPA+PVC model based on relativistic DFT Litvinova et al., PRC 75,064308 (2007)

Gamow-Teller Resonance

- **Improved description of GT resonance in ^{208}Pb**

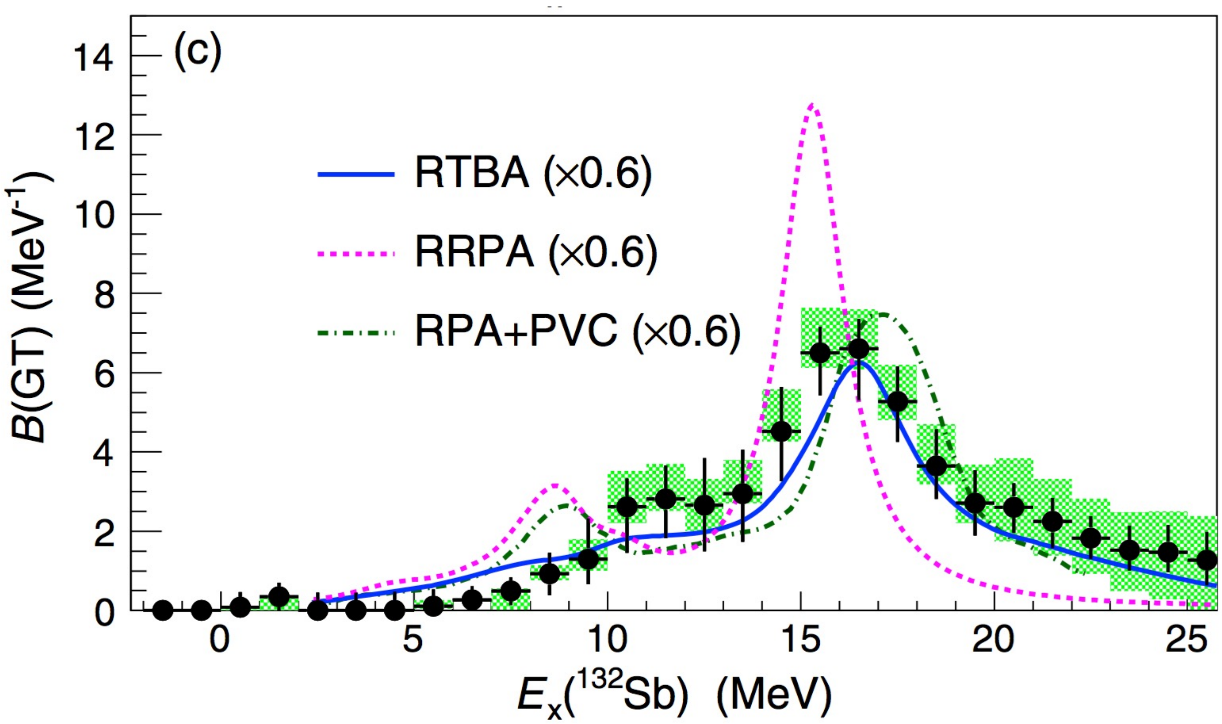


✓ **Develop a spreading width**
✓ **Reproduce resonance lineshape**

Y. F. Niu, G. Colo, and E. Vigezzi, **PRC** 90, 054328 (2014)

Gamow-Teller Resonance

- **Improved description of GT resonance in unstable nucleus ^{132}Sn**

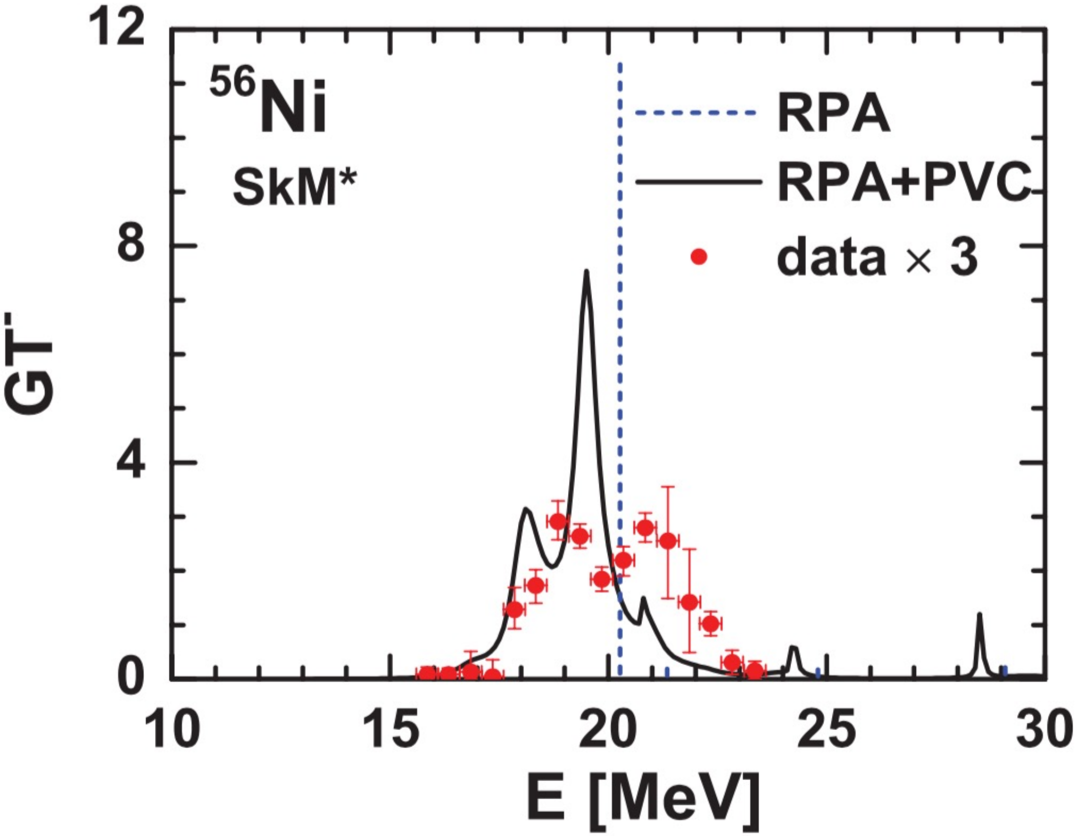


Yasuda, Sasano, et al., PRL 121, 132501 (2018)

Exp: (p,n) reaction @ RIBF, RIKEN
Yasuda, Sasano, et al., PRL 121, 132501 (2018)
RPA+PVC: Y. F. Niu, G. Colo and E. Vigezzi, **PRC** 90, 054328 (2014)
RTBA: E. Litvinova et al., PLB 730, 307 (2014)
RRPA: H. Z. Liang, and Z. M. Niu private communication

Gamow-Teller Resonance

- **Reproduction of double-peak structure of GT resonance in ^{56}Ni**

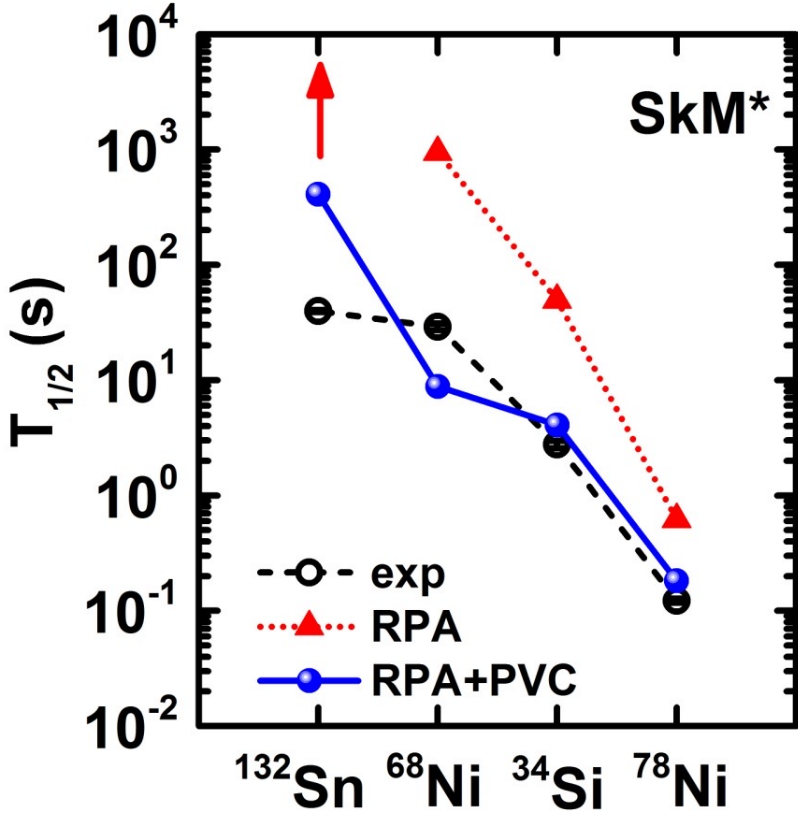


Y. F. Niu, G. Colo, M. Brenna, P.F. Bortignon, and J. Meng, **PRC** 85, 034314 (2012)

Exp: (p,n) reaction with Tp=296 MeV @ NSCL, MSU
Sasano et al., PRL 107, 202501 (2011)

β-Decay Half-Lives in Magic Nuclei

- **Improved description of β-decay half-lives**



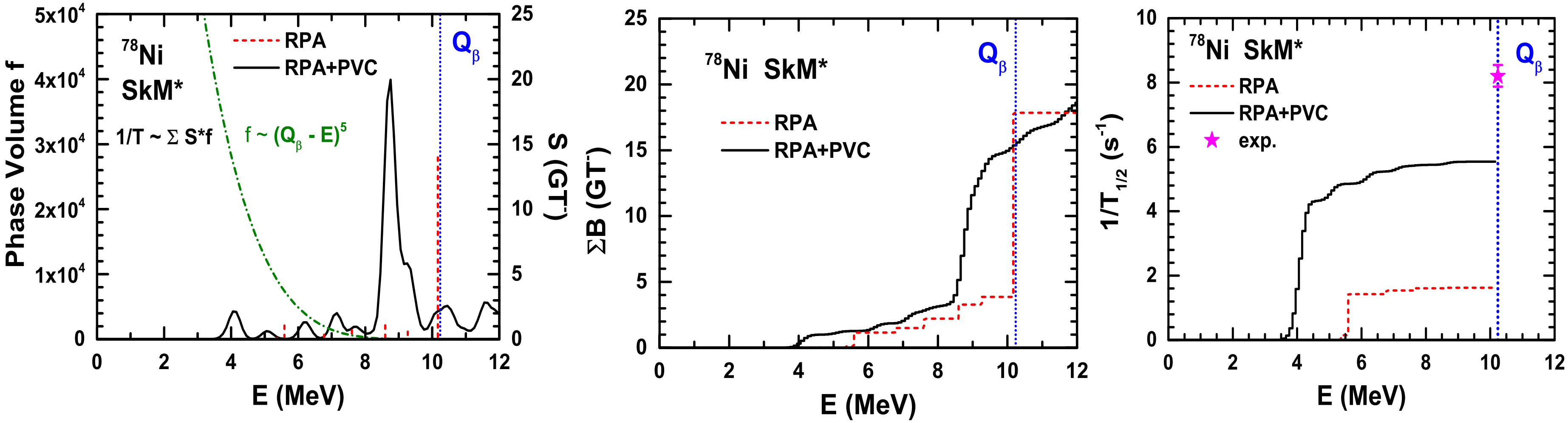
✓ **Reduce half-lives systematically**

✓ **Reproduce β-decay half-lives**

Y.F. Niu, Z. M. Niu, G. Colo, and E. Vigezzi, **PRL** 114, 142501 (2015)

Exp: G. Audi, F. G. Kondev, M. Wang, W. J. Huang, and S. Naimi, CPC 41, 030001 (2017)

How PVC reduces half-lives?



