Nuclear Spin Physics via Polarization Measurements

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Three nucleon force effects in few-nucleon systems

- Clear signature of three nucleon forces and defects in spin-dependence
- Comparison with chiral-EFT predictions
- Isospin dependence

Spin-isospin responses for stable and unstable nuclei

- Isospin dependence of spin-isospin responses and residual interactions
- Spin-isospin incompressibility and neutron skin thickness

New spin-isospin mode and application to neutrino physics

- Double Gamow-Teller transition $0\nu\beta\beta$ matrix element
- Double Gamow-Teller resonance

Emphasis on recent experimental data from RIKEN/RIBF, RCNP, NSCL/MSU
(high-precision polarization observables and spin-isospin excitations)

Three nucleon force effects in few-nucleon systems

3NF effects in finite nuclei

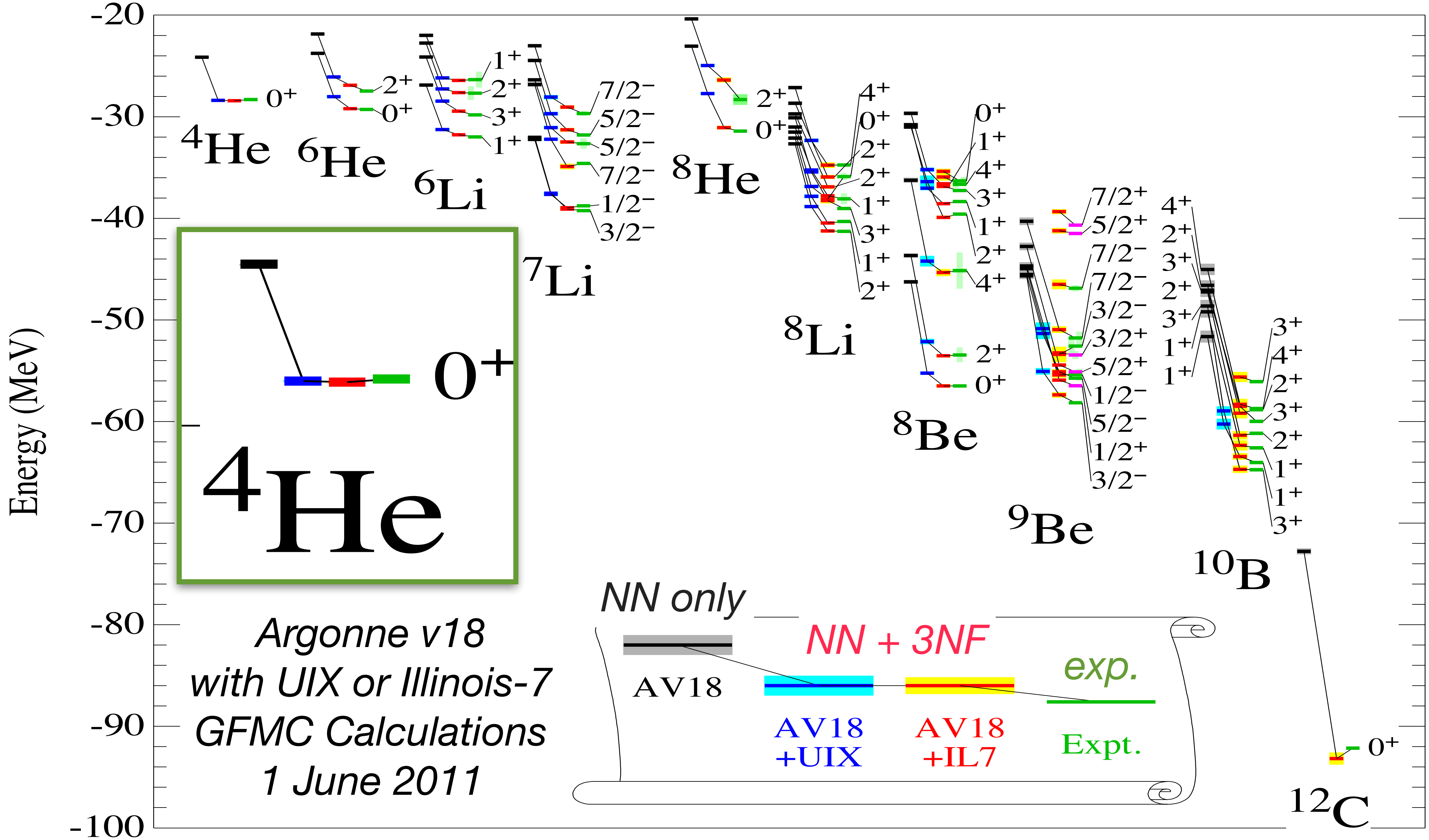
J. Carlson et al., Rev. Mod. Phys. 87, 1067 (2015).

Ab Initio calculations for light nuclei

Green’s function Monte Carlo, no-core shell model, etc.

- 2NF : provide less binding energies
- 3NF : well reproduce the data (ex. ^{4}He)

Different predictions for UIX and IL7 3NFs
*→ **What is different ?***



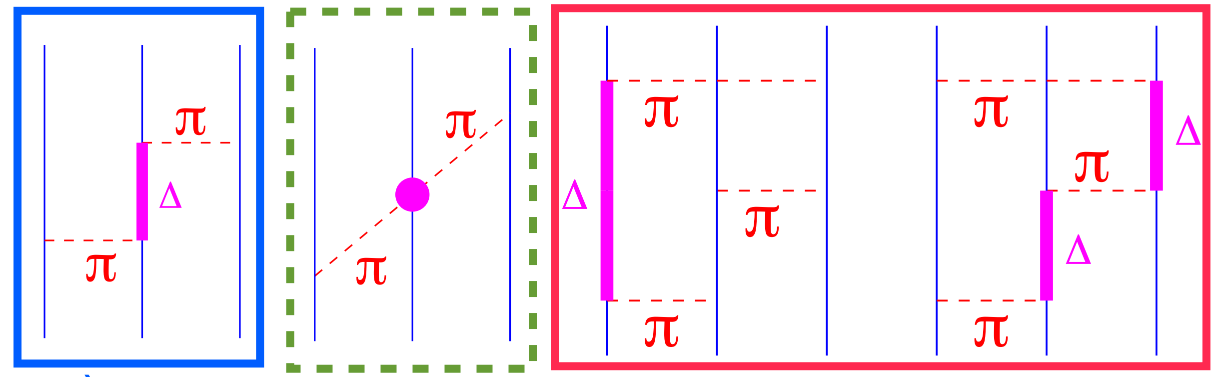
Isospin dependence of 3NF effects

J. Carlson et al., Rev. Mod. Phys. 87, 1067 (2015).

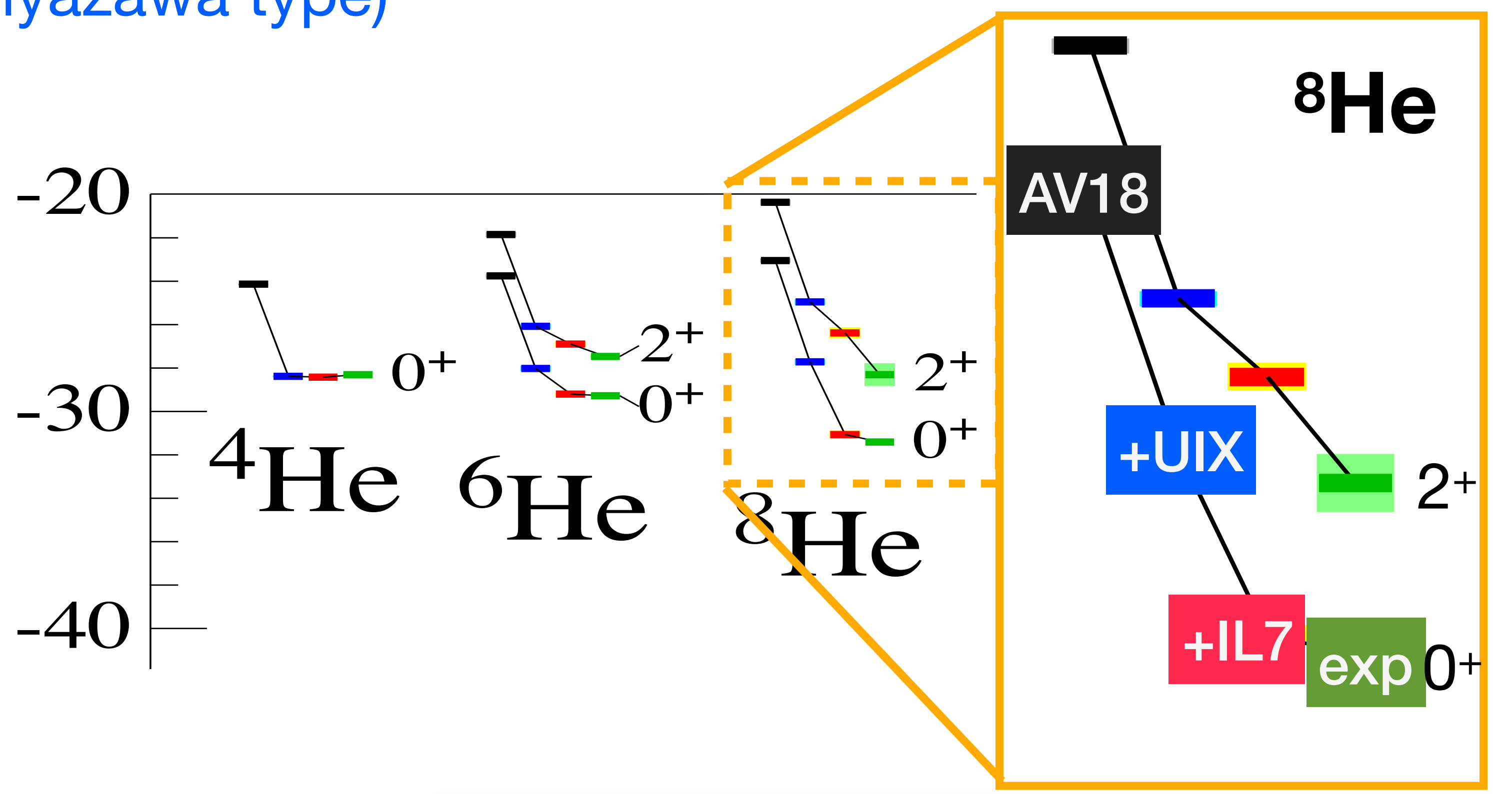
UIX and IL7 3NF

$$V_{ijk}^{\mathrm{UIX}} = V_{ijk}^{2\pi,P} + V_{ijk}^{R}$$

$$V_{ijk}^{\mathrm{ILx}} = V_{ijk}^{2\pi,P} + V_{ijk}^{R} + V_{ijk}^{2\pi,S} + V_{ijk}^{3\pi}$$



- p-wave πN scattering term (Fujita-Miyazawa type)
- isospin-independent repulsive term
- s-wave πN scattering term (∼3-4%)
- ***3π rings with Δ's (∼10%)***
  - different isospin dependence
  - more attraction for N>Z



General structure of 3NF

- *22 structure func./generators are needed* under some invariances/symmetries

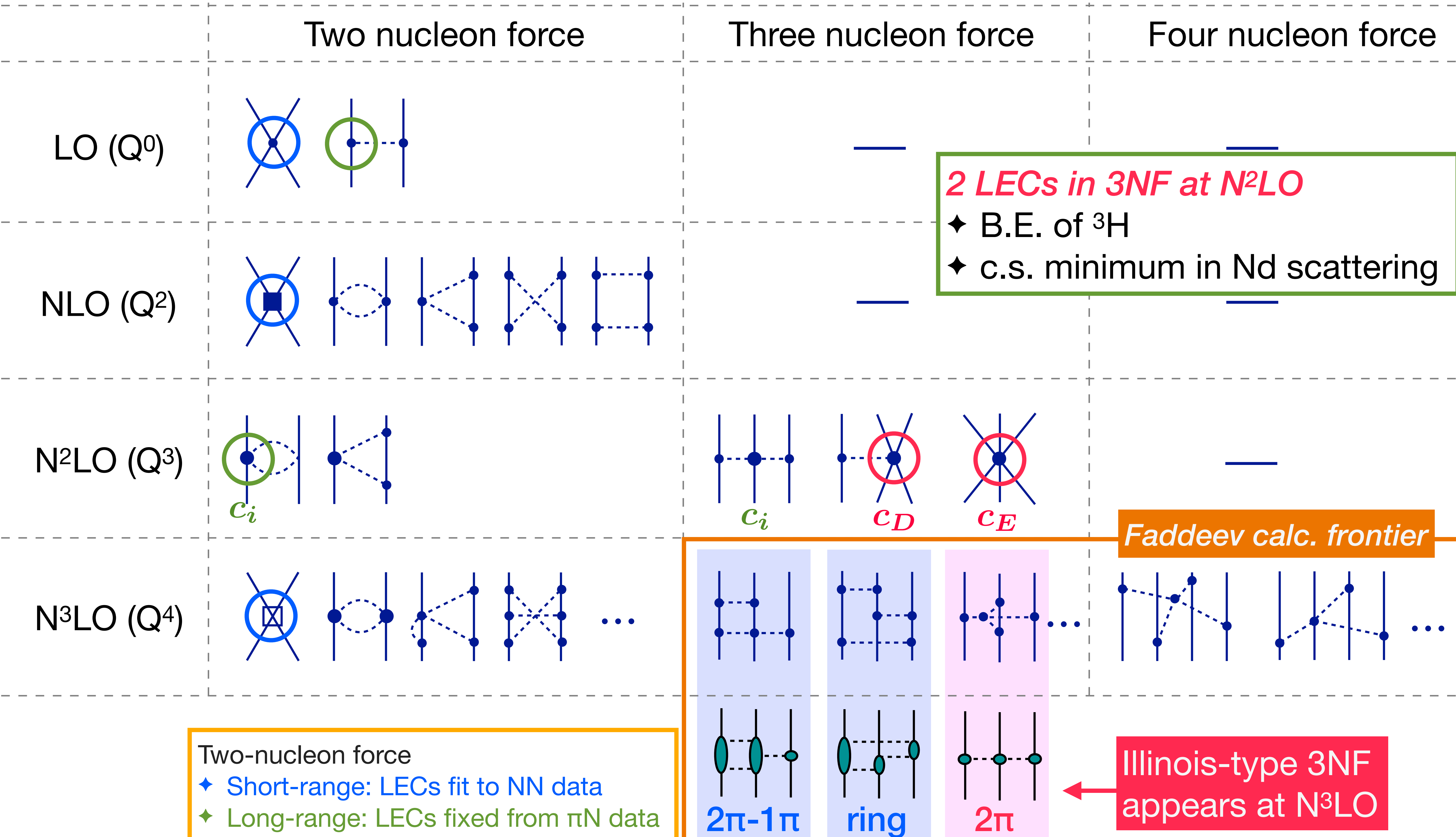
Need a systematic theoretical approach → *chiral EFT*

Generators $\mathcal{G}$ of 89 independent operators	
$\mathcal{G}_1 = 1$	$\mathcal{G}_{12} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_3 \cdot \vec{\sigma}_2$
$\mathcal{G}_2 = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3$	$\mathcal{G}_{13} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_3 \cdot \vec{\sigma}_1 \vec{q}_1 \cdot \vec{\sigma}_2$
$\mathcal{G}_3 = \vec{\sigma}_1 \cdot \vec{\sigma}_3$	$\mathcal{G}_{14} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_3 \cdot \vec{\sigma}_1 \vec{q}_3 \cdot \vec{\sigma}_2$
$\mathcal{G}_4 = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \vec{\sigma}_1 \cdot \vec{\sigma}_3$	$\mathcal{G}_{15} = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \vec{q}_2 \cdot \vec{\sigma}_1 \vec{q}_2 \cdot \vec{\sigma}_3$
$\mathcal{G}_5 = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{\sigma}_1 \cdot \vec{\sigma}_2$	$\mathcal{G}_{16} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_3 \cdot \vec{\sigma}_2 \vec{q}_3 \cdot \vec{\sigma}_3$
$\mathcal{G}_6 = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_1 \cdot (\vec{\sigma}_2 \times \vec{\sigma}_3)$	$\mathcal{G}_{17} = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_3 \vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_3 \cdot \vec{\sigma}_3$
$\mathcal{G}_7 = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_2 \cdot (\vec{q}_1 \times \vec{q}_3)$	$\mathcal{G}_{18} = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_1 \cdot \vec{\sigma}_3 \vec{\sigma}_2 \cdot (\vec{q}_1 \times \vec{q}_3)$
$\mathcal{G}_8 = \vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_1 \cdot \vec{\sigma}_3$	$\mathcal{G}_{19} = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_3 \cdot \vec{q}_1 \vec{q}_1 \cdot (\vec{\sigma}_1 \times \vec{\sigma}_2)$
$\mathcal{G}_9 = \vec{q}_1 \cdot \vec{\sigma}_3 \vec{q}_3 \cdot \vec{\sigma}_1$	$\mathcal{G}_{20} = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_1 \cdot \vec{q}_1 \vec{\sigma}_2 \cdot \vec{q}_1 \vec{\sigma}_3 \cdot (\vec{q}_1 \times \vec{q}_3)$
$\mathcal{G}_{10} = \vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_3 \cdot \vec{\sigma}_3$	$\mathcal{G}_{21} = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_1 \cdot \vec{q}_2 \vec{\sigma}_3 \cdot \vec{q}_2 \vec{\sigma}_2 \cdot (\vec{q}_1 \times \vec{q}_3)$
$\mathcal{G}_{11} = \boldsymbol{\tau}_2 \cdot \boldsymbol{\tau}_3 \vec{q}_1 \cdot \vec{\sigma}_1 \vec{q}_1 \cdot \vec{\sigma}_2$	$\mathcal{G}_{22} = \boldsymbol{\tau}_1 \cdot (\boldsymbol{\tau}_2 \times \boldsymbol{\tau}_3) \vec{\sigma}_1 \cdot \vec{q}_1 \vec{\sigma}_3 \cdot \vec{q}_3 \vec{\sigma}_2 \cdot (\vec{q}_1 \times \vec{q}_3)$

H. Krebs, A. Gasparyan, and E. Epelbaum, Phys. Rev. C 87, 054007 (2013).

Chiral expansion of nuclear forces

E. Epelbaum, presentation at YKIS2018b Symposium on Recent Development in Quark-Hadron Sciences.



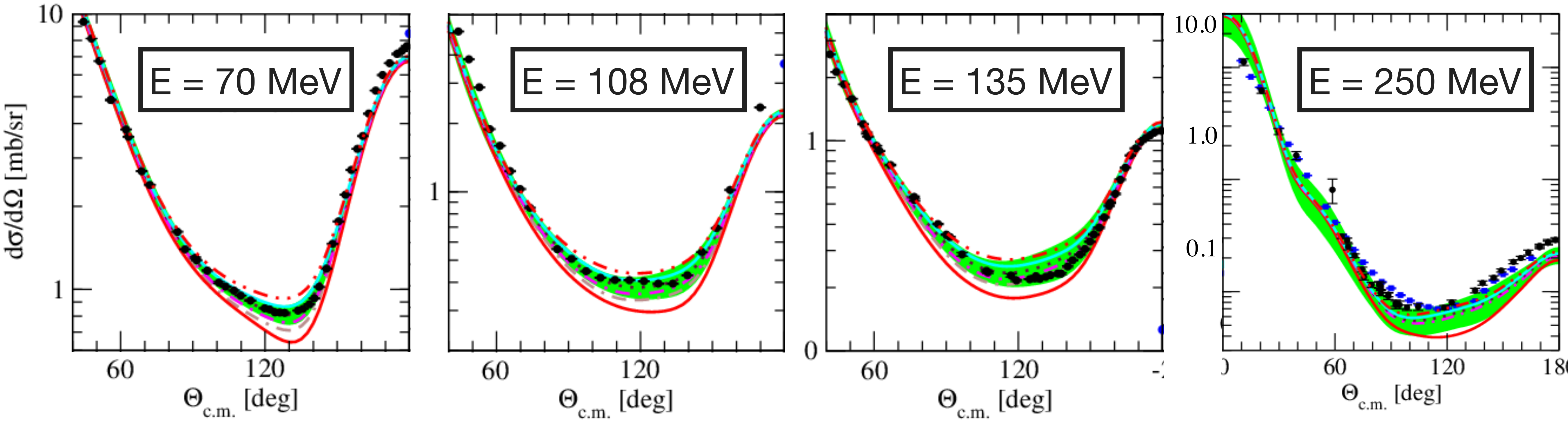
Can chiral nuclear force at N^{2}LO (consistent 2N+3N forces) reproduce 3N scattering data?

3NF effects in p+d elastic scattering

E. Epelbaum et al., arXiv:1807.02848 [nucl-th].

Differential cross section at 70-250 MeV/nucleon

- Exp. data : RIKEN, RCNP, KVI
- Theor. calc : Faddeev calc. with chiEFT potential up to N^{2}LO
  - Red : NN potential only
  - Green : NN potential + 3NF



LEC, c_D, has been determined.

← *Parameter-free predictions* →

Theoretical calculations reproduce the exp. data up to 135 MeV/A w/o free parameter!

