

# Spin-Parity Decomposition of Spin Dipole Resonances and Tensor Interaction Effects

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# Outline

## Residual interaction effects of spin-isospin responses

- GT strength (as an introduction)
- SD strength
  - Tensor force effects

## New data and analysis of $^{208}\text{Pb}(p,n)$

- Spin-parity decomposition ( $J^\pi=0^-, 1^-, 2^-$ ) of SD strengths
- Tensor force effects on SD strengths
  - Softening for  $1^-$  by triplet-even tensor force
  - Softening for  $0^-$  by triplet-odd tensor force

## Summary

# Giant Resonances

## Collective motion

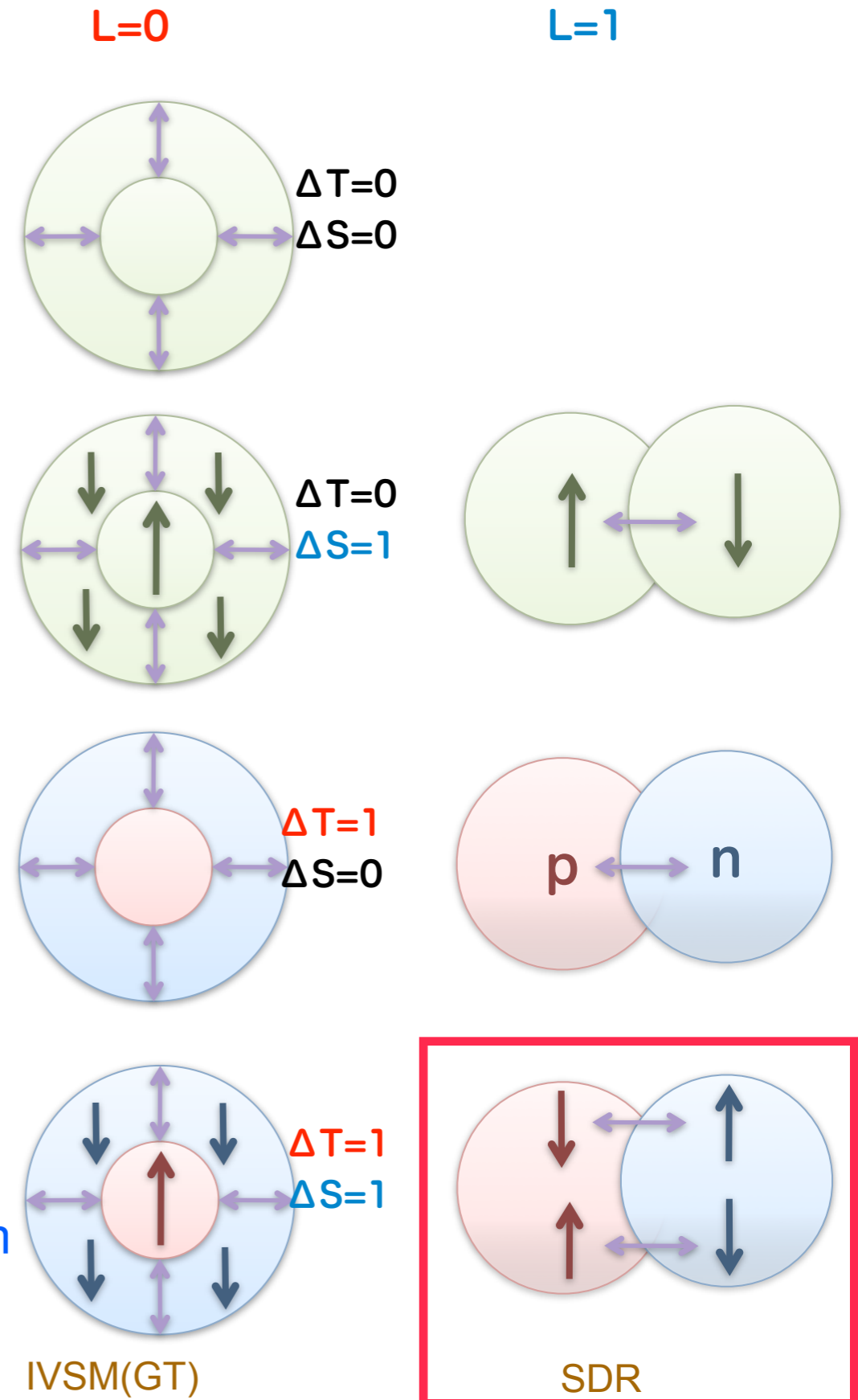
- **Many** nucleons participate **coherently**
- Classified by
  - Multipolarity : L
  - Spin : S
  - Isospin : T

## IsoVector (IV) Spin-flip Dipole (SD)

- $\Delta S = 1$  and  $\Delta T = 1$
- Macroscopic picture
  - **Dipole** oscillation of  $p \uparrow$  ( $p \downarrow$ ) against  $n \downarrow$  ( $n \uparrow$ )

## Information from GR

- **Resonance peak**  $\rightarrow$  **Residual interaction**
- **Total strength**  $\rightarrow$ 
  - Quark degrees of freedom
  - Neutron skin thickness



# Spin-Isospin Modes and Sum Rule

Spin-isospin transition operators [GR = Coherent 1p1h excitations]

- IV Spin-**scalar**  $\hat{O}_{\pm} = \sum_{\mathbf{k}} t_{\pm}(\mathbf{k}) f(\mathbf{r}_{\mathbf{k}})$
- IV Spin-**vector**  $\hat{O}_{\pm} = \sum_{\mu} \sum_{\mathbf{k}} t_{\pm}(\mathbf{k}) \sigma_{\mu}(\mathbf{k}) f(\mathbf{r}_{\mathbf{k}})$

Model-independent sum-rule

$$\underbrace{\sum_m \left| \langle m | \hat{O}_- | 0 \rangle \right|^2}_{\equiv S^-} - \underbrace{\sum_n \left| \langle n | \hat{O}_+ | 0 \rangle \right|^2}_{\equiv S^+} = \left[ N \langle (f(r))^2 \rangle_n - Z \langle (f(r))^2 \rangle_p \right] \times \begin{cases} 1 : \text{scalar} \\ 3 : \text{vector} \end{cases}$$

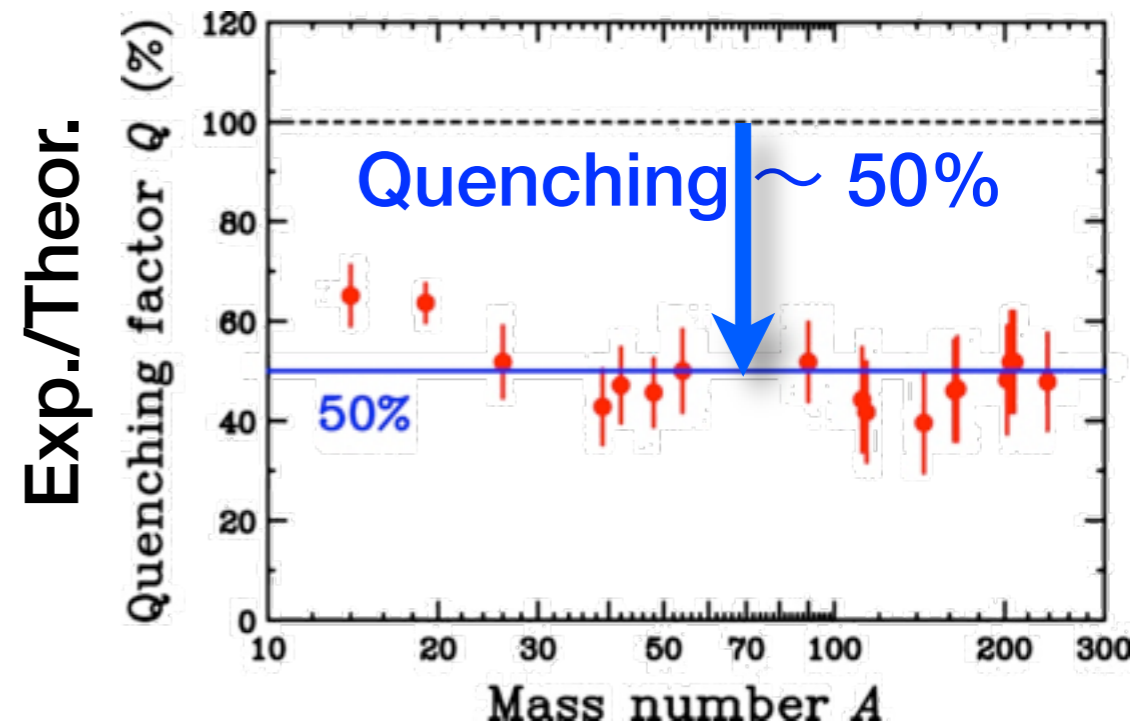
neutron                      proton

GT sum-rule (Ikeda's sum-rule)

- Gamow-Teller (L=0,  $\Delta S=1$ ,  $\Delta T=1$ )

$$S^-(\text{GT}) - S^+(\text{GT}) = 3(N - Z)$$

50% quenching of GTR  $\left\{ \begin{array}{l} \bullet \text{ Config. mix. (2p2h)} \\ \bullet \Delta \text{ (quark)} \end{array} \right.$