Exp.: Xu, et al., PRL 113, 032505, 2014

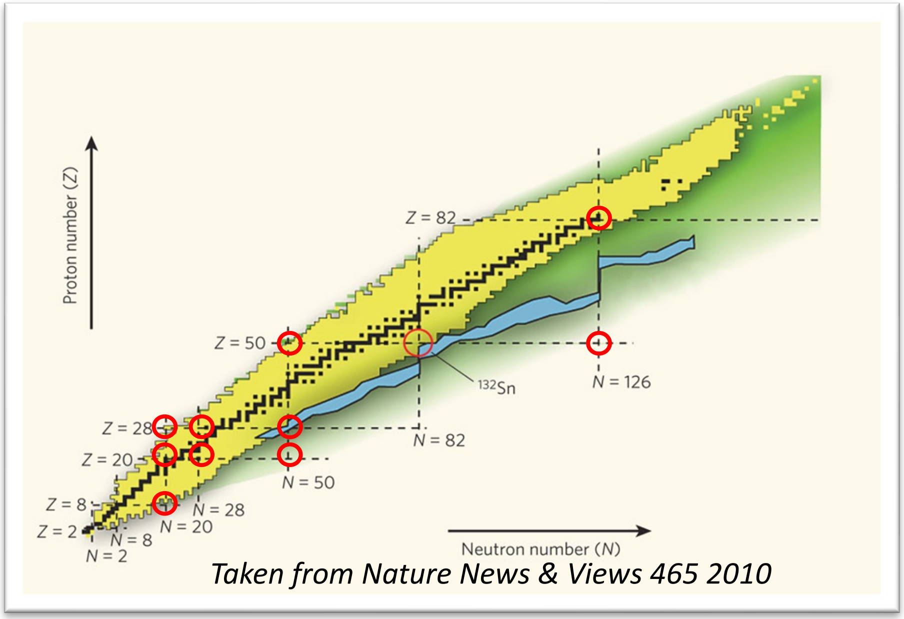
- Half-life

$$T_{1/2} = \frac{D}{g_A^2 \int^{Q_\beta} S(E) f(Z,\omega) dE},$$

- Phase Volume

$$f(Z,\omega_0) = \frac{1}{(m_e c^2)^5} \int_{m_e c^2}^{\omega_0} p_e E_e (\omega_0 - E_e)^2 F_0(Z+1, E_e) dE_e.$$

RPA+PVC: only for magic nuclei…



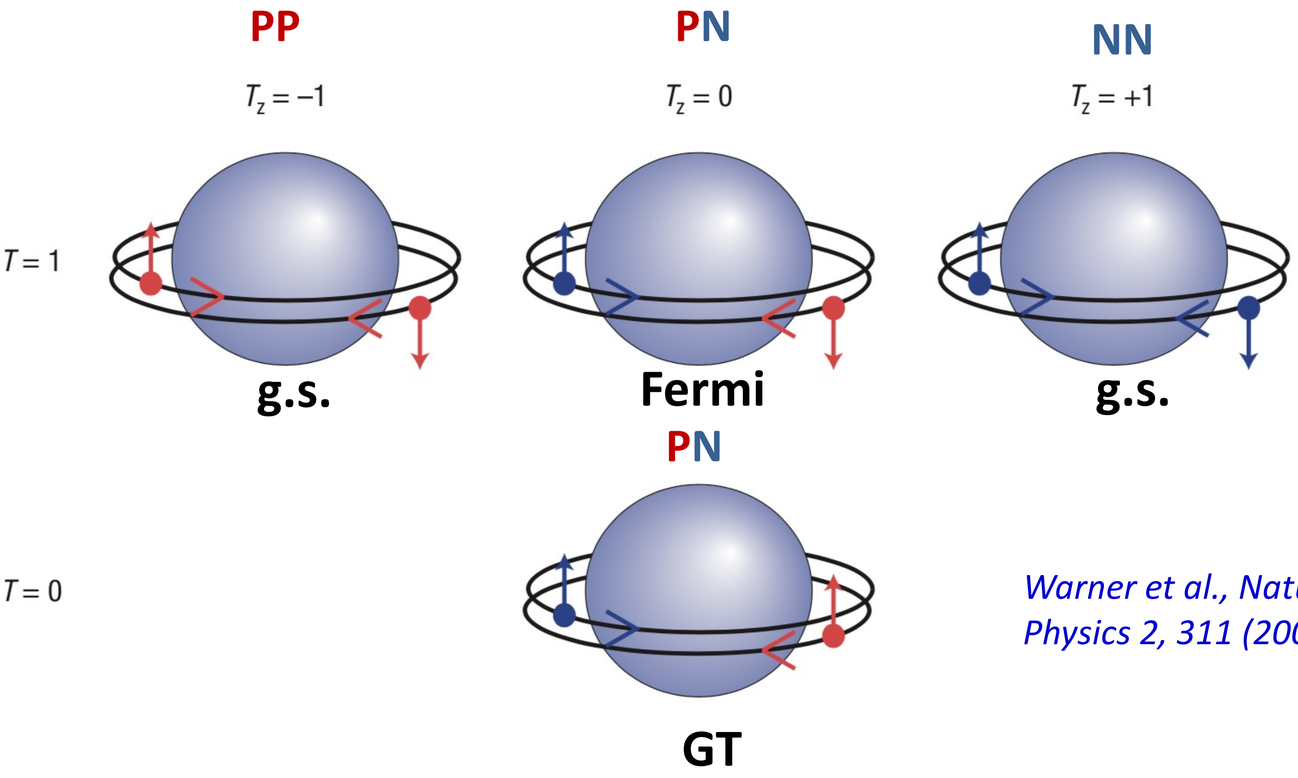
Taken from Nature News & Views 465 2010

- To include pairing correlations for superfluid nuclei

Quasiparticle RPA + quasiparticle vibration coupling
(**QRPA**) + (**QPVC**)

- ✓ for the study of Gamow-Teller resonance in superfluid nuclei
- ✓ for the study of β-decay half-lives in the whole isotopic chain

Isovector and isoscalar pairing



Warner et al., Nature Physics 2, 311 (2006)

- **Isovector Pairing**

$$V_{T=1}(\mathbf{r}_1,\mathbf{r}_2) = V_0\frac{1-P_\sigma}{2}\left(1-\frac{\rho(\mathbf{r})}{\rho_0}\right)\delta(\mathbf{r}_1-\mathbf{r}_2),$$

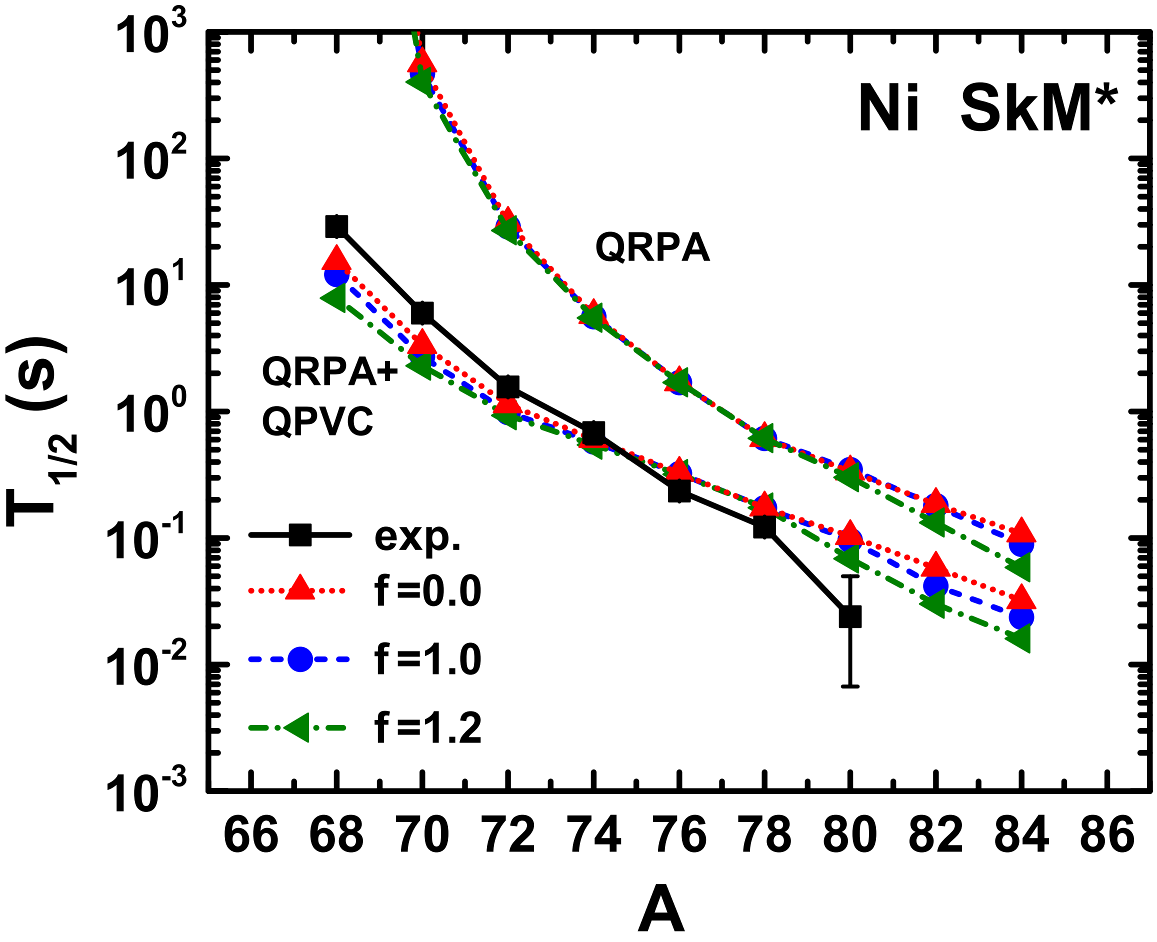
For ground state: pairing strength adjusted to reproduce empirical pairing gap

- **Isoscalar Pairing**

$$V_{T=0}(\mathbf{r}_1,\mathbf{r}_2) = f\,V_0\frac{1+P_\sigma}{2}\left(1-\frac{\rho(\mathbf{r})}{\rho_0}\right)\delta(\mathbf{r}_1-\mathbf{r}_2)$$

For GT: the same form as IV pairing, but with an adjustable pairing strength f

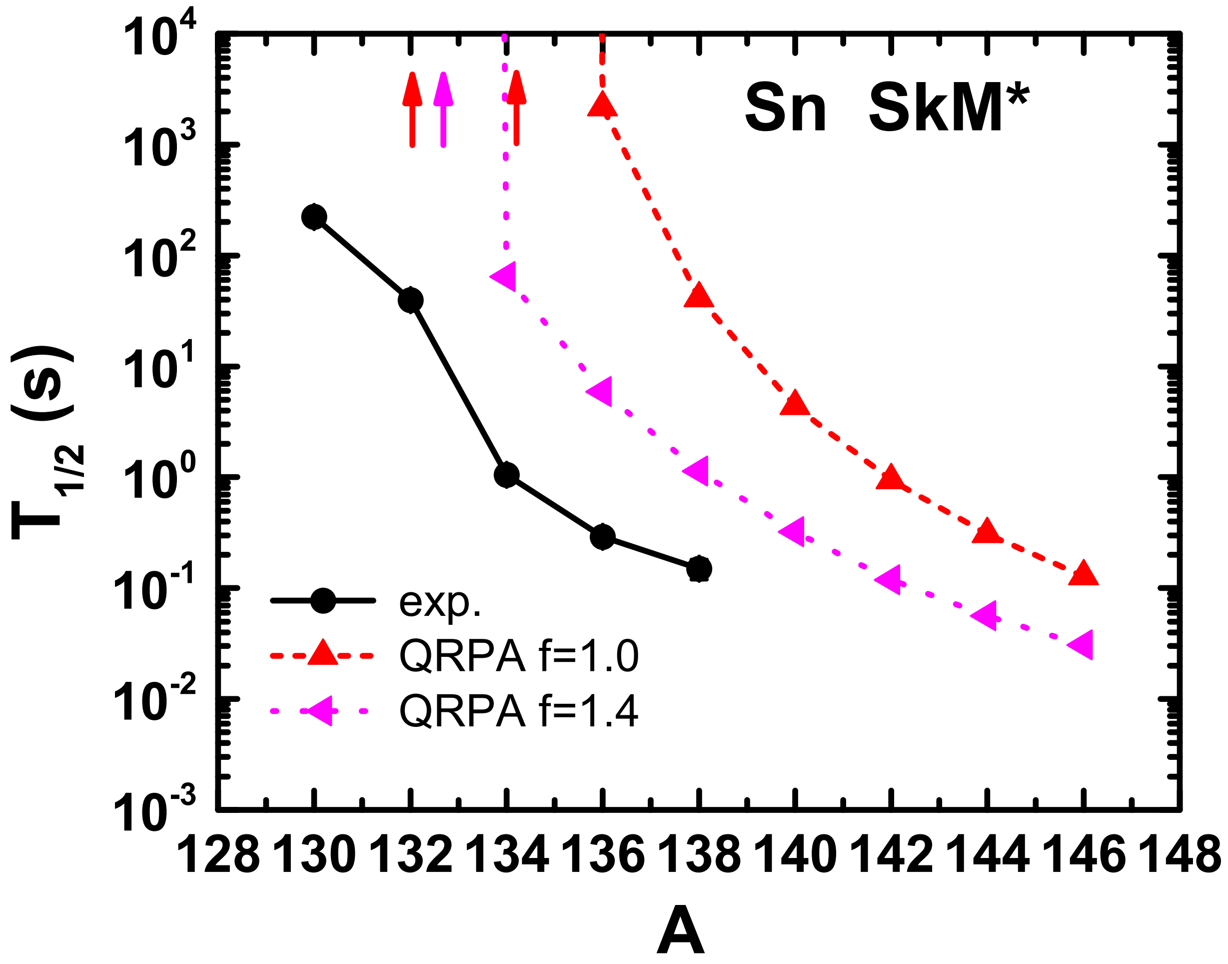
β-Decay Half-Lives in Ni isotopes



- Isoscalar Pairing:
  - similar at QRPA and QRPA+QPVC level
  - not so effective for Ni isotopes
    (nuclei before N=50 closed shell)