- Discrepancy at 250 MeV would be due to higher-order effects at higher energies

→ *How about polarization observables?*

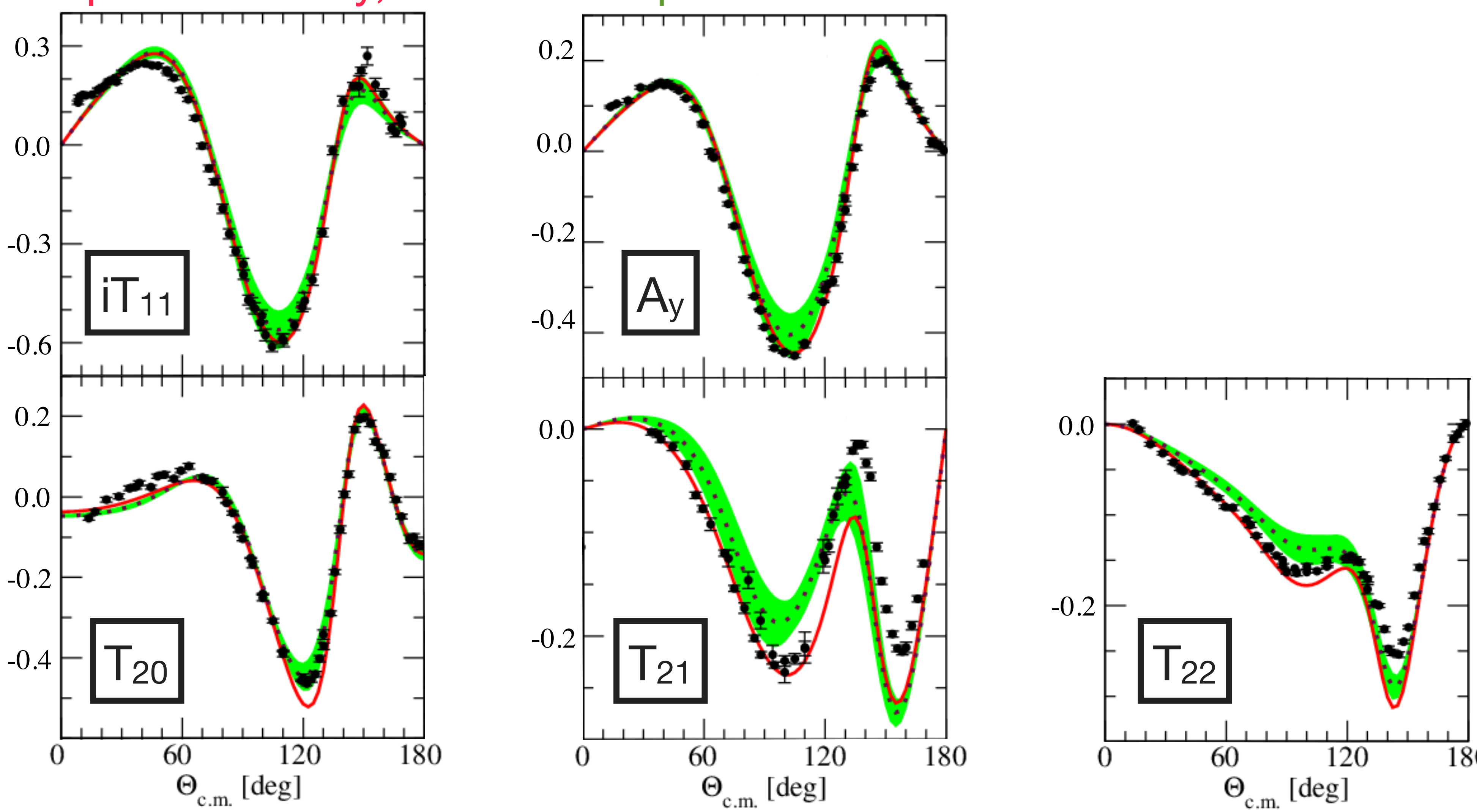
3NF effects in polarization observables

E. Epelbaum et al., arXiv:1807.02848 [nucl-th].

p+d polarization observables at 70 MeV/nucleon

- Exp. data : RIKEN(70 MeV), RCNP(65 MeV)
- Theor. calc. : Faddeev calc. with chiEFT potential up to N^{2}LO
  - Red : NN potential only, Green : NN potential + 3NF

LEC, c_D, has been determined by c.s.



Reasonable description within theor. uncertainties except for T_{21} at backward angles

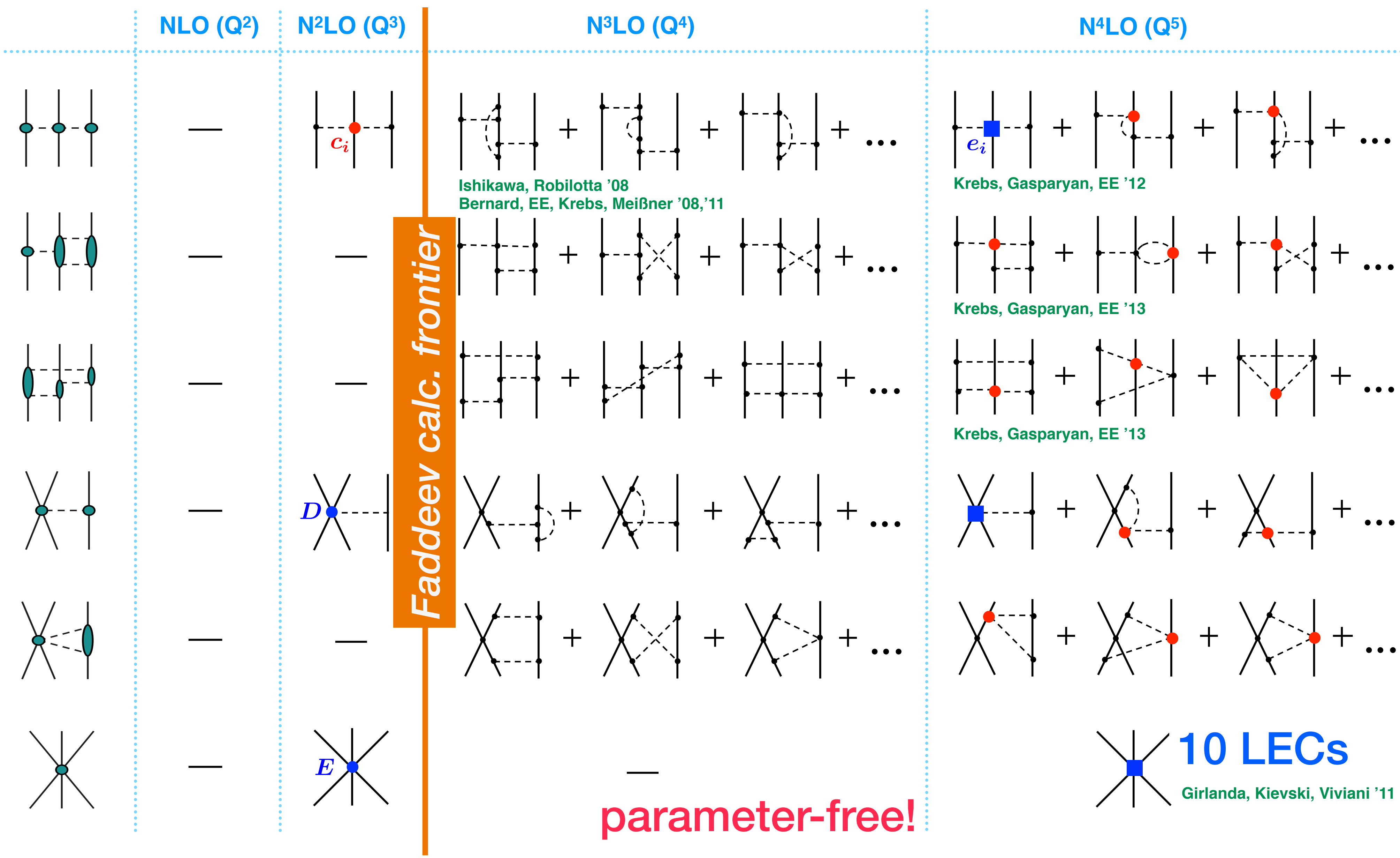
- Need to go to higher chiral orders (N^{4}LO) to improve the theoretical accuracy
- T_{21} might be sensitive to higher-order effects

Frontiers & challenges for the future

Chiral expansion of 3NF

Faddeev calc. for scattering states is limited up to N²LO

- N³LO (Q⁴): parameter-free, but large N⁴LO contributions by Δ is expected
- N⁴LO (Q⁵): new 10 LECs
  - Need ***high-precision N-d scattering data*** in wide energy region→partial wave analysis



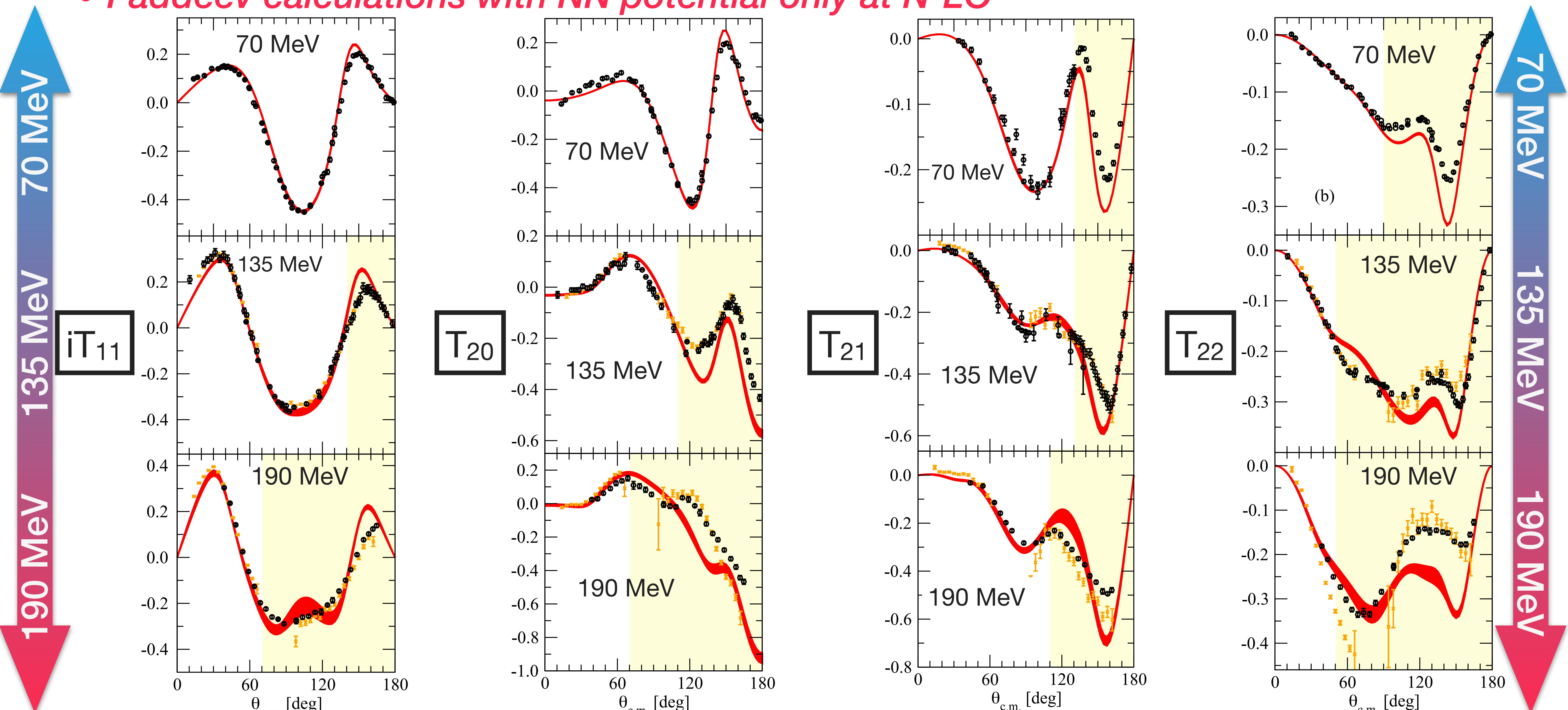
E. Epelbaum. presentation in IHEP, Peking (2014).

3NF effects at higher energies

K. Sekiguchi et al., Phys. Rev. C 96, 064001 (2017).

Comparison with data (RIKEN/IUCF) and predictions using chiral NN force (w/o 3NF)

- *Faddeev calculations with NN potential only at N^4LO*



3NF effects are clearly needed and spin-dependent:

- At 70 MeV : Clear discrepancy for T_{21} and T_{22}
- At higher energies : Generally different at backward angles

Useful for 3NF-LECs at N^4LO

✤ Limited to T=1/2 for N-d → *Four nucleon system* (p+^{3}He, etc.) for T=3/2 3NF

p+^{3}He scattering and T=3/2 3NFs

M. Viviani et al., Phys. Rev. Lett. 111, 172302 (2013).

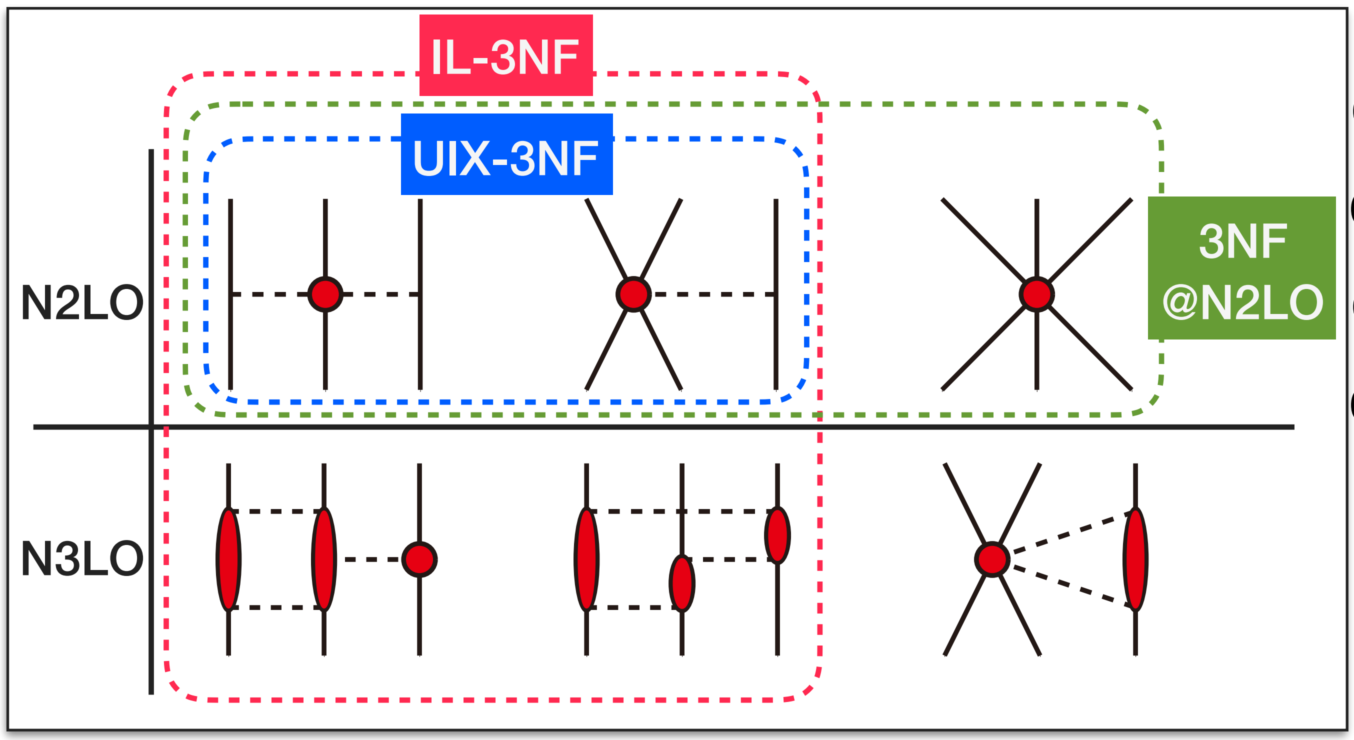
Pisa Gr. succeeds in 4-body calc.

AV18 + UIX/IL 3NF

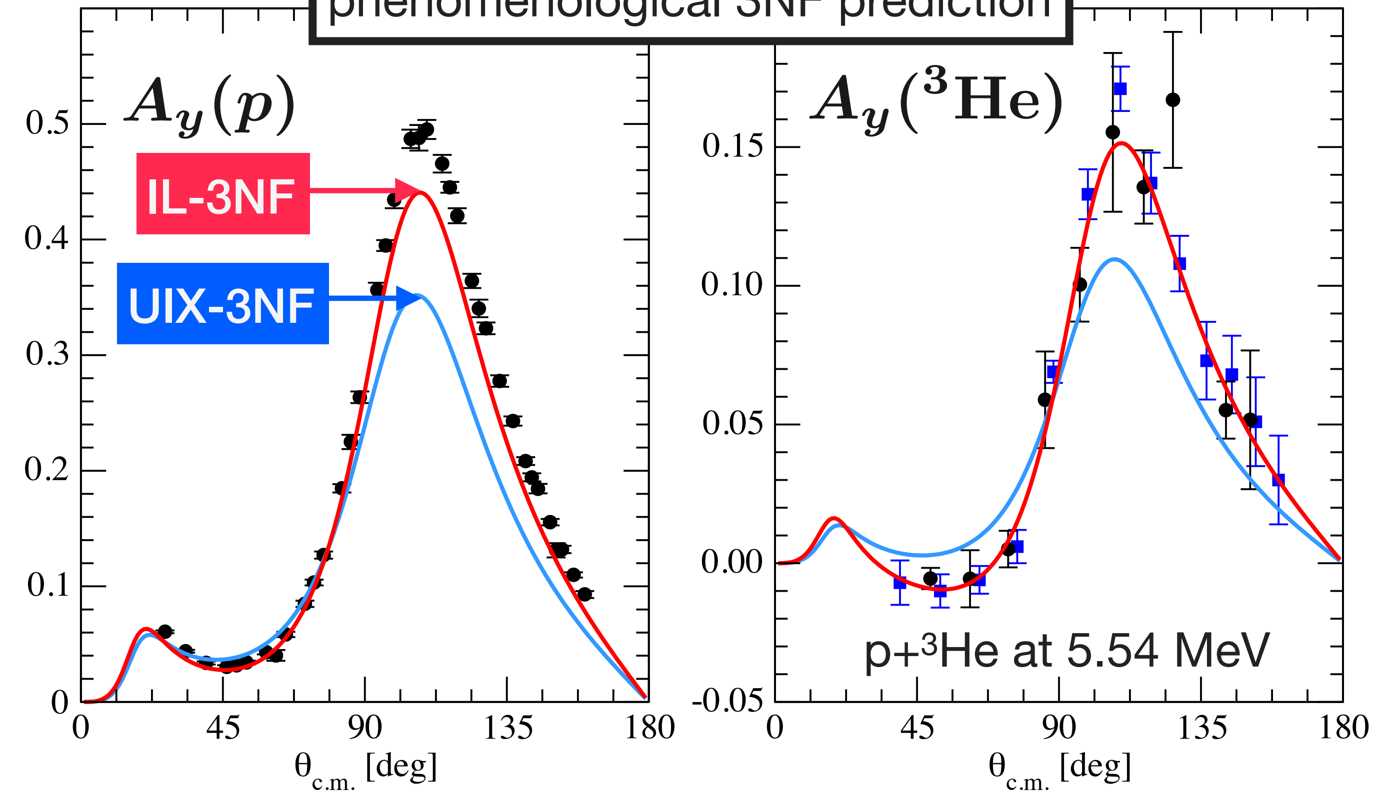
- Difference b/w UIX and IL predictions
- importance of 3π-ring with Δ in IL-3NF

chiEFT (3NF@N^{2}LO)

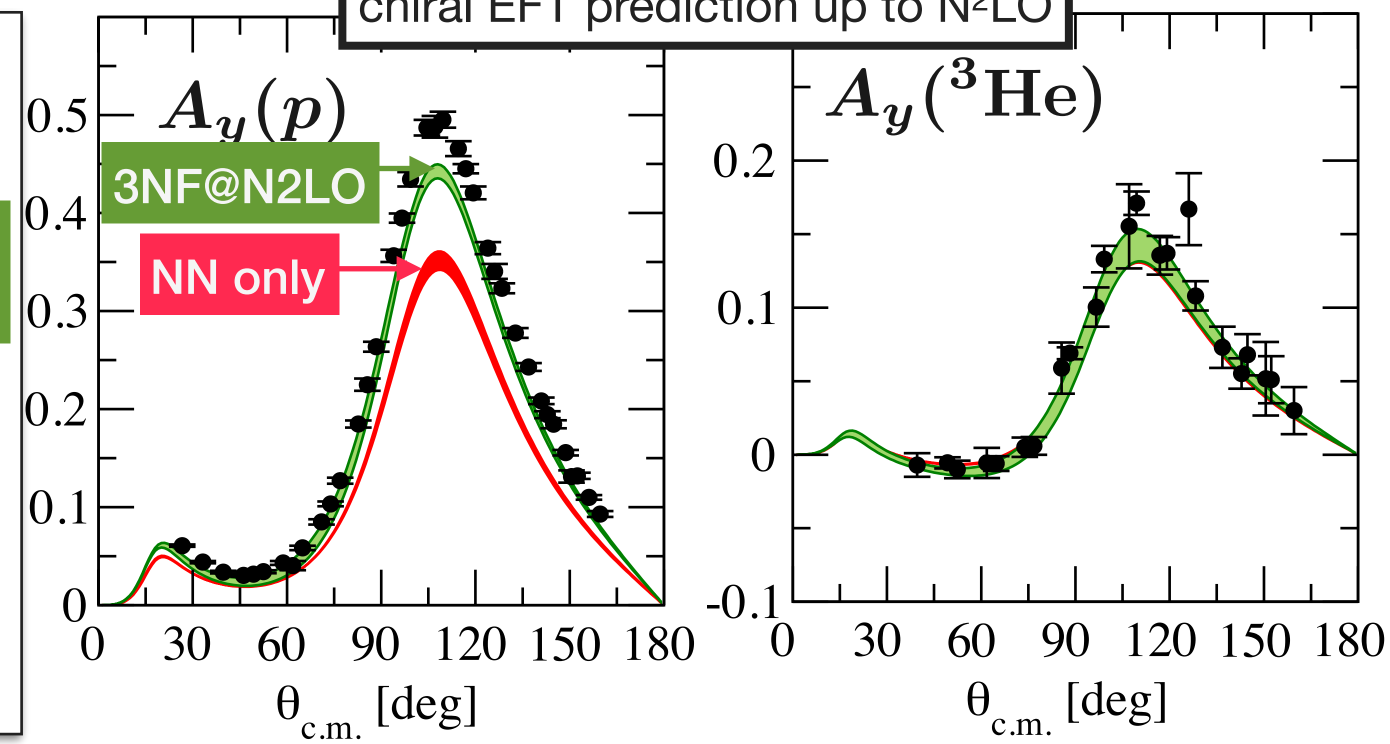
- 3NF plays an important role, but is insufficient
- 3π-ring terms @ N^{3}LO would resolve the discrepancy



phenomenological 3NF prediction



chiral EFT prediction up to N^{2}LO

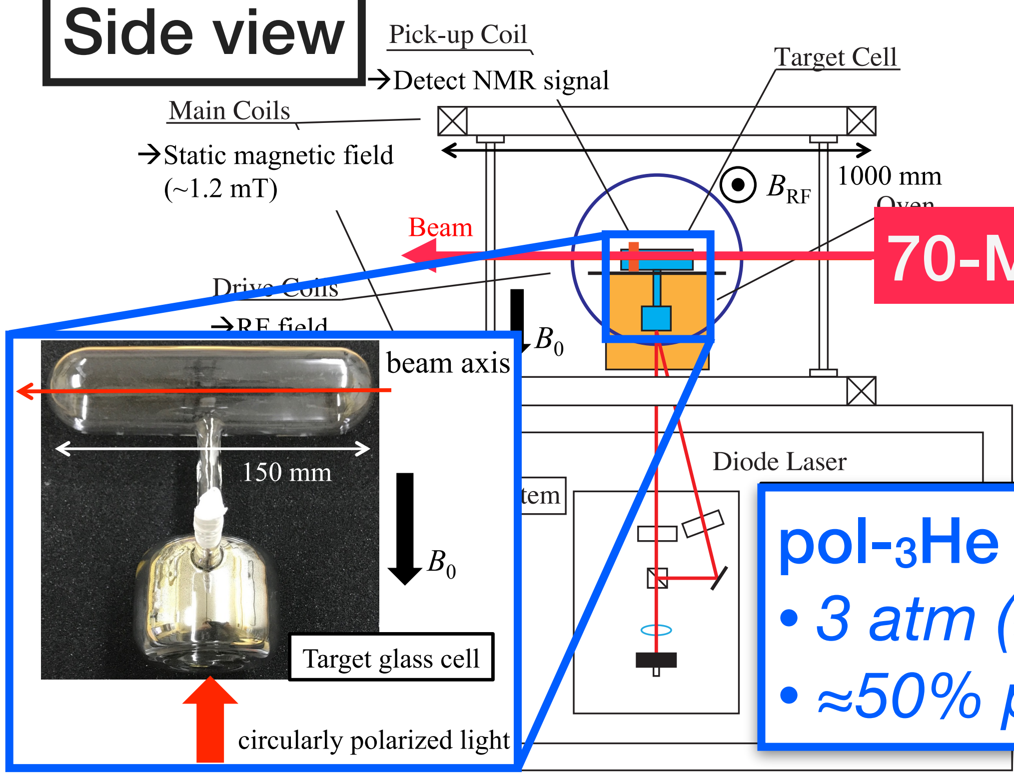


Now, it is interesting to study at higher energies for pol. observables with high accuracy!