# Residual interaction effects on GTR

## Landau-Migdal interaction at $q=0$

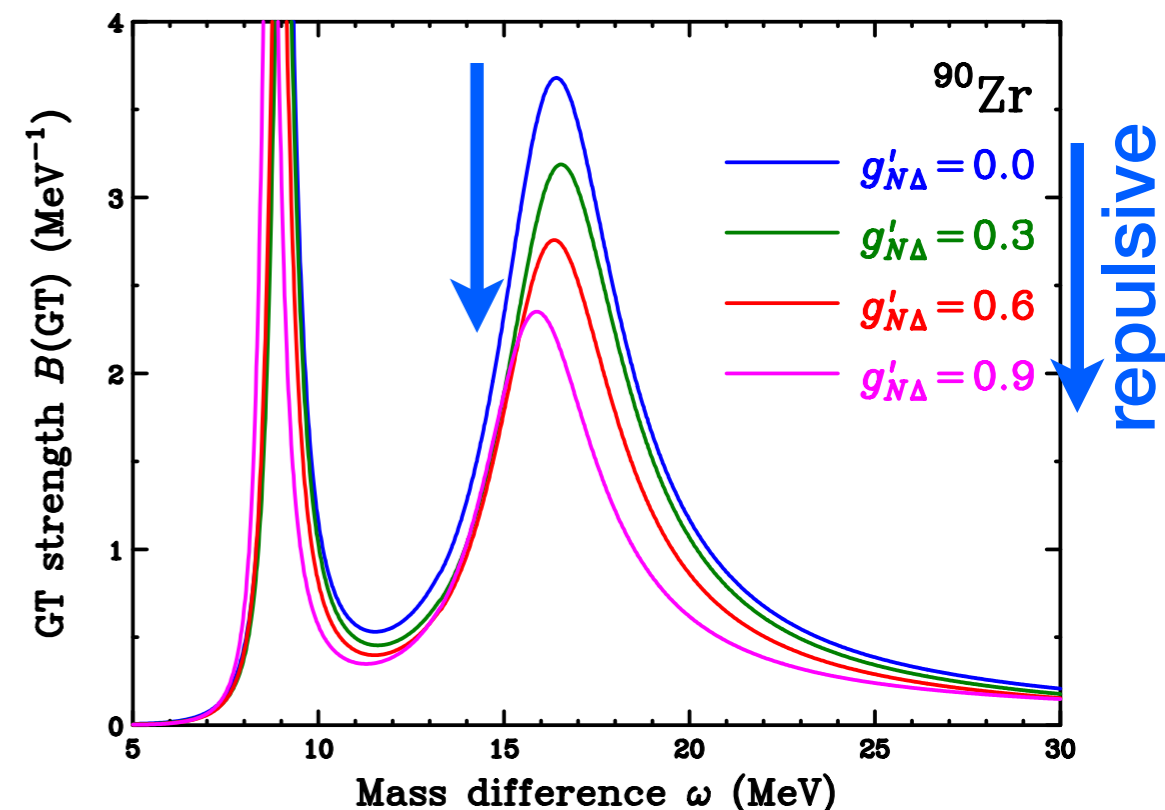
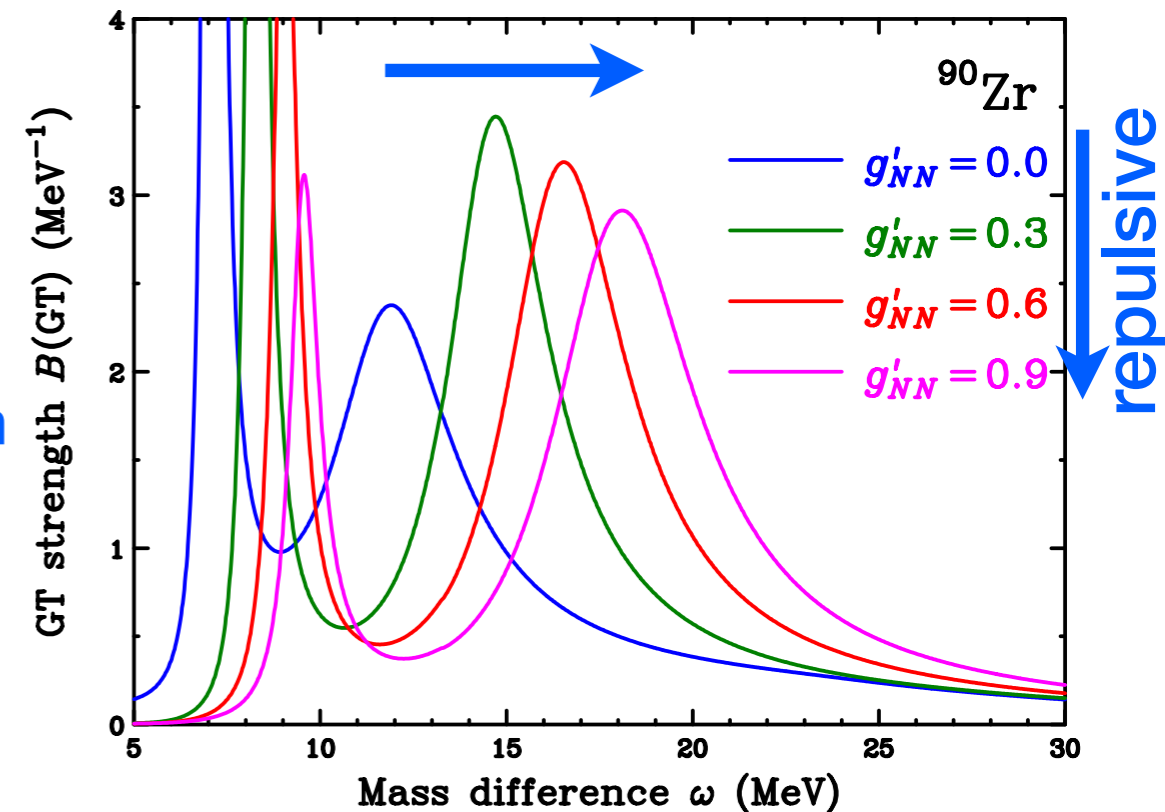
$$V_{\text{LM}} = \frac{f_{\pi NN}^2}{m_{\pi}^2} \underbrace{g'_{NN}}_{\substack{\text{repulsion between} \\ \text{particle and hole (ph)}}} + \frac{f_{\pi NN} f_{\pi N\Delta}}{m_{\pi}^2} \underbrace{g'_{N\Delta}}_{\substack{\text{coupling between} \\ \text{ph and } \Delta h}}$$

## LM parameter $g'_{NN}$

- Determine the p-h repulsion
- Larger  $g'_{NN} \rightarrow$  Stronger repulsion
  - Peak shifts to higher  $\omega$
  - Collectivity becomes large

## LM parameter $g'_{N\Delta}$

- Determine the coupling to  $\Delta$
- Larger  $g'_{N\Delta} \rightarrow$  Stronger coupling
  - Strength becomes small (quenched)  
[Strength moves to  $\Delta$  region]



# Comparison with experimental data

## $g'_{NN}$ dependence on GTR

- GTGR peak position
  - Strongly depends on  $g'_{NN}$
  - $g'_{NN} = 0.6 \pm 0.1$
- Weak  $g'_{N\Delta}$  dependence

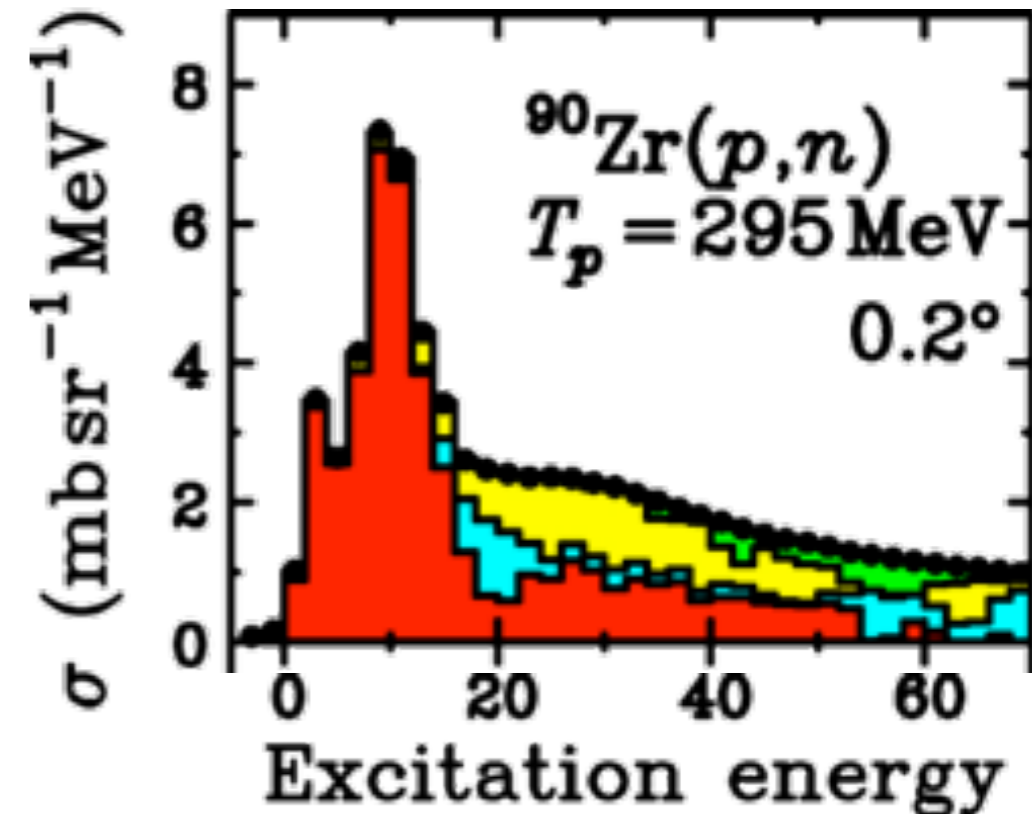
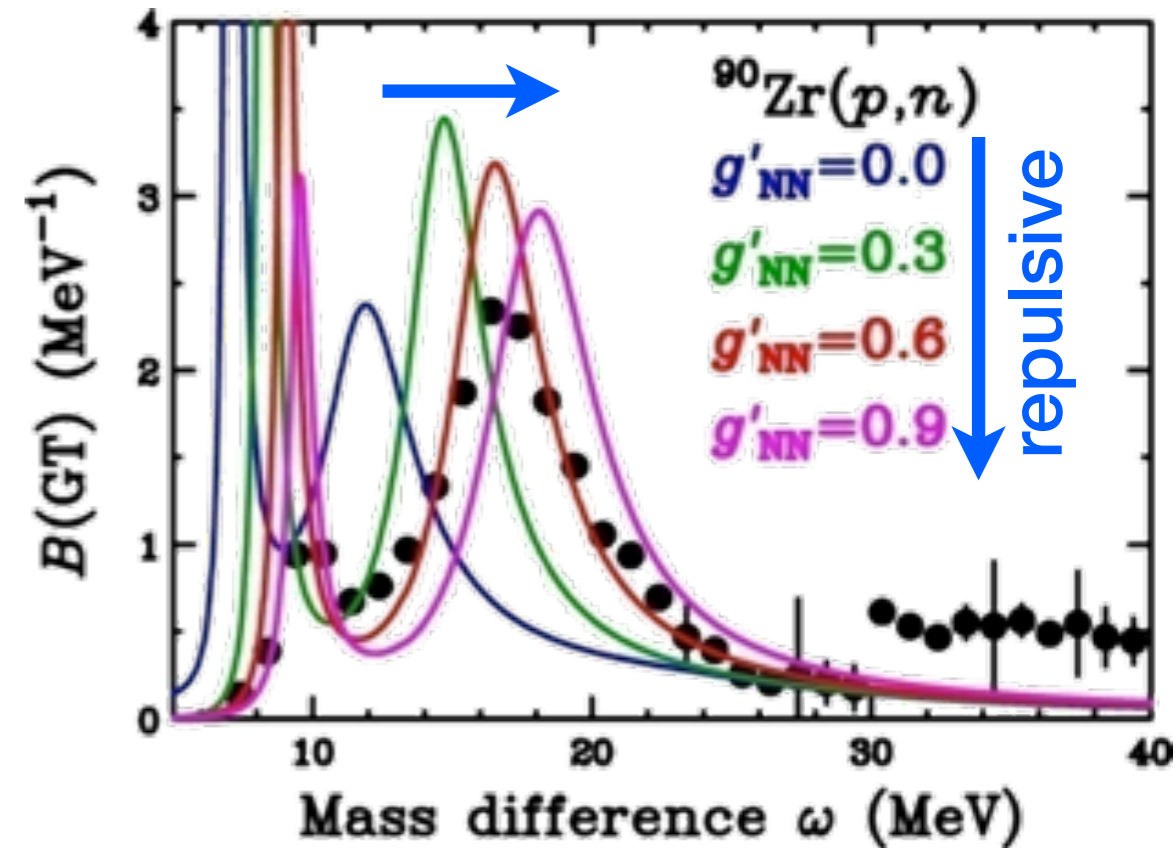
## $g'_{N\Delta}$ dependence on GT quenching Q

- $Q = 0.86 \pm 0.07$  ← from MD analysis
  - 2p2h effects are dominant
- Q evaluated in RPA
  - Strongly depends on  $g'_{N\Delta}$

$$\underline{g'_{N\Delta} = 0.35 \pm 0.16}$$

## How about other modes (SD resonances)

- Distribution (information on effective interaction)
  - Tensor force effects
- Quenching ?