- QPVC:
  reduce the half-lives

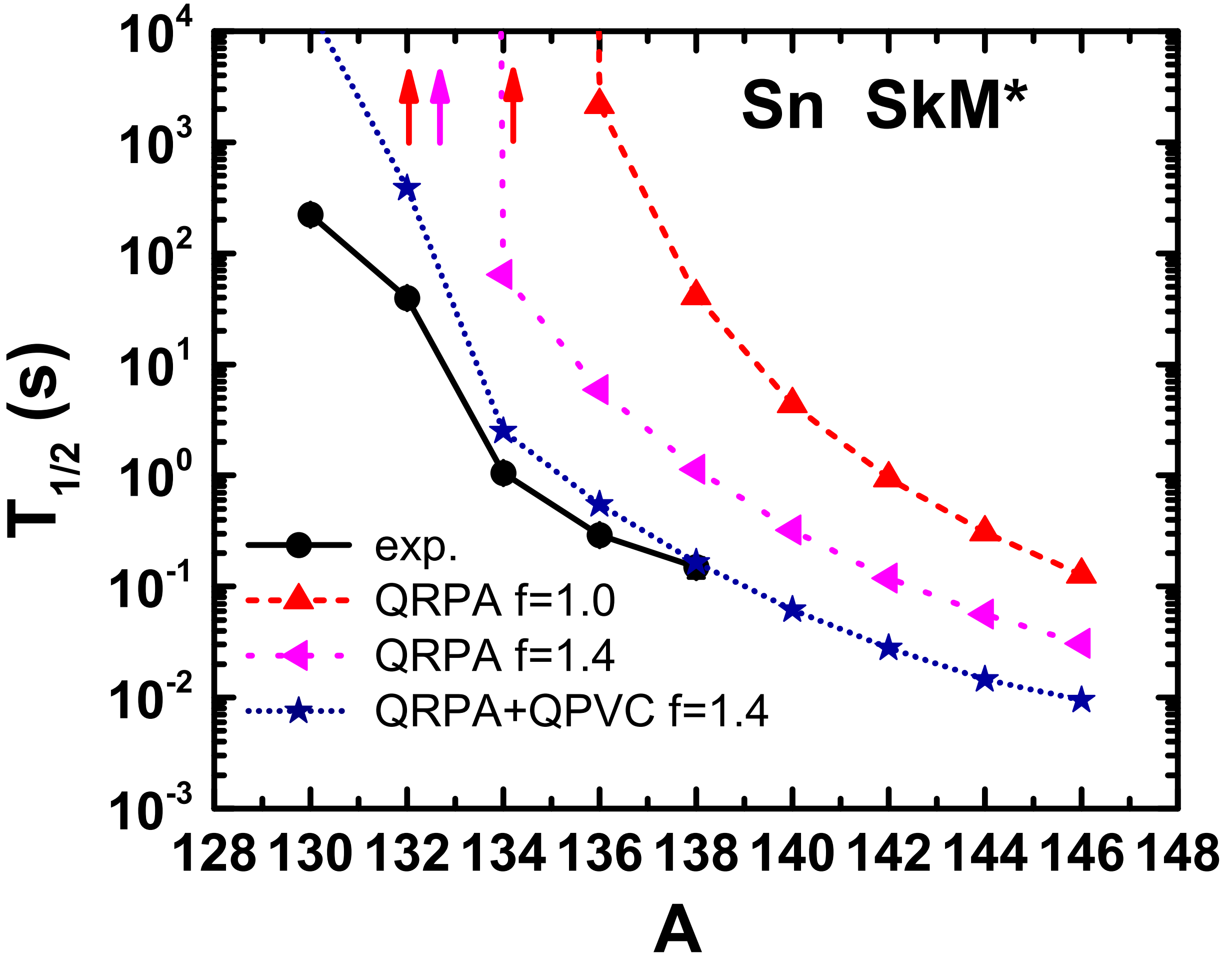
β-Decay Half-Lives in Sn isotopes



- Isoscalar Pairing:
  effective for Sn isotopes
  (nuclei above N=82 closed shell)

Y. F. Niu, Z. M. Niu, G. Colo, and E. Vigezzi, **PLB** 780, 325 (2018)

β-Decay Half-Lives in Sn isotopes

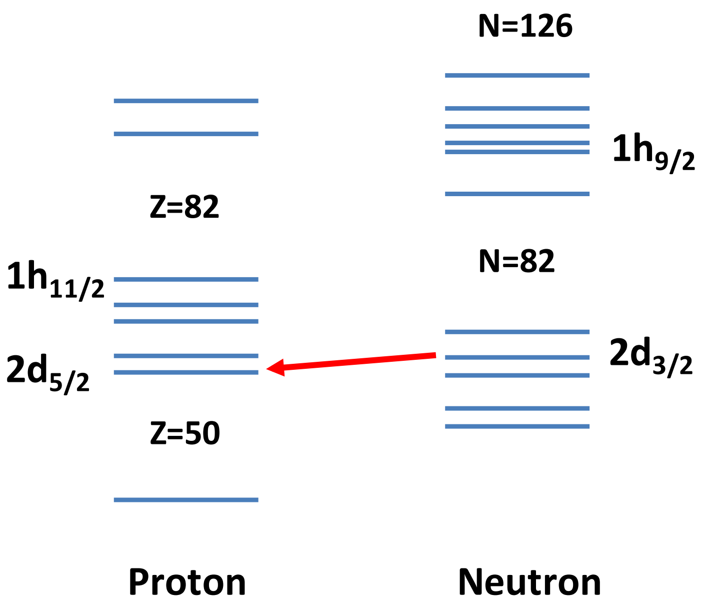


- Isoscalar Pairing:
  effective for Sn isotopes
  (nuclei above N=82 closed shell)
- Isoscalar Pairing + QPVC:
  reduce the half-lives

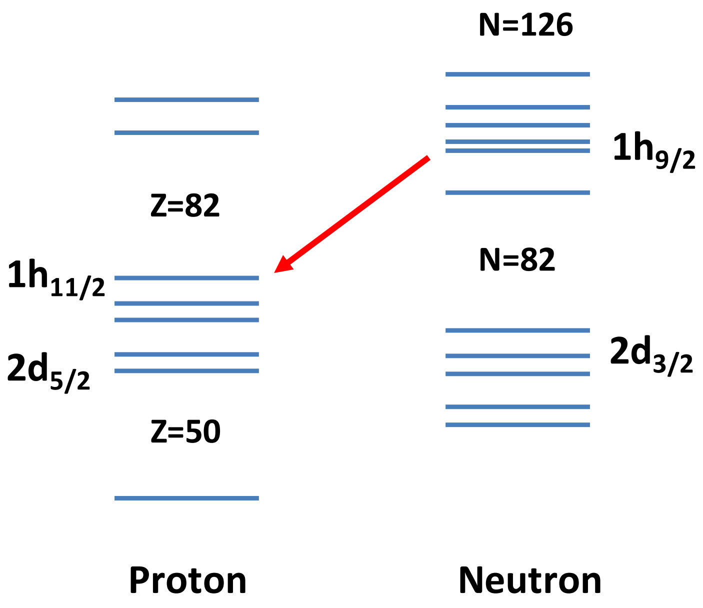
Y. F. Niu, Z. M. Niu, G. Colo, and E. Vigezzi, **PLB** 780, 325 (2018)

The role of IS pairing

- **N < 82**



- **N > 82**



$V^{pp}(2d_{3/2}\,2d_{5/2},\,2d_{3/2}\,2d_{5/2})$

-0.50 (^{130}Sn)

$u^2(2d_{3/2})u^2(2d_{5/2}) + v^2(2d_{3/2})v^2(2d_{5/2})$

0.069 (^{130}Sn)

ph type

$V^{pp}(1h_{9/2}\,1h_{11/2},\,1h_{9/2}\,1h_{11/2})$

-1.68 (^{144}Sn)

$u^2(1h_{9/2})u^2(1h_{11/2}) + v^2(1h_{9/2})v^2(1h_{11/2})$

0.89 (^{144}Sn)

pp type

Outline

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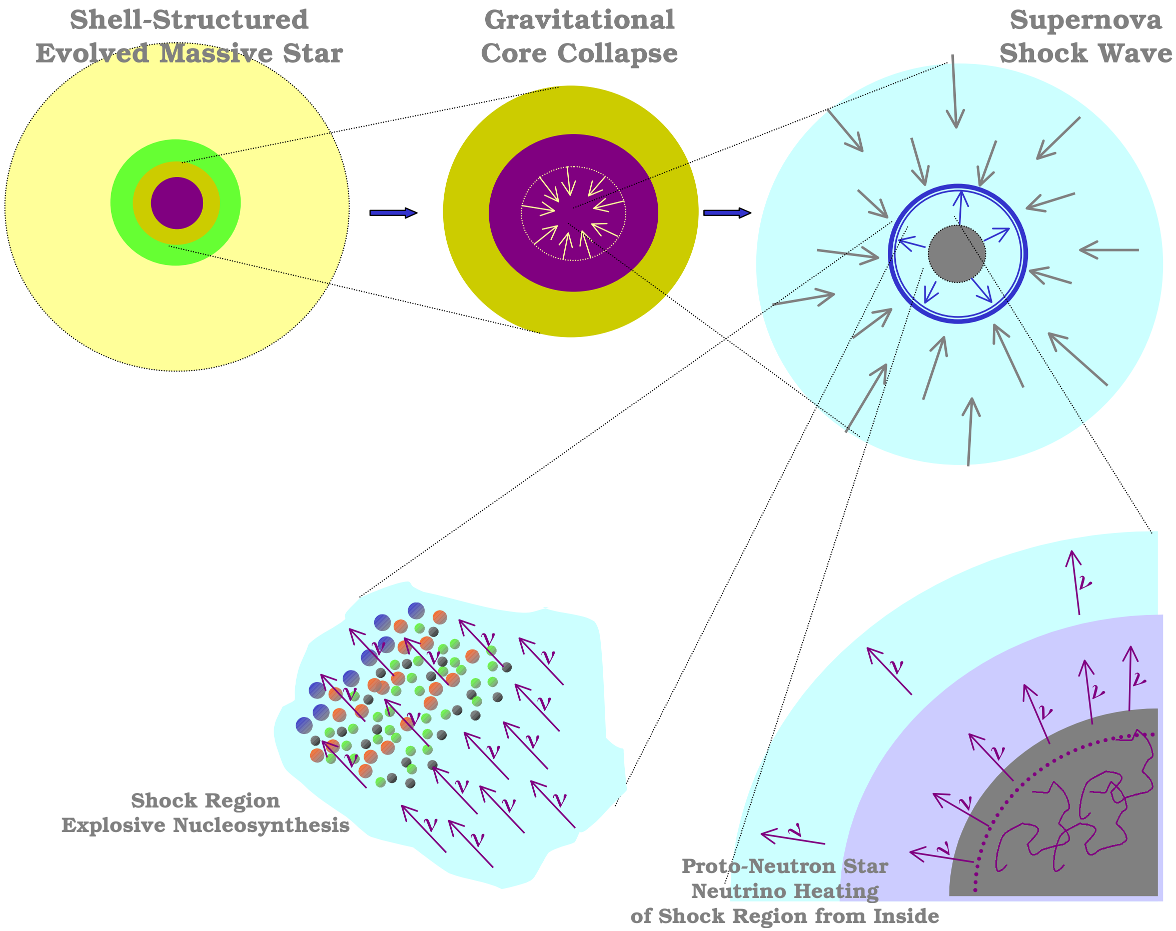
  - β-decay half-lives

- **Where does r-process happen?**
  - **Electron capture rates in core-collapse supernova**