New p-^{3}He A_y data at 70 MeV

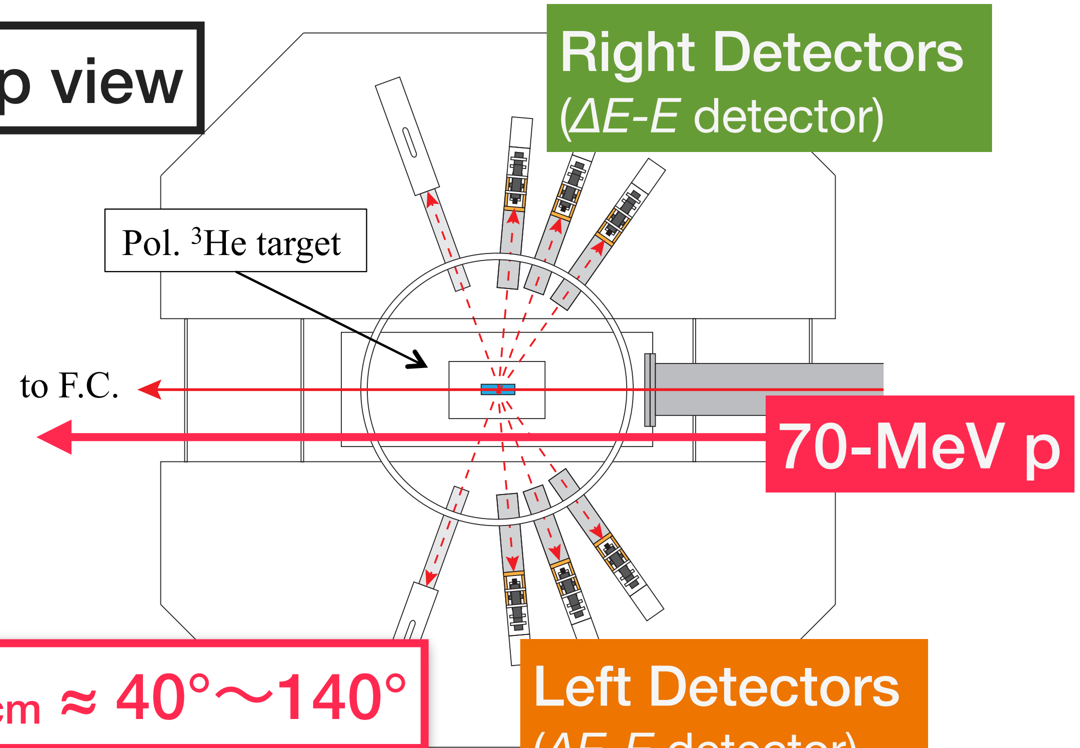
courtesy of A. Watanabe and K. Sekiguchi

New ^{3}He analyzing power exp./data for p-^{3}He by Tohoku group (Sekiguchi-Gr.)

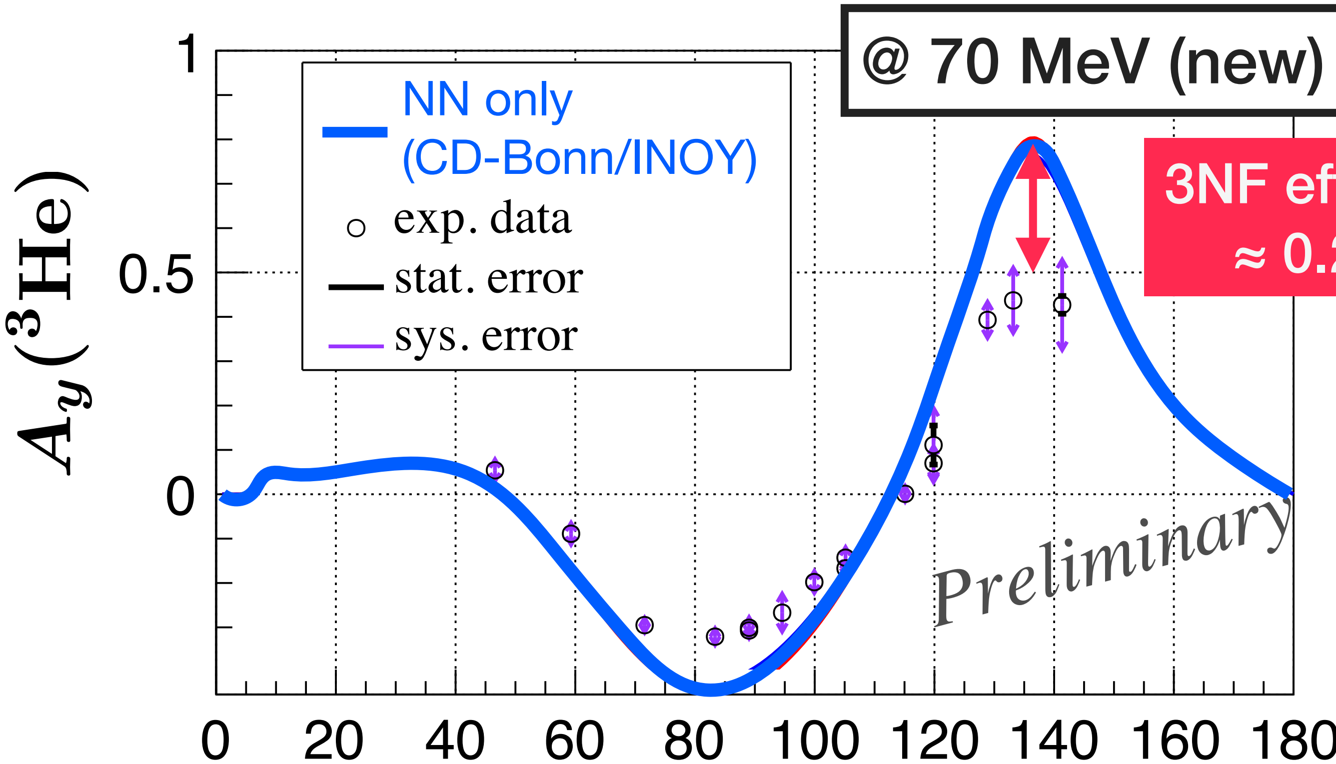


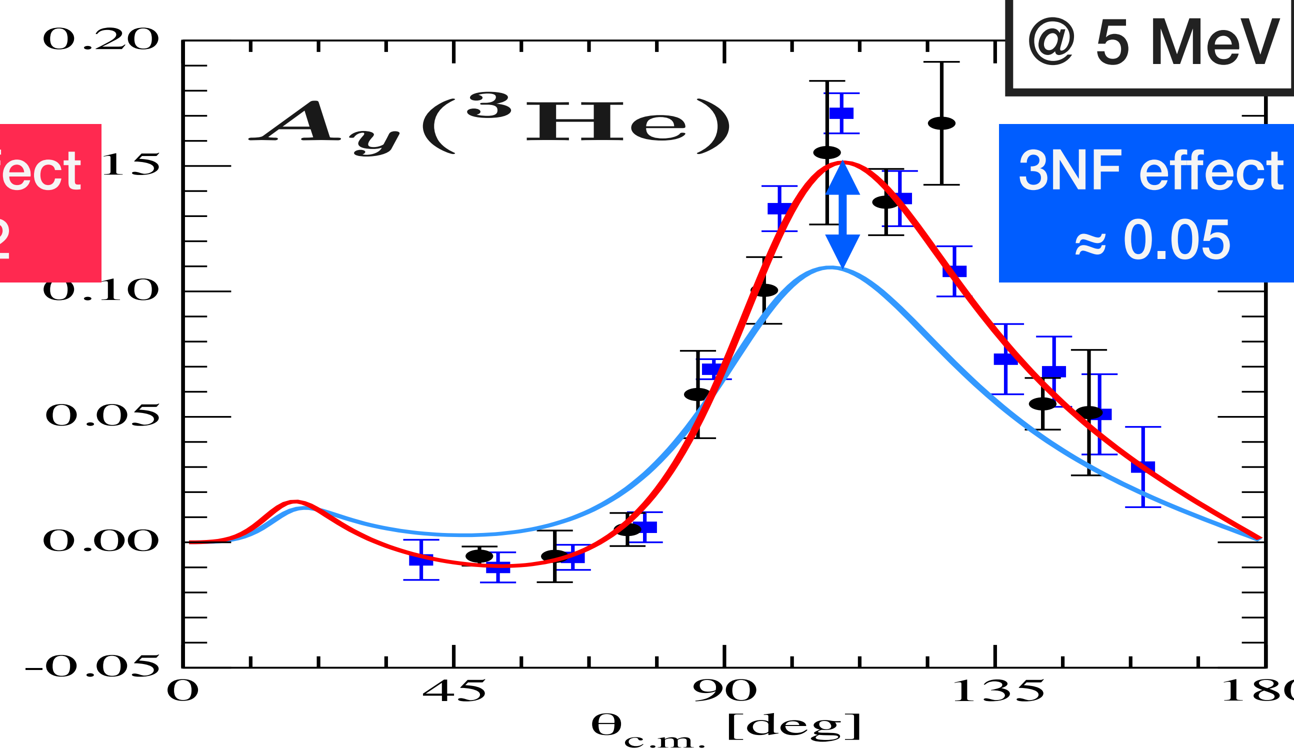
pol-$_3$He target

- *3 atm (≈2 mg/cm^2)*
- *≈50% polarization*



θ_{cm} ≈ 40°～140°





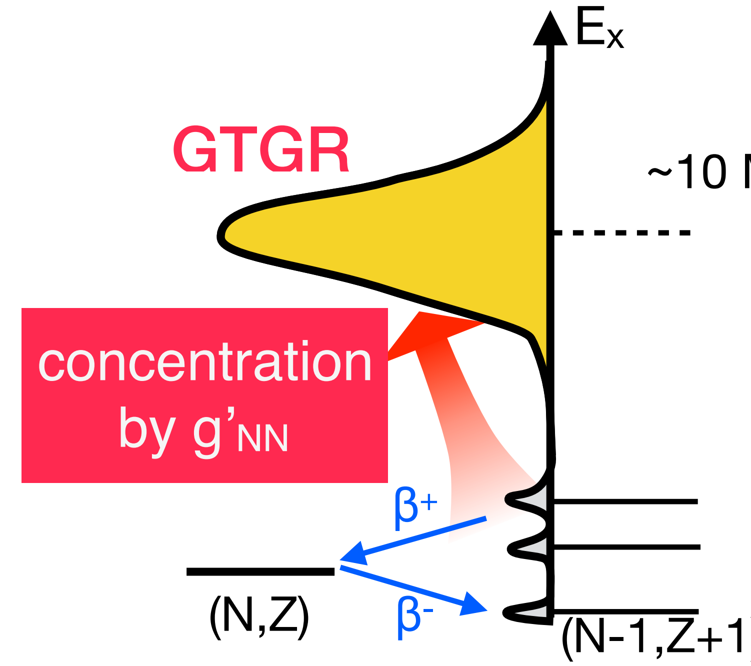
3NF effect at 70 MeV is large and is useful for understanding T=3/2 3NFs

Spin-isospin responses for stable and unstable nuclei

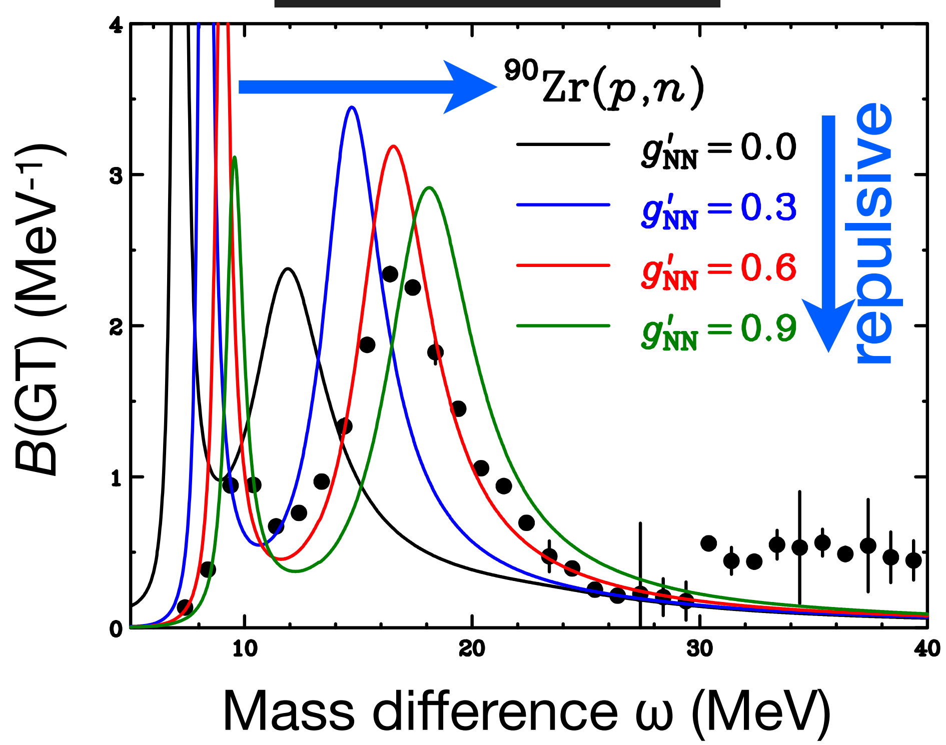
GT studies on stable nuclei and collectivity

Gamow-Teller → Most fundamental spin-isospin mode

- GTGR : collectivity by repulsive residual interaction
  - *Well described by Landau Migdal parameter g'_{NN}*
- Nuclear astrophysics : *weak processes in Type Ia, II SNe*
- Deeper understanding of nuclear structures
  → *nuclear ME in double beta decays*

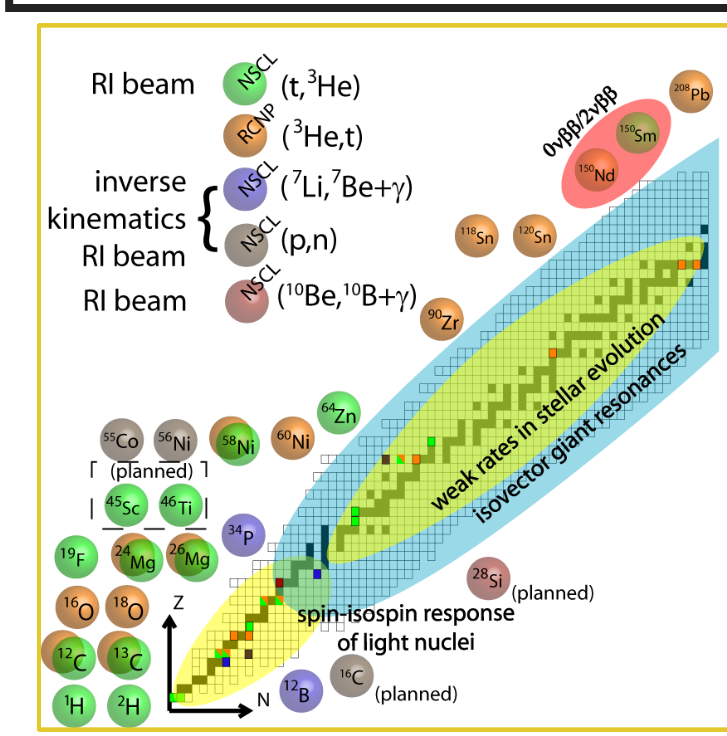


GTGR for ^{90}Zr



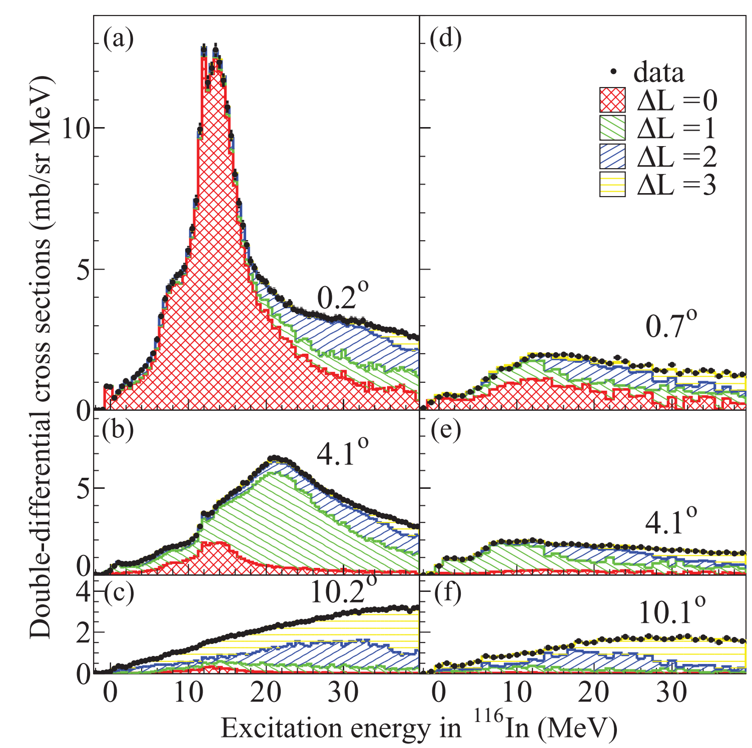
M. Ichimura, TW, et al., PPNP 56, 446 (2006)

Syst. study at NSCL/RCNP



curtesy of R.G.T. Zegers

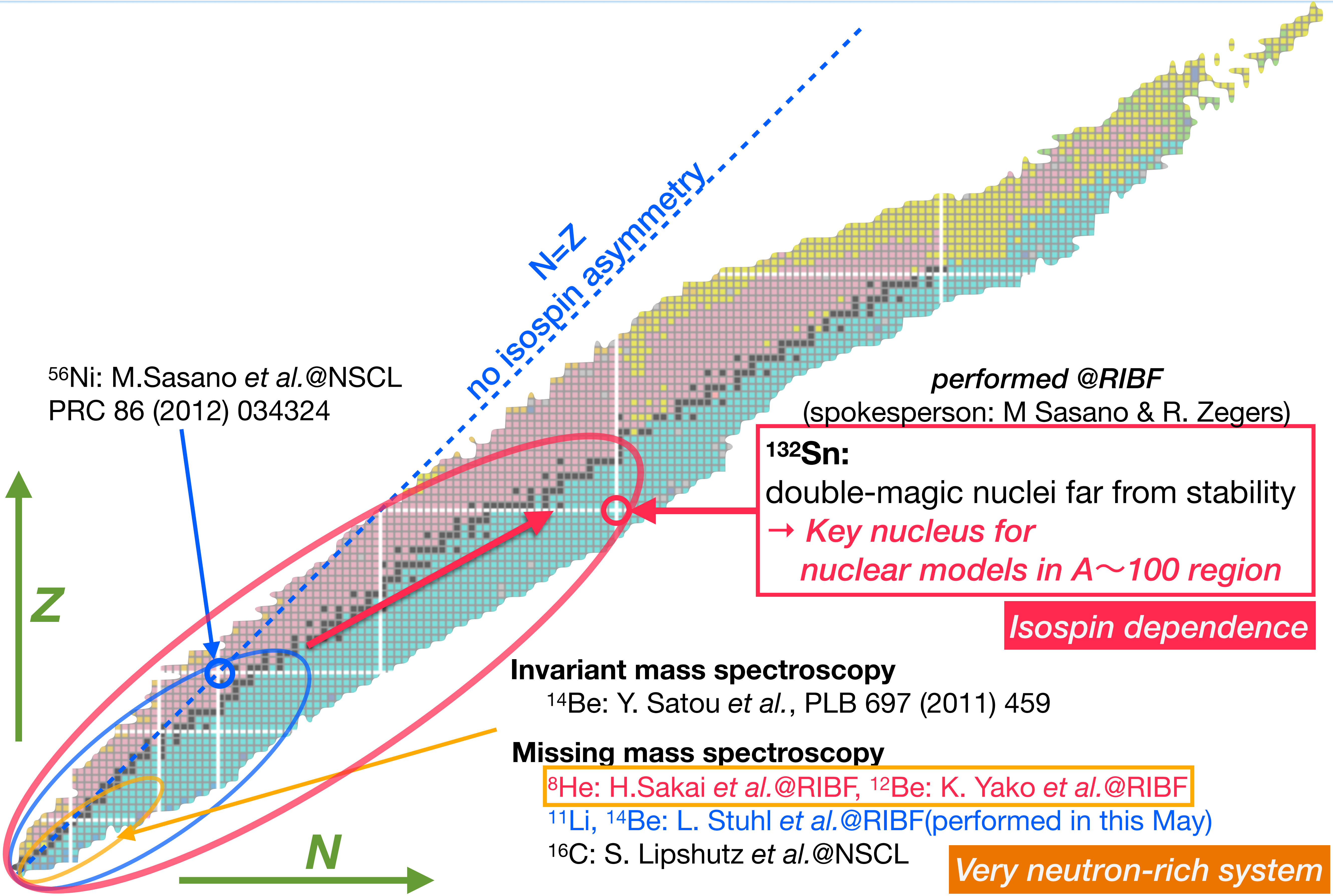
GT for ^{116}Cd ββ decay



M. Sasano et al., PRC 85, 061301 (2012)

Landau-Migdal g'_{NN} is the important key parameter and almost const. for stable nuclei
→ Extension to RI beam (isospin/density dependence?)