# SD strength distributions

## Exp. strength

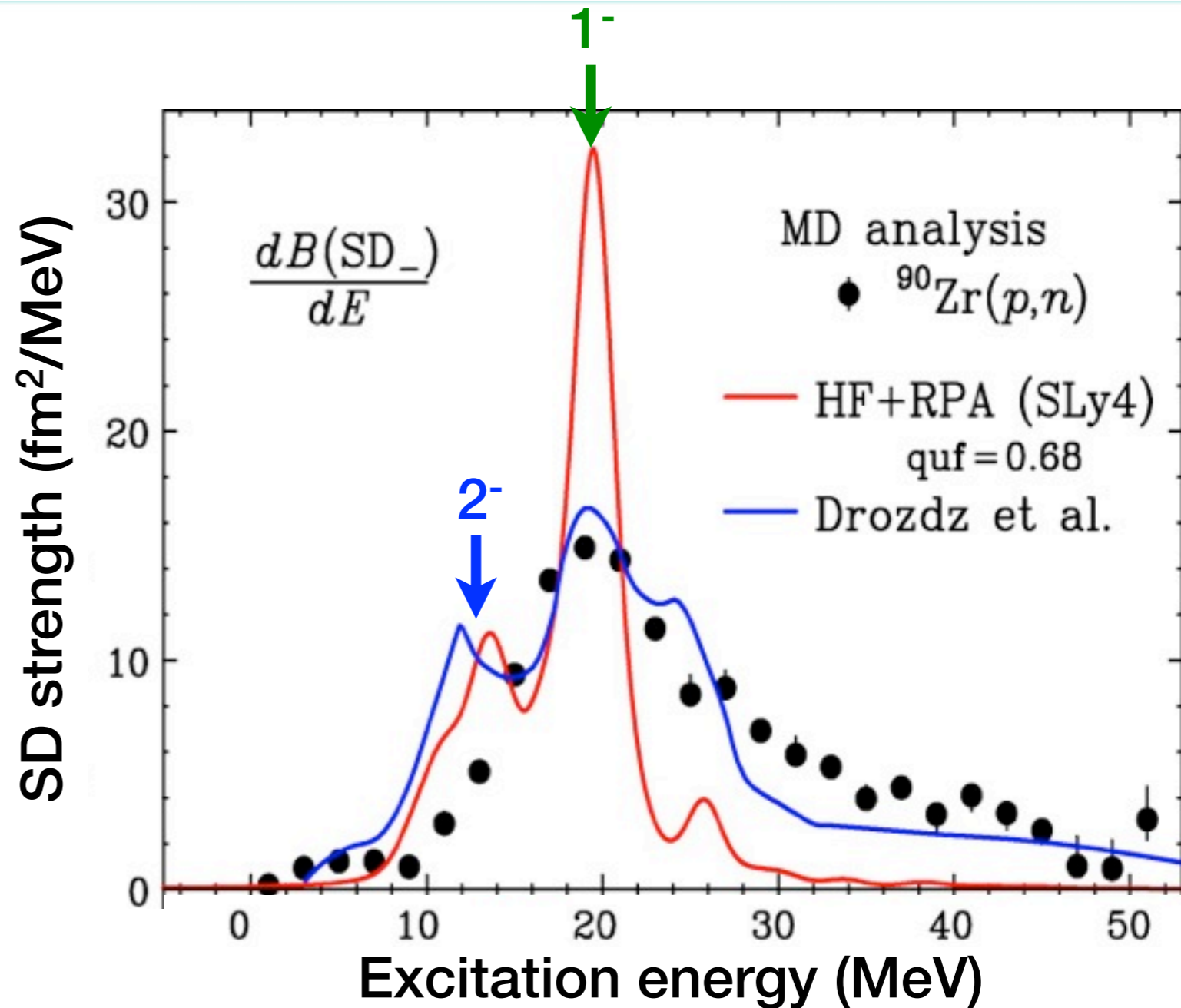
- Extends up to 50 MeV
- Configuration mix.
- **Single bump**

## HF+RPA (1p1h)

- Underestimation at  $E_x > 25$  MeV
- 2p2h is important
- **Three bumps**
- $E_x(2^-) > E_x(1^-)$

## Second-order RPA

- Reasonably reproduce in whole region
- **Three bumps**



Each  $\Delta J^\pi$  ( $0^-$ ,  $1^-$ ,  $2^-$ ) distributions  $\rightarrow$  Inconsistent (tensor correlation?)

# Tensor force effects in nuclei

## Shell-structure due to tensor force

- Due to tensor correlations, excess neutrons ( $j_>$ )
  - Pull-down proton orbit with  $j_<$
- Experimental data for Sb are well reproduced

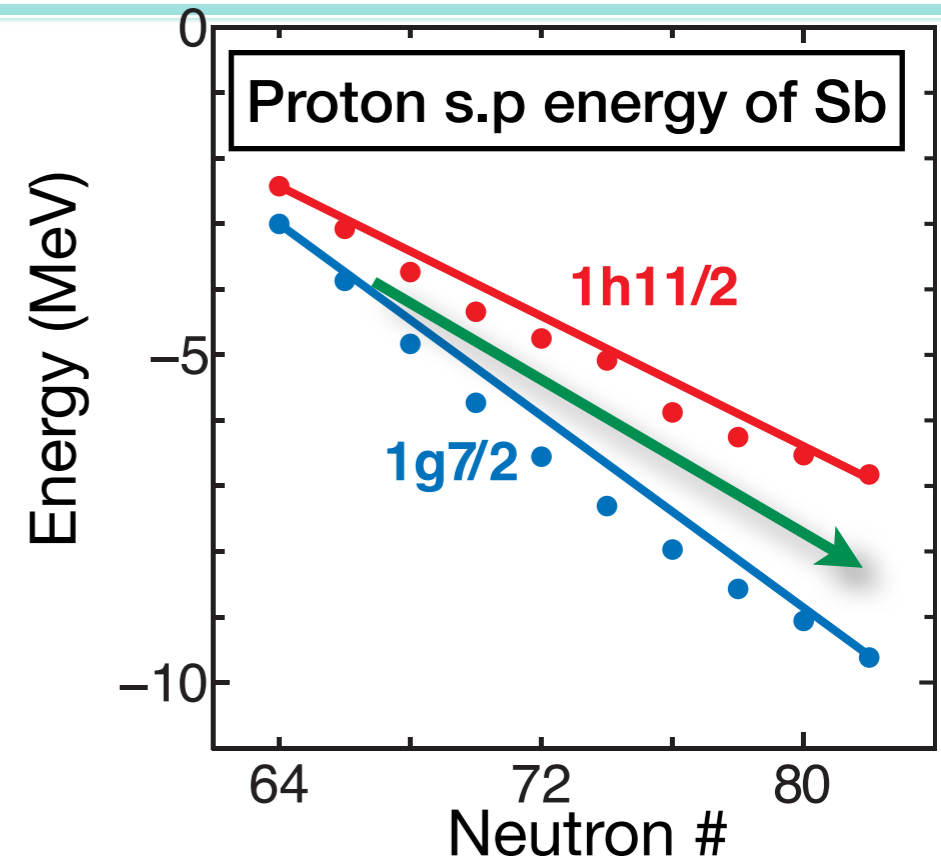
## Tensor effects in Skyrme int.

- Additional contribution to normal spin-orbit pot.

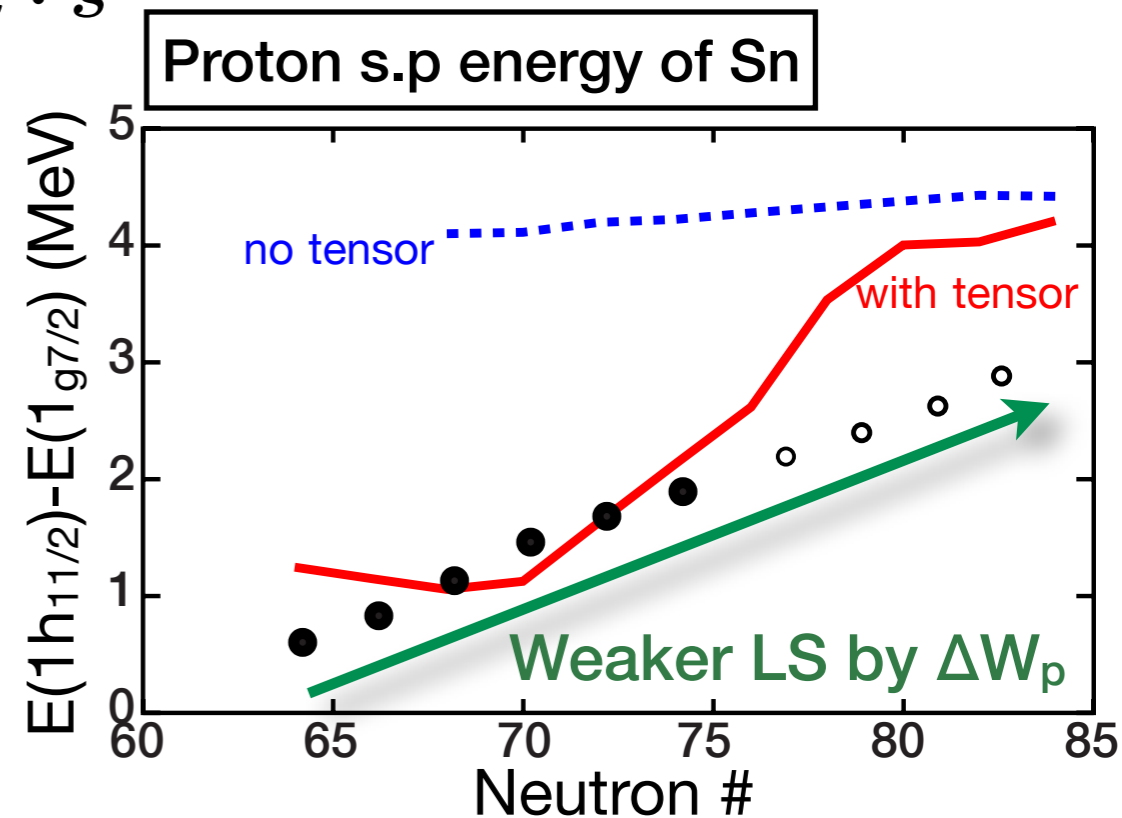
$$\Delta W_p = \underbrace{[(\alpha_C + \alpha_T) J_p]}_{pp} + \underbrace{[(\beta_C + \beta_T) J_n]}_{pn} \vec{l} \cdot \vec{s}$$

- $\beta \equiv \beta_C + \beta_T \simeq 120 \text{ MeV} \cdot \text{fm}^5$
- $\alpha \equiv \alpha_C + \alpha_T \simeq 120 \text{ MeV} \cdot \text{fm}^5$
- Tensor terms depend on central-ex. terms
- Negative  $\alpha$  values are also proposed

Further exp. informations are important



T. Otsuka et al., PRL 95, 232502 (2005).



D.M. Brink and FL. Stancu, PRC 75, 064311 (2007).

