FAIRNESS

FAIR next generation scientists Workshop
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Nuclear Structure Calculations for the r process

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UNIVERSITÄT BIELEFELD

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Outline

- *Introduction:*
  - *Goals and challenges in low-energy nuclear structure theory*
  - *β decay calculations for the r process: current status*

- *Towards a universal and precise description of nuclei within Relativistic Nuclear Field Theory*
  - *Method: from mesons to nucleons and emergent collective phenomena*
  - *Application to β decay of r-process nuclei*

- *Conclusion and future plans*

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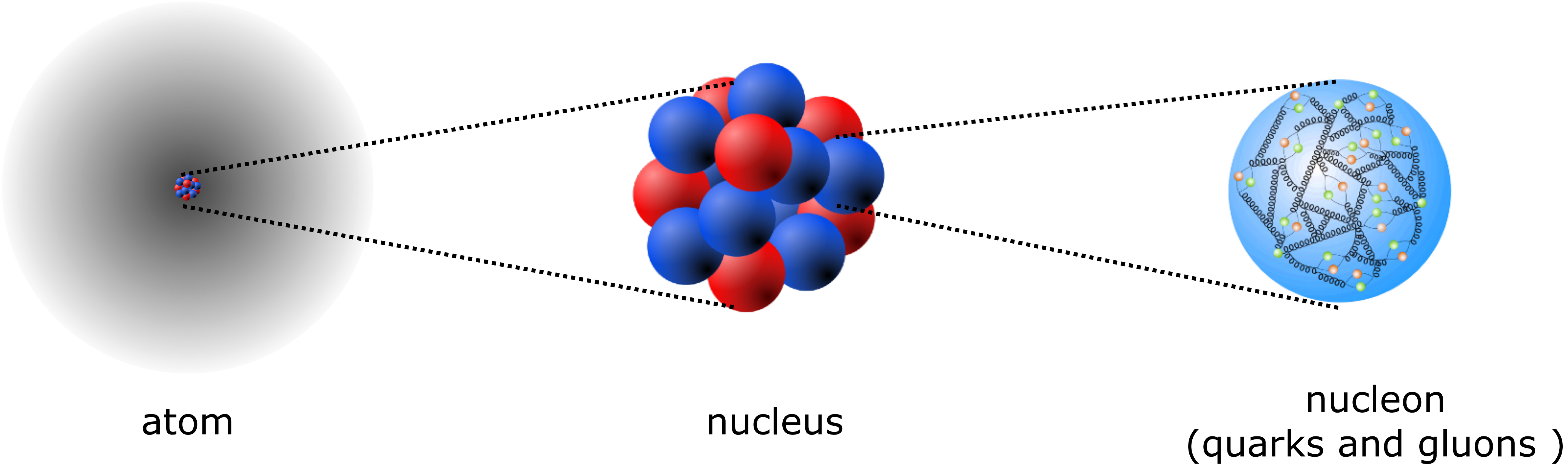
Method: from mesons to nucleons and emergent collective phenomena
Application to β decay of r-process nuclei

★ *Conclusion and future plans*

Motivations and challenges in low-energy nuclear theory

The nucleus is a unique quantum many-body system

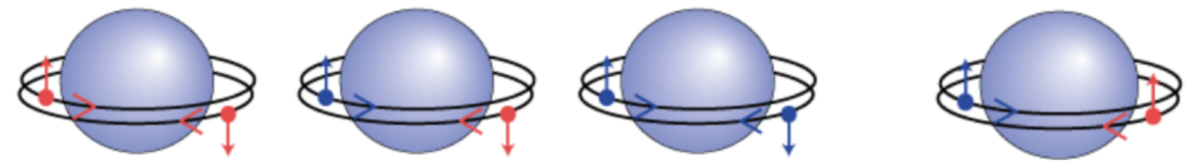


at the frontiers between microscopic and macroscopic worlds

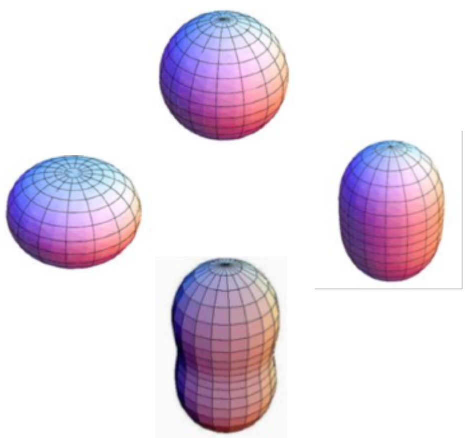
- Made of two types of non-elementary particles: protons and neutrons
- Sensitive to 3 fundamental interactions: strong, electromagnetic, weak.
- $2 \lesssim A \lesssim 300 \Rightarrow$ very rich variety of phenomena

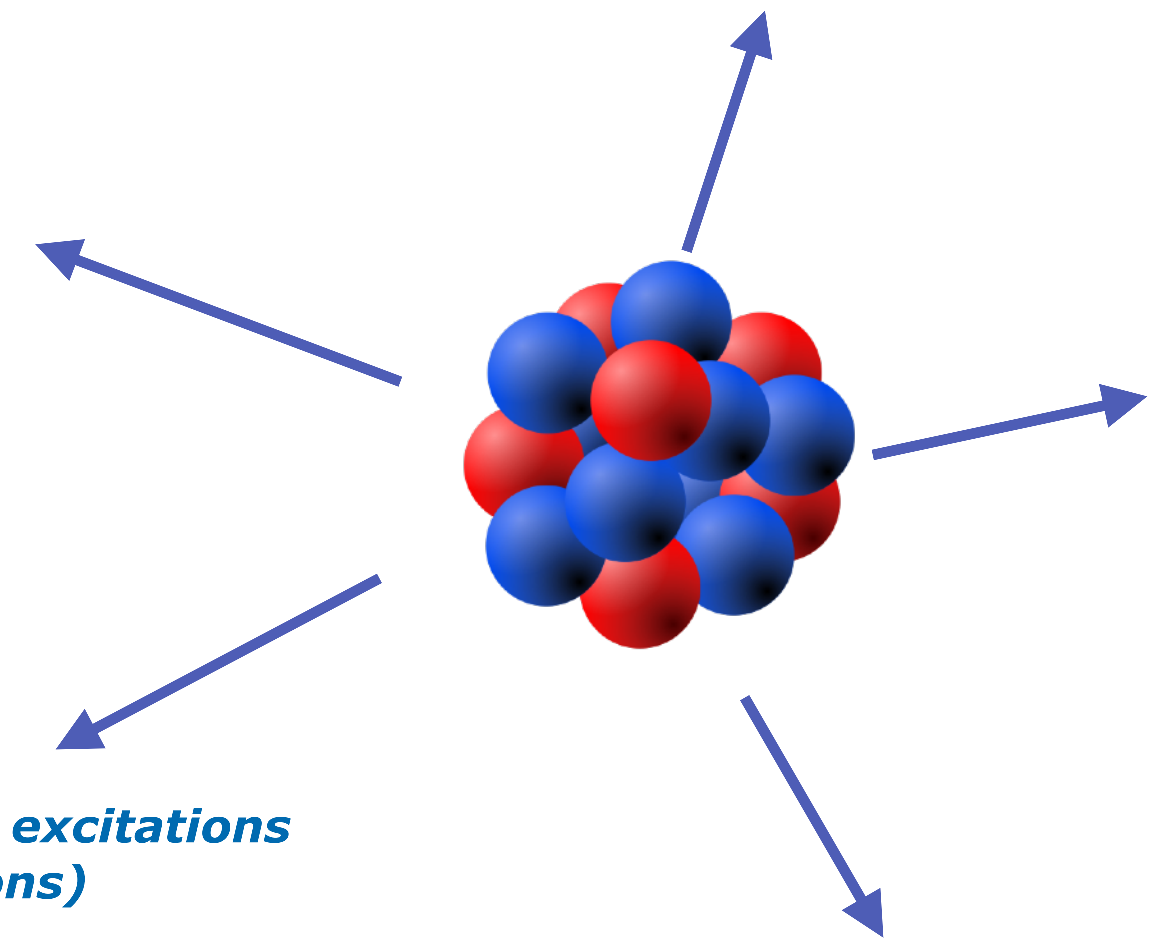
Motivations and challenges in low-energy nuclear theory

superfluid pairing



deformation

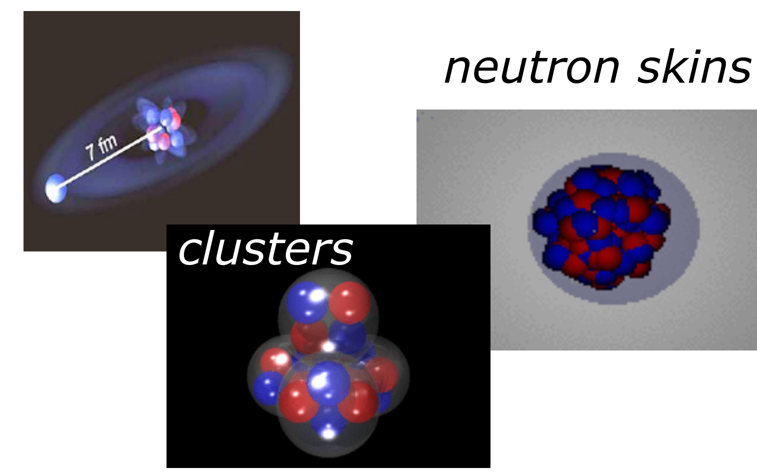




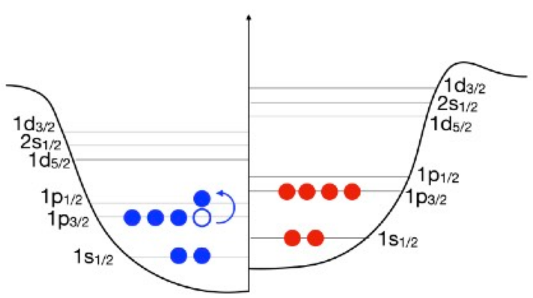
exotic structures

halos

neutron skins

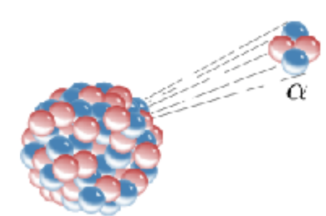


single-particle & collective excitations (vibrations, rotations)



radioactive decays

γ, β, ββ, α, p, 2p, cluster, fission…



Motivations and challenges in low-energy nuclear theory

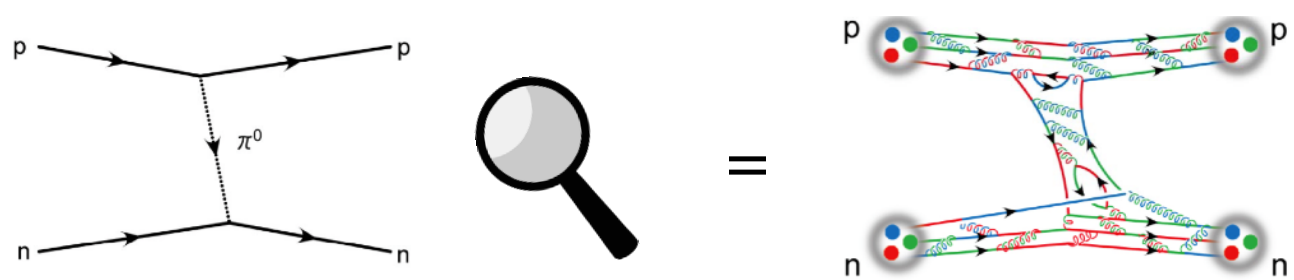
Goal of nuclear structure theory:

describe these phenomena by solving the nuclear A-body problem

Two major challenges:

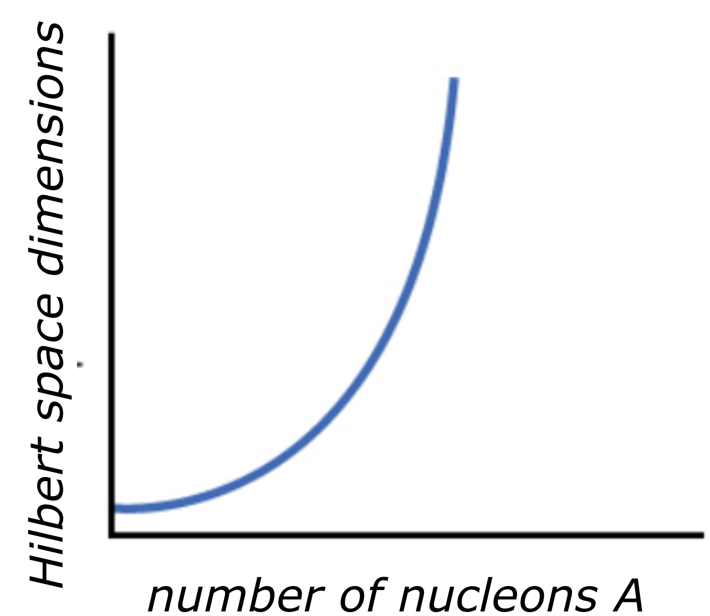
★ The nuclear force is not fully understood

→ NN interaction = residue of the strong interaction between quarks and gluons = complicated, non-perturbative



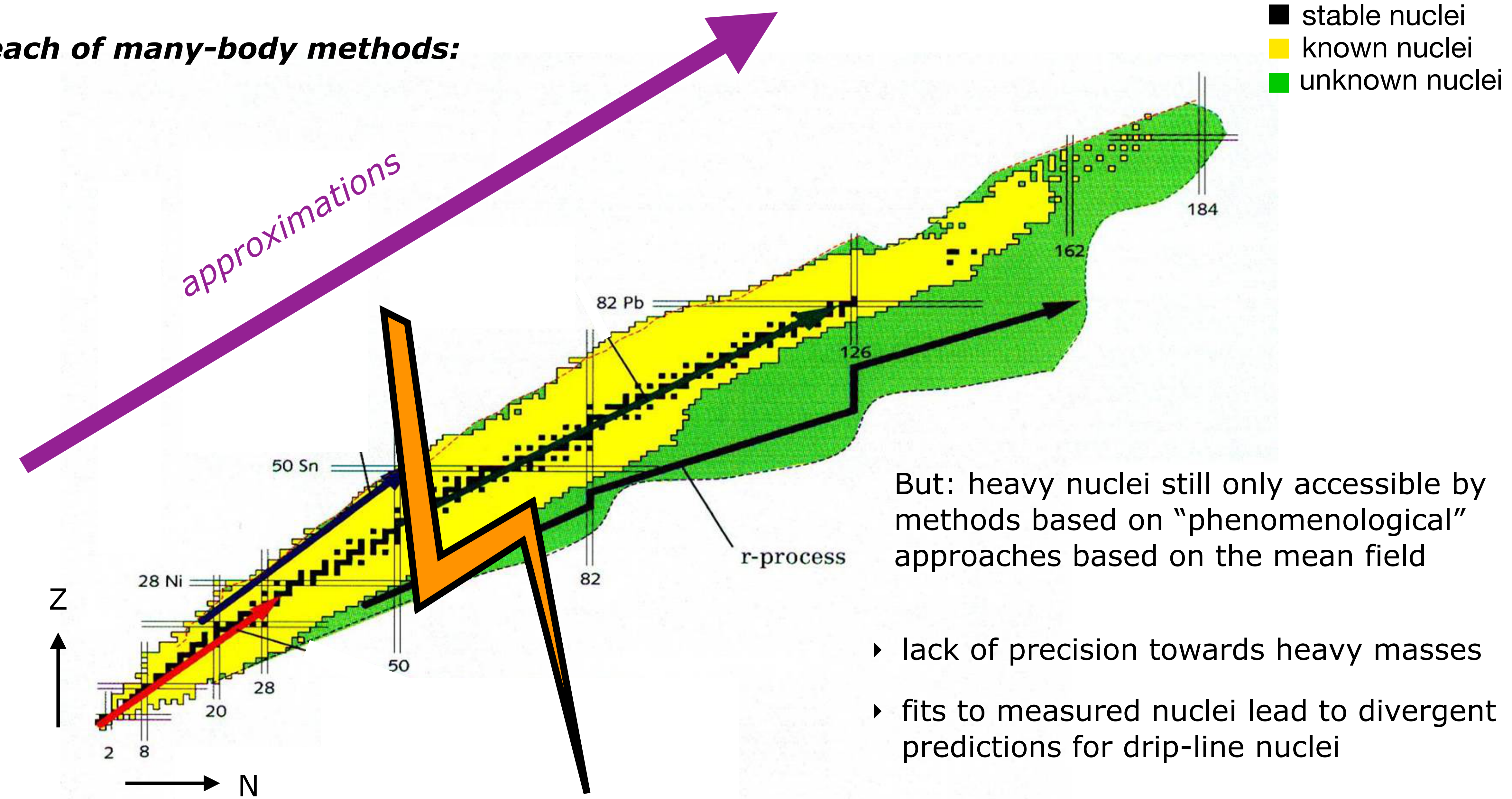
★ Solving the A-body problem for 2≲A≲300 is very difficult!

→ The size of the Hilbert space increases exponentially -> drastic approximations



Motivations and challenges in low-energy nuclear theory

Current reach of many-body methods:



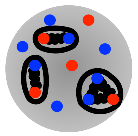
But: heavy nuclei still only accessible by methods based on "phenomenological" approaches based on the mean field

- lack of precision towards heavy masses
- fits to measured nuclei lead to divergent predictions for drip-line nuclei