Overview of (p,n) studies for RI beam



Why ^{132}Sn ?

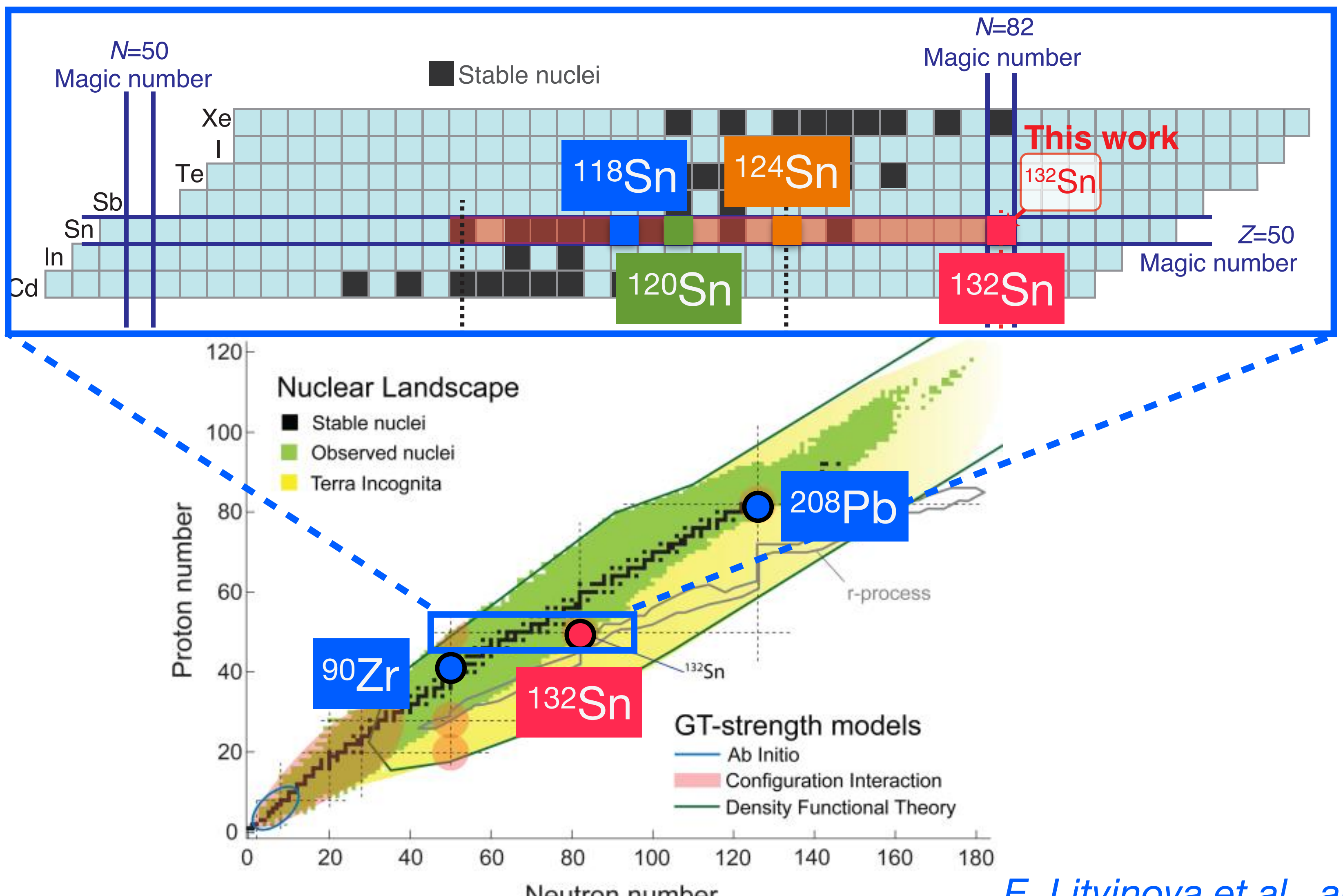
^{132}Sn is the doubly-magic nucleus between ^{90}Zr and ^{208}Pb (well studied nuclei)

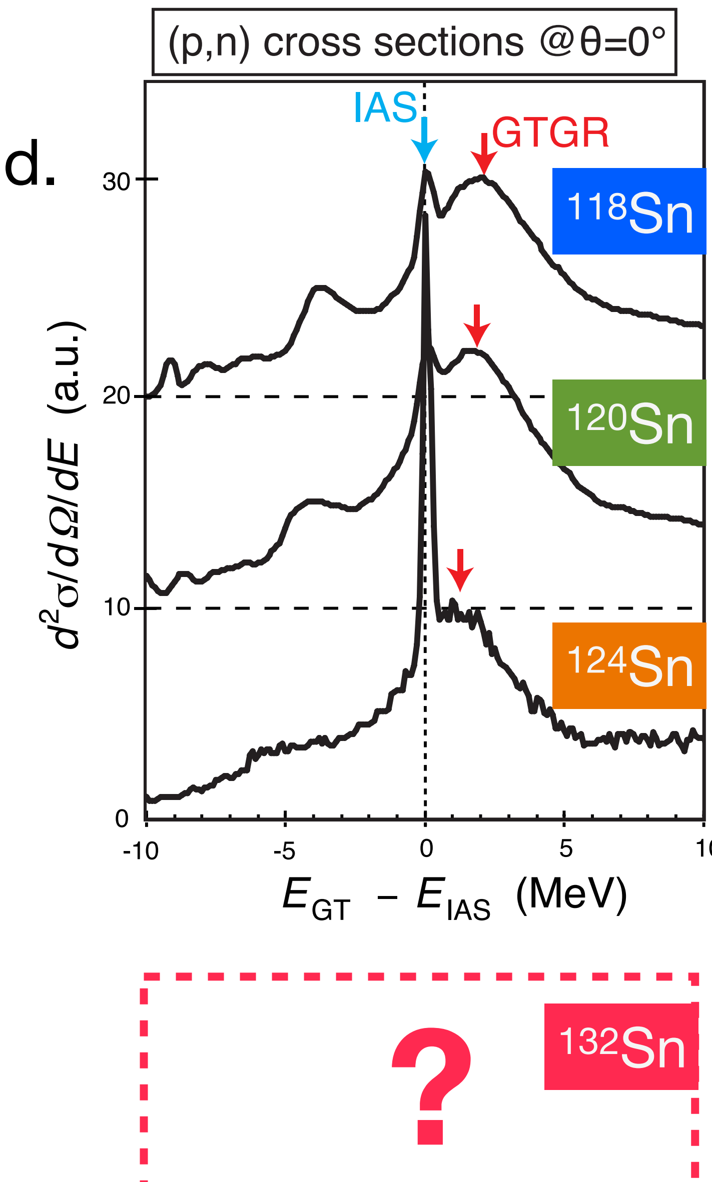
Benchmarking nucleus for nuclear models in medium heavy region

- NR-RPA, R-RPA, R-TBA, NR-RPA+PVC, etc.

Long isotope chain (A=112→132)

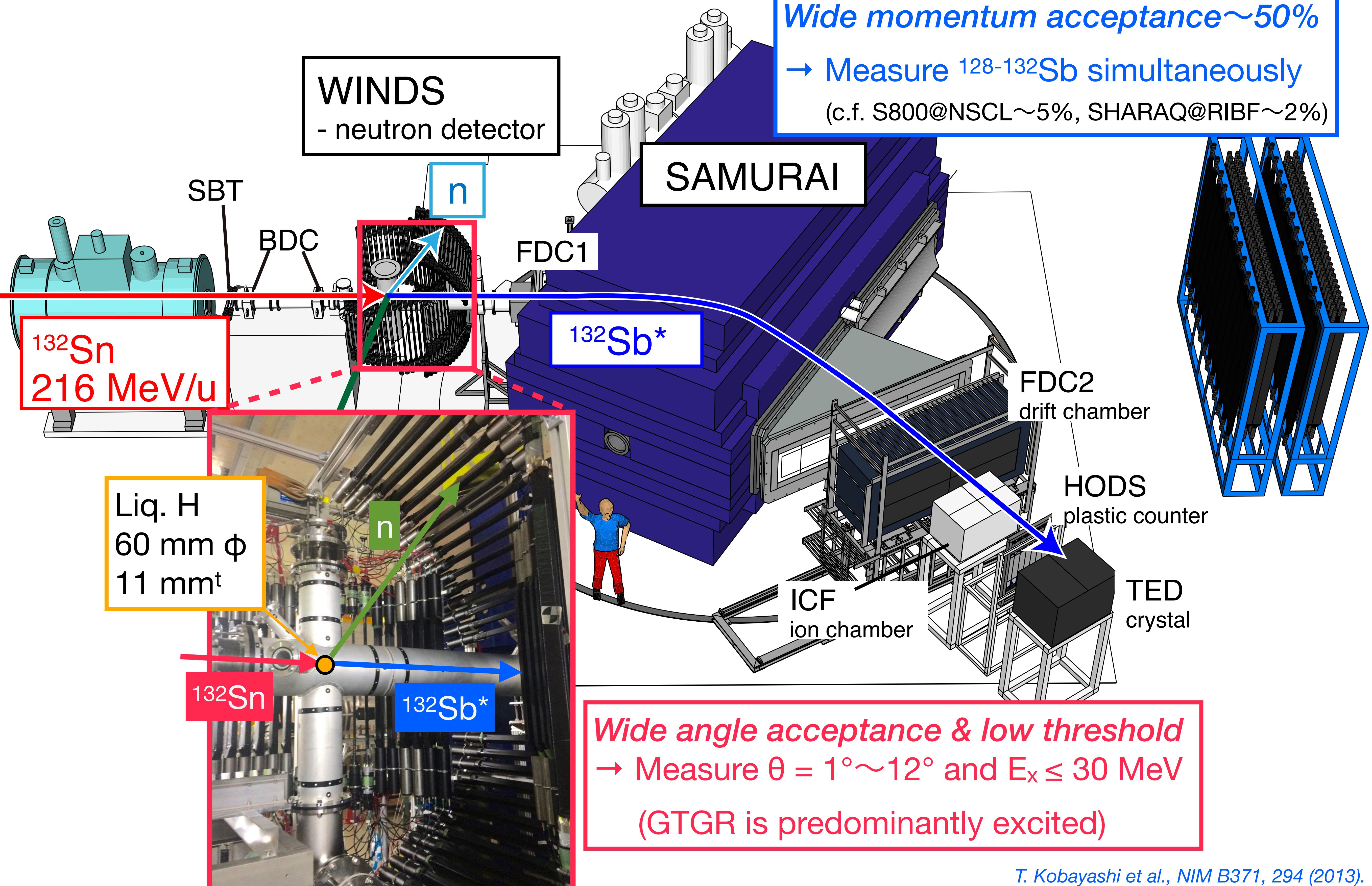
- *Isospin-dependence of GTGR peak (g'_{NN})*
- GTGR peak for ^{132}Sn might be deviate from the systematic trend.





E. Litvinova et al., arXiv:1308.3183 [nucl-th].

Experimental setup at SAMURAI in RIKEN/RIBF



Wide momentum acceptance～50%

→ Measure $^{128\text{-}132}$Sb simultaneously

(c.f. S800@NSCL～5%, SHARAQ@RIBF～2%)

Wide angle acceptance & low threshold

→ Measure $\theta = 1° \sim 12°$ and $E_x \leq 30$ MeV

(GTGR is predominantly excited)

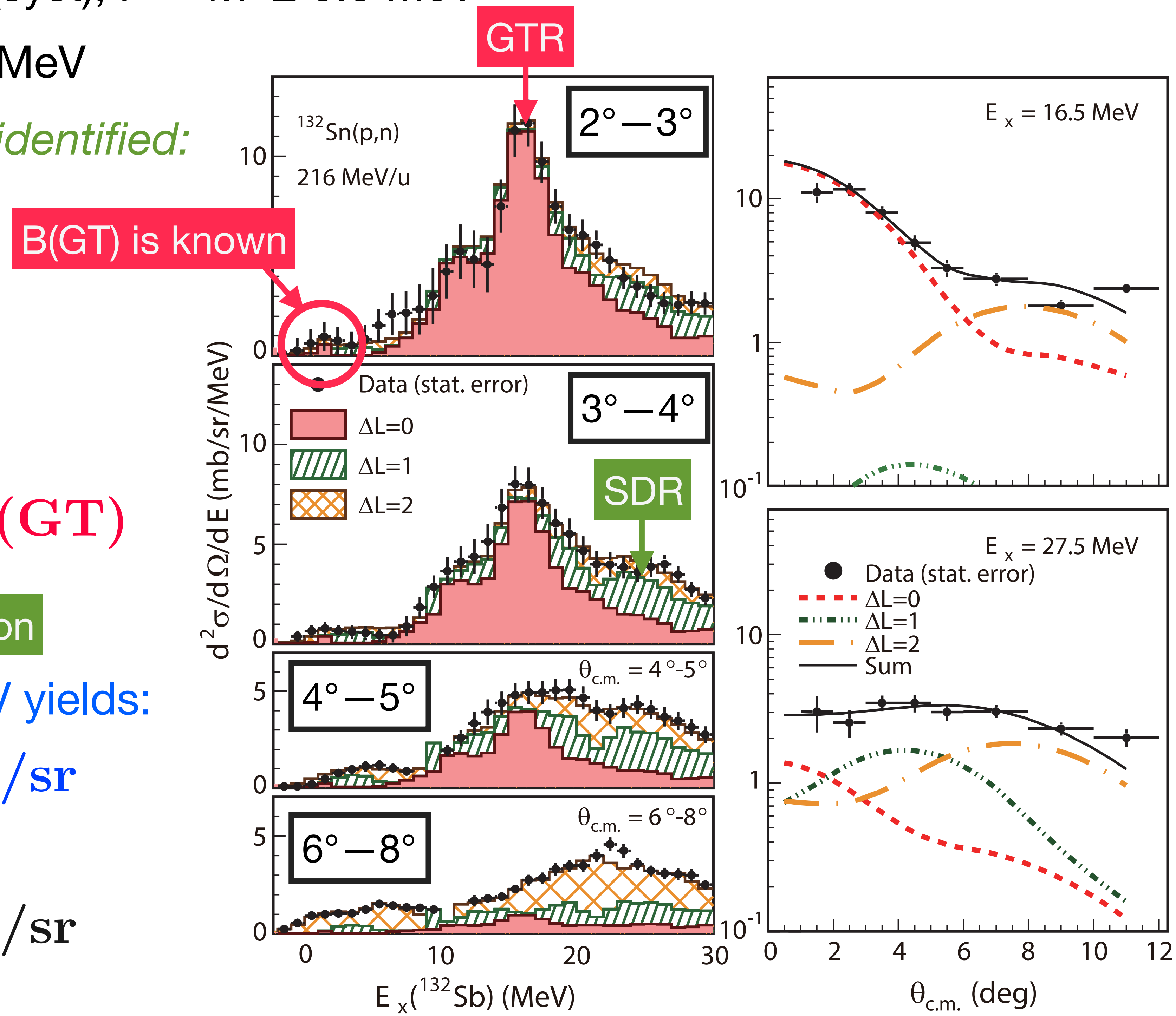
T. Kobayashi et al., NIM B371, 294 (2013).

Experimental results

J. Yasuda, M. Sasano, R.G.T. Zegers et al., accepted for publication in PRL.

Experimental results and multipole decomposition analysis

- *GTR(ΔL=0) is observed/identified:*
  - $E_x = 16.3 \pm 0.4(\mathrm{stat}) \pm 0.4(\mathrm{syst})$, $\Gamma = 4.7 \pm 0.8$ MeV
  - has a shoulder at $E_x \approx 10$ MeV
- *SDR(ΔL=1) is also observed/identified:*
  - $E_x \approx 25$ MeV



Extraction of GT strength B(GT)

Proportionality relation

$$\sigma_{\Delta L=0}(q,\omega) = \hat{\sigma}_{\mathrm{GT}} F(q,\omega) B(\mathrm{GT})$$

unit cross section

(q,ω) correction

- Systematic study at 200 MeV yields:

$$\hat{\sigma}_{\mathrm{GT}} = 2.7 \pm 0.5\ \mathrm{mb/sr}$$

- Known B(GT) values yield:

$$\hat{\sigma}_{\mathrm{GT}} = 3.8 \pm 2.0\ \mathrm{mb/sr}$$

B(GT) and Landau-Migdal parameter g'$_{NN}$

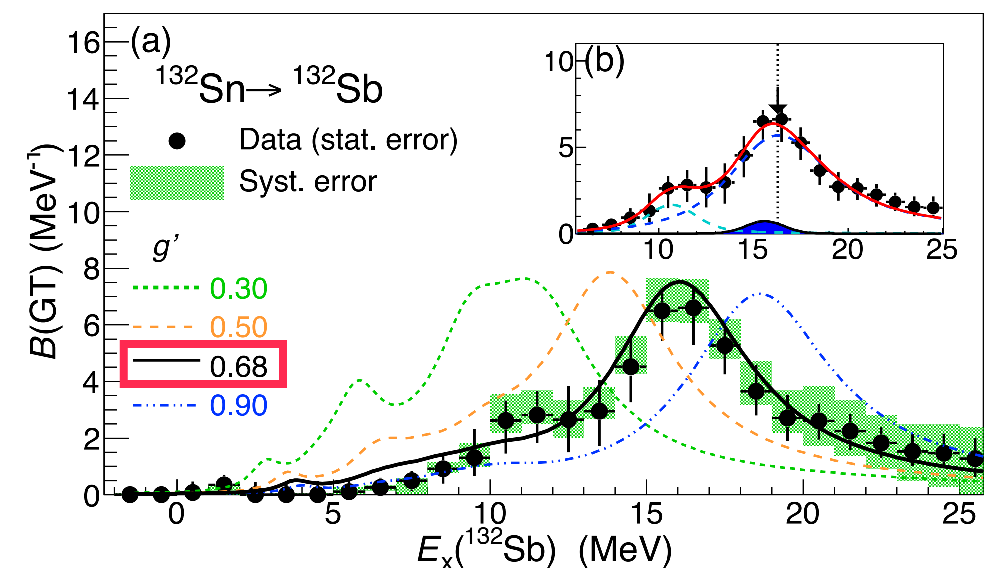
J. Yasuda, M. Sasano, R.G.T. Zegers et al., submitted to PRL.