# Tensor force effects on SD strengths

## HF+RPA prediction for $^{208}\text{Pb}$

- HF : Tensor forces hardly change LS splitting [ (nn/pp contribution) + (np contribution)  $\sim 0$  ]

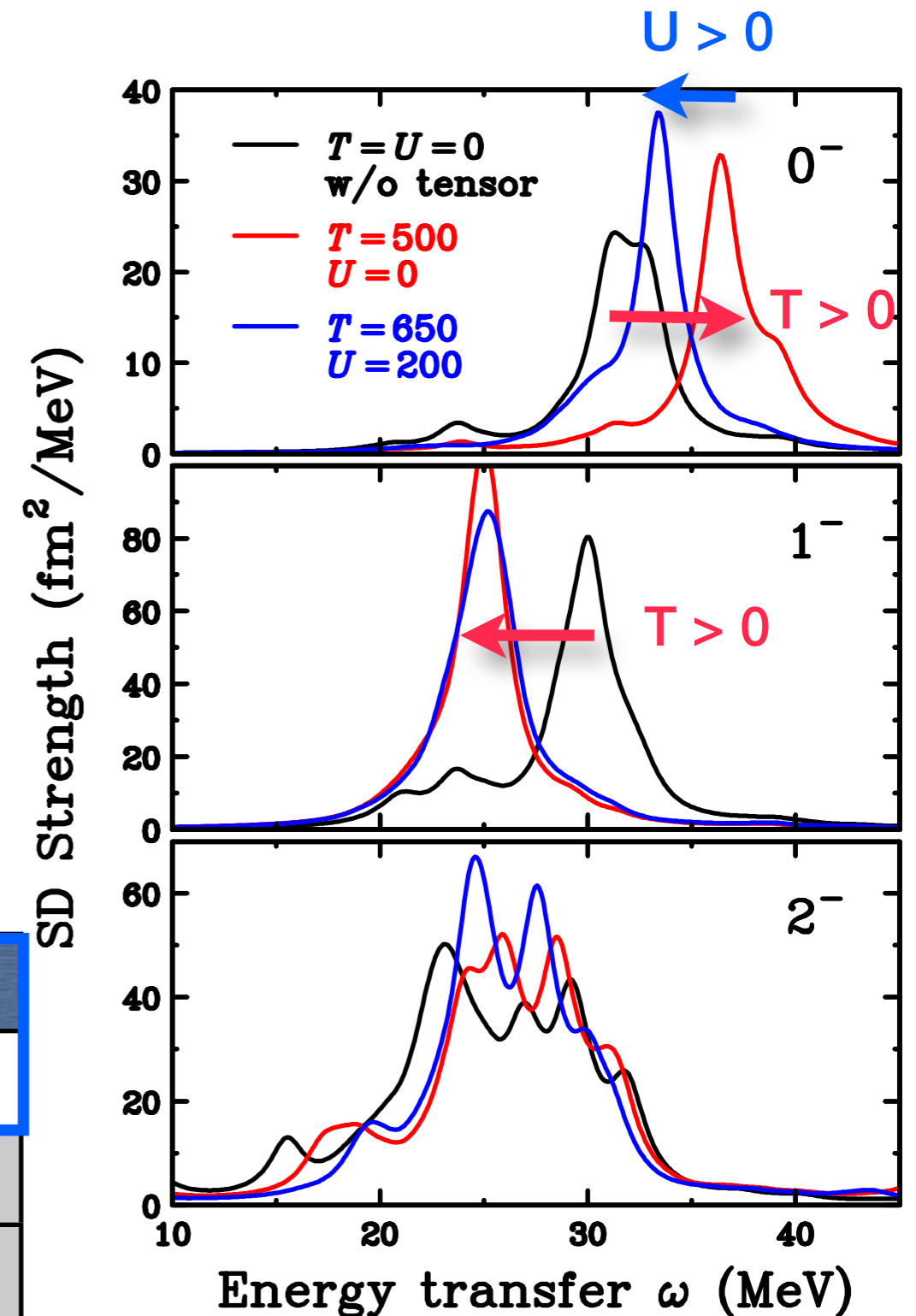
- RPA : Tensor effects depend on  $J^\pi$

$$V^T \propto \underbrace{T(\text{TE})}_{\text{triplet-even}} + \underbrace{U(\text{TO})}_{\text{triplet-odd}}$$

$$\alpha_T = \frac{5}{12} U \text{ for } nn/pp$$

$$\beta_T = \frac{5}{24} (T + U) \text{ for } np$$

	$T > 0$ ( $\beta_T > 0$ )	$U > 0$ ( $\alpha_T > 0$ )	$U < 0$ ( $\alpha_T < 0$ )
$0^-$	hardening	softening	hardening
$1^-$	softening	insensitive	
$2^-$	insensitive		



Separated SD strengths would constrain both  $T$  and  $U$  ( $\alpha_T$  and  $\beta_T$ )

# This “experimental” work for $^{208}\text{Pb}(p,n)$

## New data and analysis for $^{208}\text{Pb}(p,n)$

- Cross sections and analyzing powers at  $\theta = 0.0^\circ \sim 10.0^\circ$  (11 angles)
- Complete sets of polarization transfers at  $\theta = 0.0^\circ \sim 7.0^\circ$  (5 angles)

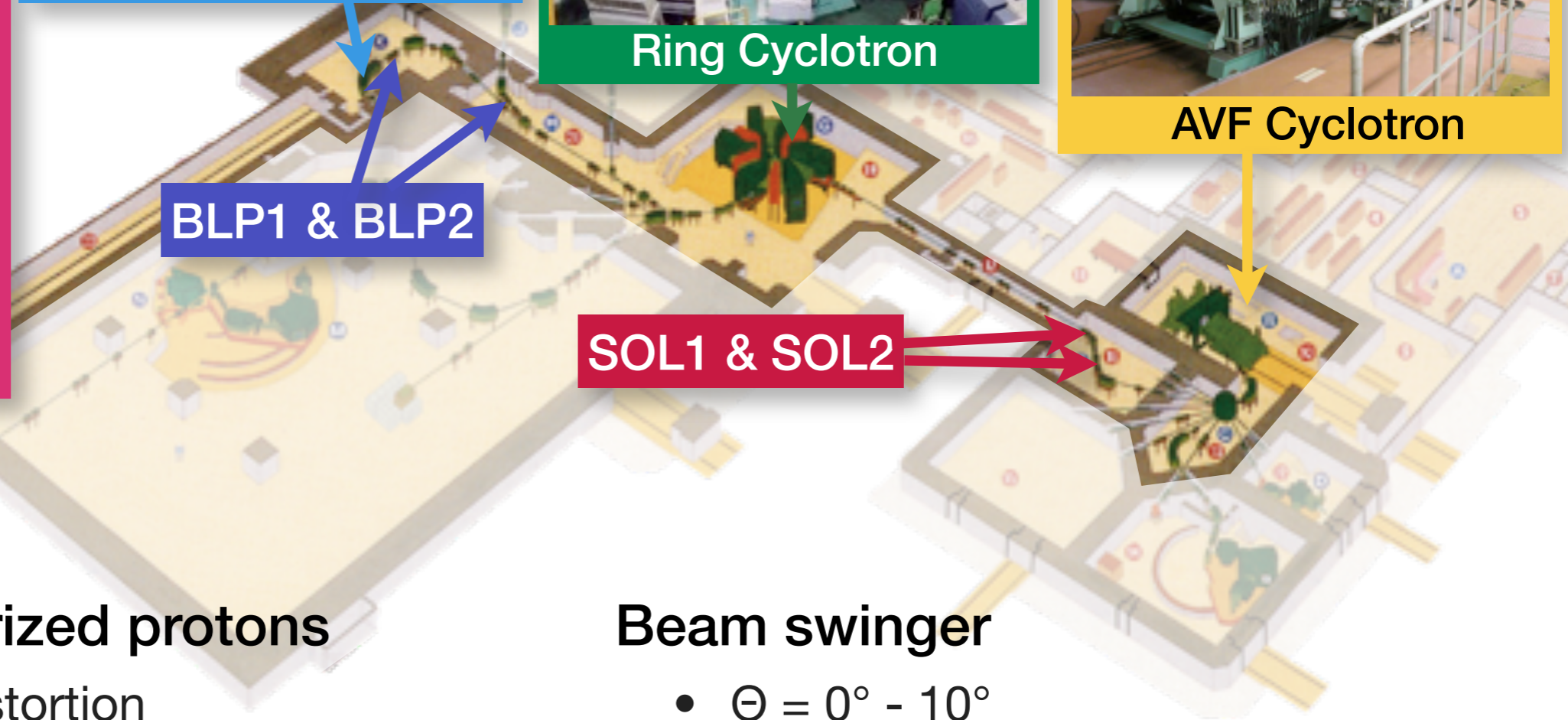
## Goal

- Spin-parity  $J^\pi$  separated SD strengths for  $^{208}\text{Pb}$ 
  - Distribution of separated SD strengths
    - Tensor correlation effects on SD strengths
  - Quenching of separated SD strengths
    - $J^\pi$  dependence  
(c.f. total SD strength is not quenched for  $^{90}\text{Zr}$ )

## Tools

- Polarization transfer  $D_{ij}$ 
  - Sensitive to  $\Delta J^\pi$  ( $0^-$ ,  $1^-$ ,  $2^-$ )
- Multipole decomposition analysis (MDA) with  $D_{ij}$ 
  - Based on reliable DWIA+RPA calculations

# Ring Cyclotron Facility @ RCNP, Osaka



## 300 MeV polarized protons

- Smallest distortion

## Beam polarization

- Controlled by two solenoids
- Measured by two BLPs (p+p)