→ large uncertainties in astrophysical modeling

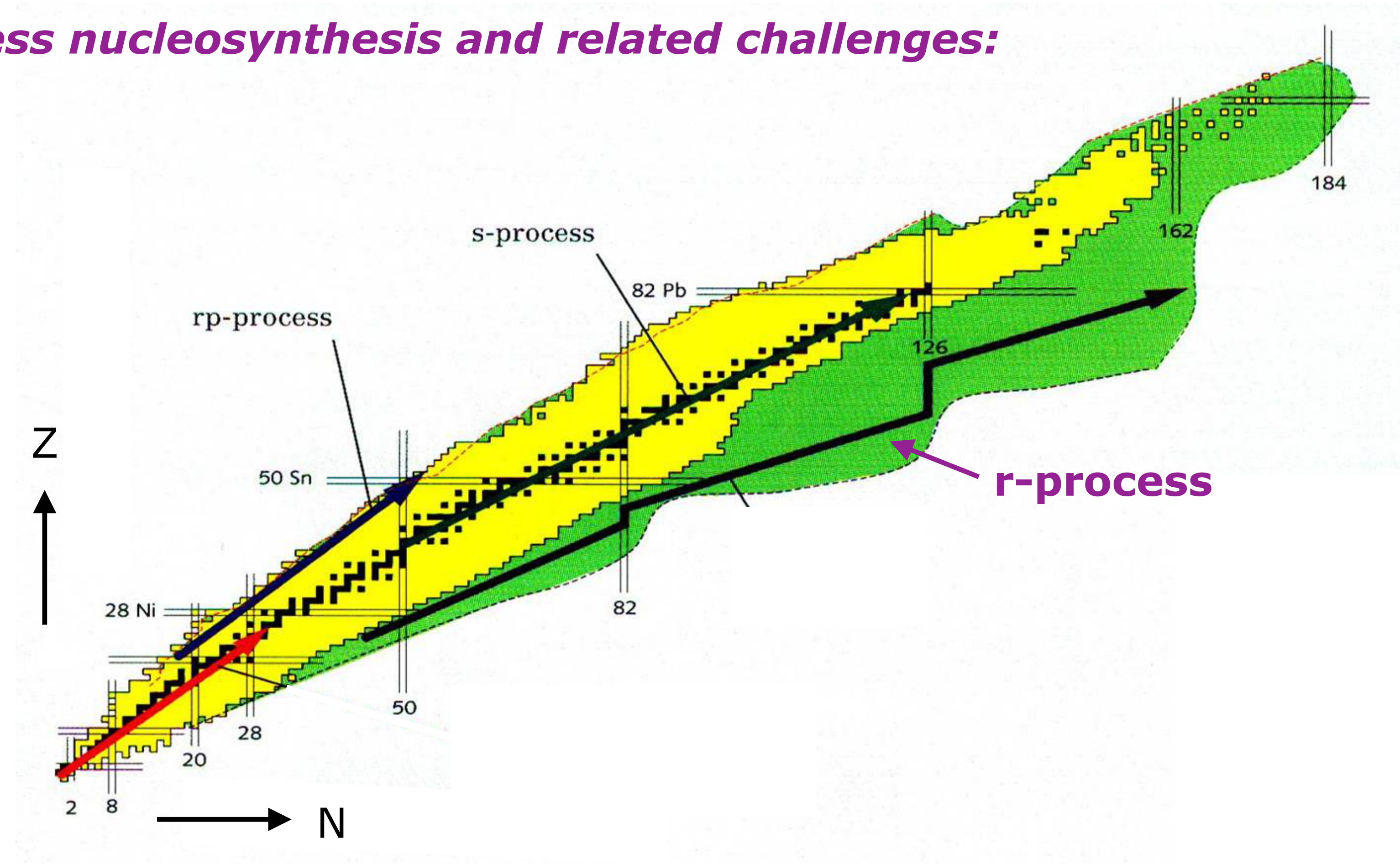
→ urgent need for improvement

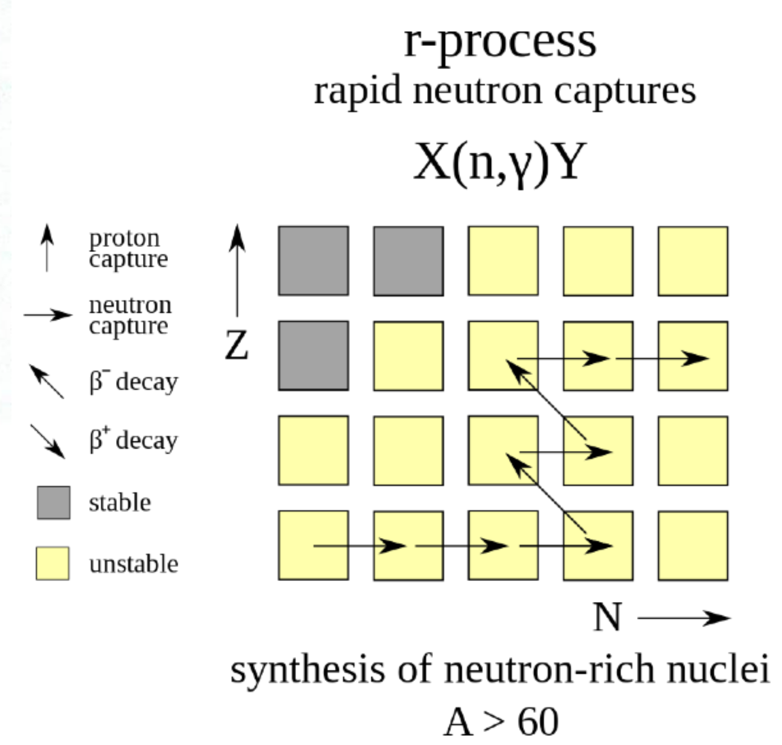
Big progress of "*ab-initio*" methods since development of forces based on chiral effective field theory combined with novel many-body methods (up to A ~ 100)



β decay calculations for the r process: current status

✳ ***r-process nucleosynthesis and related challenges:***





- The r-process nucleosynthesis brings into play thousands of extremely unstable nuclei
- Most of them cannot be synthesized in the lab ⇒ simulations have to rely mostly on theoretical inputs
- Many inputs needed: ***β-decay rates***, neutron-capture rates, fission rates….
- Typically the Quasi-Particle Random Phase Approximation (time-dependent mean-field) is the method of choice to calculate β-decay rates but QRPA has shortcomings (lack of correlations, fitted parameters) which makes it unreliable in unknown regions of the chart

β decay calculations for the r process: current status

Three global sets of beta-decay rates:

1. *QRPA approach based on FRDM for the Gamow-Teller + gross theory for the first-forbidden*

   Moeller, Pfeiffer, Kratz, PRC 67, 055802 (2003)

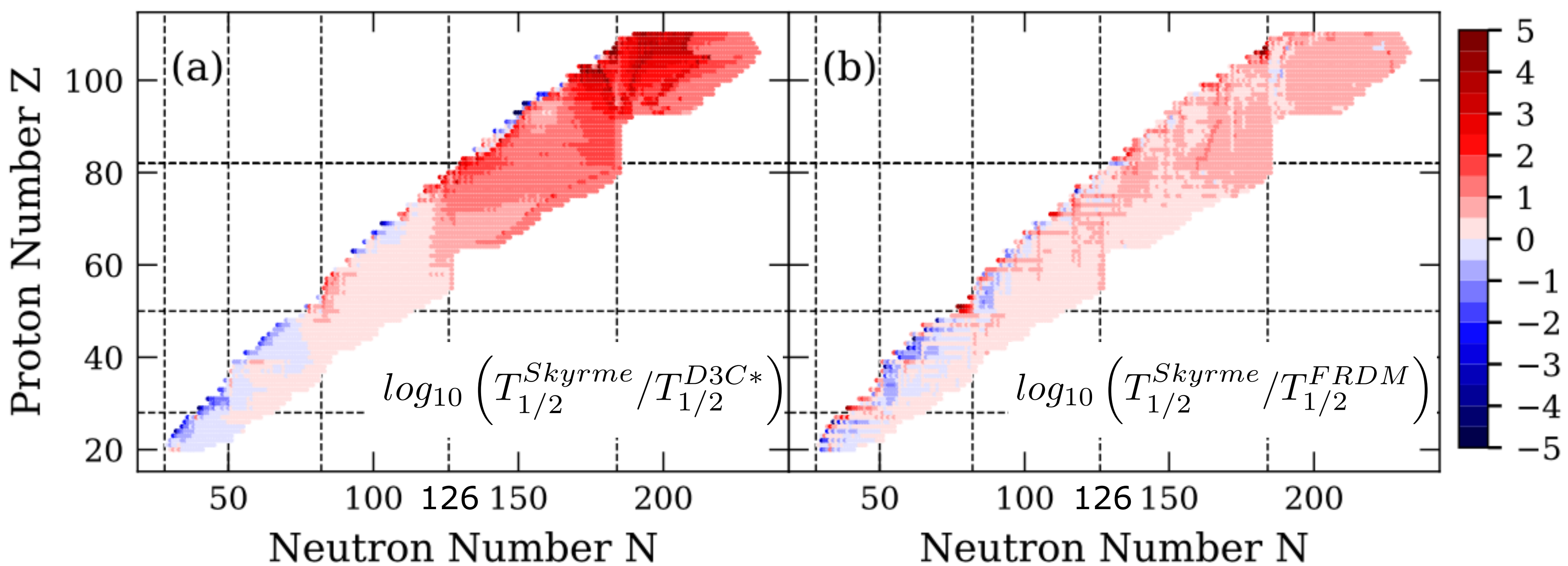
2. *Relativistic QRPA based on D3C* functional*

   Marketin, Huther, Martínez-Pinedo PRC 93, 025805 (2016)

3. *Non relativistic QRPA based on Skyrme functional SKO'*

   Ney, Engel, Li, Schunck PRC102, 034326 (2020)

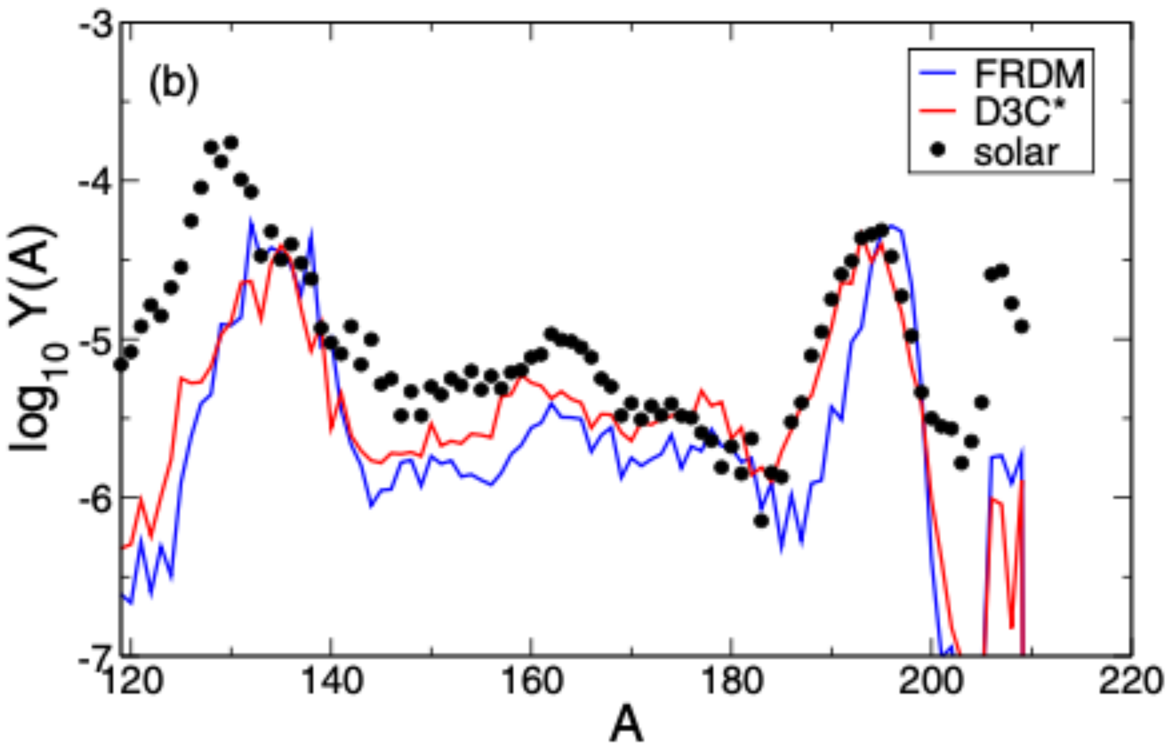
- ~ agreement between the 3 approaches below N<126
- Above N>126 the relativistic QRPA predicts considerably shorter half-lives than the other ones



Ney et al. PRC102, 034326 (2020)

β decay calculations for the r process: current status

✳ ***Impact of shorter half-lives on elemental abundances:***



Marketin, Huther, Martínez-Pinedo PRC 93, 025805 (2016)

Broadening of the third peak (A~195)
towards lower masses

The spread of different QRPA predictions can result in large uncertainties in astrophysical modeling

→ need to extend QRPA by including a better treatment of nucleonic correlations

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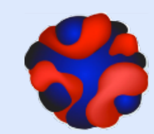
Relativistic Nuclear Field Theory (RNFT): overview