- Summary and Perspectives

Electron capture in core-collapse supernova

Collapse of a massive star and a supernova explosion



Langanke, Acta Physica Polonica B, 39, 2008

Electron capture (EC) on nucleus

$${}^{A}_{Z}X_{N} + e^{-} \rightarrow {}^{A}_{Z-1}X^{*}_{N+1} + \nu_{e}$$

↓

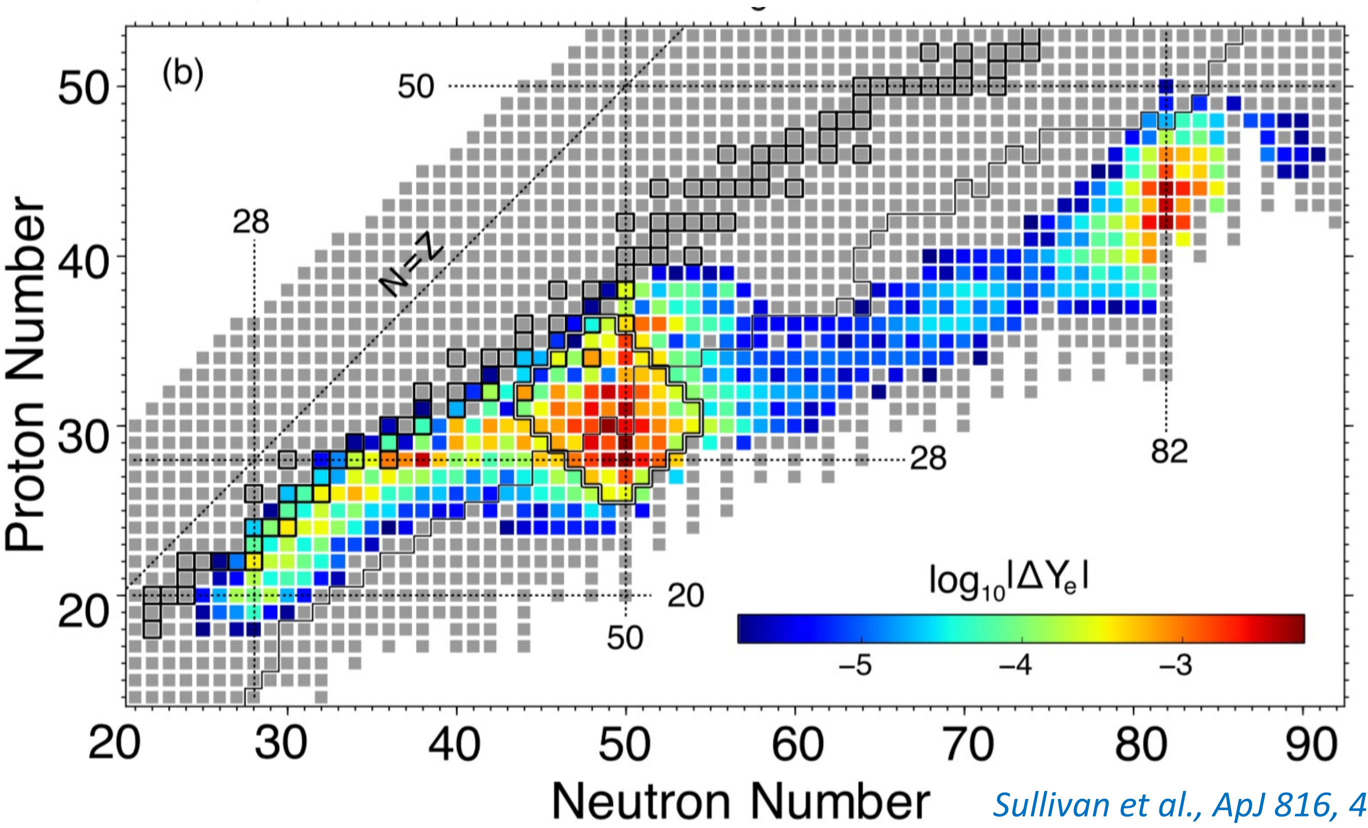
change Y_e
change entropy

↓

affect the strength of bounce shock and supernova evolution

Important electron-capturing nuclei

Top 500 electron-capturing nuclei with the largest absolute change to the electron fraction (Y_e) up to neutrino trapping



Sullivan et al., ApJ 816, 44 2016

- The integrated contribution to core deleptonization up to neutrino trapping

$$Y_e(t = t_{\text{trapping}}) \simeq Y_e(t = 0) - \sum_i \Delta Y_e^i$$

- Primary contributors: neutron rich nuclei near **N=50** and N=82 closed neutron shells

Theoretical study of electron-capture rates

Electron Capture Rate:

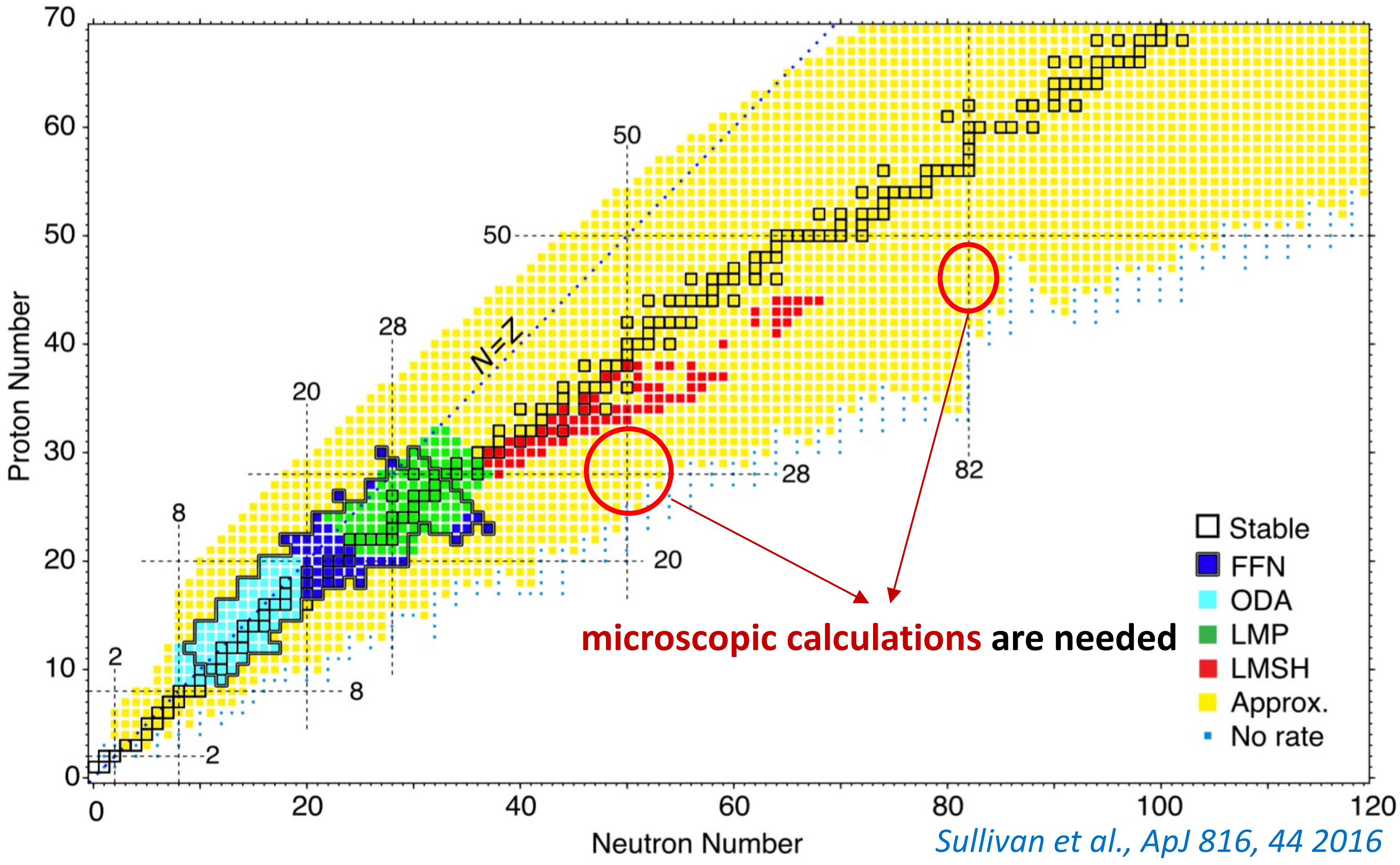
phase space factor

$$\lambda^{\mathrm{ec}} = \frac{\ln 2}{6150\ \mathrm{s}} \sum_J \sum_i \Phi_{Ji}^{(+)} F_i^{\mathrm{ec}} = \sum_J \sum_i \lambda_{Ji}^{\mathrm{ec}}$$

transition strength of **spin-isospin excitations** in T⁺ direction:
Fermi, Gamow-Teller, Spin-Dipole transitions …

- **Independent Particle Model (IPM)**
  - ✓ **first tabulation of weak interaction rates 21 ≤ A ≤ 60**
    Fuller, Fowler, Newman ApJ 252, 715, 1982; ApJ 293, 1, 1985 **FFN**
- **Large Scale Shell Model**
  - **sd shell nuclei 17 ≤ A ≤ 39** ^{16}O core + effective interaction of Wildenthal
    Oda et al., ADNDT 56, 231, 1994 **ODA**
  - **pf shell nuclei 45 ≤ A ≤ 65** modified KB3 interaction
    Langanke and Martinez-Pinedo, NPA 673, 481 (2000); ADNDT 79, 1 (2001) **LMP**
- **Hybrid Model**
  - **Shell Model Monte Carlo (SMMC) + Random Phase Approximation(RPA) pfg/sdg shell nuclei 65 ≤ A ≤ 112**
    Langanke et al., PRL 90, 241102 (2003) **LMSH**

Theoretical study of electron-capture rates



microscopic calculations are needed

Sullivan et al., ApJ 816, 44 2016

- Approx. - Approximate Rates estimated by $\lambda = \frac{(\ln 2)B}{K}\left(\frac{T}{m_e c^2}\right)^5 [F_4(\eta) - 2\chi F_3(\eta) + \chi^2 F_2(\eta)]$
- Fitted by shell model calculation for nuclei not far from stability line

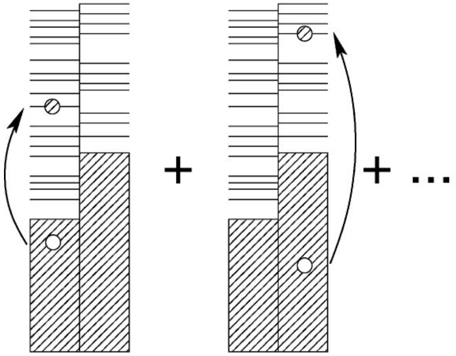
  ⇒ For neutron rich nuclei, the formulas is not a good approximation

Langanke et al., PRL 90, 241102 (2003)

Random Phase Approximation (RPA)

- **RPA:** widely used for the description of spin-isospin excitations
  - **The RPA excited state is generated by**

$$Q_\nu^\dagger = \sum_{mi} X_{mi}^\nu a_m^\dagger a_i - \sum_{mi} Y_{mi} a_i^\dagger a_m$$



RPA

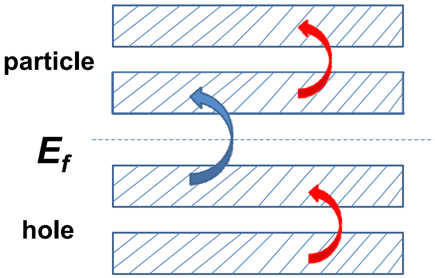
  - **Full 1p1h configuration space ⇒ almost whole nuclear chart**

To study the electron capture in core-collapse supernova, inclusion of temperature effect is necessary! (T ~ 0 – 2 MeV)

- **Finite Temperature RPA (FTRPA):** takes into account temperature self-consistently both in Hartree and RPA level
  - **Temperature is introduced by thermal occupation of each nucleon**

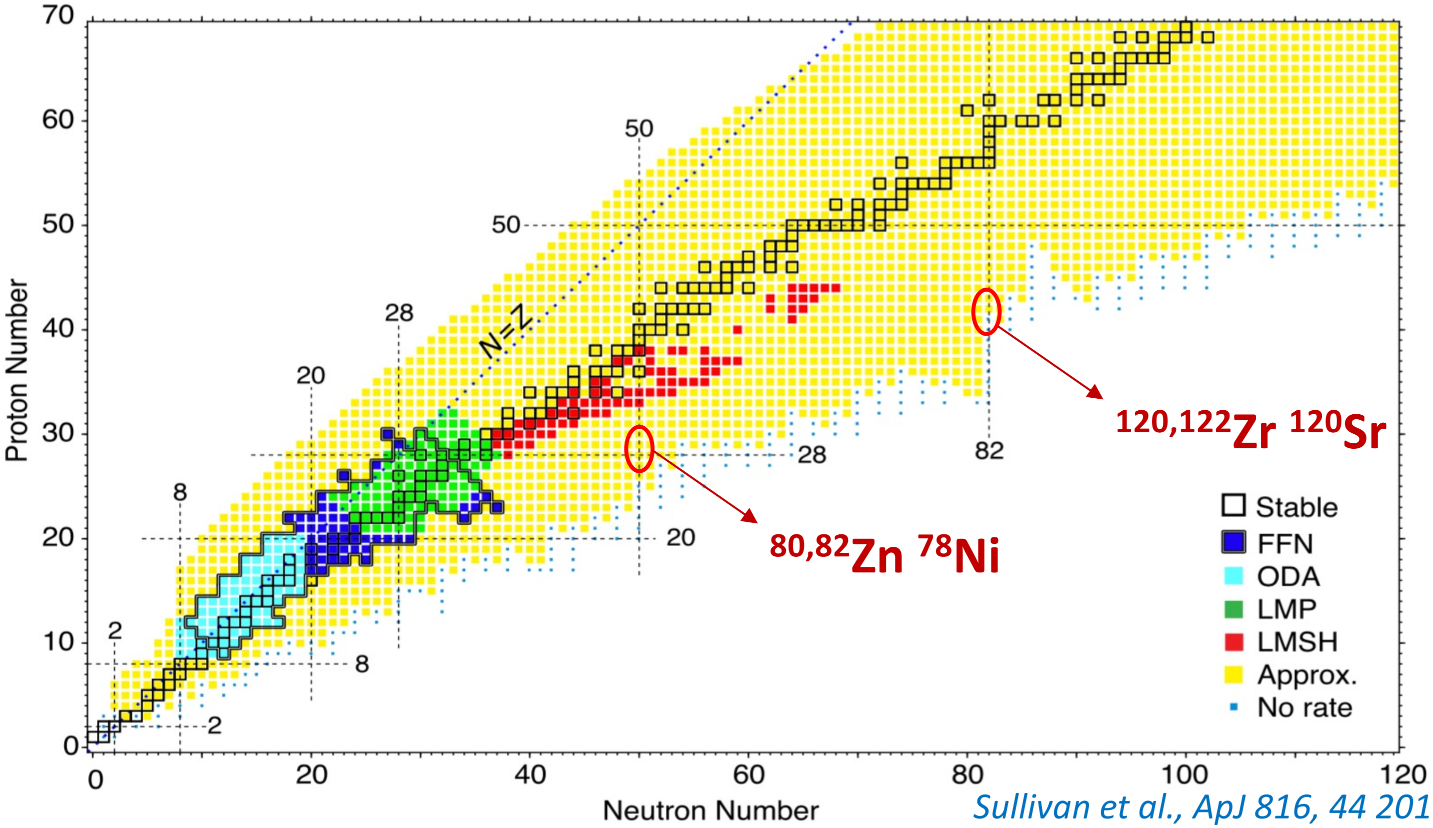
$$f_{p(n)} = \frac{1}{1+\exp(\frac{\epsilon_{p(n)}-\mu_{p(n)}}{kT})}$$