B(GT) distribution

g'$_{NN}$ is sensitive to GT peak and evaluated in RPA

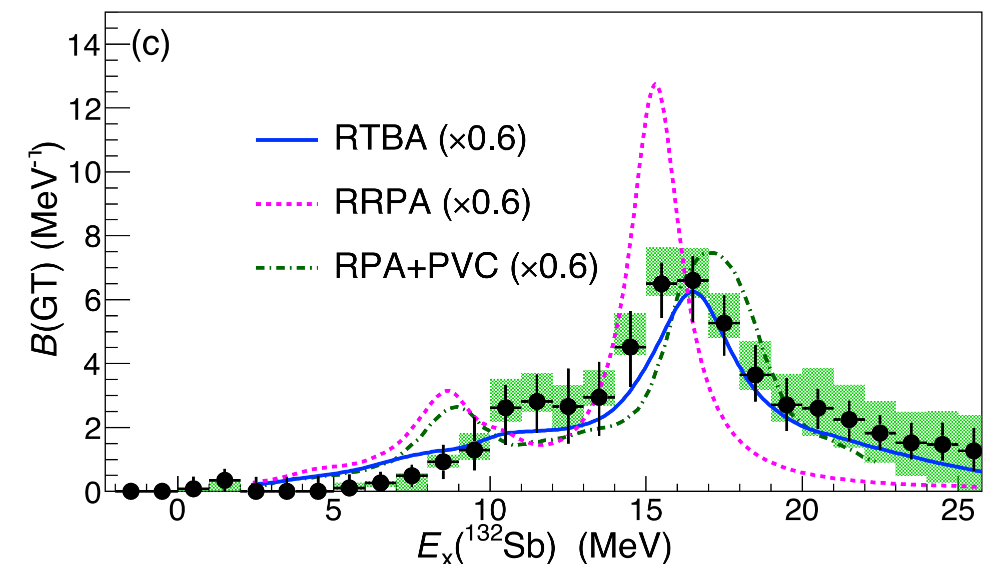
- $g'_{NN} = 0.68 \pm 0.07$
- Consistent with 0.6 for ^{90}Zr and 0.64 for ^{208}Pb

g'$_{NN}$ is constant for isospin asymmetry (N-Z)/A of 0.11(^{90}Zr) to 0.24(^{132}Sn)



Comparison with theoretical models

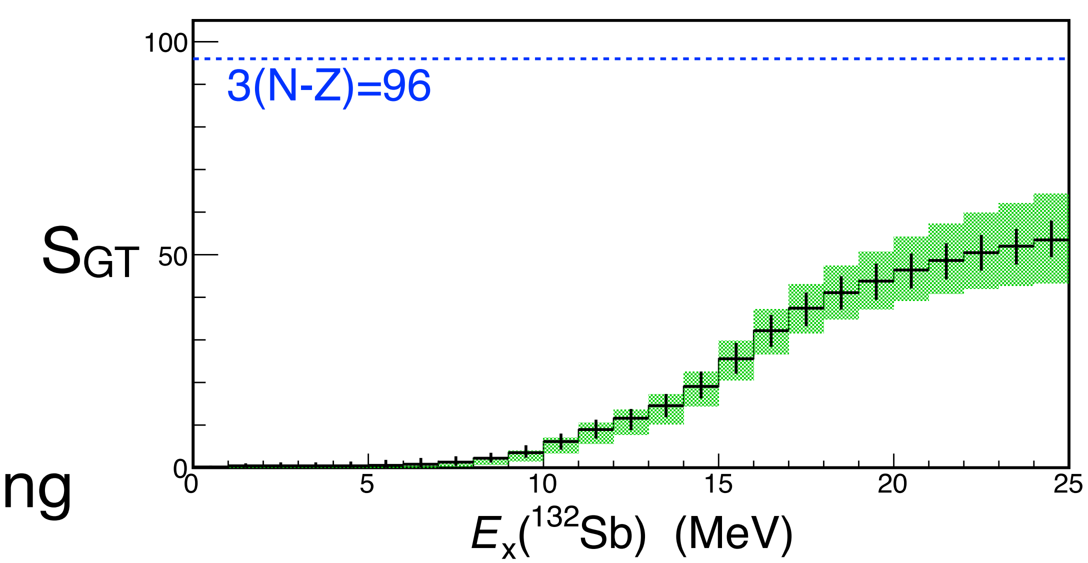
- Reasonably reproduce the GTR in ^{132}Sn
- The shoulder structure depends on shell structure



Total strength of B(GT) up to 25 MeV (up to GTR)

$$S^{-}_{\mathrm{GT}} = 53 \pm 5(\mathrm{stat})^{+11}_{-10}(\mathrm{syst})$$

- **56%** of sum-rule value of 3(N-Z)=96
- ***Consistent with the systematics in stable nuclei***
    - A future study for higher excitations is challenging



GT resonance for neutron-rich nuclei

Gamow-Teller resonance for very neutron-rich nuclei, ^{8}He and ^{12}Be

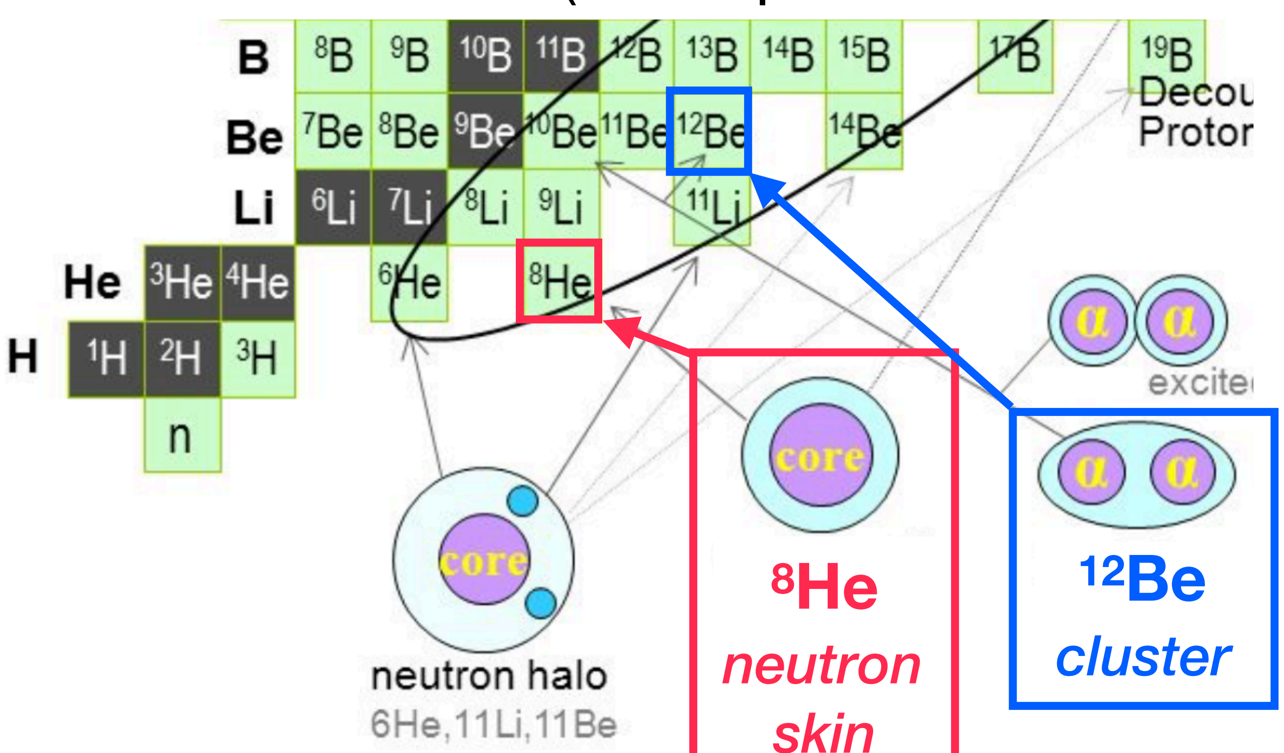
- ^{8}He: (N-Z)/A = 0.50 → *Largest isospin asymmetry* (cf. 0.21 for ^{208}Pb)
- ^{12}Be: (N-Z)/A = 0.33

^{8}He and ^{12}Be can be used to study isospin dependence of residual interaction

- ***How to change (or NOT change) the repulsive spin-isospin interaction, g'_{NN}?***
- How about the effects on Gamow-Teller resonance (collectivity)?

Also interesting:

- Halo/skin/cluster effects
- Deformation effects (ex. ellipsoid ratio = 2:1 for ^{12}Be)



First (p,n) measurements in inverse kinematics at RIBF

courtesy of Y. Kanada-Enkyo

Systematics for stable nuclei

Gamow-Teller (ΔS=1) and IAS (ΔS=0) peak difference is given by

ΔS=1 (GT) ΔS=0 (IAS)

$$E_{\mathrm{GT}} - E_{\mathrm{IAS}} = \Delta E_{ls} + \mathrm{const.}\left(\boxed{g'_{NN}} - \boxed{f'}\right)\boxed{\frac{(N-Z)}{A}}$$

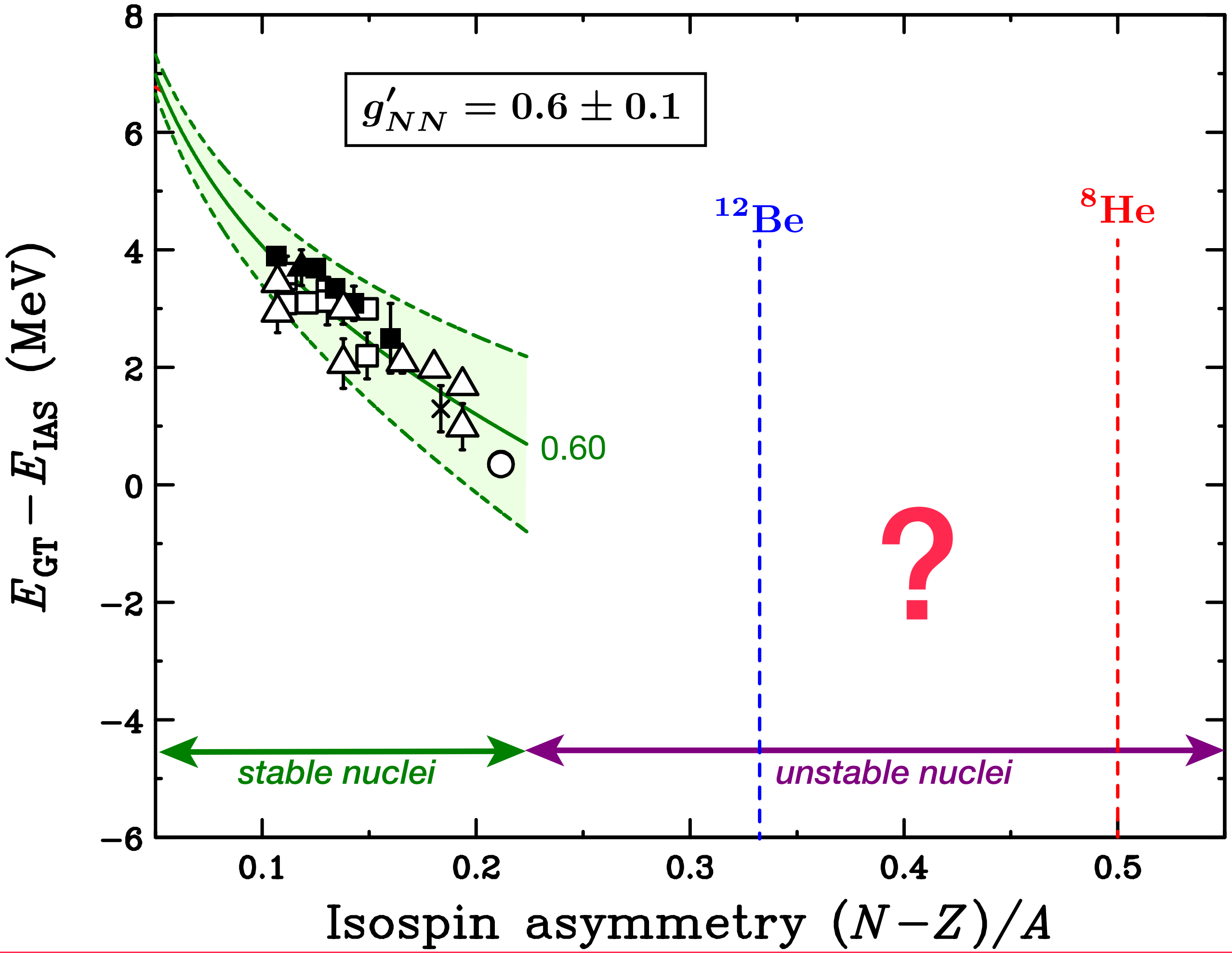
Isospin asymmetry

$$\mathrm{const.} = 2\left(\frac{f_\pi^2}{m_\pi^2}\right)\rho\gamma$$

- ΔE_{ls} : energy spacing b/w spin-orbit partners $\simeq 20(l\cdot s)A^{-2/3}$ MeV

Energy difference would be ***proportional to isospin asymmetry: (N-Z)/A***

- Exp. data: Zr, Nb, Mo, Sn, Tm, Pb
- Almost proportional to (N-Z)/A
  - ***Support constancy of g'$_{NN}$***
  - Slightly modified by ΔE_{ls}



K. Nakayama et al., Phys. Lett. B 114, 217 (1982).
Bohr and Mottelson, Nuclear Structure.

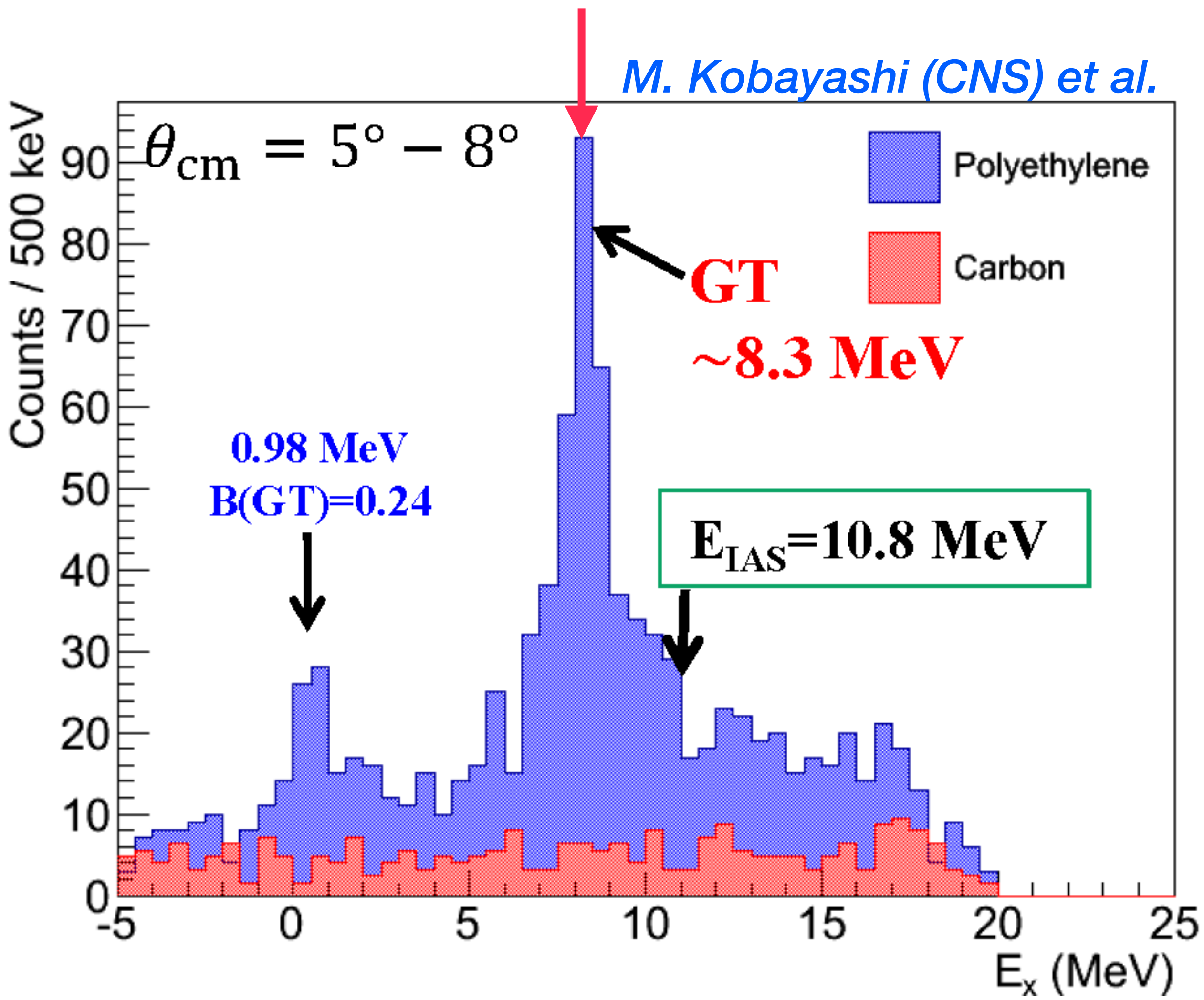
Existing data for stable nuclei support the constancy of g'$_{NN}$=0.6±0.1 up to (N-Z)/A=0.21
→ ***How about very neutron-rich nuclei for ^{12}Be and ^{8}He with (N-Z)/A=0.33 and 0.50***

Experimental results

Gamow-Teller resonances have been *successfully observed* for ^{8}He and ^{12}Be

^{8}He(p,n) at 200 MeV/A

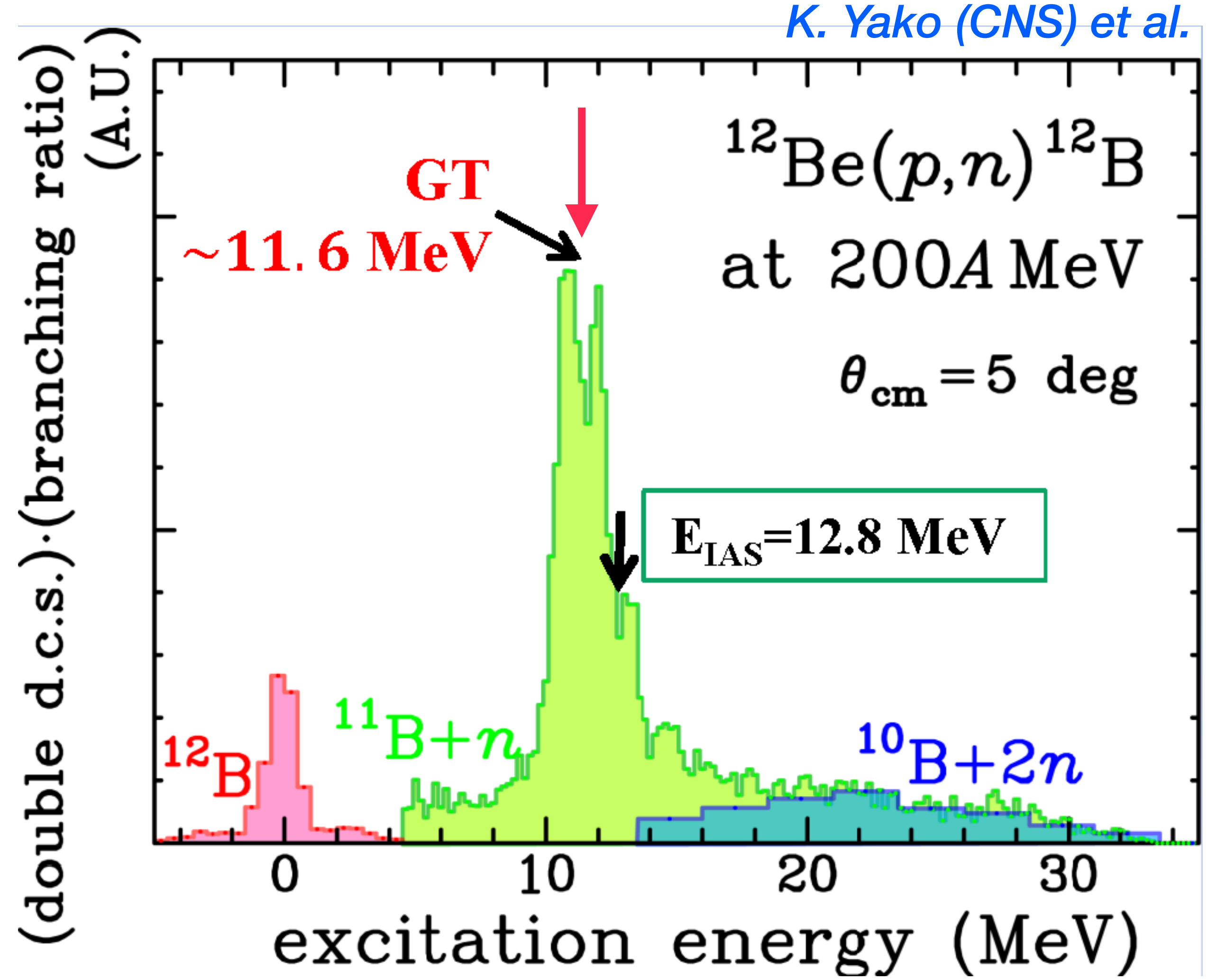
M. Kobayashi (CNS) et al.



$E_{GT} - E_{IAS}$ = -2.5 ± 0.5 MeV

^{12}Be(p,n) at 200 MeV/A

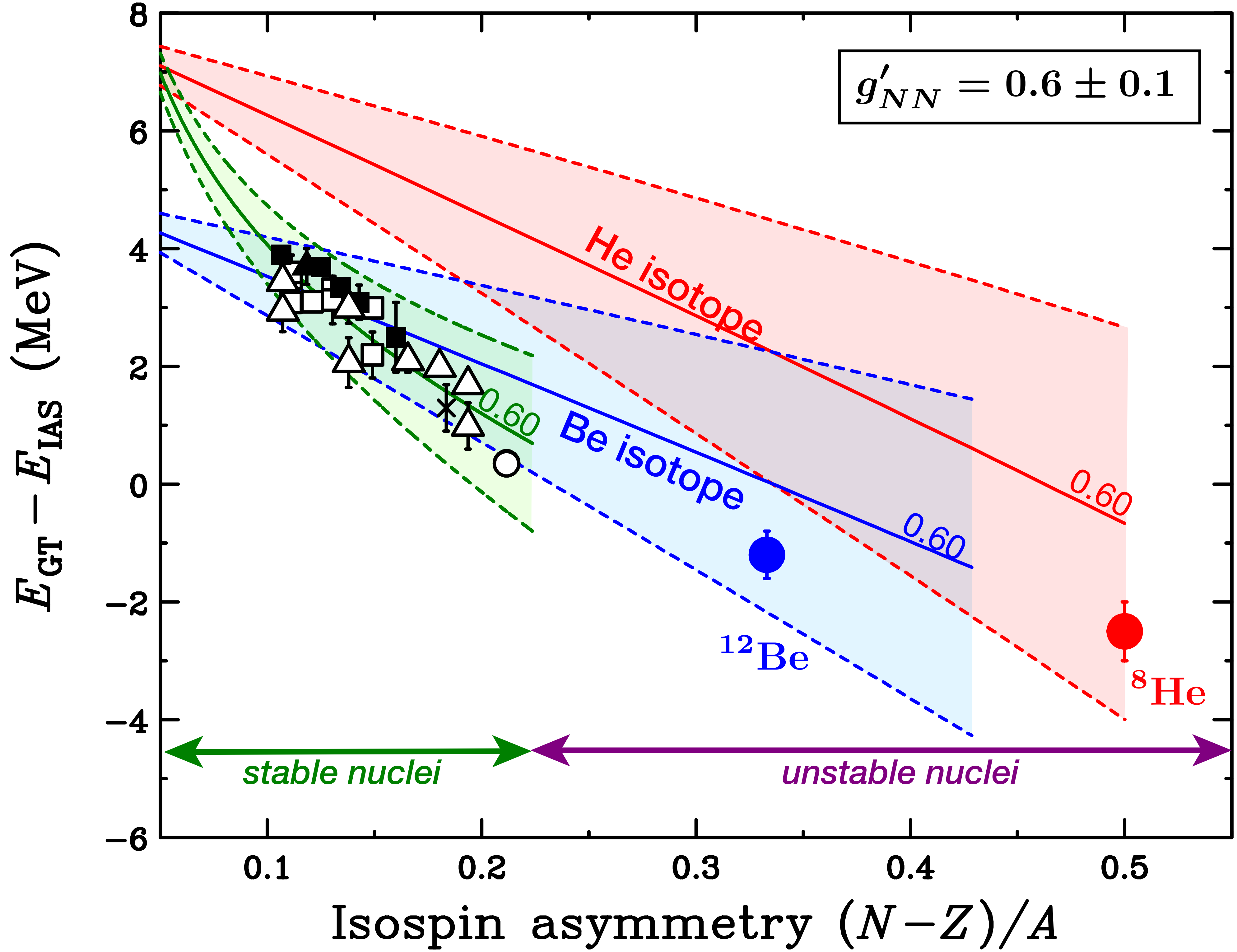
K. Yako (CNS) et al.