Degrees of freedom in RNFT:

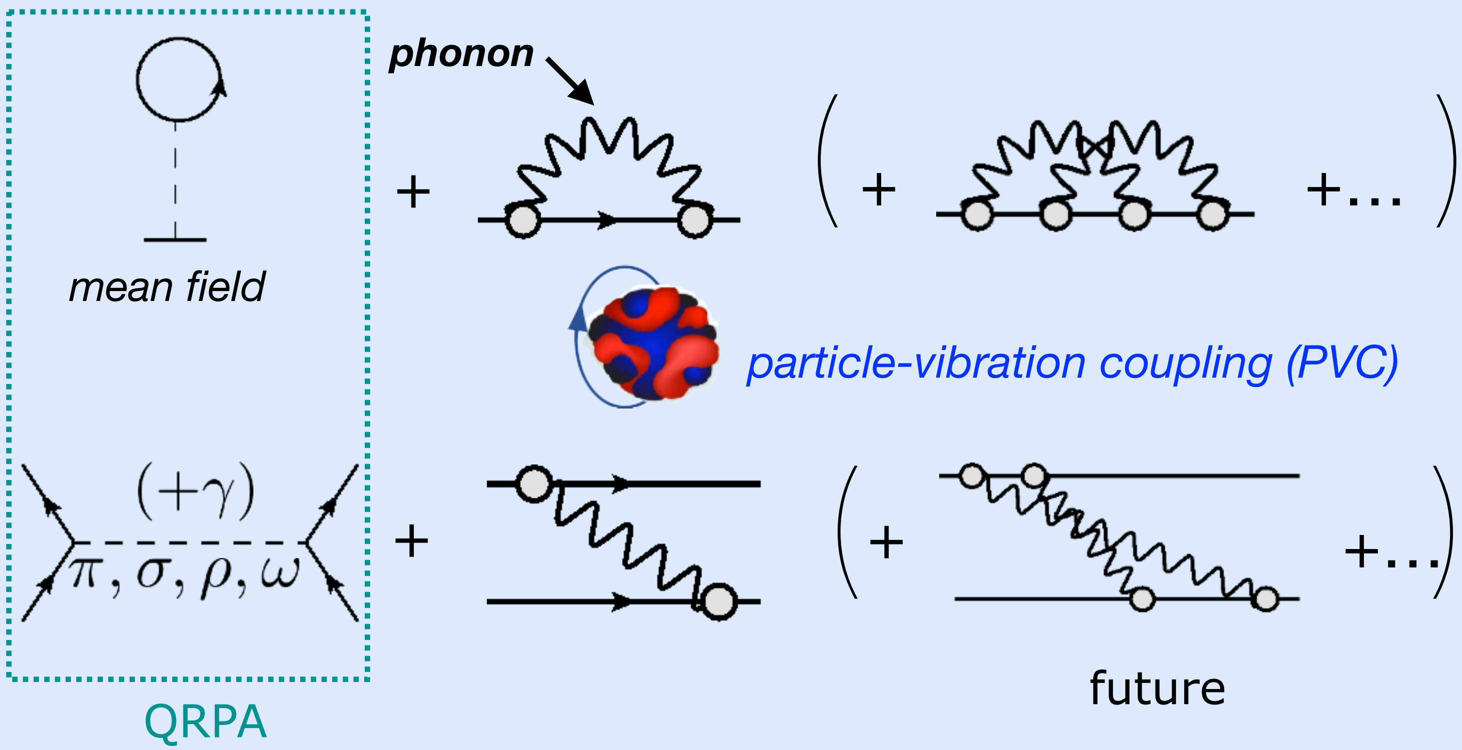
 =

- ✳ relativistic effective mesons π σ ω ρ (m ~ 140-800 MeV) *quantum hadrodynamics*
- ✳ relativistic nucleons p n (S_n ~ 10 MeV)
- ✳ phonons (collective vibrations of the nucleus)  (E ~ few MeV)

systematic expansion in the PVC vertex

Nucleonic motion =

Effective NN interaction =



Advantages:

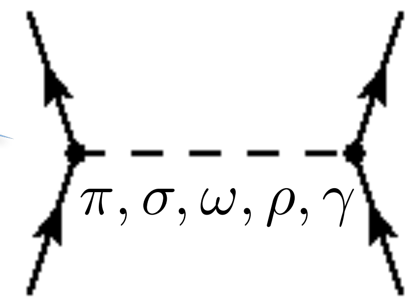
- *Applicability up to heavy/superheavy masses* *to be useful for astrophysical applications*
- *while allowing for a* *precise description of nuclear phenomena*

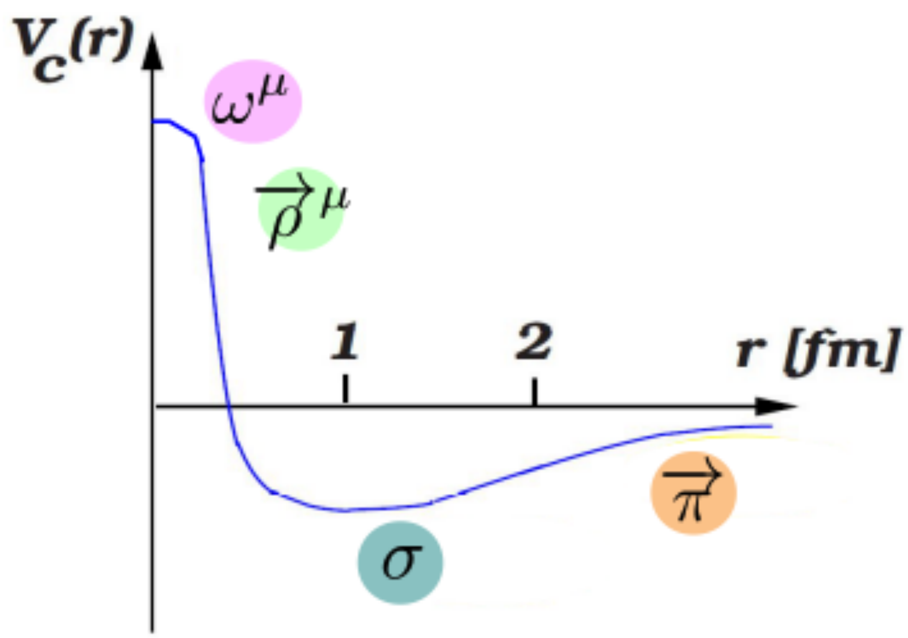
From the relativistic Lagrangian to the relativistic mean field

★ Nucleus = system of **relativistic** nucleons interacting via meson exchange (+ photon)

governed by an effective Lagrangian

$$\mathcal{L}_{eff} = \mathcal{L}_{nucleons} + \mathcal{L}_{mesons} + \mathcal{L}_{interaction}$$



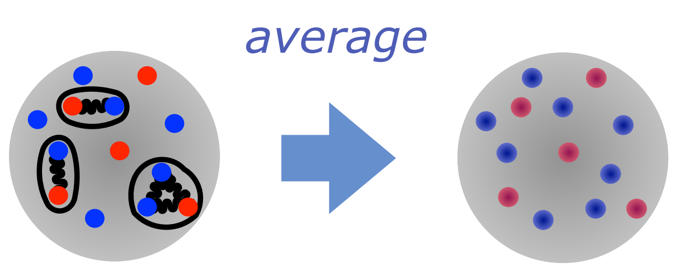


$\Rightarrow$ When both nucleons and mesons are quantized
the equations of motion are too complicated to solve…

From the relativistic Lagrangian to the relativistic mean field

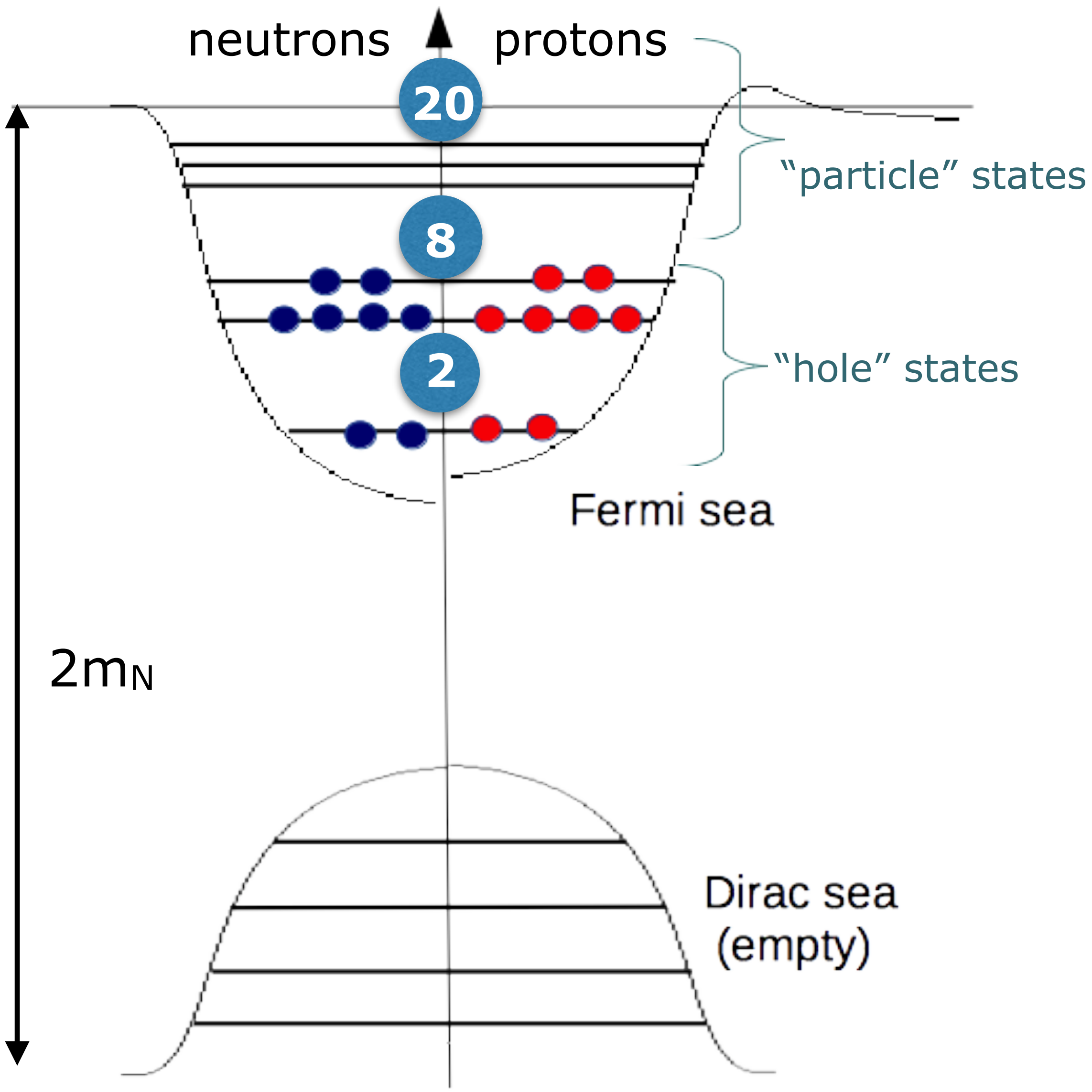
★ First approximation = **Mean-field approximation**