  - **Configuration space: p-h, p-p, and h-h pairs**



N. Paar et al., PRC 80, 055801 (2009)
Y. F. Niu et al., PLB 681, 315 (2009)

Electron capture study for important nuclei



^{80,82}Zn ^{78}Ni

^{120,122}Zr ^{120}Sr

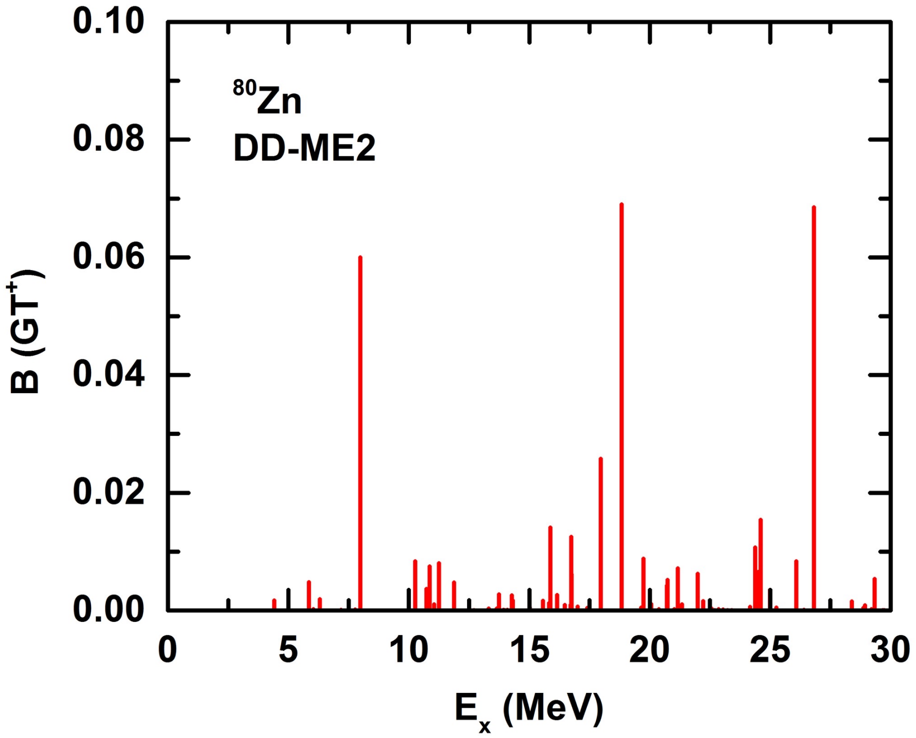
Sullivan et al., ApJ 816, 44 2016

Finite temperature RPA (FTRPA) can provide a universal tool to study the electron capture for almost the whole nuclear chart, so the important nuclei for supernova explosion will be studied, including

N~50: ^{78}Ni ^{80}Zn ^{82}Zn
N~82: ^{120}Sr ^{120}Zr ^{122}Zr

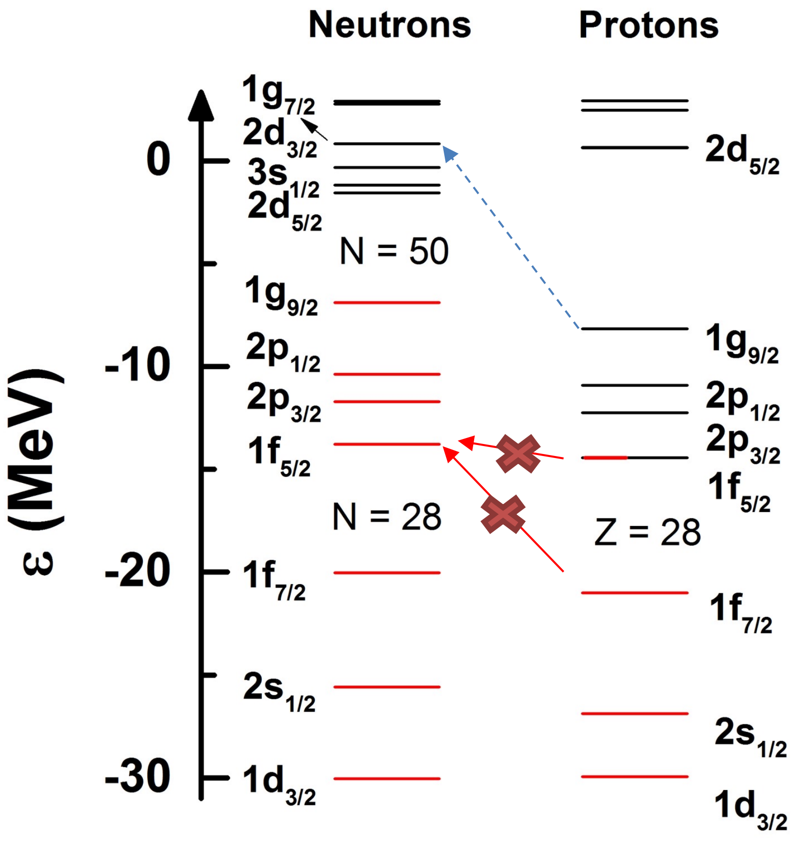
Gamow-Teller strength distribution (T$^+$)

- **GT operator** $$\hat{F}^{\pm}_{\mathrm{GT}} = \sum_{i=1}^{A} \sigma(i)\tau_{\pm}(i)$$



with respect to daughter nucleus ^{80}Cu

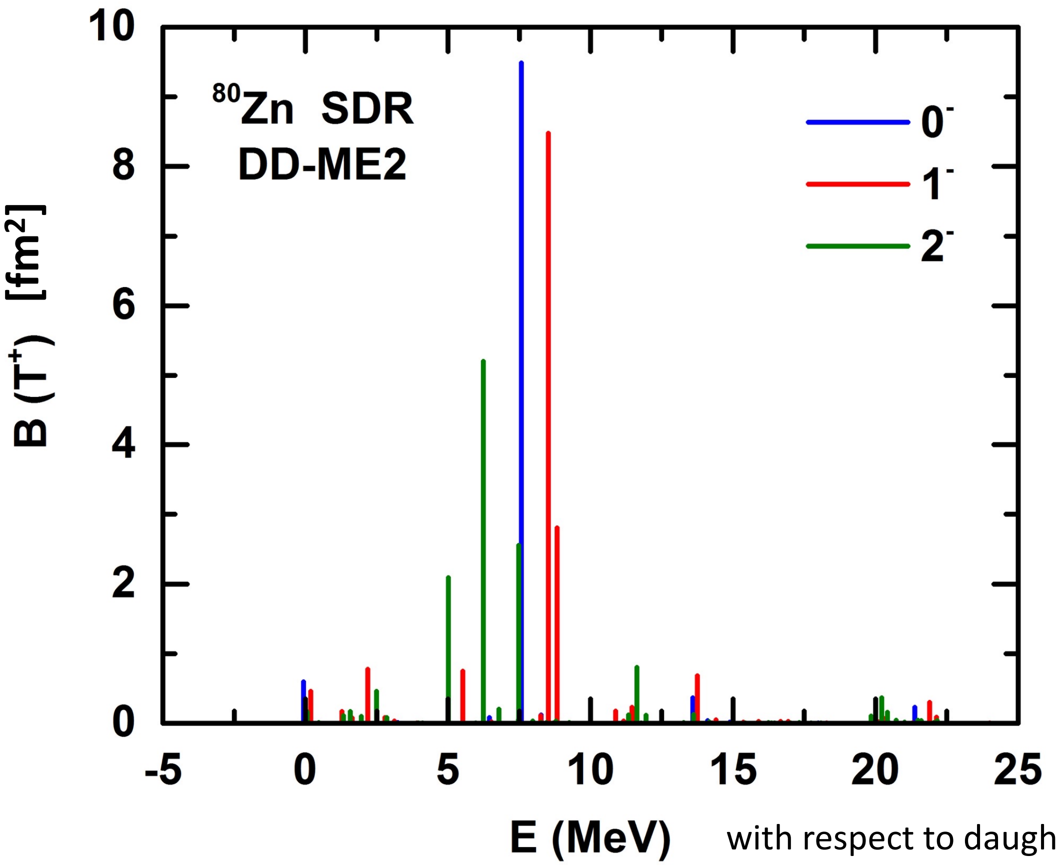
J$^\pi$ = 1$^+$



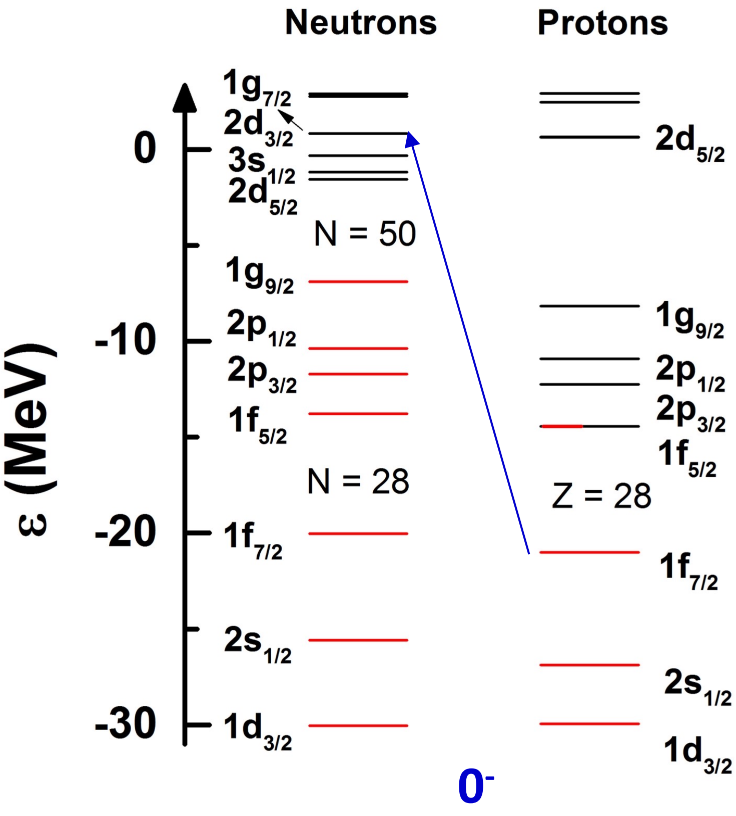
- ✓ GT$^+$ transitions are almost blocked (Ikeda sum rule = 60)
- ✓ Pairing correlations or transitions across major shells make little transition strength possible

Spin-Dipole strength distribution (T^+)

- **SD operator** $\hat{F}^{\pm}_{\mathrm{SDR}} = \sum_{i=1}^{A} [r_i Y_1(i) \otimes \boldsymbol{\sigma}(i)]_{J=0,1,2} \tau_{\pm}(i)$ **$J^\pi = 0^-, 1^-, 2^-$ ΔS=1, ΔL=1**



with respect to daughter nucleus ^{80}Cu



- ✓ Spin-Dipole transitions have significant strength
- ✓ SD transitions will dominate EC cross section of ^{80}Zn

Spin-Dipole strength distribution (T^{+})