## Beam swinger

- $\Theta = 0^\circ - 10^\circ$

## Neutron measurement

- NPOL3 with 70m TOF
- $D_{ij}$  measurement with NSR

# DWIA+RPA calculations

## Computer code: crdw

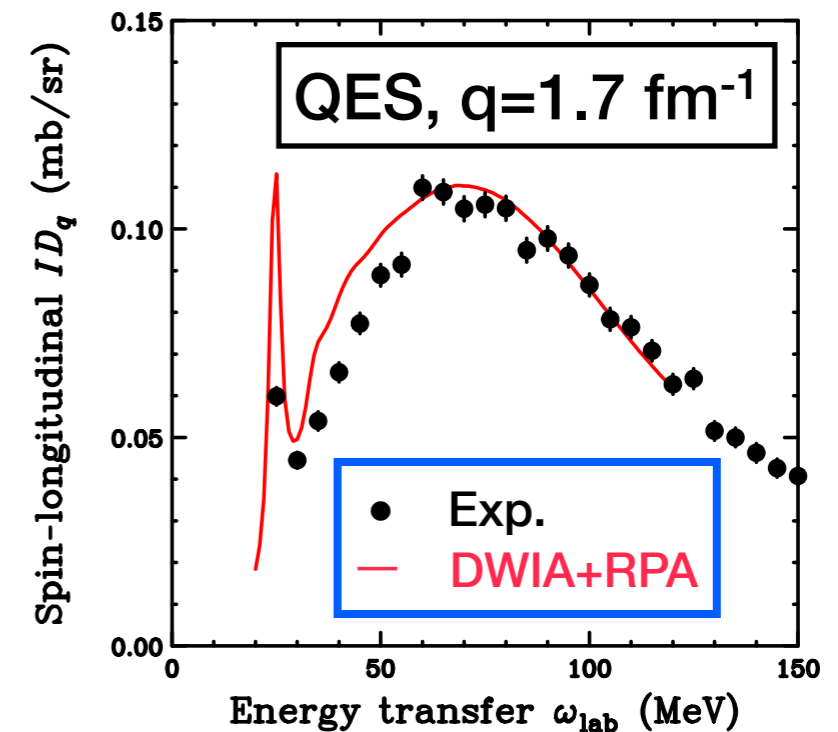
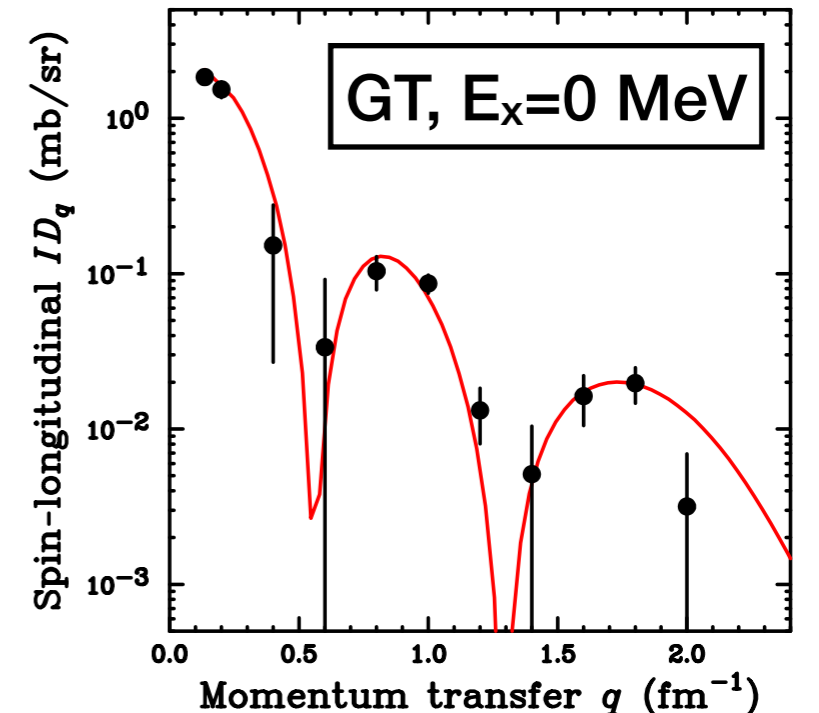
- Developed by Ichimura group

## DWIA

- Global optical potentials for  $^{208}\text{Pb}$ 
  - Proton: Hama et al.
  - Neutron: Shen et al.
- NN t-matrix
  - Franey and Love t-matrix

## RPA

- $\pi+\rho+g'$  p-h interaction
    - $g'_{\text{NN}} = 0.60 \pm 0.10$
    - $g'_{\text{N}\Delta} = 0.35 \pm 0.16$
- ←  $^{90}\text{Zr}(p,n)$  data



- No free parameter
- Well reproduce pionic modes for  $^{12}\text{C}(p,n)$  in wide momentum-transfer region
  - Absolute values are reliable

# Results — Polarized cross section—

Separate into 3 components using  $D_{ij}$

$$I = \boxed{ID_0} + \boxed{ID_L} + \boxed{ID_T}$$

scalar   longitudinal   transverse

- $ID_L$  : unnatural parity ( $0^-$  and  $2^-$  for SD)
- $ID_T$  : both parities ( $1^-$ ,  $2^-$  for SD)
- $0^-$  contributes to  $ID_L$  only (special case)

Comparison with DWIA+RPA at  $4^\circ$

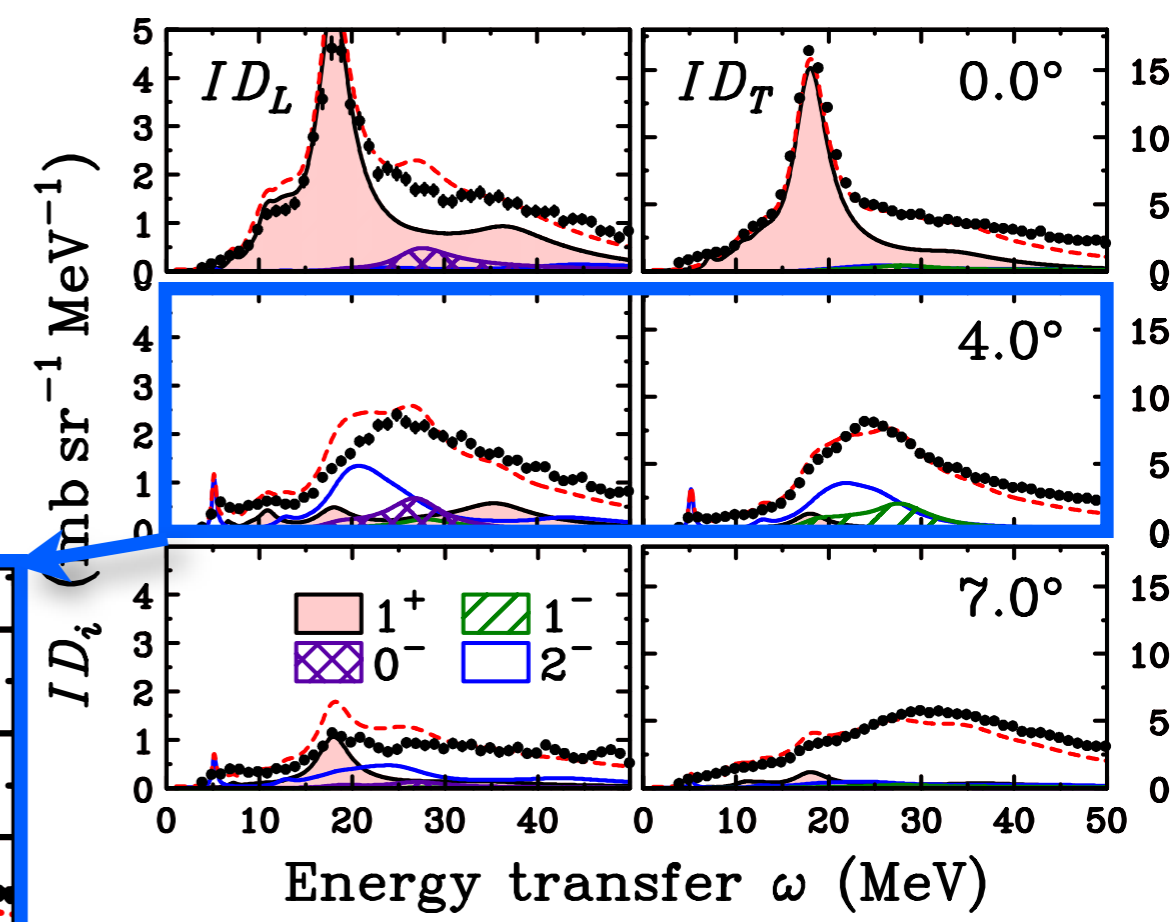
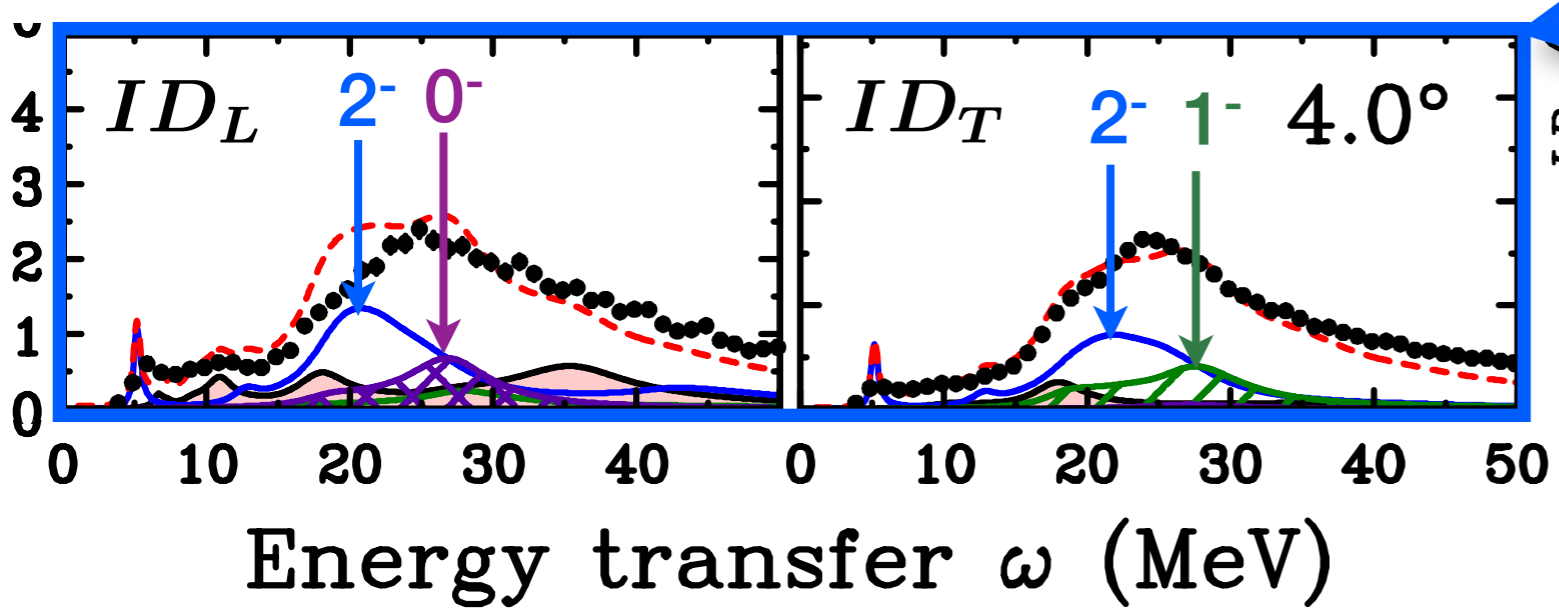
- Exp: Narrow bump in both  $ID_L$  and  $ID_T$
- Theory : Broad bump [ $\omega(2^-) < \omega(1^-) \sim \omega(0^-)$ ]