$E_{GT} - E_{IAS}$ = -1.2 ± 0.5 MeV

M. Kobayashi et al., JPS Conf. Proc. 1, 013034 (2014).
courtesy of K. Yako

Collectivity in (N-Z)/A > 0.21; Very neutron-rich nuclei



Data are consistent with predictions employing g'$_{NN}$=0.6±0.1

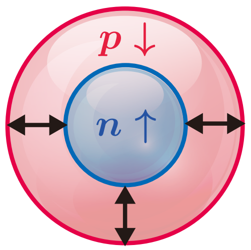
→ Suggests the constancy of residual interaction for up to (N-Z)/A=0.5 (very neutron-rich)

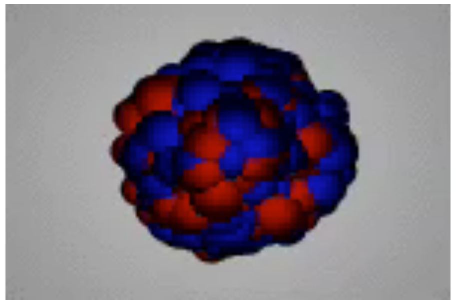
Isovector (IV) spin-monopole (IVSM) response

Spin-isospin (ΔS = ΔT = 1) modes with ΔL = 0

- Gamow-Teller $\quad 0\hbar\omega \quad \mathrm{GT}^{\pm}(\mu) = \sum_k t_{\pm}(k)\sigma_{\mu}(k)$
- IV spin monopole (IVSM) $\quad 0\hbar\omega + 2\hbar\omega \quad \mathrm{IVSM}^{\pm}(\mu) = \sum_k t_{\pm}(k)\sigma_{\mu}(k)r(k)^2$

Compression mode





Energy centroid E and width Γ of IVSMR

- Isovector spin-incompressibility
- *Effective interaction in spin-isospin channel*: Landau-Migdal parameter g'_{NN}

Sum-rule (model-independent)

$$S_- - S_+ = 3(N\langle r^4\rangle_n - Z\langle r^4\rangle_p)$$

neutron *proton*

Sensitive to neutron skin by 4th power for r

- **Neutron skin thickness :** $\delta_{np} \equiv \sqrt{\langle r^2\rangle_n} - \sqrt{\langle r^2\rangle_p}$

$$\simeq \frac{\sqrt{3/5}}{\sqrt[4]{3/7}}\left(\sqrt[4]{\langle r^4\rangle_n} - \sqrt[4]{\langle r^4\rangle_p}\right)$$

δ_{np} constrains L and J in EOS

IVSM and sum-rule give constraint on neutron matter equation of state (EOS)

IVSM probed by HI charge-exchange

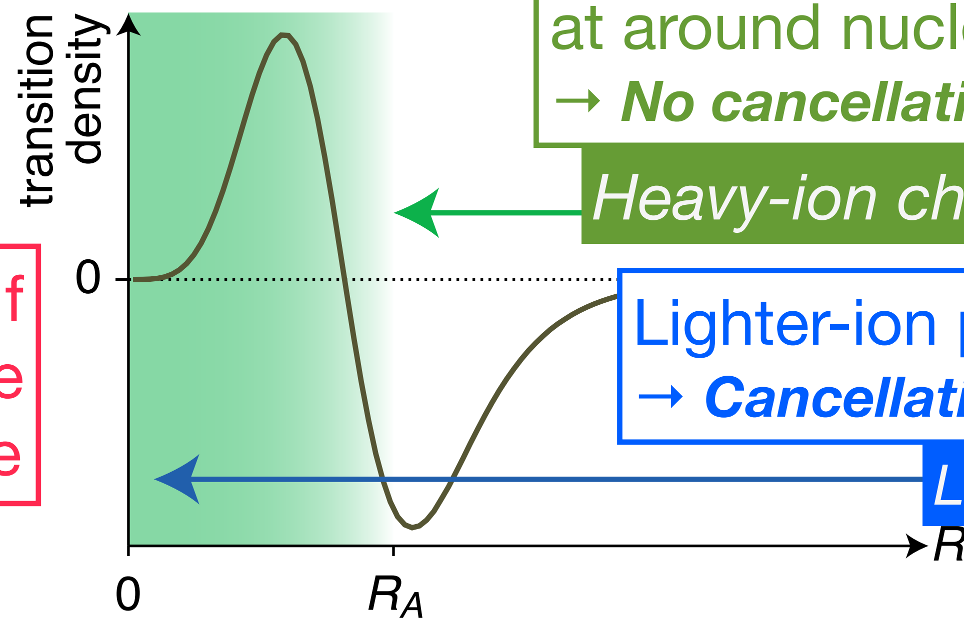
courtesy of S. Noji

Surface absorption in HI charge-exchange enhances monopole cross section

Heavy-ion probes get absorbed at around nuclear surface
→ ***No cancellation*** *b/w the inner and outer portions*

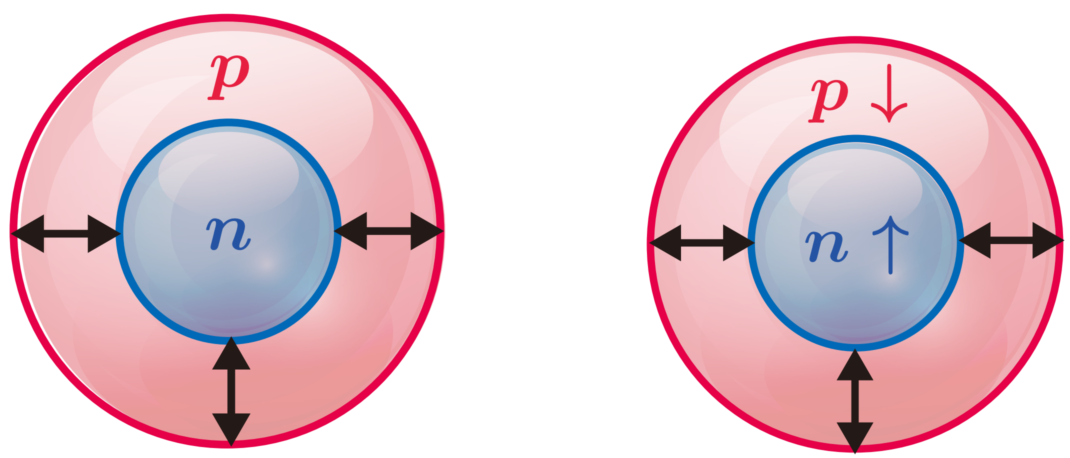
Heavy-ion charge-exchange: (^{12}N,^{12}C),(t,^{3}He)

Transition densities of ***monopole*** resonances have ***a node*** near nuclear surface



Lighter-ion probes scan throughout target
→ ***Cancellation*** b/w the inner and outer portions

Light-ion charge-exchange: (p,n),(n,p)



IVGMR **IVSGMR**

New data for IVSM by (^{12}N,^{12}C) and (t,^{3}He) on ^{90}Zr at RIKEN/RIBF with SHARAQ

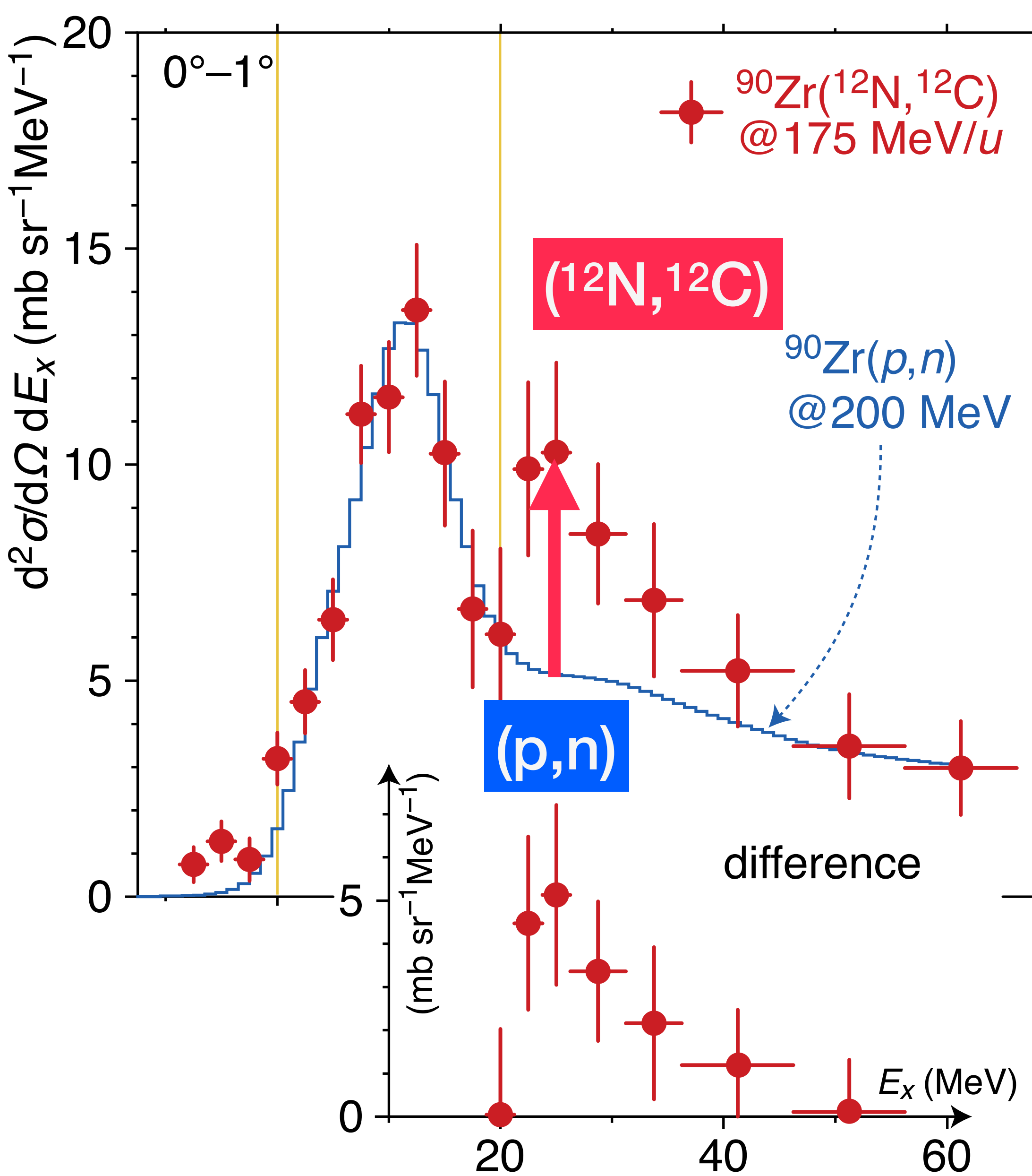
Experimental results

β-: $^{90}Zr(^{12}N, ^{12}C)$

S. Noji et al., PRL 120, 172501 (2018).

- (p,n): GTR at Ex≈10 MeV only
  → ***insensitive to IVSM***
- (^{12}N,^{12}C): GTR and ***IVSM*** at Ex≈25 MeV
  → ***sensitive to IVSM***

→ Powerful new tool for IVSM

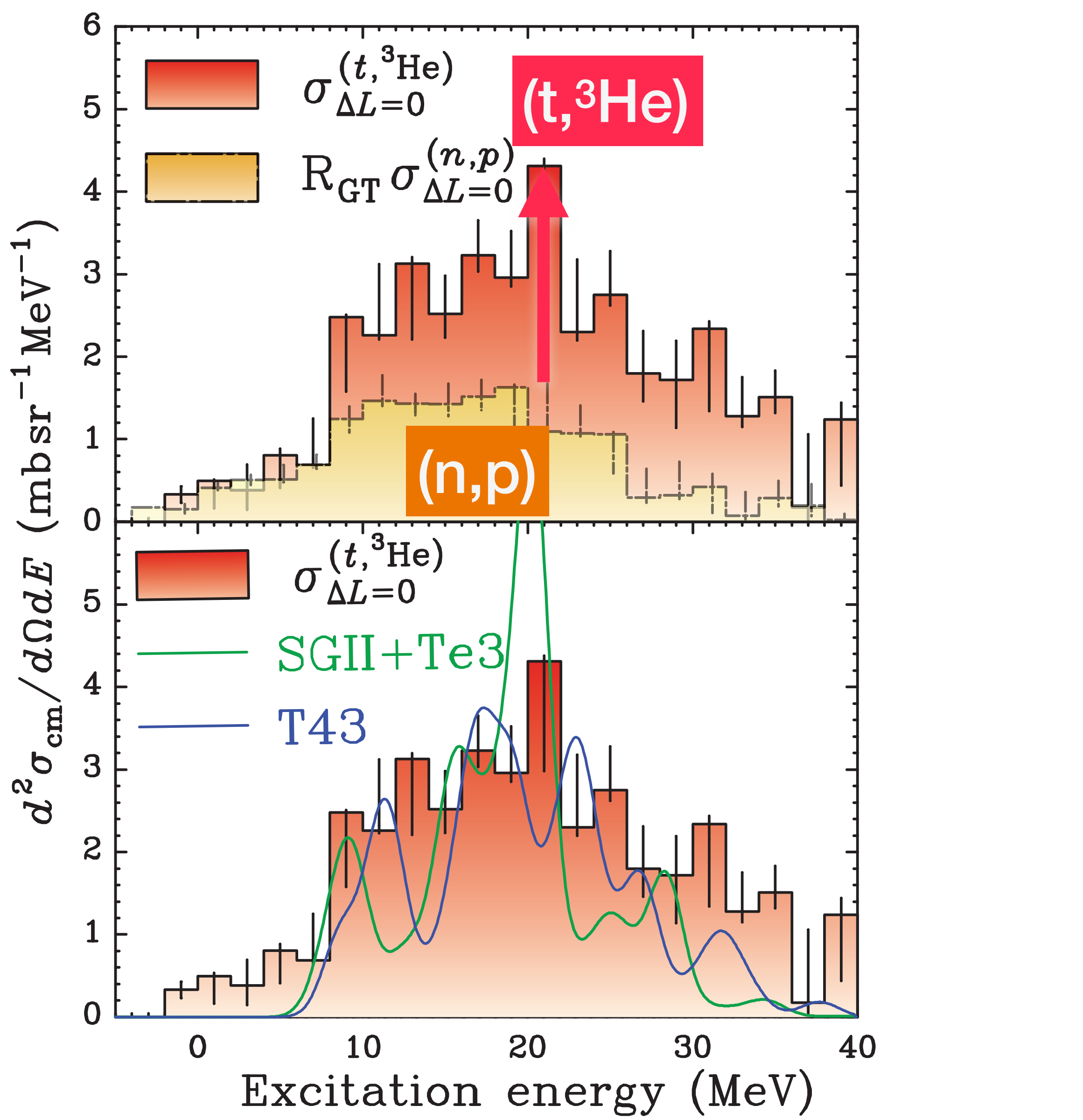


β+: $^{90}Zr(t, ^3He)$

K. Miki et al., PRL 108, 262503 (2012).

- Significant ***enhancement*** Ex≈20 MeV by IVSM compared with (p,n) data
- Consistent with HF-RPA (blue)

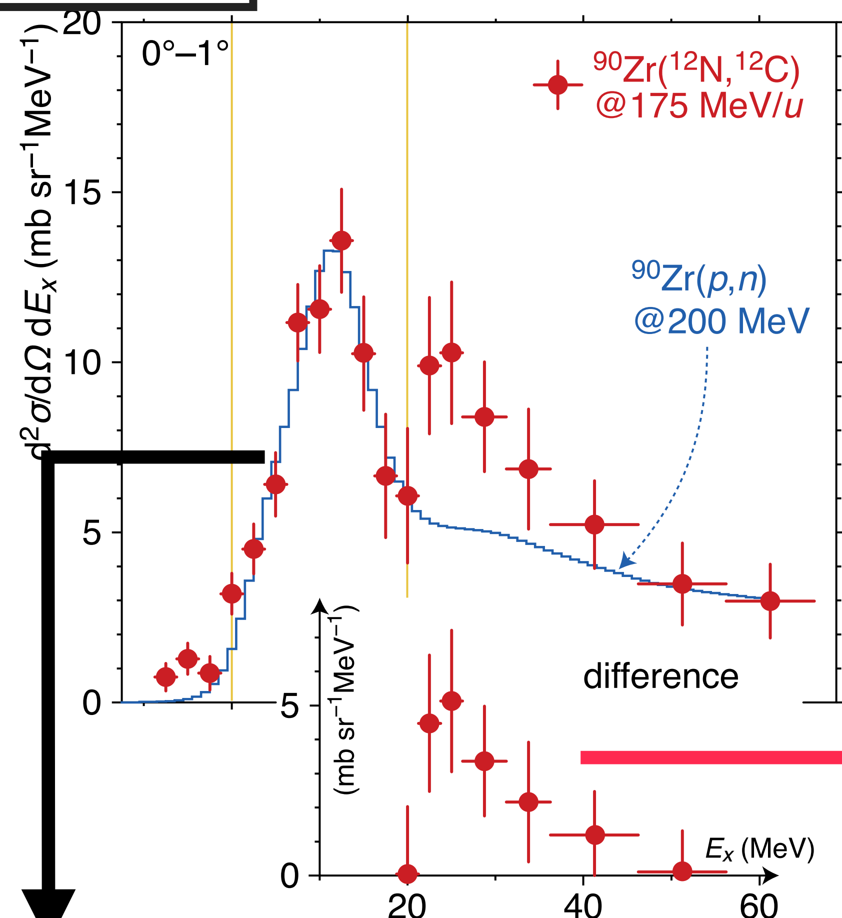
→ Clearest identification of β+-IVSM



Sum-rule and neutron skin thickness

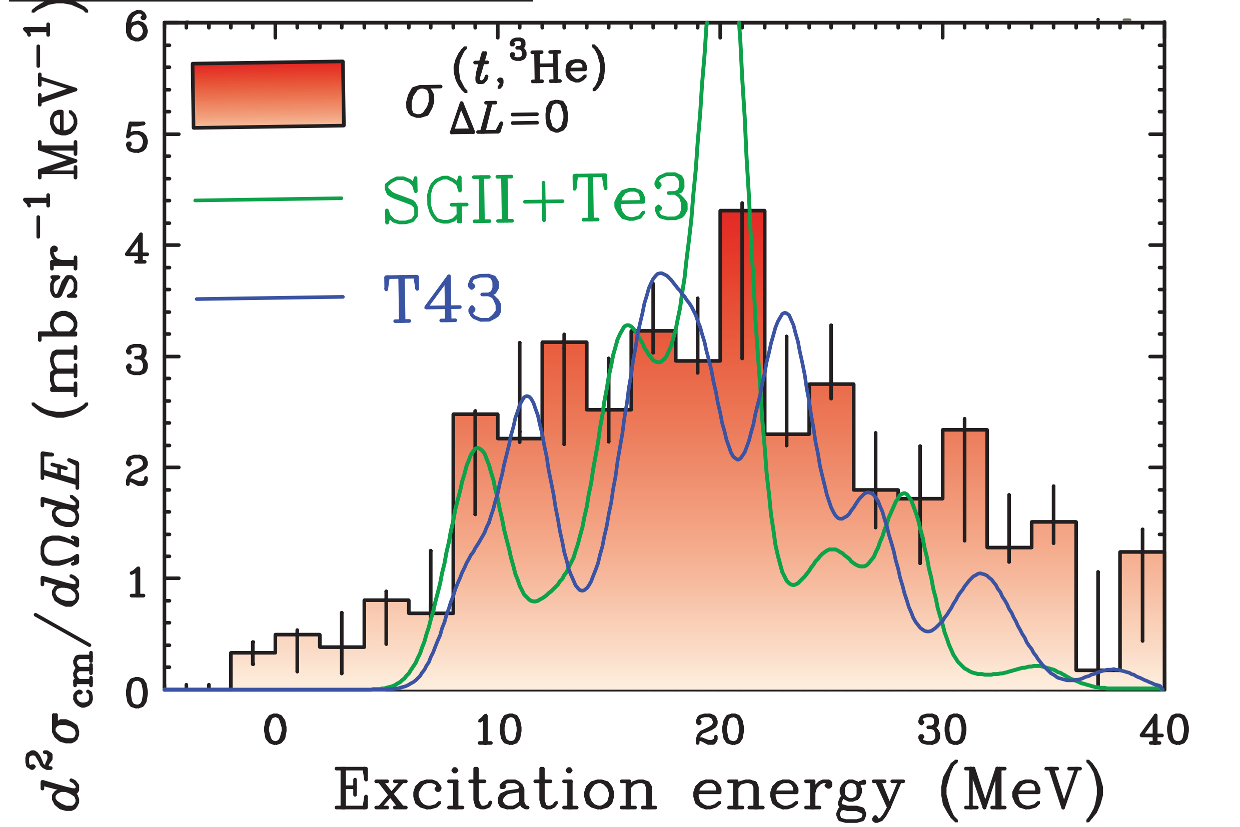
β⁻: $^{90}Zr(^{12}N, ^{12}C)$

S. Noji et al., PRL 120, 172501 (2018).



β⁺: $^{90}Zr(t, ^{3}He)$

K. Miki et al., PRL 108, 262503 (2012).



$0\hbar\omega$:
86 ± 7% (GT Quenching)

$2\hbar\omega$:
90 ± 54% (This exp.)