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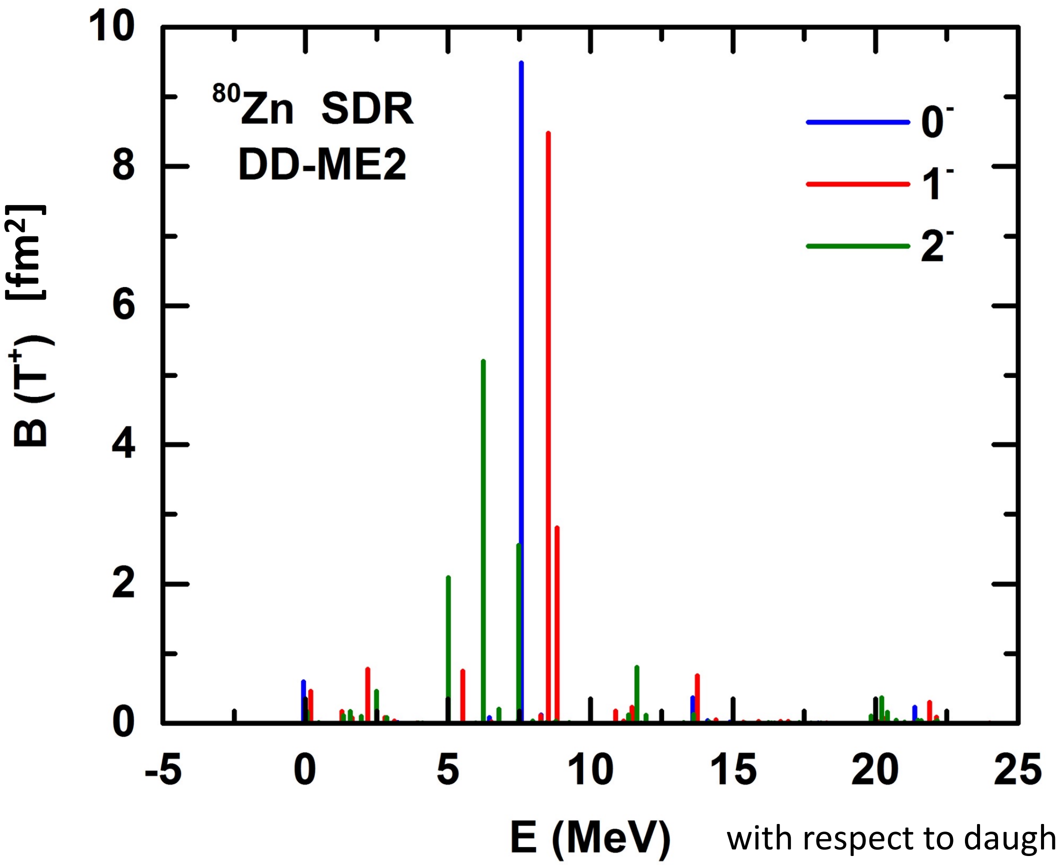
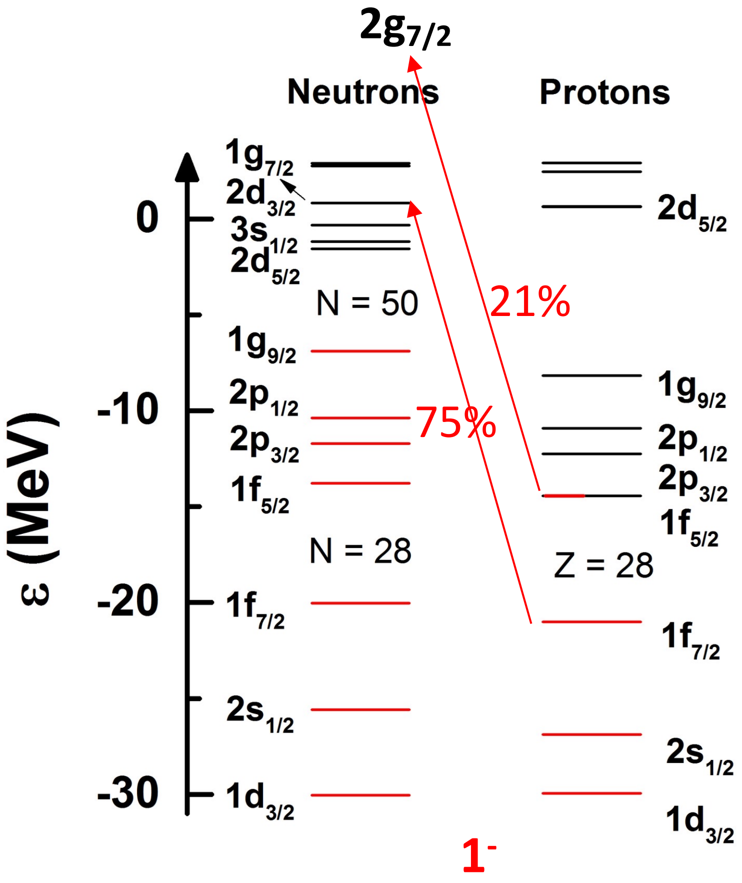


with respect to daughter nucleus ^{80}Cu



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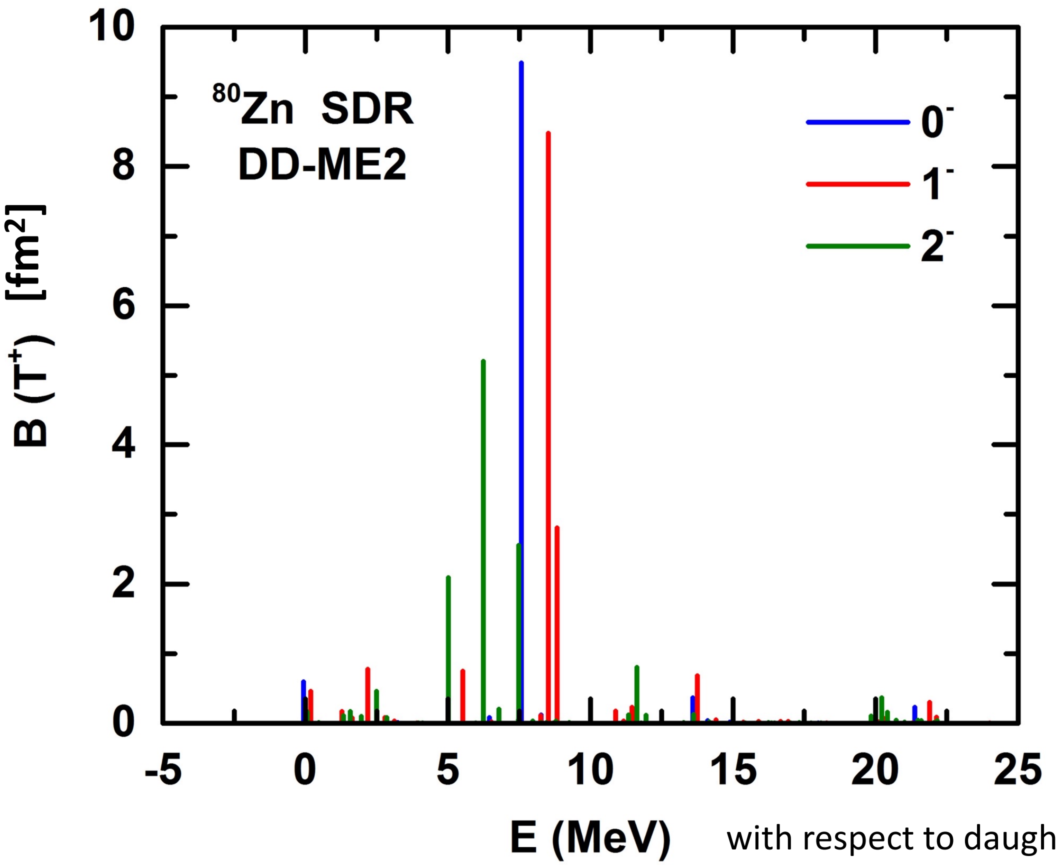
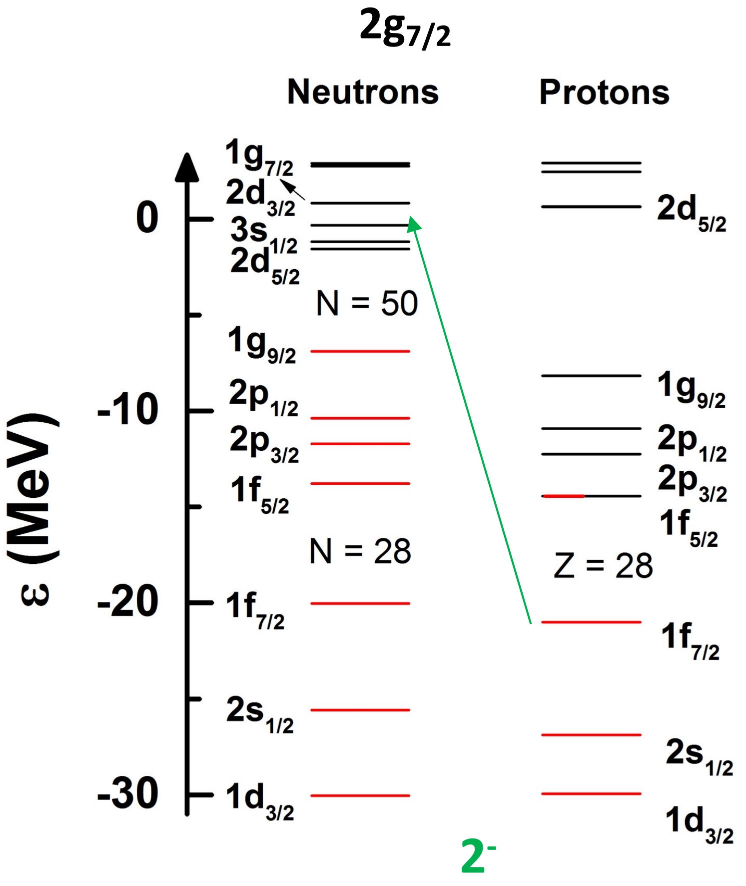


with respect to daughter nucleus ^{80}Cu



- ✓ Spin-Dipole transitions have significant strength
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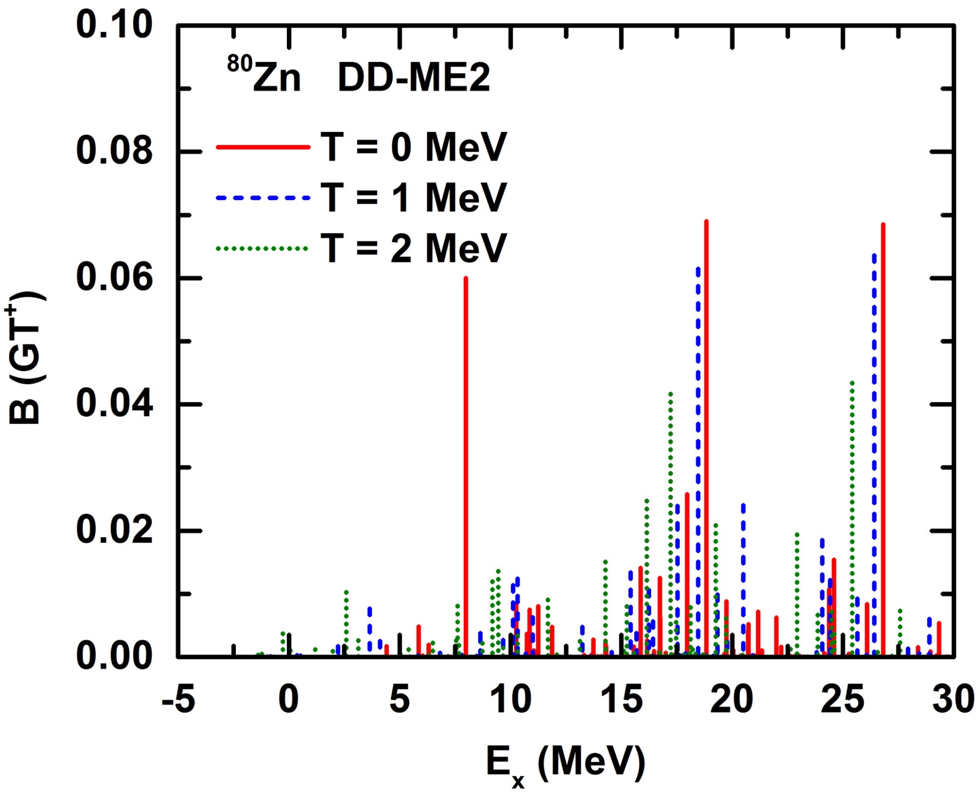
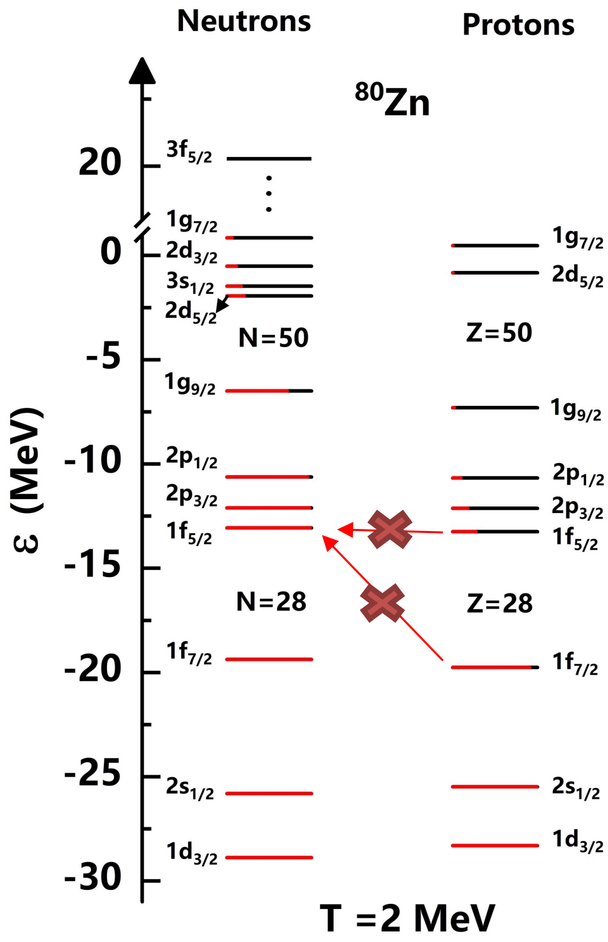
Temperature effects