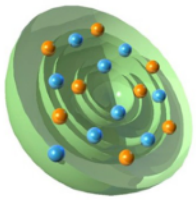
= Treat the mesons as classical fields: $\phi_m \rightarrow \langle \phi_m \rangle$

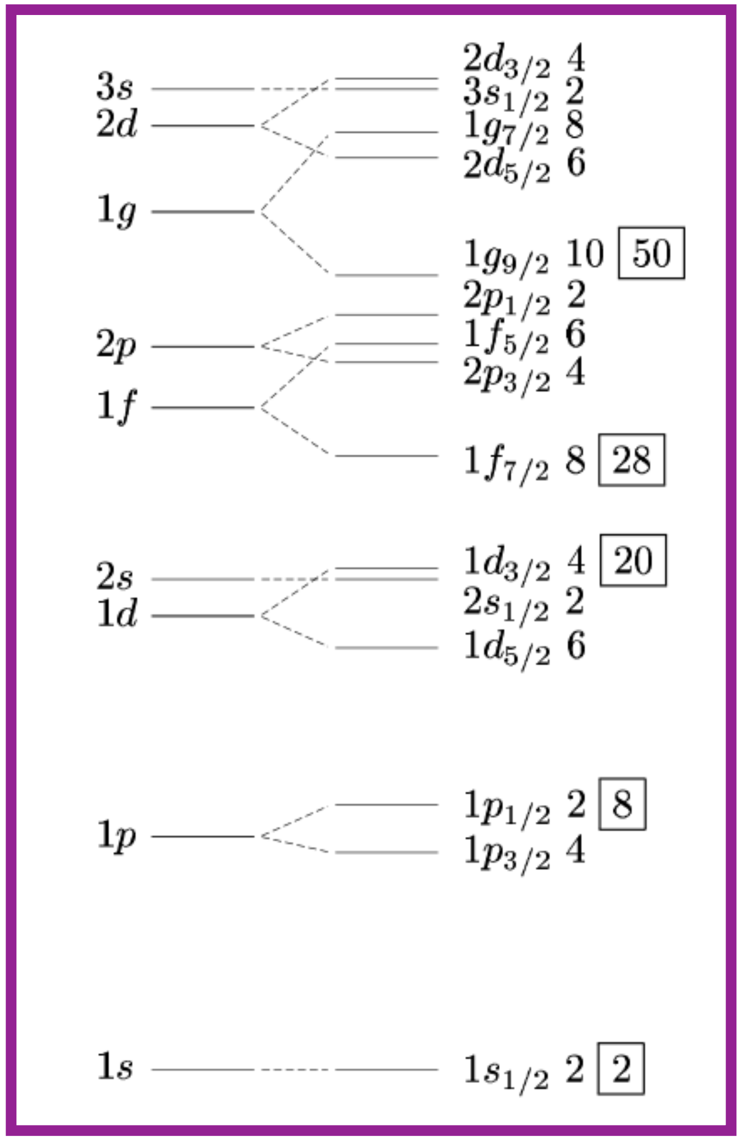


⇒ nucleons evolve independently in an average potential

⇒ reduces one A-body problem to A one-body problems







Shell structure /Magic numbers (M.Goeppert Mayer, J. Jensen, E. Wigner, Nobel Prize 1963)

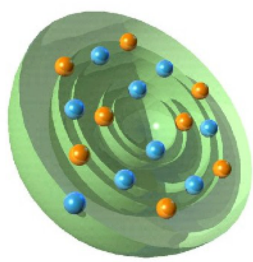
Going beyond the mean field: nucleons coupled to vibrations

★ But in reality there are correlations between nucleons:

1st order approximation:

= relativistic mean field

=independent nucleons

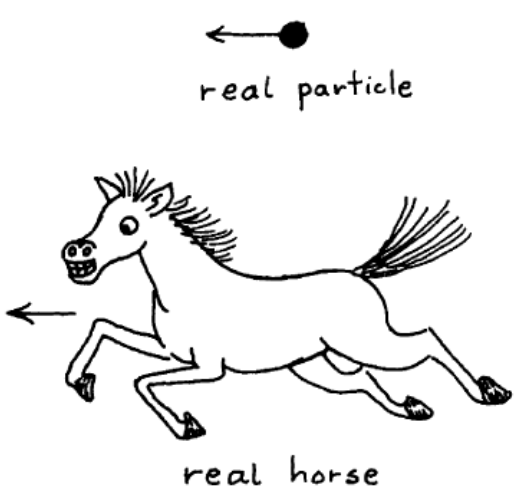


The nucleon propagates "freely" in the nucleus

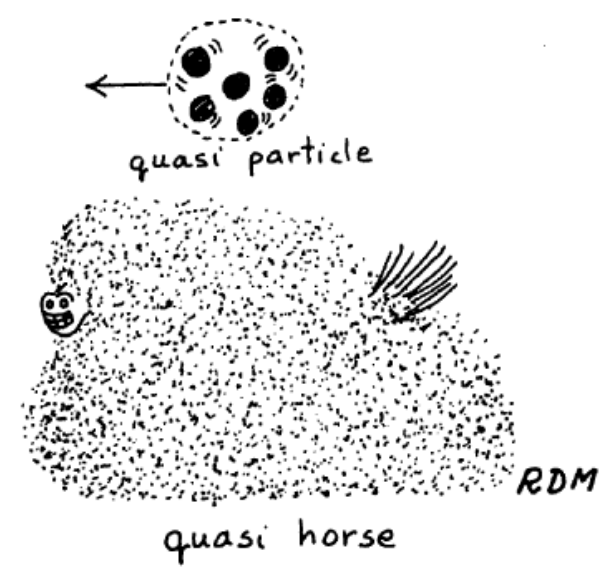
beyond mean field

correlations

In reality the nucleon interacts with the particles around it

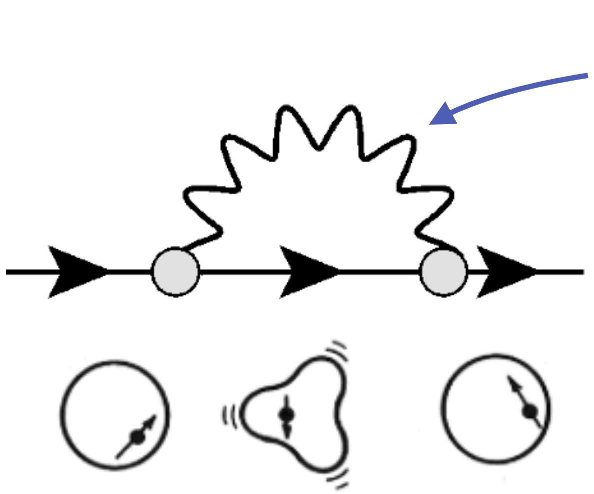


R.D. Mattuck
"a guide to Feynman diagrams in the many-body problem"

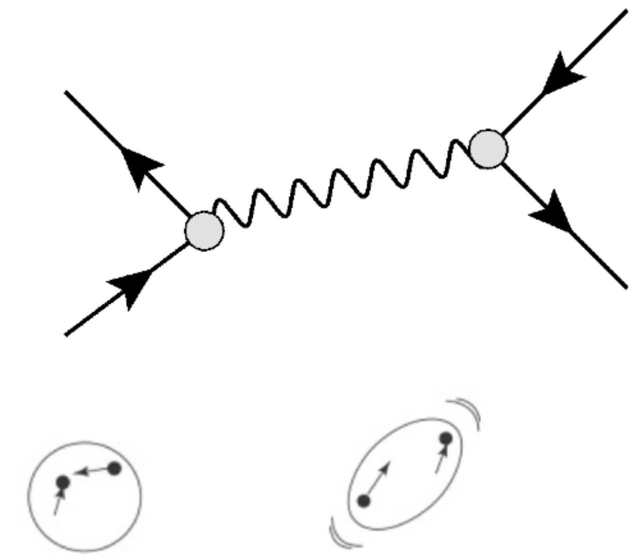


Going beyond the mean field: nucleons coupled to vibrations

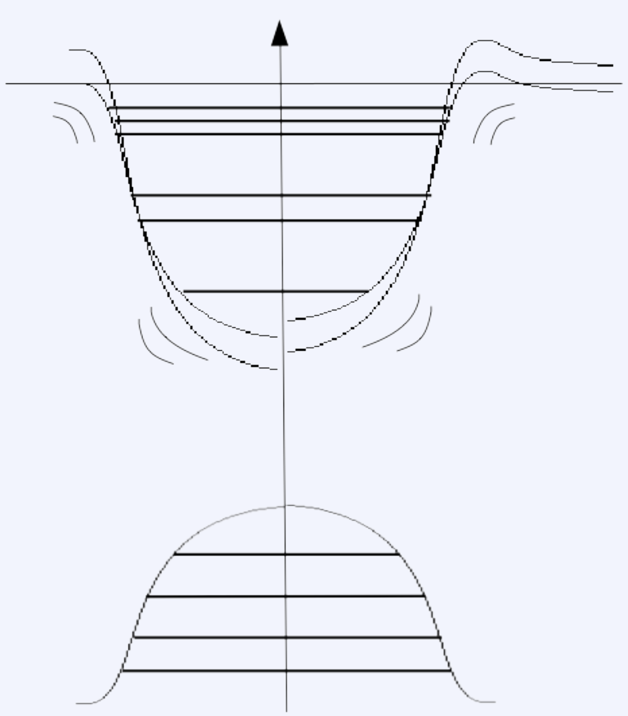
⇒ single-nucleon motion:



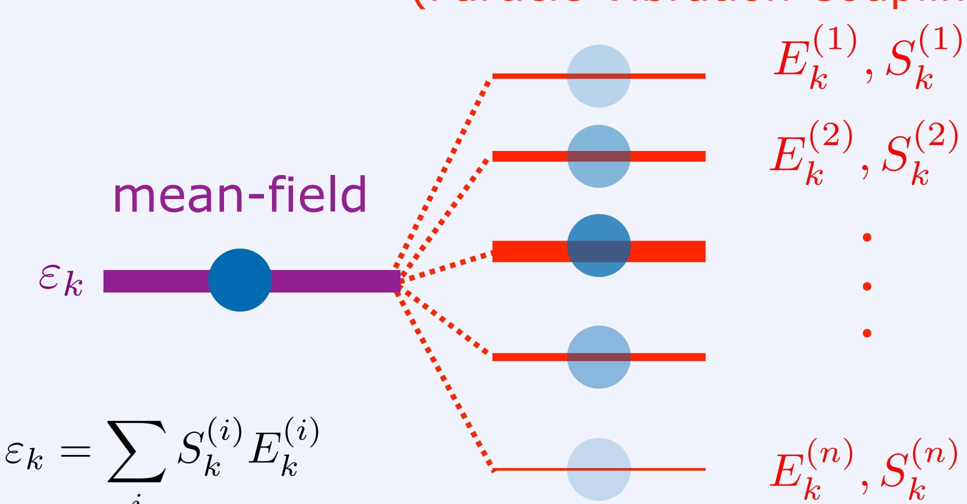
⇒ induced phonon-exchange interaction:



the shell structure becomes dynamical:



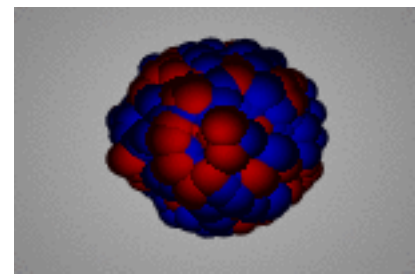
➡ *fragmentation of single-particle states:*



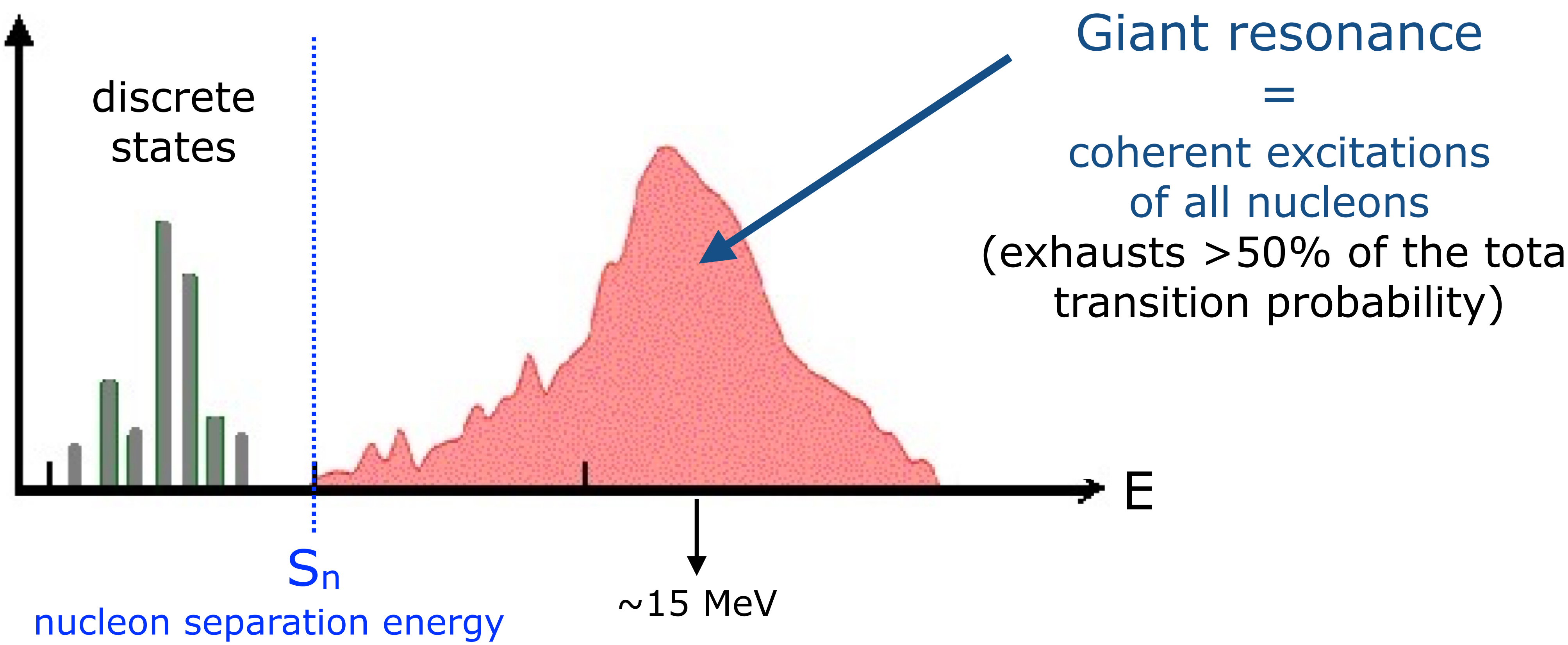
$$\varepsilon_k = \sum_i S_k^{(i)} E_k^{(i)}$$

★ Response of the nucleus to an external probe:

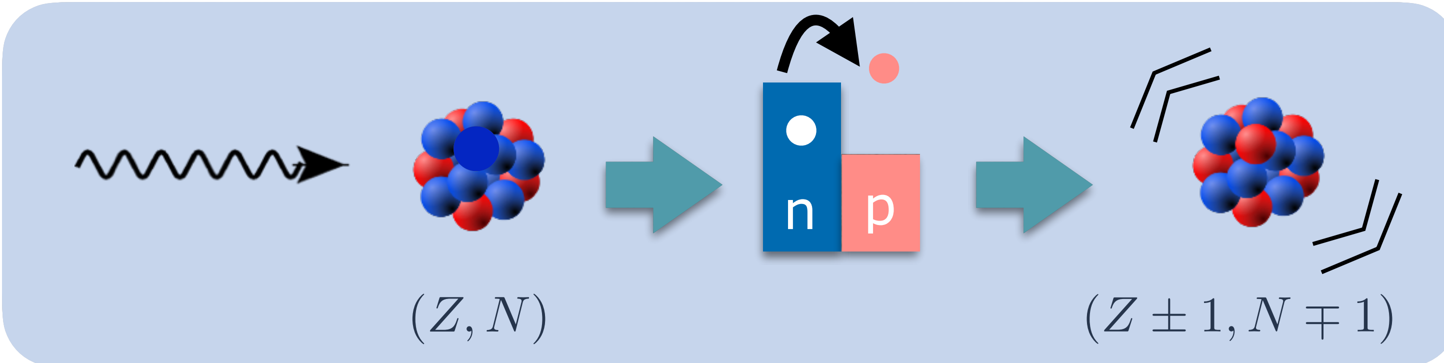
External field F
(electromagnetic, hadronic or weak current…)

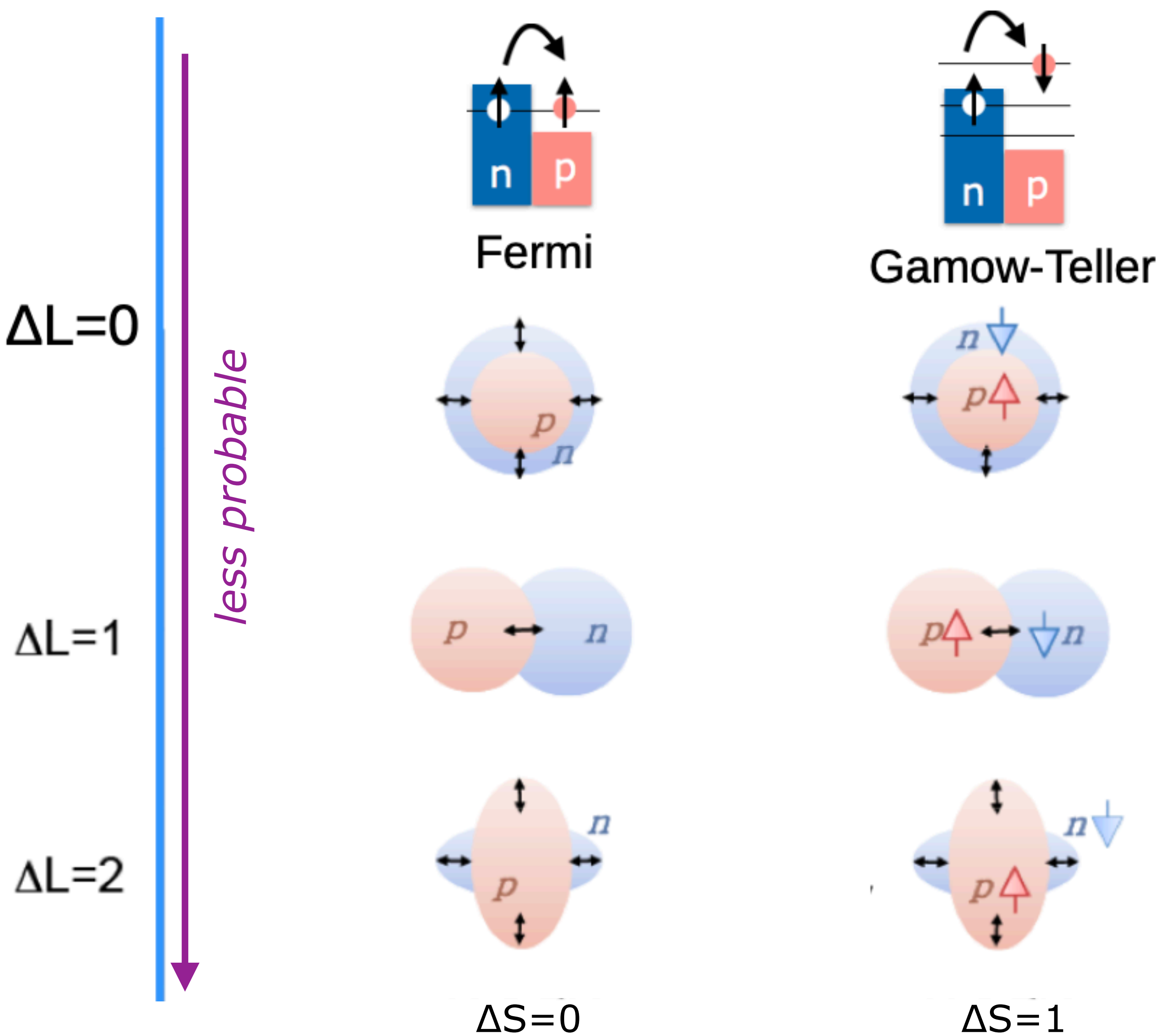


transition strength distribution $S(E) = \sum_f |\langle \Psi_f | \hat{F} | \Psi_i \rangle|^2 \delta(E - E_f + E_i)$