→ MDA should be performed

Example at  $0^\circ$

$$ID_L = \frac{I}{4}(1 - 2D_{NN} + D_{LL})$$

$$ID_T = \frac{I}{2}(1 - D_{LL})$$



# Separation of SDR into each $J^\pi$

Separation of SDR ( $L=1$ ) into  $0^-$ ,  $1^-$ ,  $2^-$  is important

- Tensor effects depends on  $J^\pi$

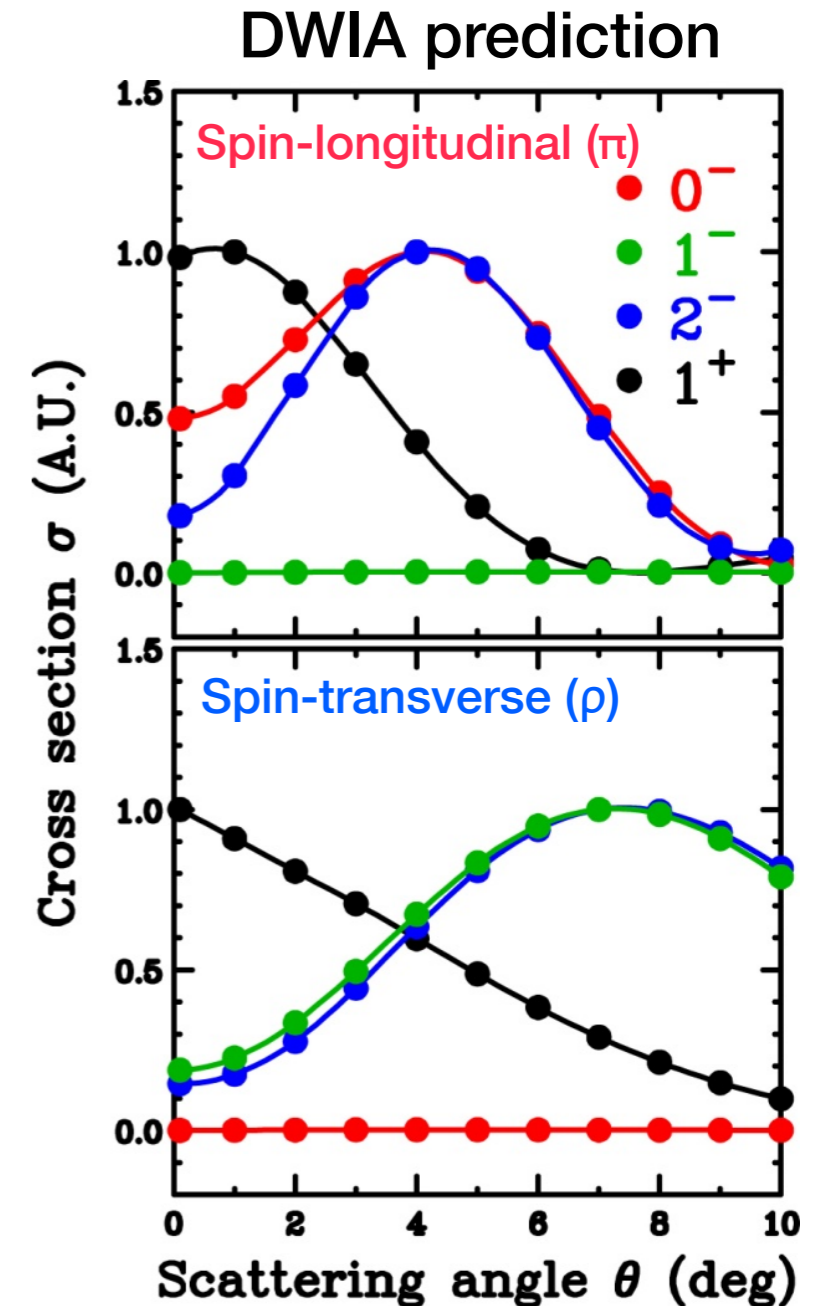
Normal multipole decomposition

- Separate into each  $L$  component
- Works very well to extract GT ( $L=0$ )
- Could NOT separate into  $J^\pi$  with same  $L$
- Angular distributions are governed by  $L$

Idea to separate SDR into each  $J^\pi$

- Polarization observables are sensitive to  $J^\pi$
- Separate c.s. into longitudinal ( $\pi$ ) - transverse ( $\rho$ )
  - $0^-$ : Spin-longitudinal ( $\pi$ ) only
  - $1^-$ : Spin-transverse ( $\rho$ ) only
  - $2^-$ : Both

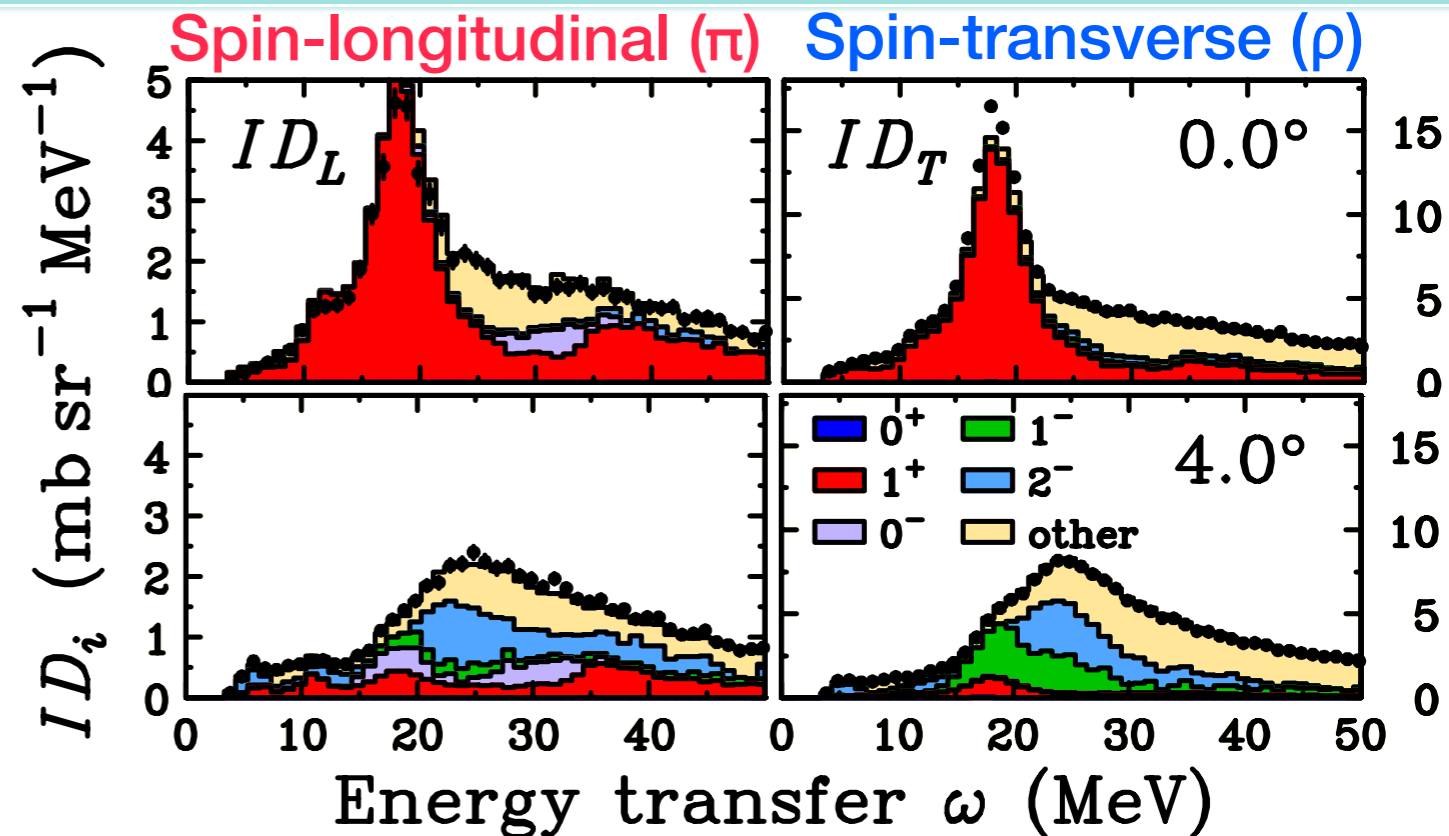
Multipole decomposition for longitudinal ( $\pi$ ) and transverse ( $\rho$ ) c.s.  
→ Can separate/specify not only  $L$ , but also  $J^\pi$



# Results of multipole decomposition

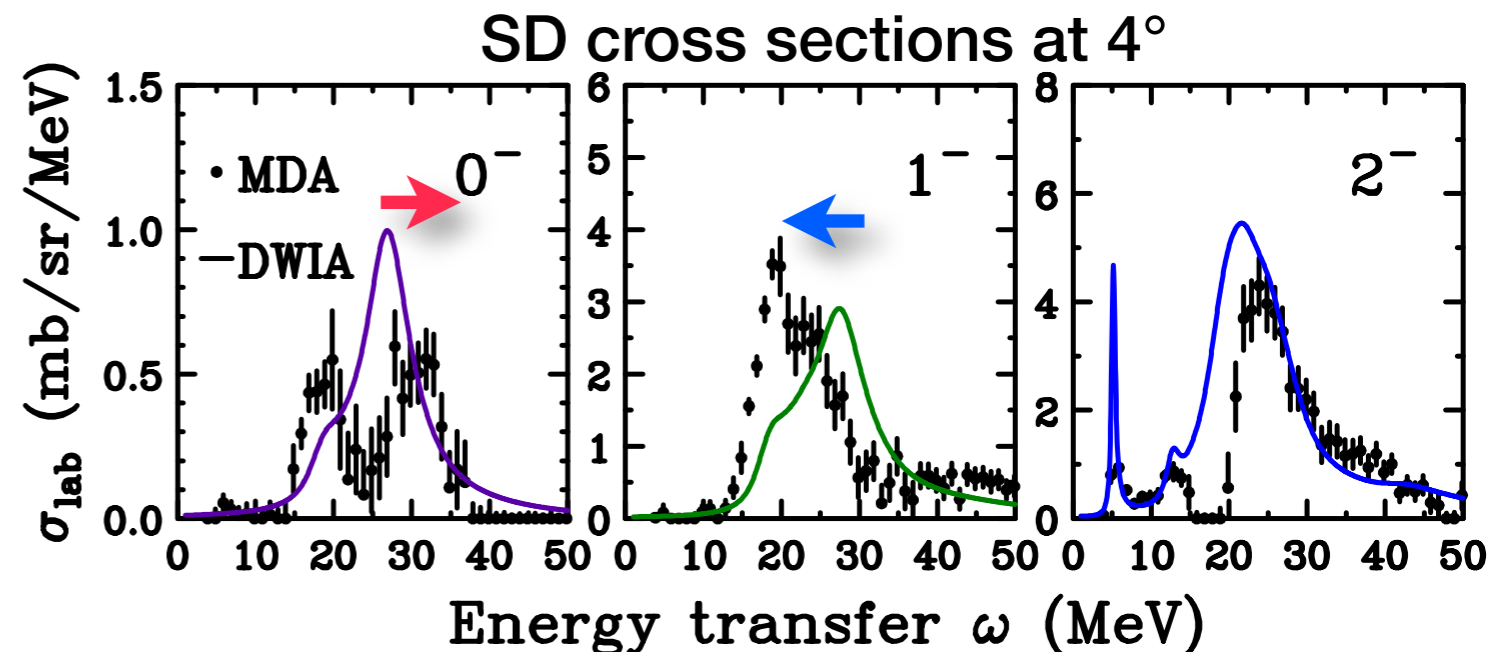
## L=0 (GT) contribution

- Large contribution up to 50 MeV
- Configuration mixing (2p2h)
- IVSM contribution



## L=1 SD ( $0^-$ , $1^-$ , $2^-$ ) contributions

- Theory :  $\omega(2^-) < \omega(1^-) \sim \omega(0^-)$
- Exp. :  $\omega(2^-) \sim \omega(1^-) < \omega(0^-)$
- Softening on  $1^-$



- Multipole ( $J^\pi$ ) decomposition is successful
- $J^\pi$  dependence on SD resonances could not be reproduced
  - Signature of tensor force effects ?