GT transitions at finite temperature



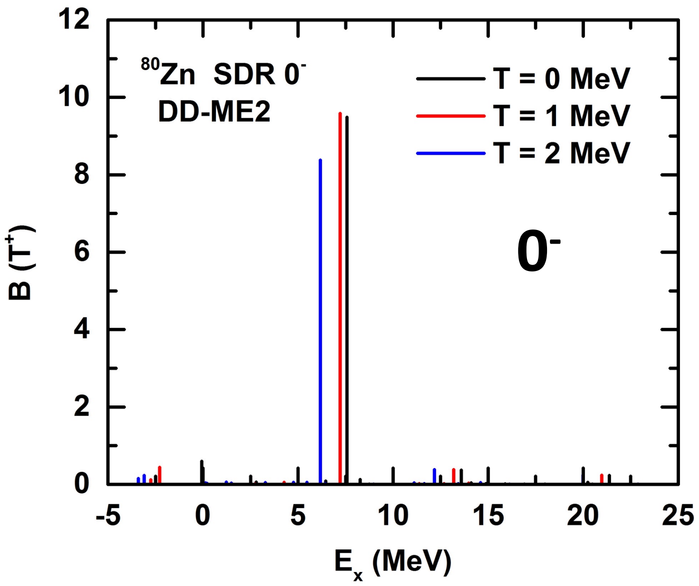


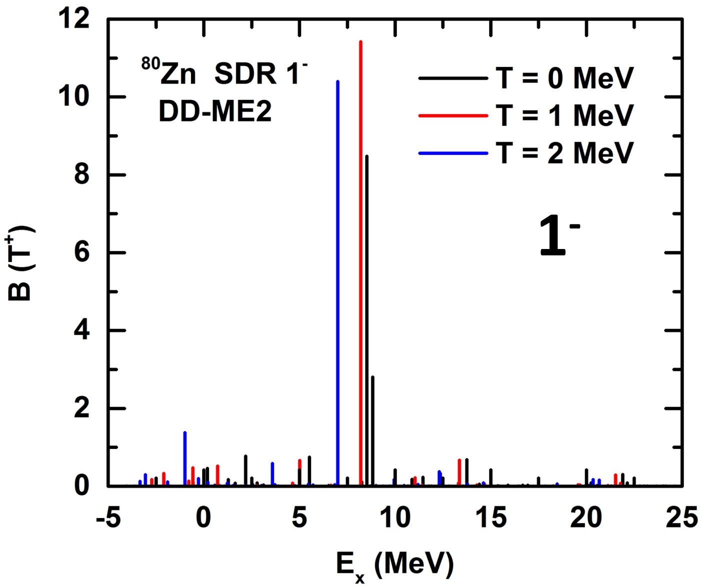
✓ Even temperature cannot unblock the GT$^+$ transition due to large neutron excess

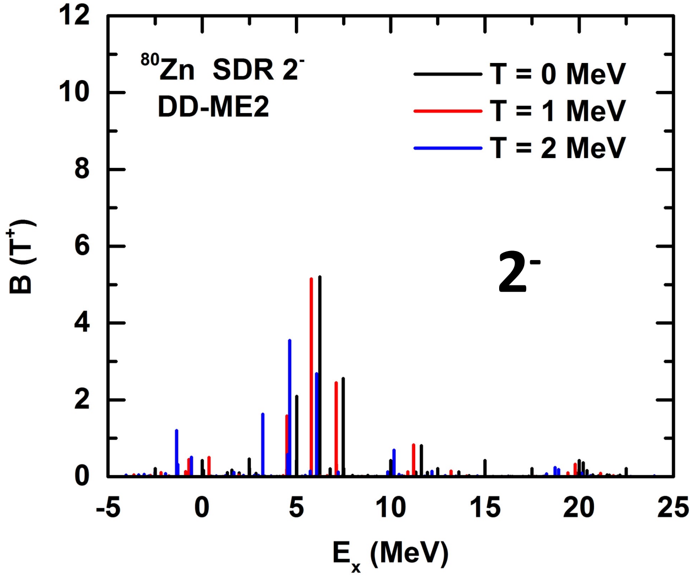
➢ In stellar environment, GT$^+$ still cannot contribute much to EC rates

Temperature effects

Spin Dipole Transitions at finite temperature





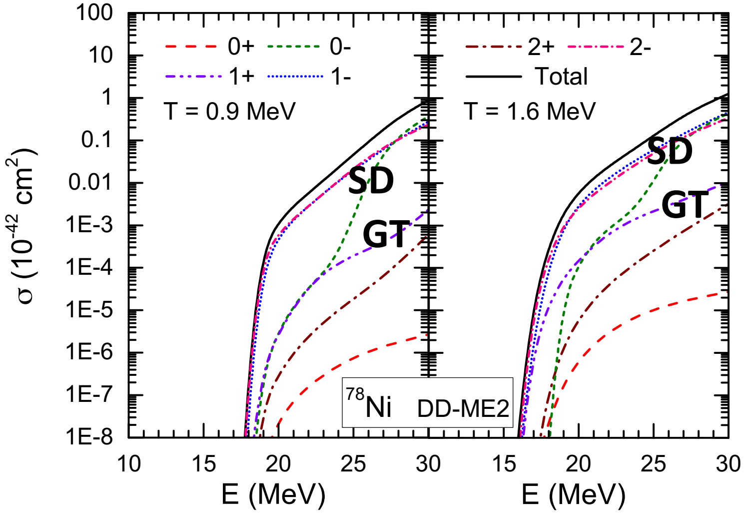


- ✓ Temperature decreases energies, but changes are small.
- ➢ Spin-dipole transition data measured at Lab (zero temperature) can still be applied to EC study in supernova.

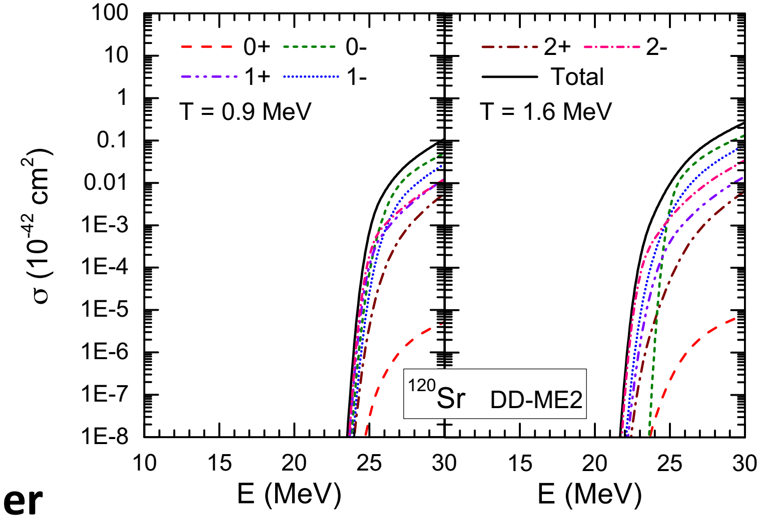
L. Guo, W. L. Lv, Y. F. Niu, D. L. Fang, B.S. Gao, K. A. Li, and X. D. Tang, Phys. Rev. C submitted

Electron capture cross sections

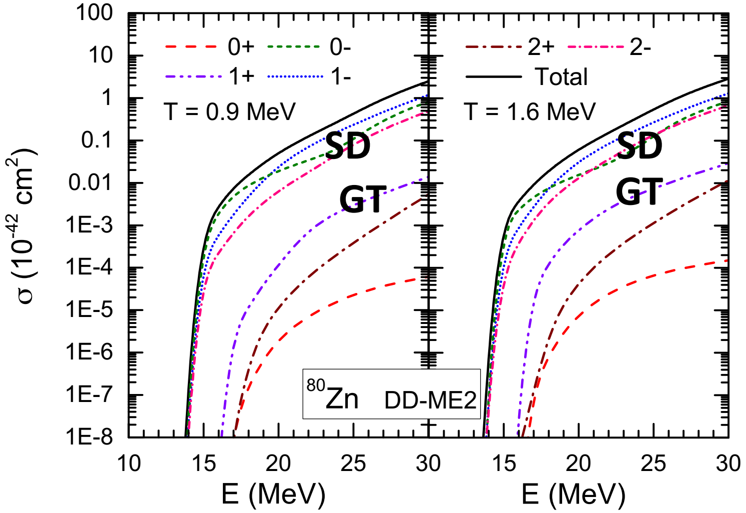
N = 50

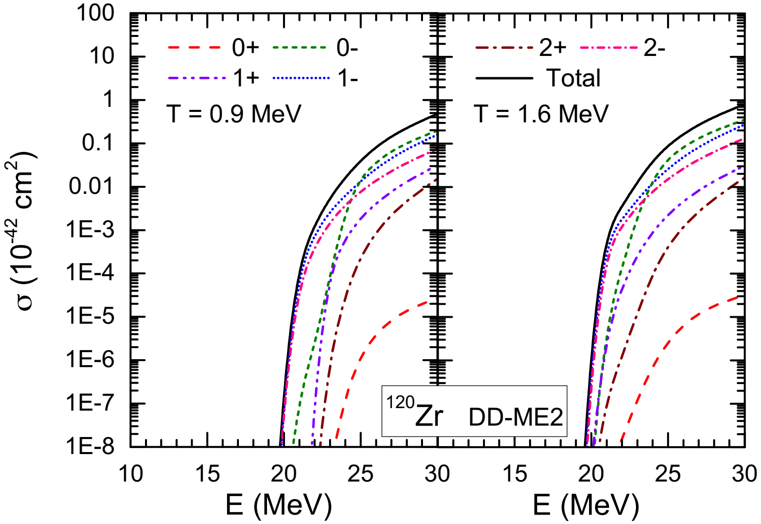


N ≃ 82



smaller →

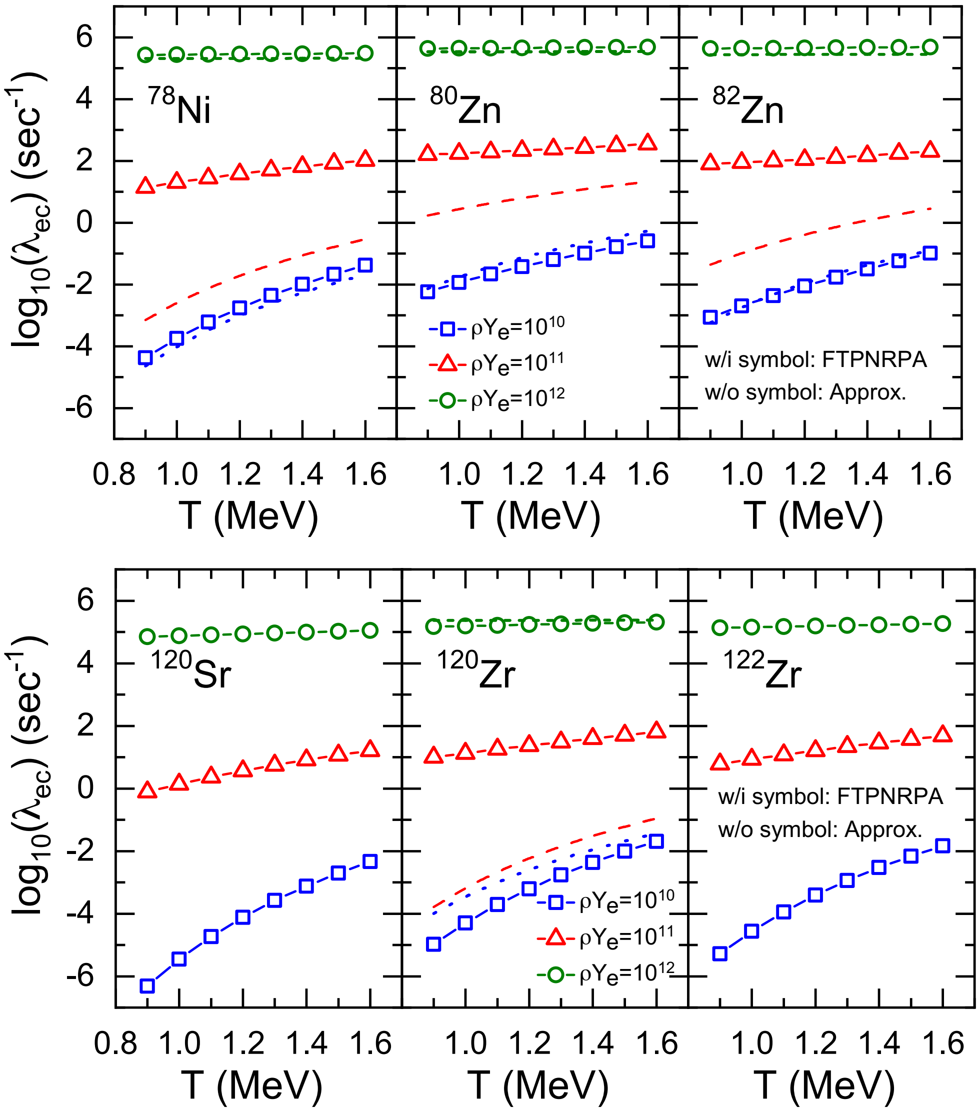




- For these neutron rich nuclei, spin dipole transitions dominate the cross section
- Even at high temperatures, GT transitions are not considerably unblocked