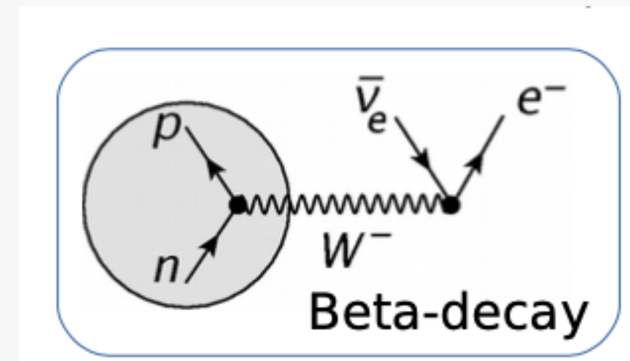


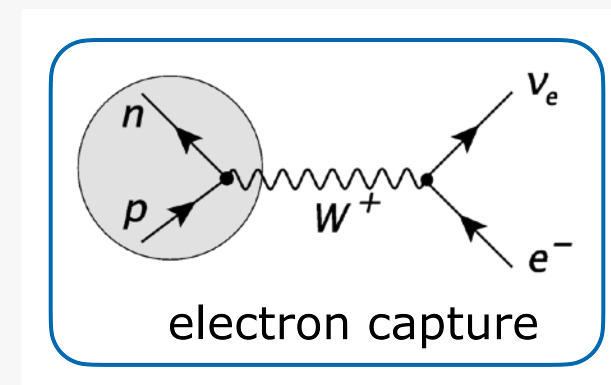
Nuclear charge-exchange transitions

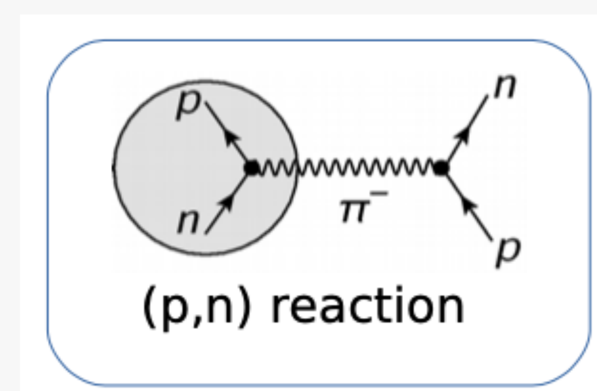




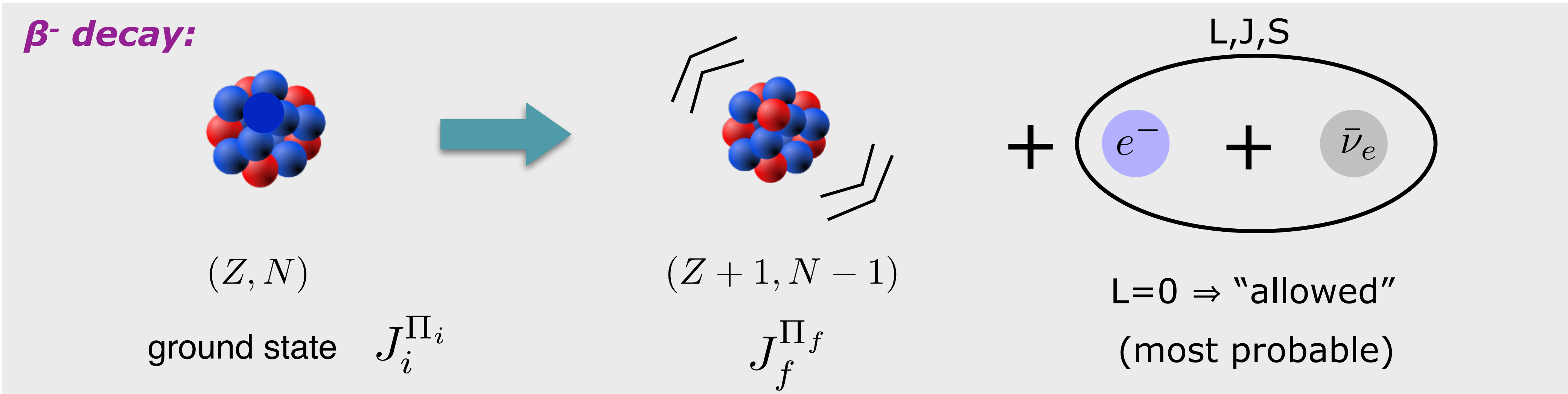
→ can be reached in:



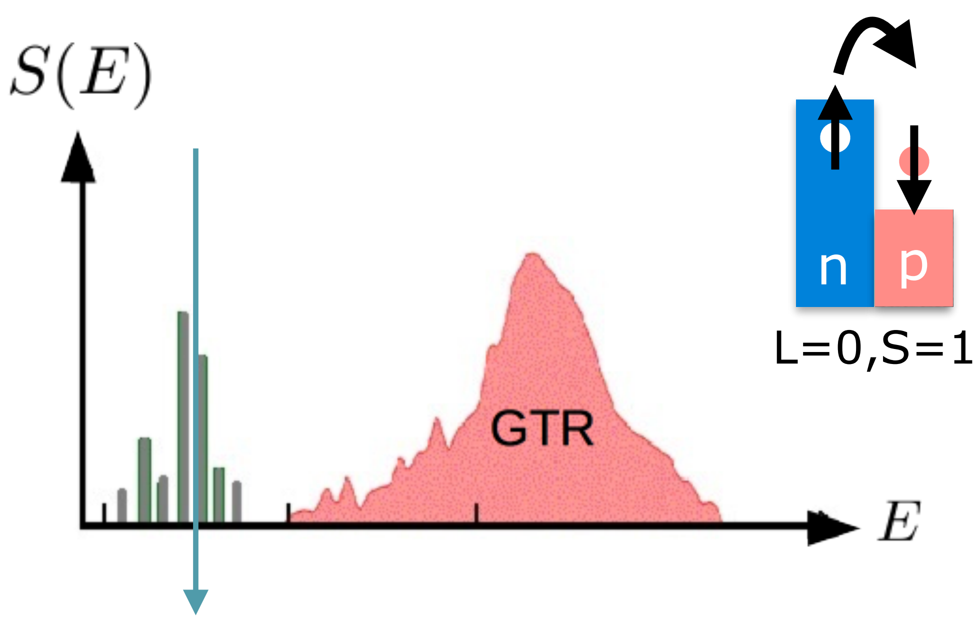




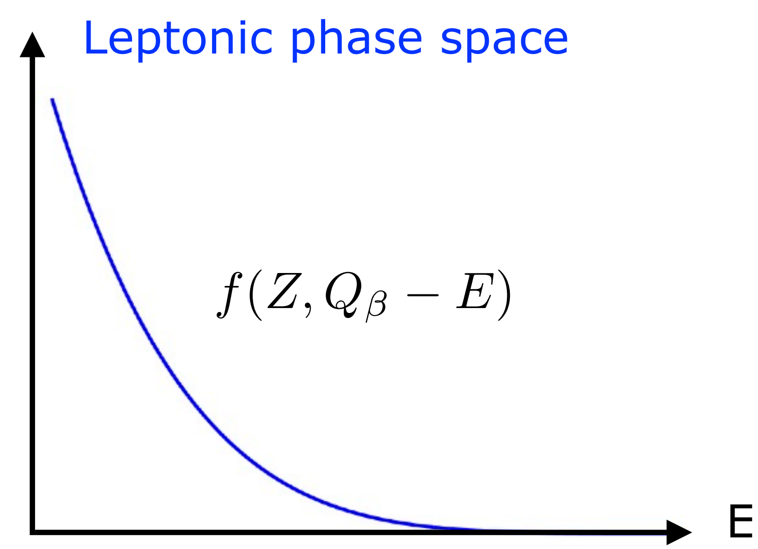
Gamow-Teller and β decay of nuclei near the r-process path



- In the allowed approximation, β decay is determined by the low-lying Gamow-Teller strength distribution:



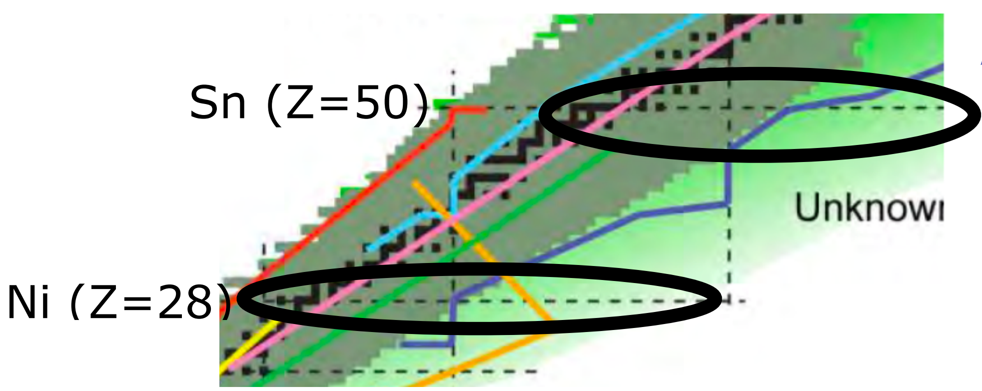
$Q_\beta = M(Z,N) - M(Z+1,N-1) - m_e$



→ beta-decay half-lives: $\frac{1}{T_{1/2}} = \frac{g_a^2}{D}\int^{Q_\beta} f(Z,Q_\beta - E)S(E)dE$