# SD unit cross section and B(SD)

## SD unit cross section

- Maximum cross section at  $\sim 4^\circ$
- Proportionality relation

$$\sigma_{\text{SD};J^\pi}(4^\circ) \simeq \hat{\sigma}_{\text{SD};J^\pi} B(\text{SD}, J^\pi)$$

## DWIA calculations (■)

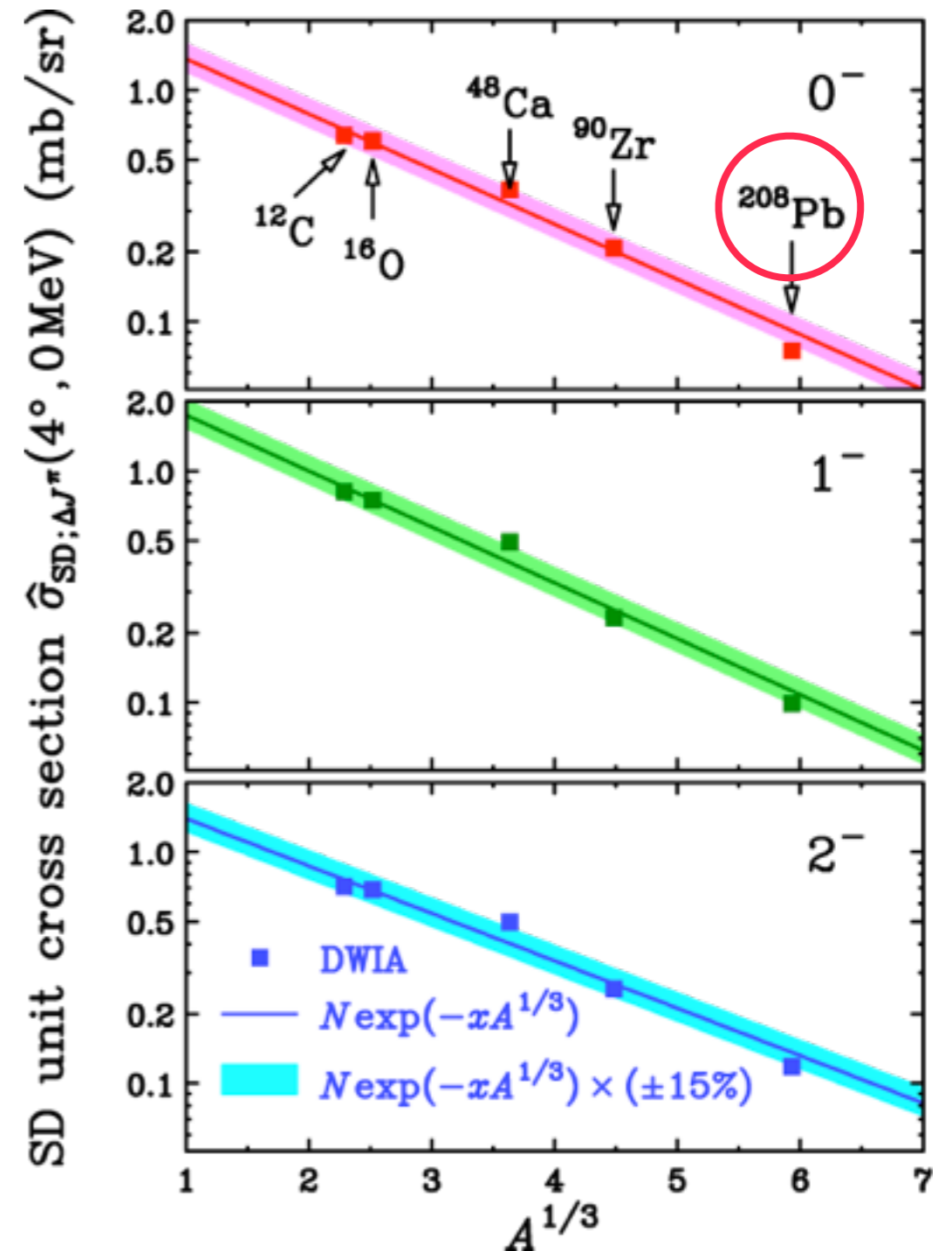
- $^{12}\text{C}$ ,  $^{16}\text{O}$ ,  $^{48}\text{Ca}$ ,  $^{90}\text{Zr}$ ,  $^{208}\text{Pb}$
- SD excitation at  $\omega=0$  MeV

## A-dependence

- $\hat{\sigma}_{\text{SD};J^\pi}(A) = N \exp(-xA^{1/3})$ 
  - Proper description for A-dep.
  - Reproduce DWIA results within  $\sim 15\%$

## Experimental SD strength

$$\frac{B^{\text{exp}}(\text{SD}, J^\pi)}{\text{Exp}} = \frac{\sigma_{\text{SD};J^\pi}^{\text{exp}}}{\hat{\sigma}_{\text{SD};J^\pi}} = \frac{\sigma_{\text{SD};J^\pi}^{\text{exp}}}{\sigma_{\text{SD};J^\pi}^{\text{calc}} / B^{\text{calc}}(\text{SD}, J^\pi)} = \frac{a_{J^\pi}}{\text{MDA}} \frac{B^{\text{calc}}(\text{SD}, J^\pi)}{\text{RPA}}$$



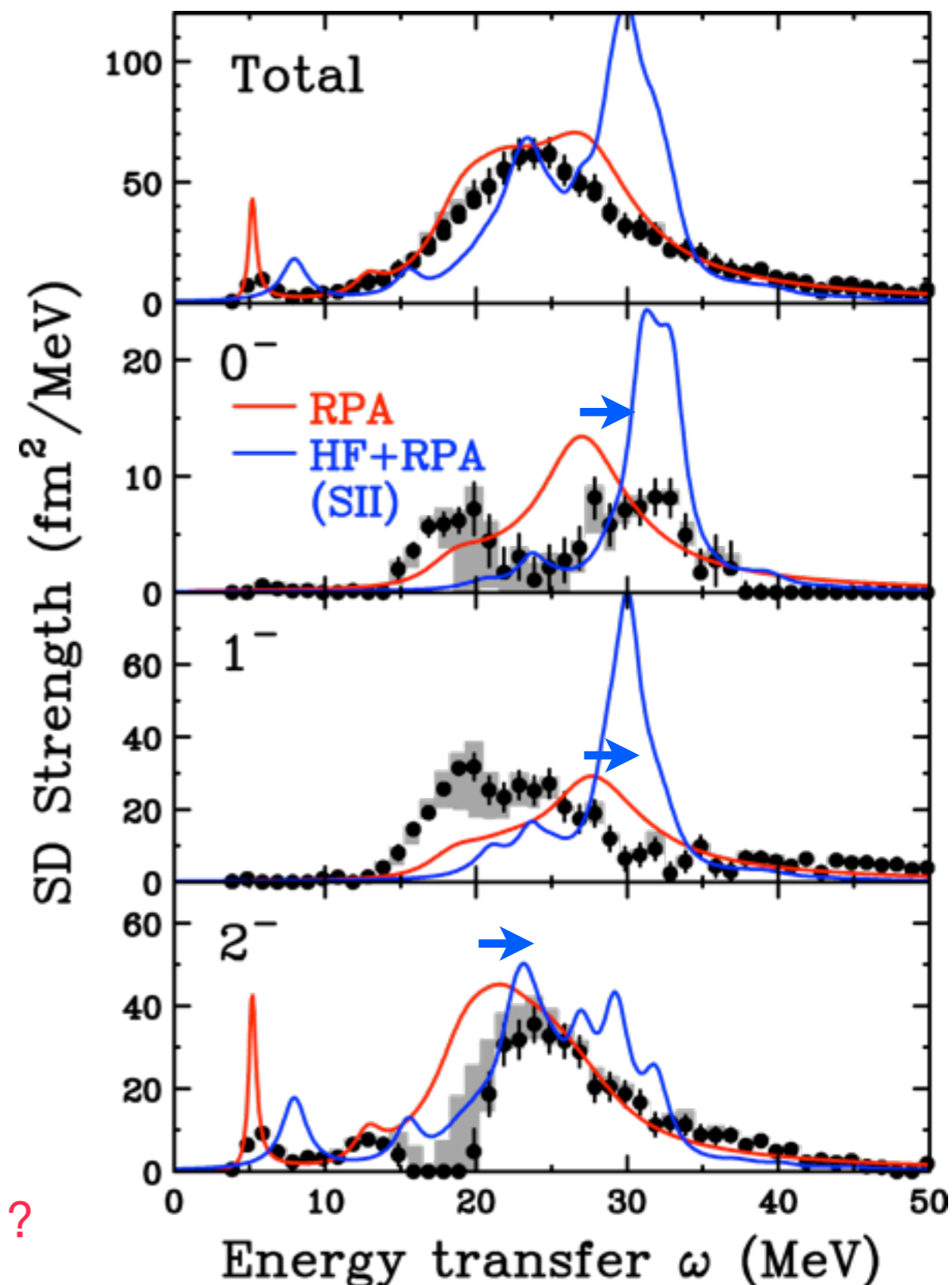
# Comparison with RPA and self-consistent HF+RPA

## RPA (used in DWIA+RPA calc.)

- $\pi+\rho+g'$  residual interaction
- Systematically lower than HF+RPA
- Different mean field

## Self-consistent HF+RPA

- SII (w/o tensor)
- Reproduce  $2^-$  strength
  - c.f. Tensor correlations are insensitive to  $2^-$
- Significantly higher for  $1^-$ 
  - Softening effect by T(TE) ?
- Roughly consistent for  $0^-$ 
  - Hardening effect by T(TE)
  - Cancelled by softening effect by  $U(TO) > 0$  ?