Electron capture rates

Electron capture rates at different stellar environment



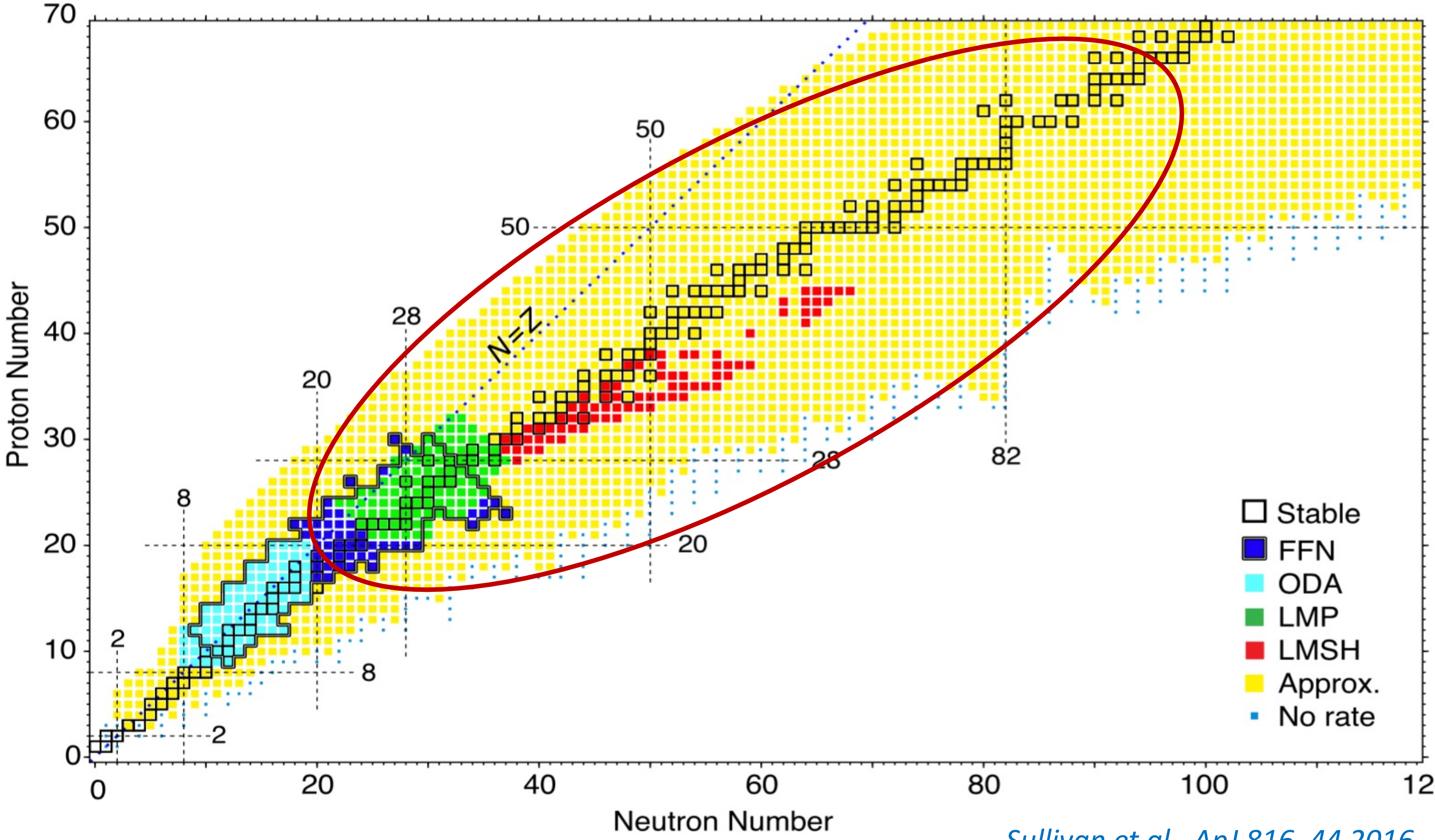
Z. H. Wang, and Y. F. Niu, in preparation

- With the increase of electron density, the EC rates are increased by several orders of magnitude.
- At lower electron densities, the EC rates have big increase with temperature, but at high densities, the rate is not sensitive to temperature.
- Approx.

$$\lambda = \frac{(\ln 2)B}{K}\left(\frac{T}{m_e c^2}\right)^5[F_4(\eta) - 2\chi F_3(\eta) + \chi^2 F_2(\eta)]$$

Rates from approximation formula at 10^{11} g/cm^3 is much underestemated compared to our results

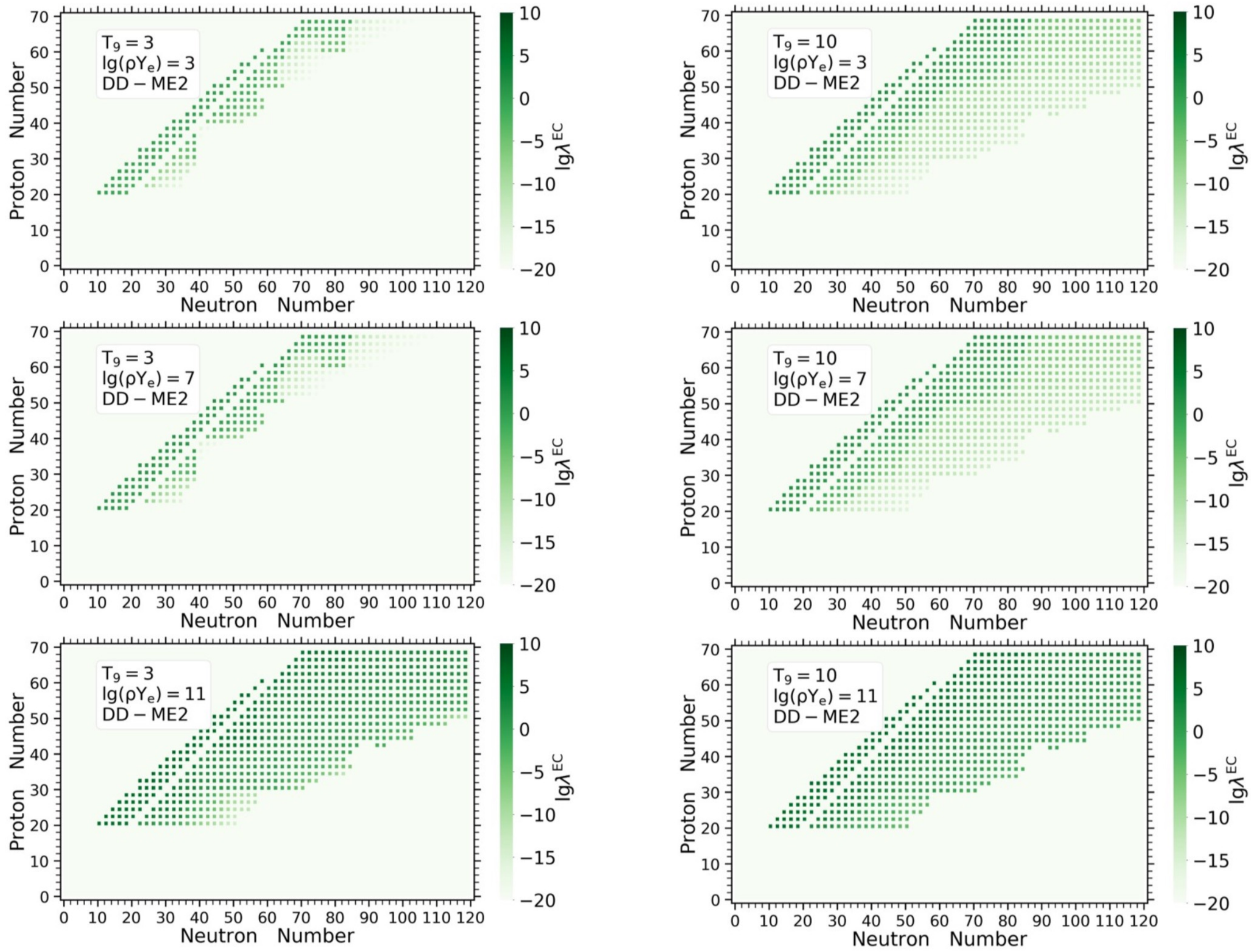
Systematic calculations for Z=20-68 even-even nuclei



Sullivan et al., ApJ 816, 44 2016

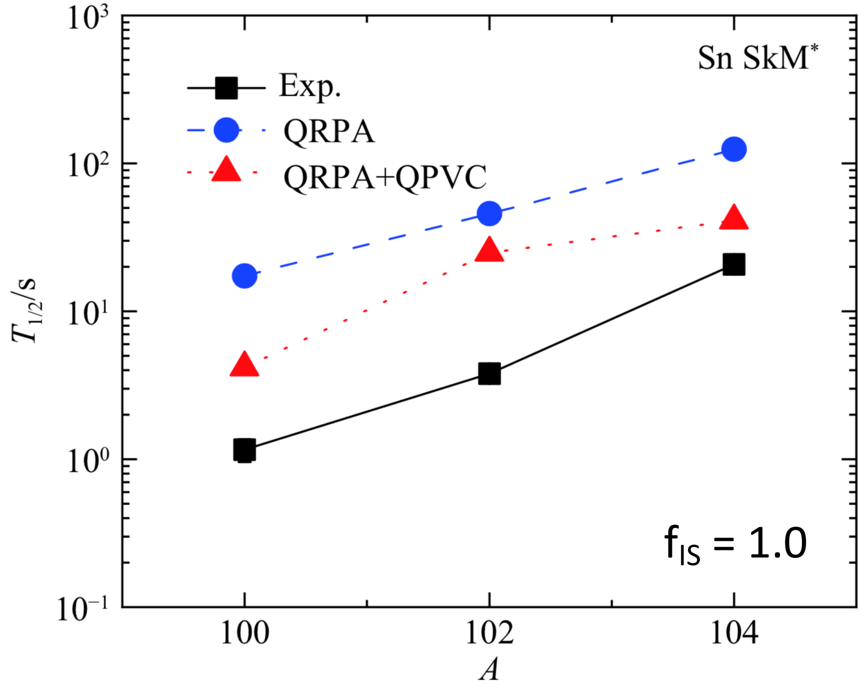
- FTRRPA model is used for systematic calculation of EC rates for Z=20-68 even-even nuclei
- Only GT transitions are considered for simplification.

Systematic calculations for Z=20-68 even-even nuclei



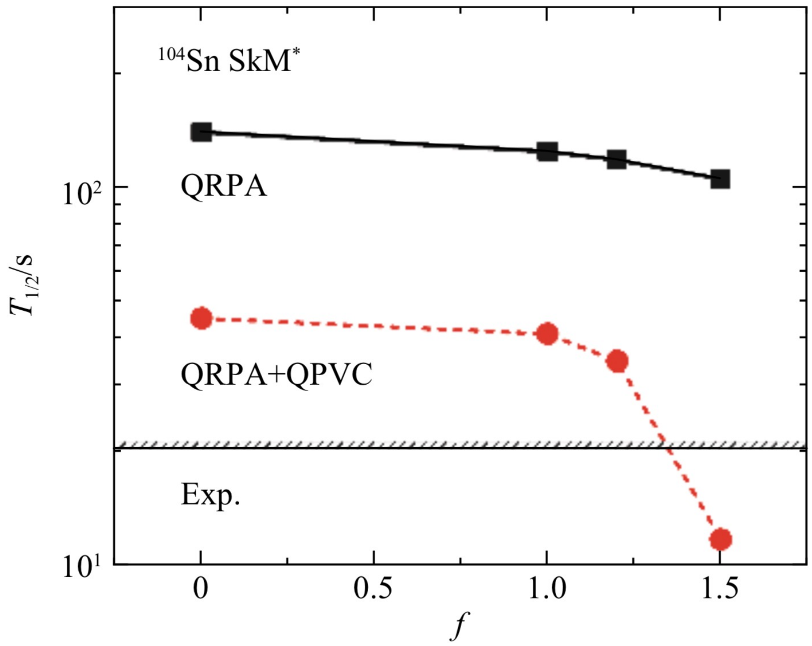
β^+/ EC Half-lives by QRPA+QPVC

- β^+/ EC Half-lives of neutron-deficient nuclei



- The β^+/ EC half-lives are overestimated by one order of magnitude.
- QPVC reduces the half-lives of these nuclei.

- The effect of isoscalar pairing



- With the increase of isoscalar pairing strength, β^+/ EC half-lives decrease.
- QPVC results decrease faster than QRPA.
- QRPA results cannot reproduce exp. even at large f_{IS}, while QPVC reproduces exp. at f_{IS} ~ 1.25.

Summary and Perspectives

Towards the understanding of origin of heavy elements

- Accurate Nuclear Physics Inputs: β-decay
  - ✓ Go beyond RPA/QRPA: we developed self-consistent RPA+PVC / QRPA+QPVC model
  - ✓ Successfully describe the GT resonance and β-decay half-lives in doubly magic nuclei and superfluid nuclei using the same Skyrme interaction
- Electron Capture Rates in core-collapse supernova
  - ✓ FTRPA provides a universal tool for the calculation of EC rates for core-collapse supernova

Perspective:

- Extend QRPA+QPVC model to finite-temperature case, and apply it for EC study in core-collapse supernova

Acknowledgement

Collaborators:

- Sichuan University: Bai Chunlin
- IMP: Fang Dongliang, Gao Bingshui, Li Kuoang, Tang Xiaodong, Xu Xiaodong
- Anhui University: Niu Zhongming
- Lanzhou University: Qu Teng, Guo Liang, Wang Zhiheng, Lv Wanli, Long Wenhui

- University of Milan: P. F. Bortignon, G. Colo, E. Vigezzi
- University of Aizu & RIKEN: Hiroyuki Sagawa
- Zagreb University: N. Paar, A. Ravlic

Thank you!