$0\hbar\omega + 2\hbar\omega$:
151 ± 61% (This exp.)

$S^{-} = (25 \pm 6)\times 10^{3}\ \mathrm{fm}^{4}$

$S^{+} = (16 \pm 6)\times 10^{3}\ \mathrm{fm}^{4}$

method	δ_{np} (fm)
p elastic	0.09 ± 0.07
p-bar X-ray	0.09 ± 0.02
SDR	0.07 ± 0.04

$$\boxed{S^{-} - S^{+} = (9 \pm 9) \times 10^{3}\ \mathrm{fm}^{4}}$$

$$\boxed{S^{-} - S^{+} = 3(N\langle r^{4}\rangle_{n} - Z\langle r^{4}\rangle_{p}) \rightarrow \delta_{np} = 0.10 \pm 0.16\ \mathrm{fm}}$$

New spin-isospin mode and application to neutrino physics

0vββ decay and double charge exchange

J. Engel and J. Menendez, Rep. Prog. Pays. 80, 046301 (2017).

Quest for detection of 0vββ decay

- lepton-number violation/Majorana type
- *absolute neutrino mass*

effective mass

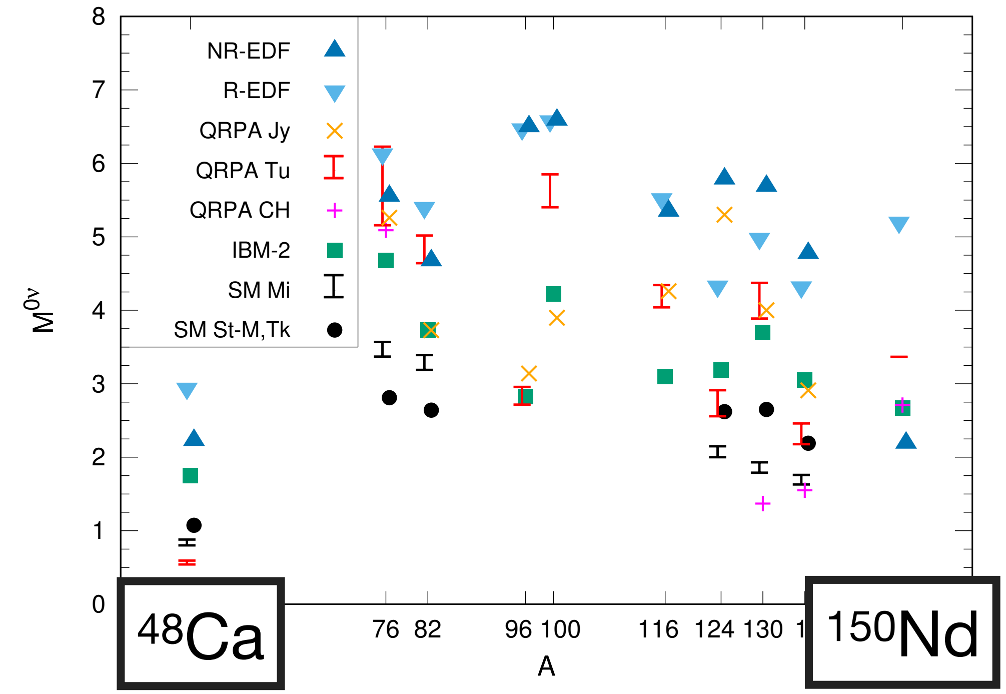
phase space

$$[T_{1/2}^{0\nu\beta\beta}(0^+ \rightarrow 0^+)]^{-1} = \boxed{G_{0\nu}} \left|\boxed{M^{0\nu\beta\beta}}\right|^2 \left(\frac{\boxed{\langle m_\nu \rangle}}{m_e}\right)^2$$

matrix element

Large diff. in matrix element calc: factor=2-3

- *How can experiments guide 0vββ decay?*



Double charge-exchange (DCX)

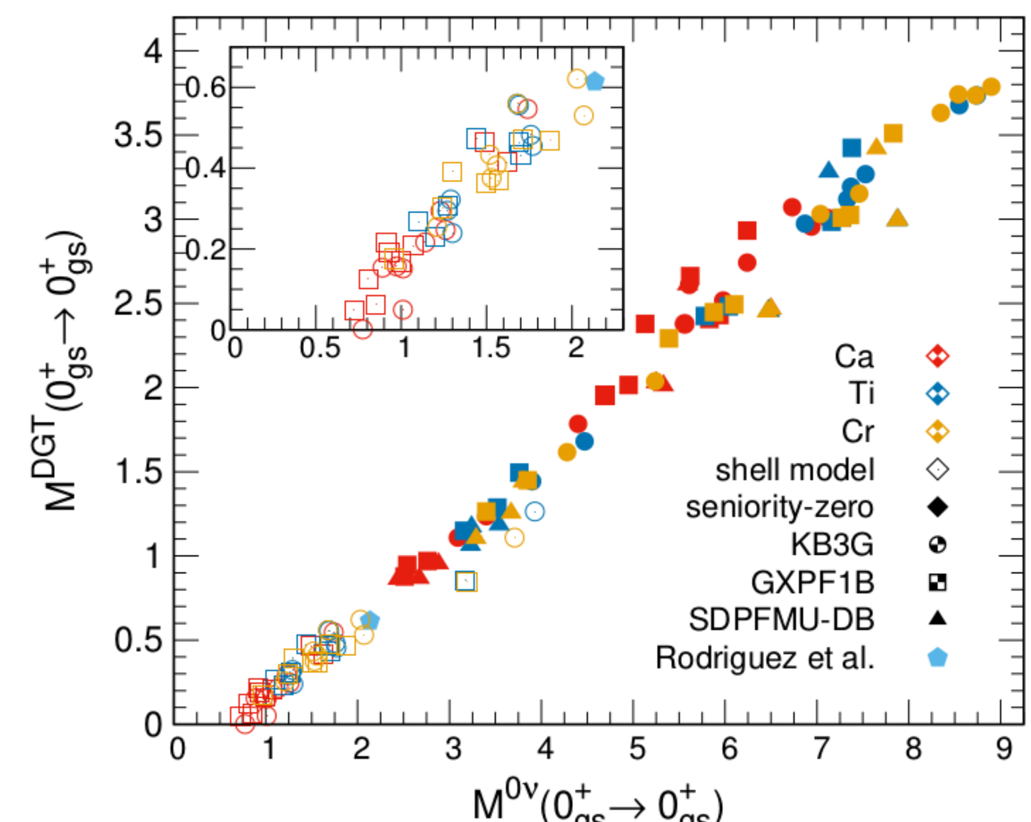
- *resemble 0vββ decay*

Operators: 0vββ vs. Double GT by DCX

$$\hat{O}_{\mathrm{GT}}^{0\nu} = \sum_{i<j} V_{\mathrm{GT}} \sigma_i \sigma_j \tau_i^- \tau_j^-$$

$$\hat{O}_{\mathrm{GT}}^{\mathrm{DCX}} = \sum_{i<j} [\sigma_i \tau_i^- \times \sigma_j \tau_j^-]^0$$

Difference: v-potential V



Linear corr. b/w 0vββ and DGT matrix elements → DCX (^{18}O,^{18}Ne) could provide $M^{0\nu\beta\beta}$

HI double charge exchange (DCX) reaction I

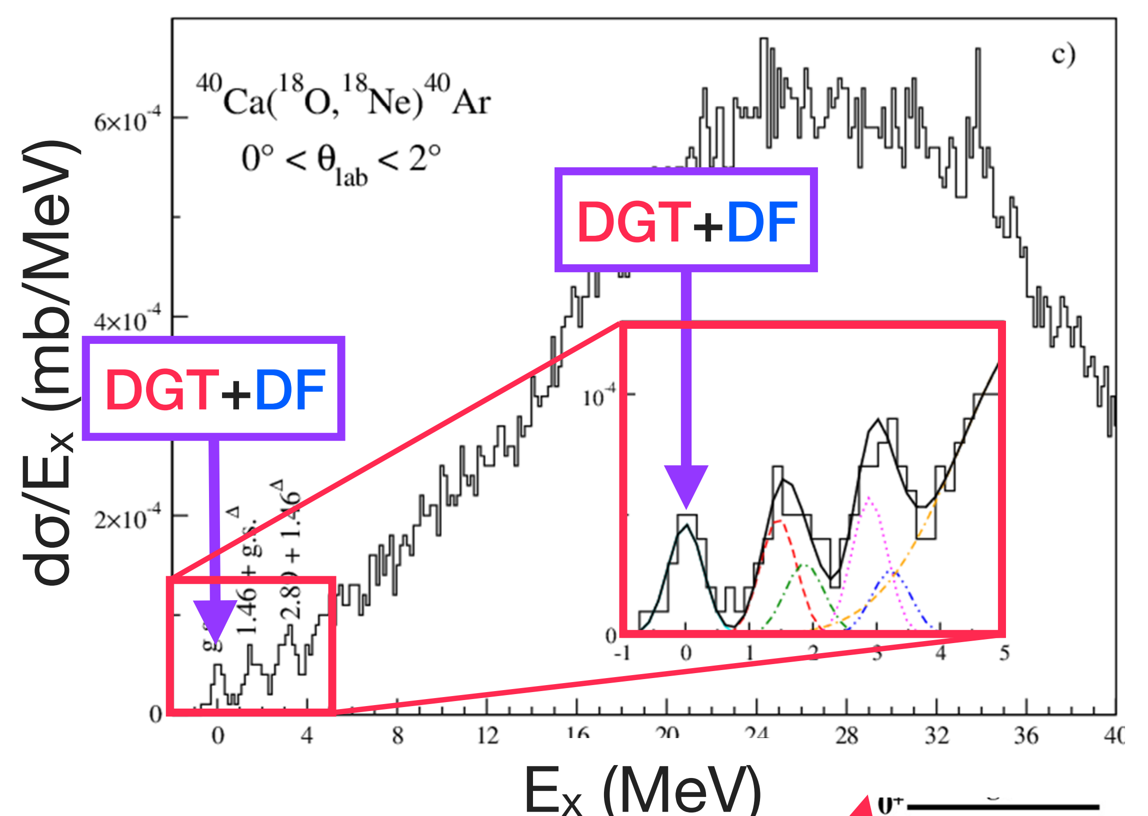
F. Cappuzzello et al., Eur. Phys. J. A 51, 145 (2015).

^{40}Ca(^{18}O,^{18}Ne)^{40}Ar at 270 MeV at INFN-LNS

Observe ^{40}Ca(0$^+$)→^{40}Ar(0$^+$) with σ(0°) = 11 μb/sr

ΔL=0 transition with

- Double Gamow-Teller (DGT)
- Double Fermi (DF)



Nuclear matrix element

$$\sigma(0^\circ) = \sigma_{\mathrm{DGT}} + \sigma_{\mathrm{F}}$$

55 μb/sr projectile=1.14

$$= \hat{\sigma}_{\mathrm{DGT}} F_{\mathrm{DGT}} \boxed{B_P(\mathrm{DGT})} B_T(\mathrm{DGT})$$

$$+ \hat{\sigma}_{\mathrm{DF}} F_{\mathrm{DF}} \boxed{B_P(\mathrm{DF})} B_T(\mathrm{DF})$$

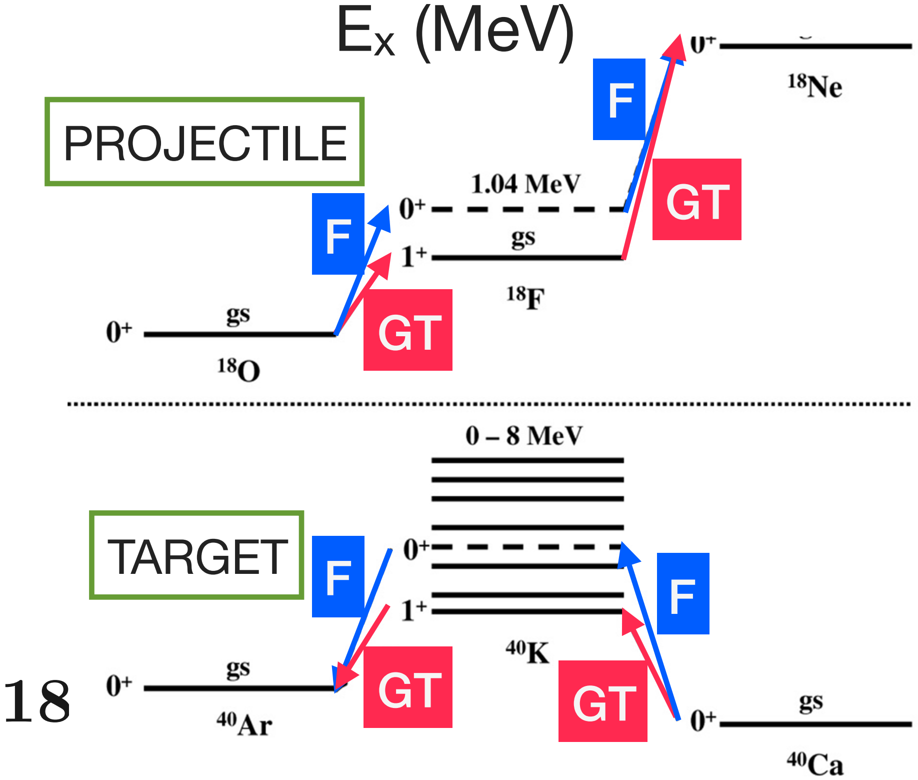
35 μb/sr projectile=4

$$B(\mathrm{DGT}) : B(\mathrm{DF}) = \sum_m B(\mathrm{GT}^-)B(\mathrm{GT}^+) : \sum_m B(\mathrm{F}^-)B(\mathrm{F}^+)$$

$$M_{\mathrm{DGT}} = \sqrt{B(\mathrm{DGT})} = 0.22$$

$$M_{\mathrm{DF}} = \sqrt{B(\mathrm{DF})} = 0.24$$

$$M^{0\nu\beta\beta}(^{40}\mathrm{Ca}) \simeq M_{\mathrm{DGT}} + \left(\frac{g_V}{g_A}\right)^2 M_{\mathrm{DF}} = 0.37 \pm 0.18$$



Pauli blocking collection → $M^{0\nu\beta\beta}(^{48}\mathrm{Ca}) = 2.6 \pm 1.3$ *Consistent w/ theor. prediction of 2.28*

J. Area et al., Phys. Rev. Lett. 109, 042501 (2012).

Double GT (DGT) resonance by double charge exchange

2νββ decay matrix element: $M^{2\nu}$

- Exhaust only less than 0.1% of sum-rule
- Similar to delay of single β-decay (missing strength)
    - Missing strength → GT resonance (GTR)
    - Observed by *single charge exchange, (p,n) etc.*

Missing strength would be found as Double GTR

- DGT : new spin-isospin mode predicted 30y ago
- Excited by *double charge exchange (DCX)*

DCX reaction

(π^+,π^-)

- Successfully observe Double IAS
- Populates Spin-flip states (DGT) only weakly

New idea/probe: (^{12}C,$^{12}Be[0_2^+]$) at RCNP/RIBF

- Large projectile transition
- Clear identification by γ-tagging

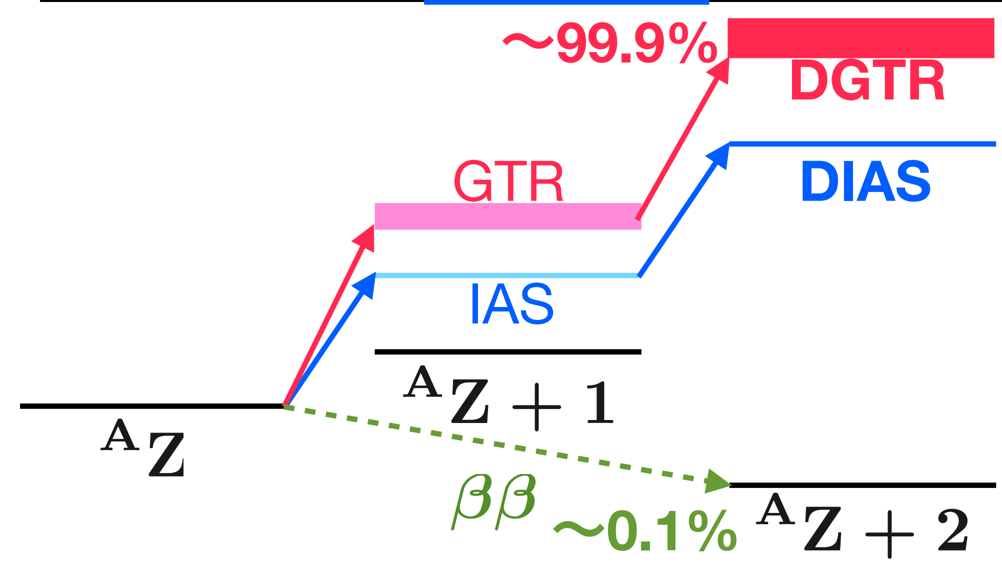
Promissing DGTR data

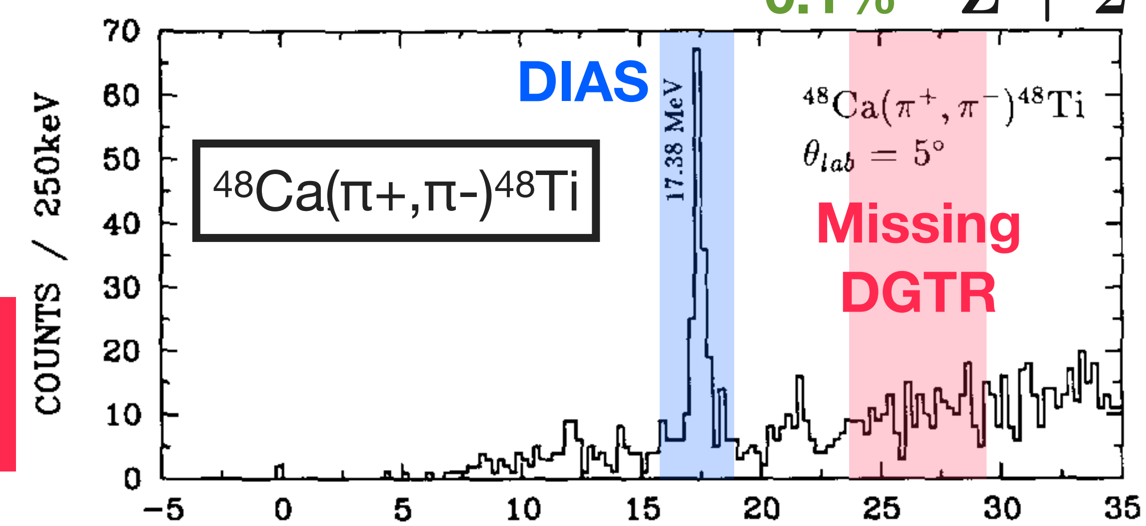
M. Takaki et al., JPS Conf. Proc. 6, 020038 (2015).