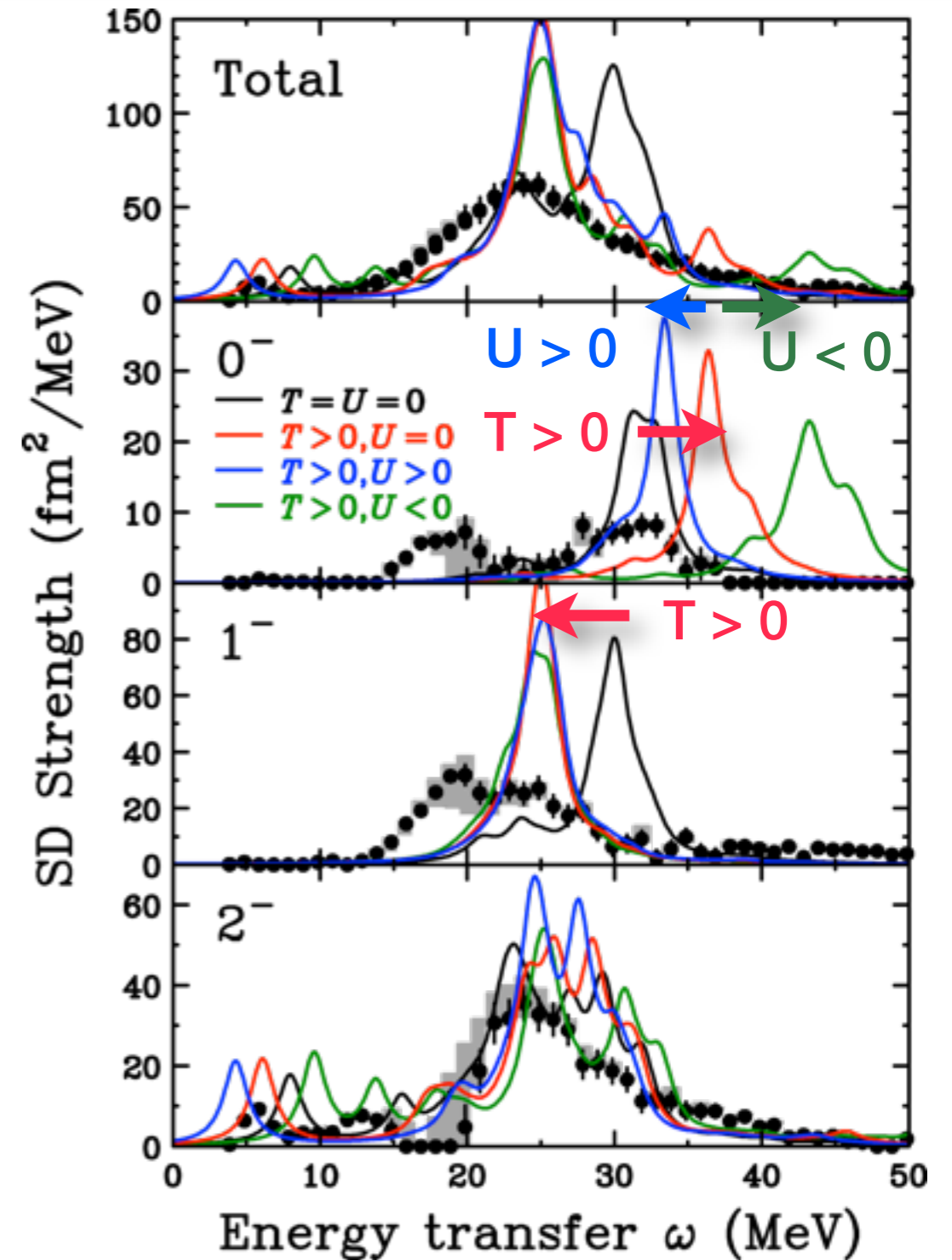
# Tensor force effects on SDR

## Tensor force effects on SDR

$$V^T \propto \underbrace{T(\text{TE})}_{\text{triplet-even}} + \underbrace{U(\text{TO})}_{\text{triplet-odd}}$$

	T>0	U>0	U<0
0 <sup>-</sup>	hardening	softening	hardening
1 <sup>-</sup>	softening	insensitive	
2 <sup>-</sup>	insensitive		

- T(TE) > 0 tensor interaction
  - Softening for 1<sup>-</sup> :  $\omega^{\text{calc.}} \sim \omega^{\text{exp.}}$
  - Hardening for 0<sup>-</sup> :  $\omega^{\text{calc.}} > \omega^{\text{exp.}}$
- T(TE) > 0 + U(TO) > 0 tensor interaction
  - Softening for 0<sup>-</sup> :  $\omega^{\text{calc.}} \sim \omega^{\text{exp.}}$
- T(TE) > 0 + U(TO) < 0 tensor interaction
  - Hardening for 0<sup>-</sup> :  $\omega^{\text{calc.}} \gg \omega^{\text{exp.}}$



• Softening on 1<sup>-</sup> is reproduced by T>0

• Tensor effect on 0<sup>-</sup> is weak

• Hardening by T>0 should be cancelled by softening by U>0

• T(TE)  $\sim$  650 MeV fm<sup>5</sup>

• U(TO)  $\sim$  200 MeV fm<sup>5</sup>

# Integrated SD strengths

## Integrated strength

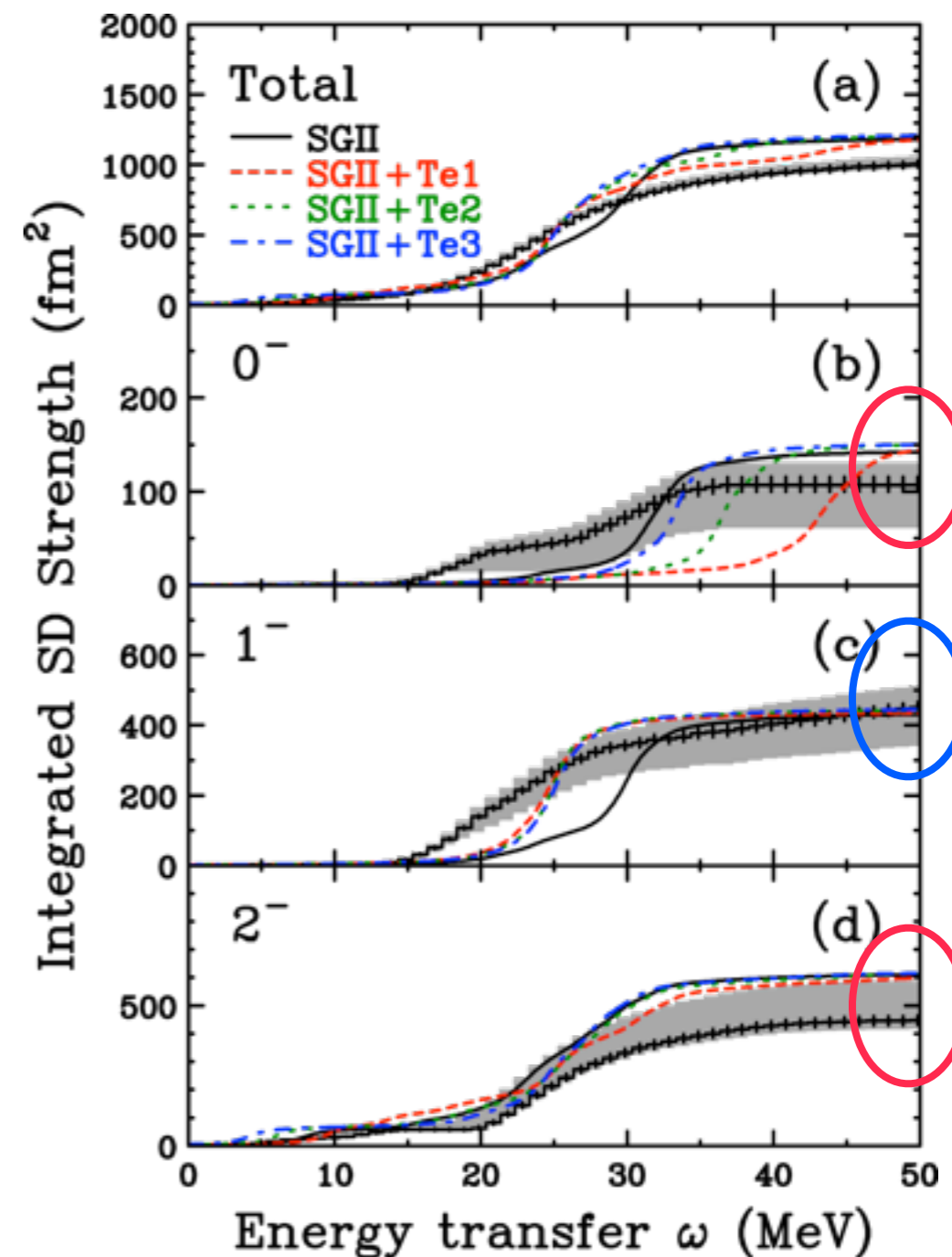
$$S_{SD, J^\pi}(\omega) = \int^\omega B(SD, J^\pi) d\omega$$

## Total strength ( $\omega < 50$ MeV)

- Exp. :  $(1.00 \pm 0.05) \times 10^3 \text{ fm}^2$
- Theory :  $(1.18 - 1.21) \times 10^3 \text{ fm}^2$
- Quenching fac.:  $0.84 \pm 0.04$
- Systematic uncertainty  $\sim 15\%$

## Each $J^\pi$ strength

- $0^-$  and  $2^-$  :  $\sim 70\%$  of RPA prediction
- $1^-$  :  $\sim 100\%$  of RPA prediction
- Systematic uncertainty  $\sim 30\%$  (Correlation between each strength)



- $84 \pm 4\%$  of total SD strength is found
  - Quenching might depend on  $J^\pi$
- } Not conclusive (Large uncertainties)

# Summary

## New experimental data for $^{208}\text{Pb}(p,n)$

- Cross sections and analyzing powers at  $\theta = 0.0^\circ \sim 10.0^\circ$  (11 angles)
- Complete sets of polarization transfers at  $\theta = 0.0^\circ \sim 7.0^\circ$  (5 angles)

## Extended multipole decomposition (MD) analysis

- Polarization observables were used, for the first time, in MD analysis
  - Reasonable agreement with experimental data
- Successful separation into individual  $J^\pi$  components

## SD strength for $^{208}\text{Pb}$

- Softening effect for  $1^-$ 
  - $T(\text{TE}) \sim 650 \text{ MeV fm}^5$  ( $\beta_T \sim 200 \text{ MeV fm}^5$ )
- Small effect for  $0^-$  (= hardening effect by  $T(\text{TE})$  is NOT observed)
  - Hardening effect by  $T$  should be cancelled by softening effect by  $U > 0$
  - $U(\text{TO}) \sim 200 \text{ MeV fm}^5$  ( $\alpha_T \sim 100 \text{ MeV fm}^5$ )
- Similar to  $\beta_T = 238 \text{ MeV fm}^5$  and  $\alpha_T = 135 \text{ MeV fm}^5$  by low- $q$  limit of G-matrix calc.

First exp./theor. findings for “tensor force effects in nuclear spin excitations”