E. Carrier et al., Phys. Lett. B, 711 (2012).

Decay	$M^{(2\nu)}$ (MeV^{-1})	$T^{2\nu}_{1/2}$(y)
$^{48}Ca \to {}^{48}Ti$	0.047 ± 0.003	4.4×10^{19}
$^{76}Ge \to {}^{76}Se$	0.140 ± 0.005	1.5×10^{21}
$^{82}Se \to {}^{82}Kr$	0.098 ± 0.004	9.2×10^{19}
$^{96}Zr \to {}^{96}Mo$	0.096 ± 0.004	
$^{100}Mo \to {}^{100}Ru$	0.246 ± 0.007	
$^{116}Cd \to {}^{116}Sn$	0.136 ± 0.005	
$^{128}Te \to {}^{128}Xe$	0.049 ± 0.006	1.9×10^{24}
$^{130}Te \to {}^{130}Xe$	0.034 ± 0.003	6.8×10^{20}
$^{136}Xe \to {}^{136}Ba$	0.019 ± 0.002	2.1×10^{21}
$^{150}Nd \to {}^{150}Sm$	0.063 ± 0.003	8.2×10^{18}

< 0.1% of sum-rule





M. Kaletka et al., Phys. Lett. B 199, 336 (2012).

HI double charge exchange (DCX) reaction II

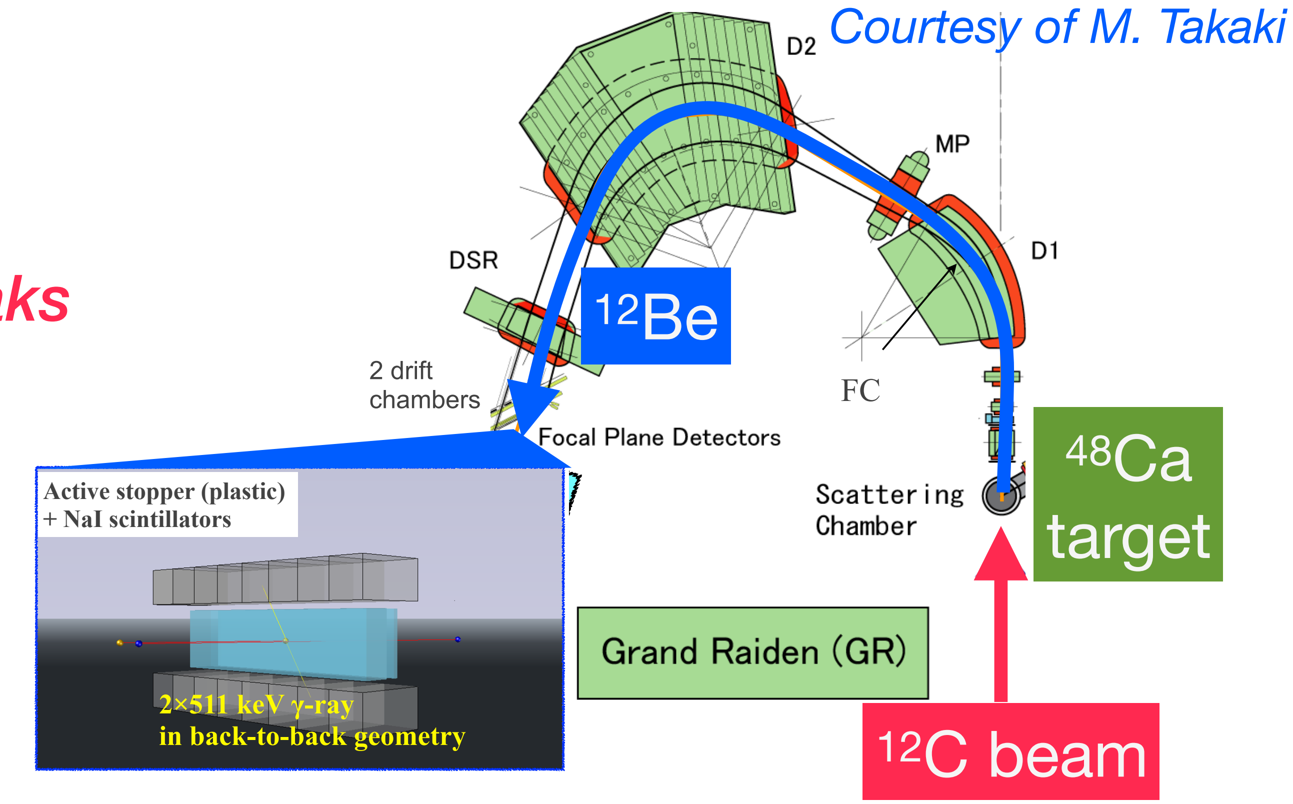
^{48}Ca(^{12}C,^{12}Be[0_2^+]) at 100 MeV/A at RCNP

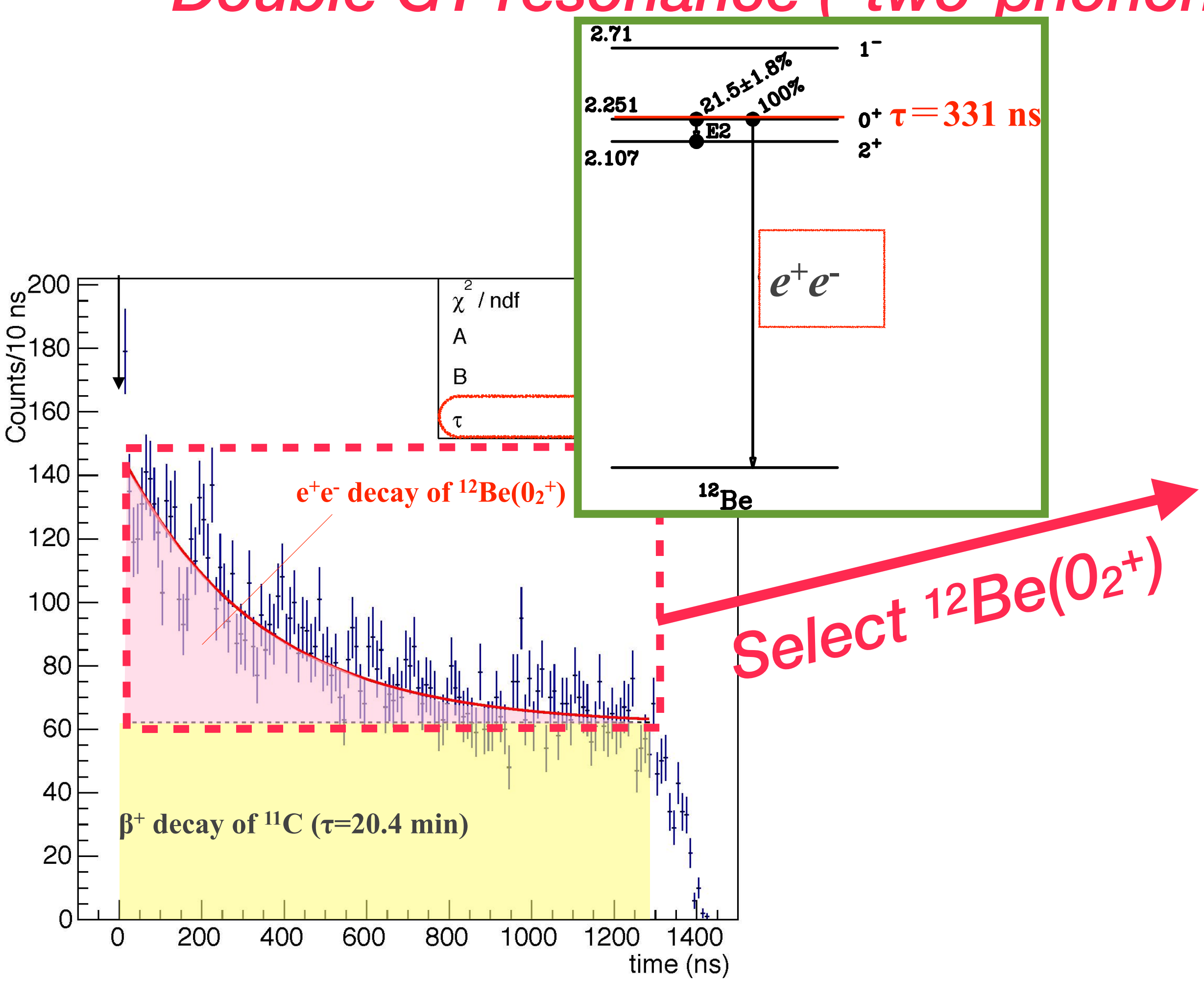
Identify ^{12}Be(0_2^+) with *γ-ray tagging*

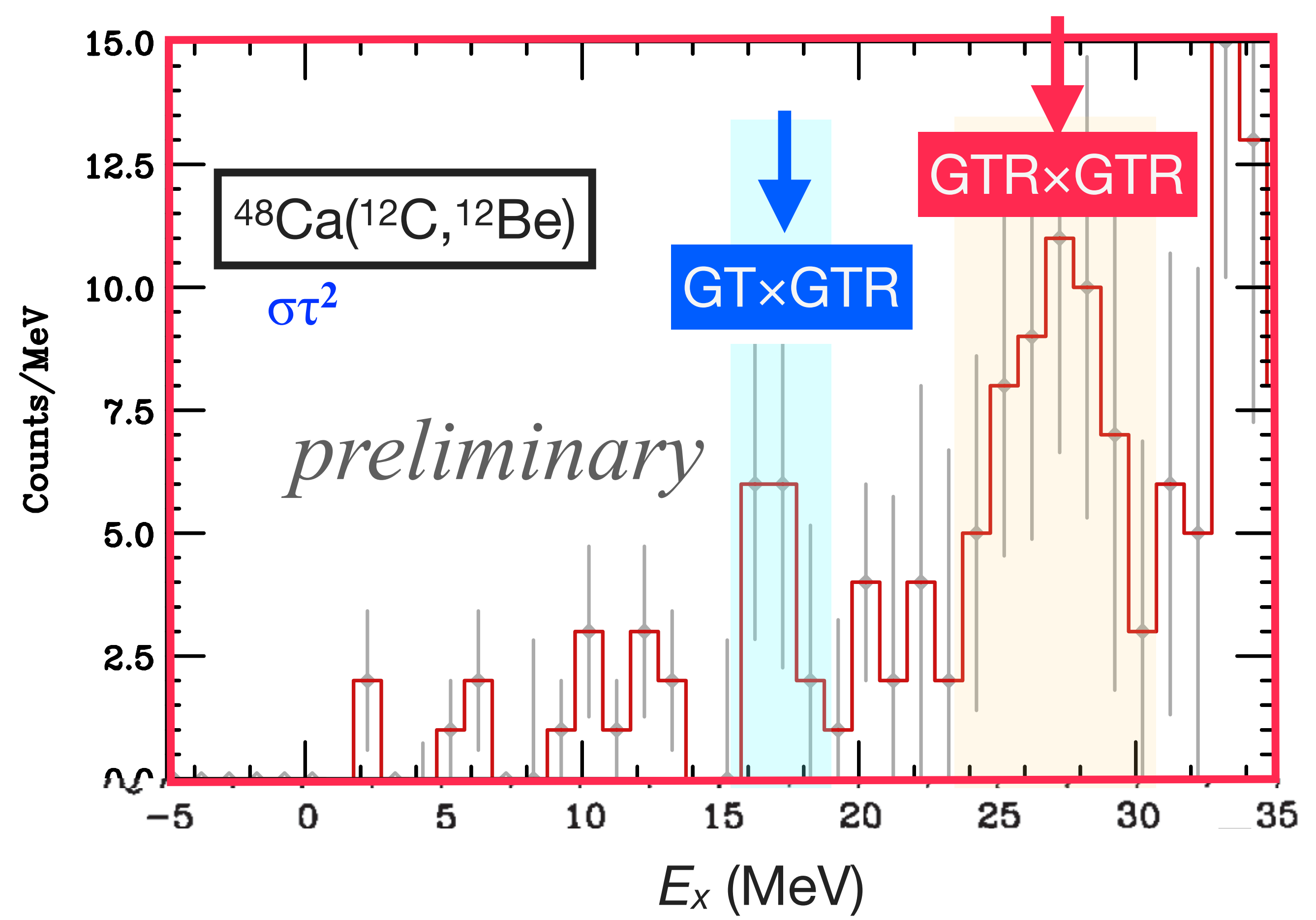
Clearly observed "forward-peaking" two peaks

- *$E_x \approx$ 17 MeV; relatively **narrow** peak*
  - *Single GT resonance (one-phonon)*
- *$E_x \approx$ 27 MeV; **broad** beak*
  - ***Double GT resonance ("two-phonon")***

Courtesy of M. Takaki







DGT and its relation to 0νββ decay

Theoretical prediction of DGT of ^{48}Ca

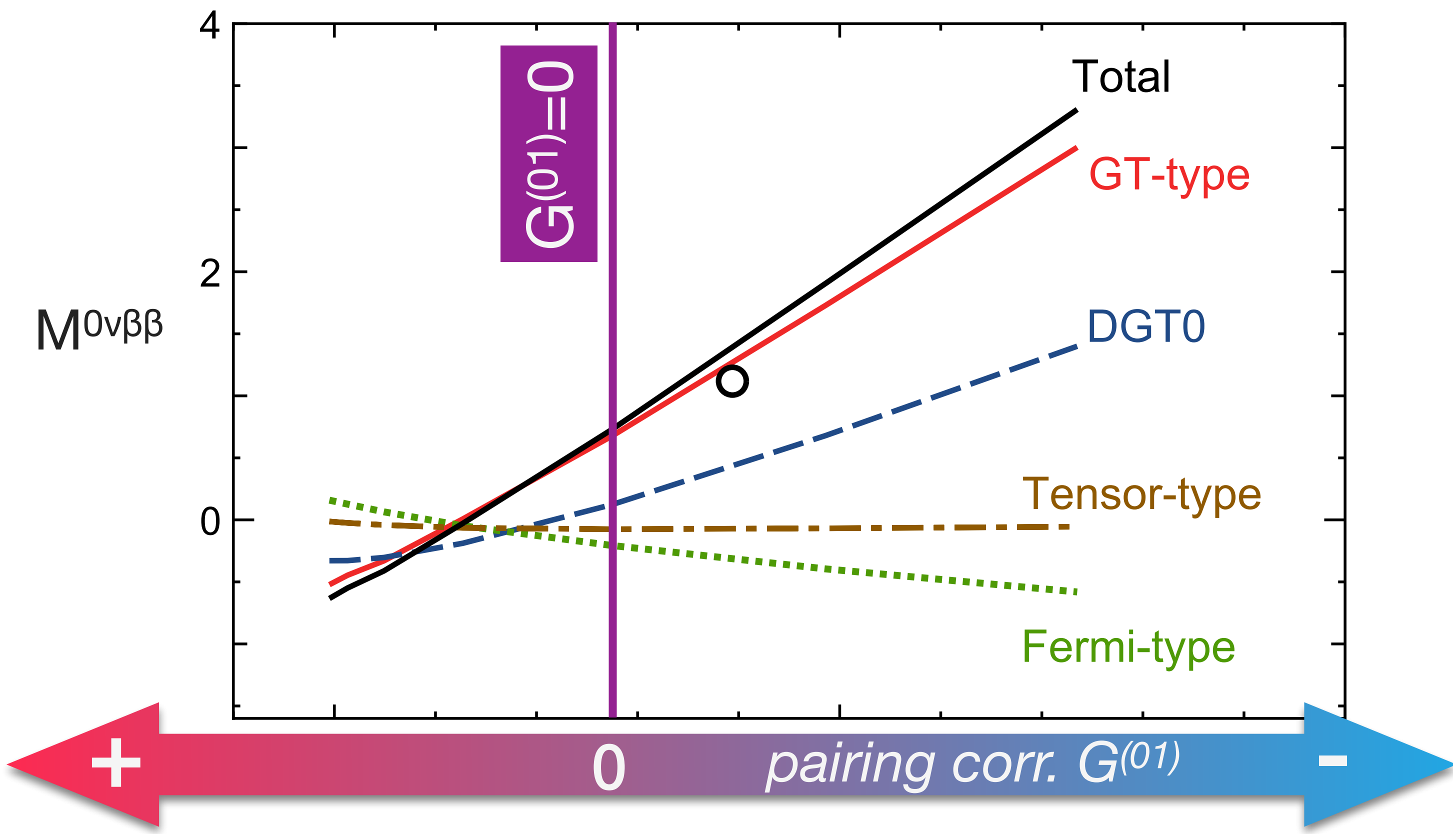
Shell-model predictions with GXPF1B int.

- Double peaks → consistent with exp. data
- Double GT resonance at $E_x \approx$ 26 MeV
  - ***Consistent with exp. result of ≈ 27 MeV***

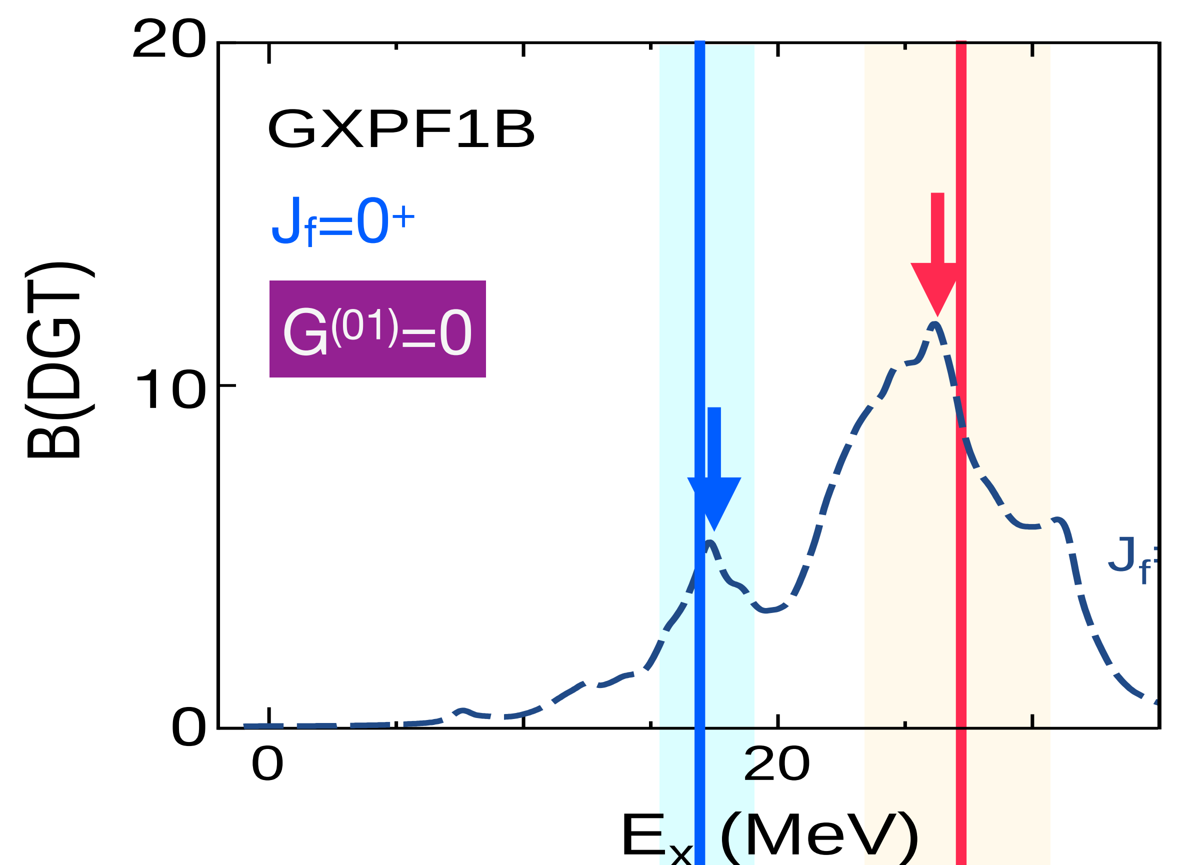
Theoretical prediction b/w E_x and $M^{0\nu\beta\beta}$

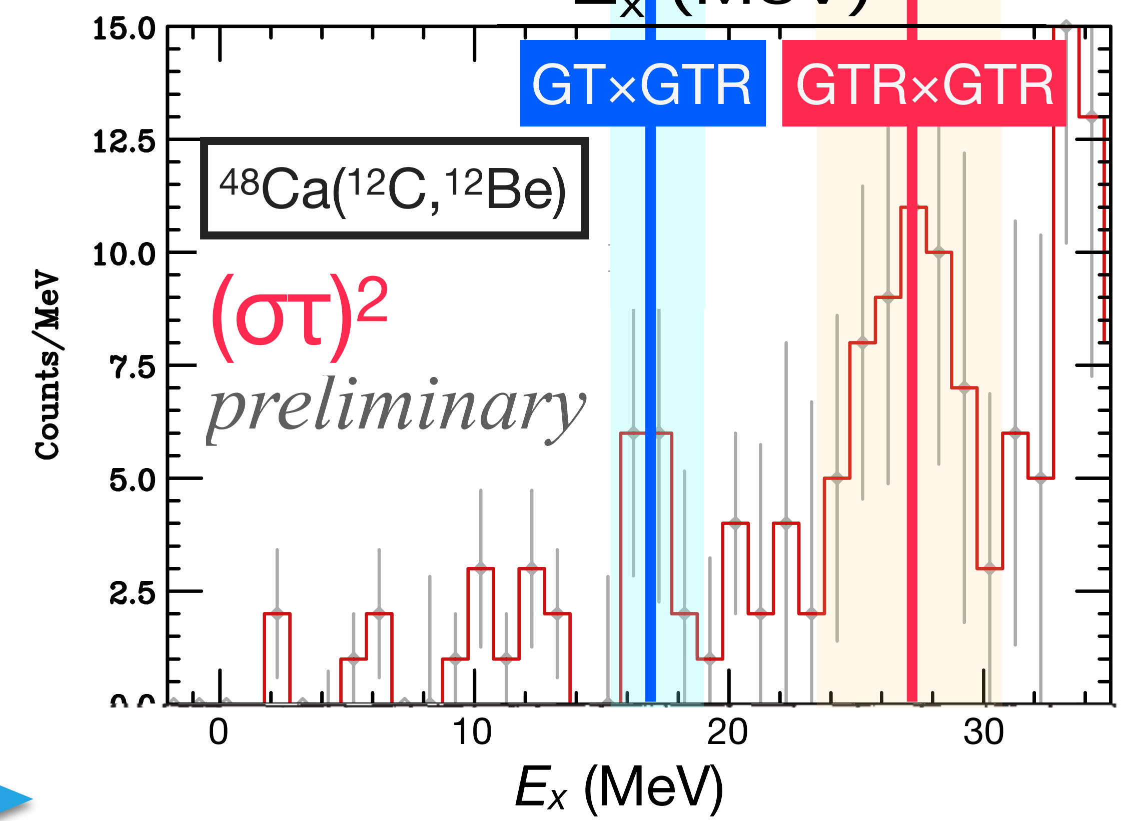
- DGT dist. → sensitive to paring corr.: $G^{(01)}$
- $M^{0\nu\beta\beta}$ → sensitive to $G^{(01)}$

Present data: $G^{(01)} \approx 0$ → useful for $M^{0\nu\beta\beta}$



N. Shimizu et al., Phys. Rev. Lett. 120, 142502 (2018).





Courtesy of M. Takaki

Summary and Outlook

Three nucleon force effects in few nucleon systems

Data is accumulating → 3NF effects are clear

3NFs at N^2LO are insufficient especially for spin-isospin dependence (pol. obs.)

- *Push the chiral expansion to N^4LO*
- *More N-d scattering data for phase-shift analysis and p-^{3}He data for T=3/2 3NFs*

Spin-isospin responses for stable and unstable nuclei

Observe Gamow-Teller resonances for ^{8}He&^{12}Be (n-rich) and ^{132}Sn (double magic)

Constancy of g'_{NN} in wide nuclear chart region with A≈8–208 and (N-Z)/A≈0.1–0.5

- *Further investigations for the total strength and higher multipole modes such as SD*

IVSM → clearly observed by HI charge-exchange

Double charge-exchange/Gamow-Teller and neutrino-related physics

DCX reaction → constraint on $M^{0\nu\beta\beta}$; the double beta-decay nuclear matrix element

Candidate of Double GT resonance → useful to observe new collective motion

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- K. Miki (Tohoku University)
- M. Takaki (CNS, University of Tokyo)

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Thank you for your attention.