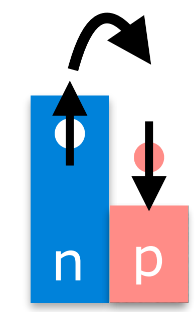
⇒ ***need highly precise description of masses and transition strength distributions***

Gamow-Teller and β decay of nuclei near the r-process path

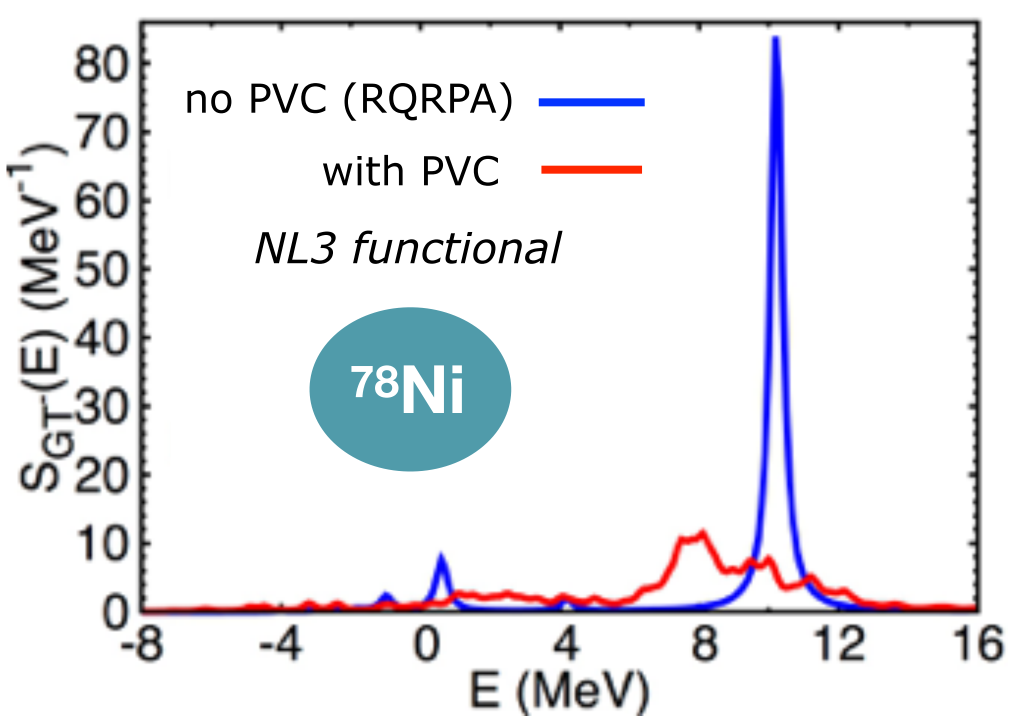


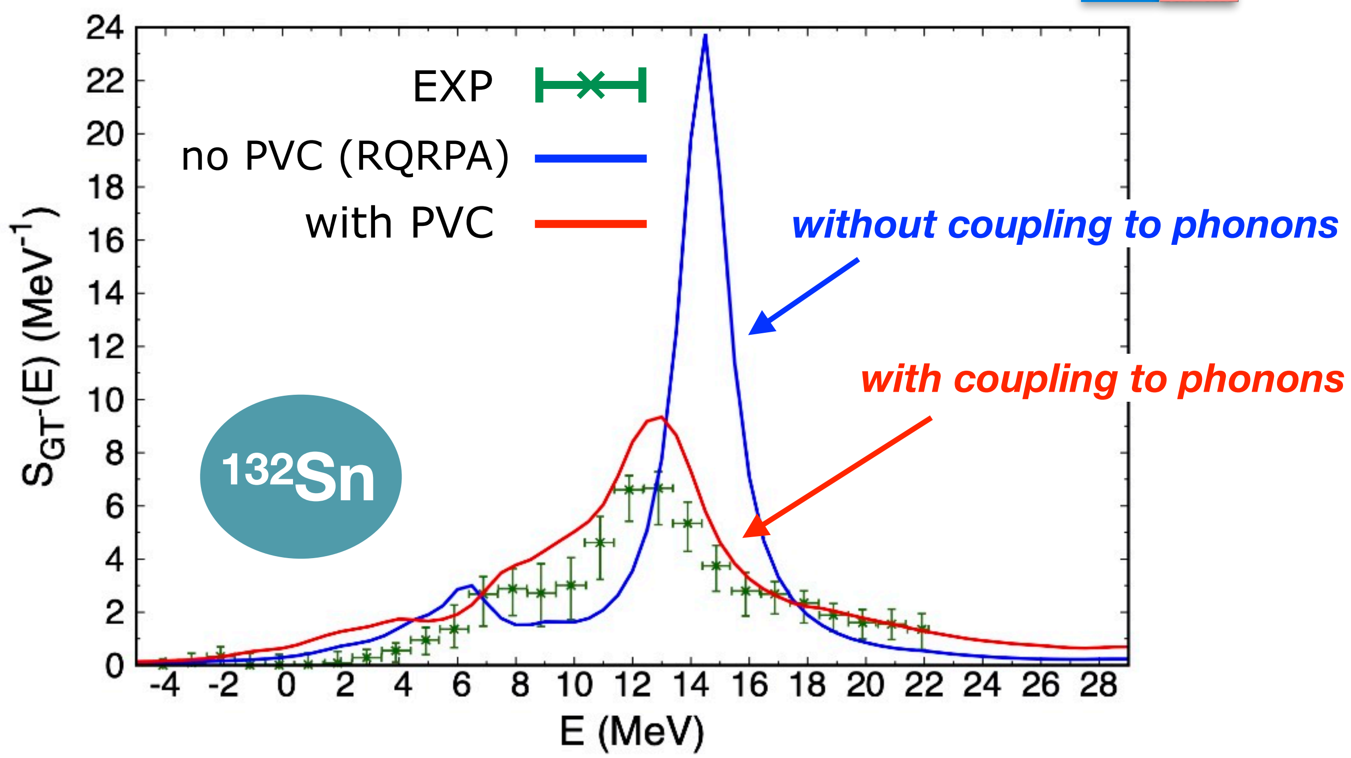
CR and E. Litvinova EPJA 52, 205 (2016) & PRC 98, 051301 (2018).

EXP: Yasuda et al., PRL 121, 132501 (2018).

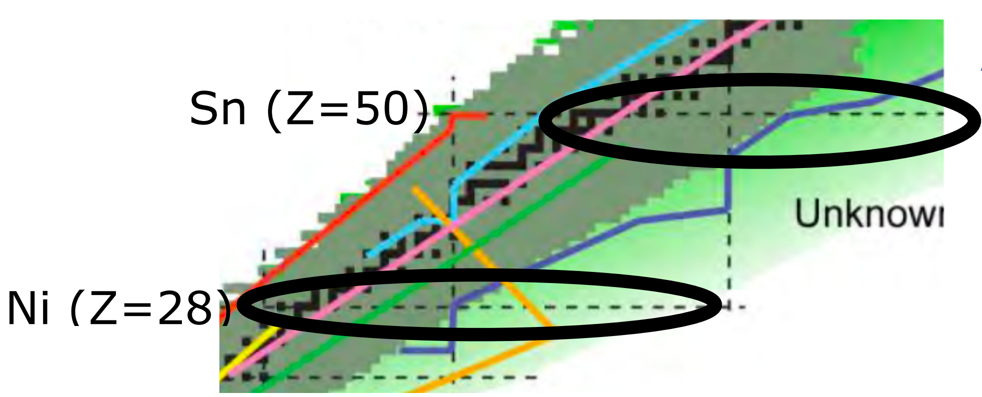


✦ ***Gamow-Teller transition strength:***





Gamow-Teller and β decay of nuclei near the r-process path



r-process path

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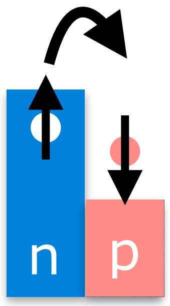

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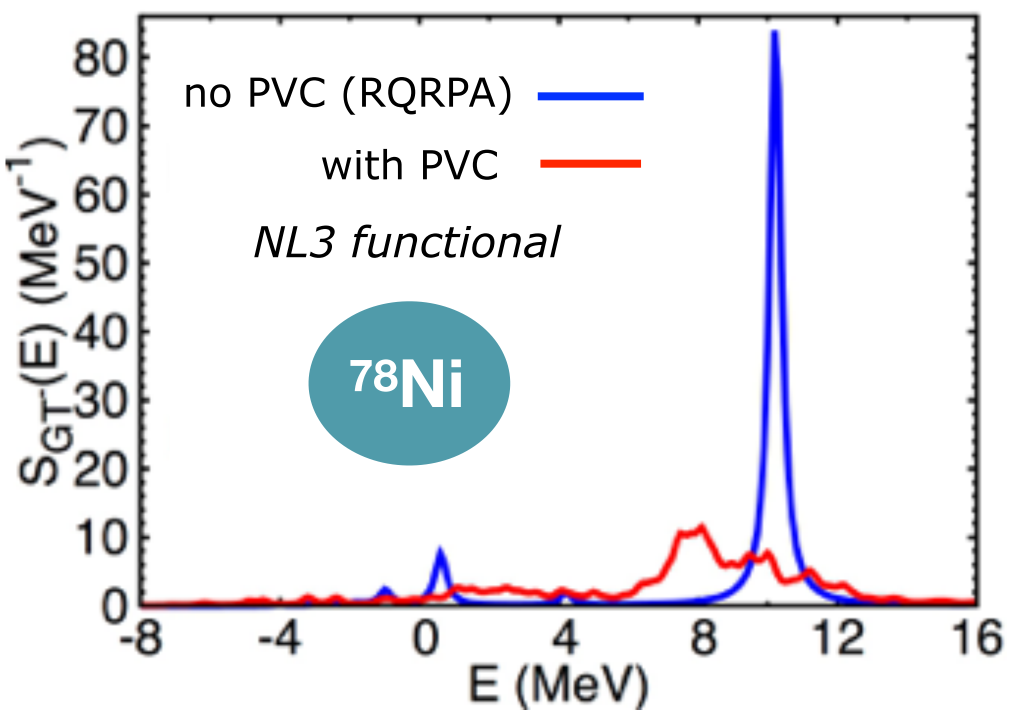
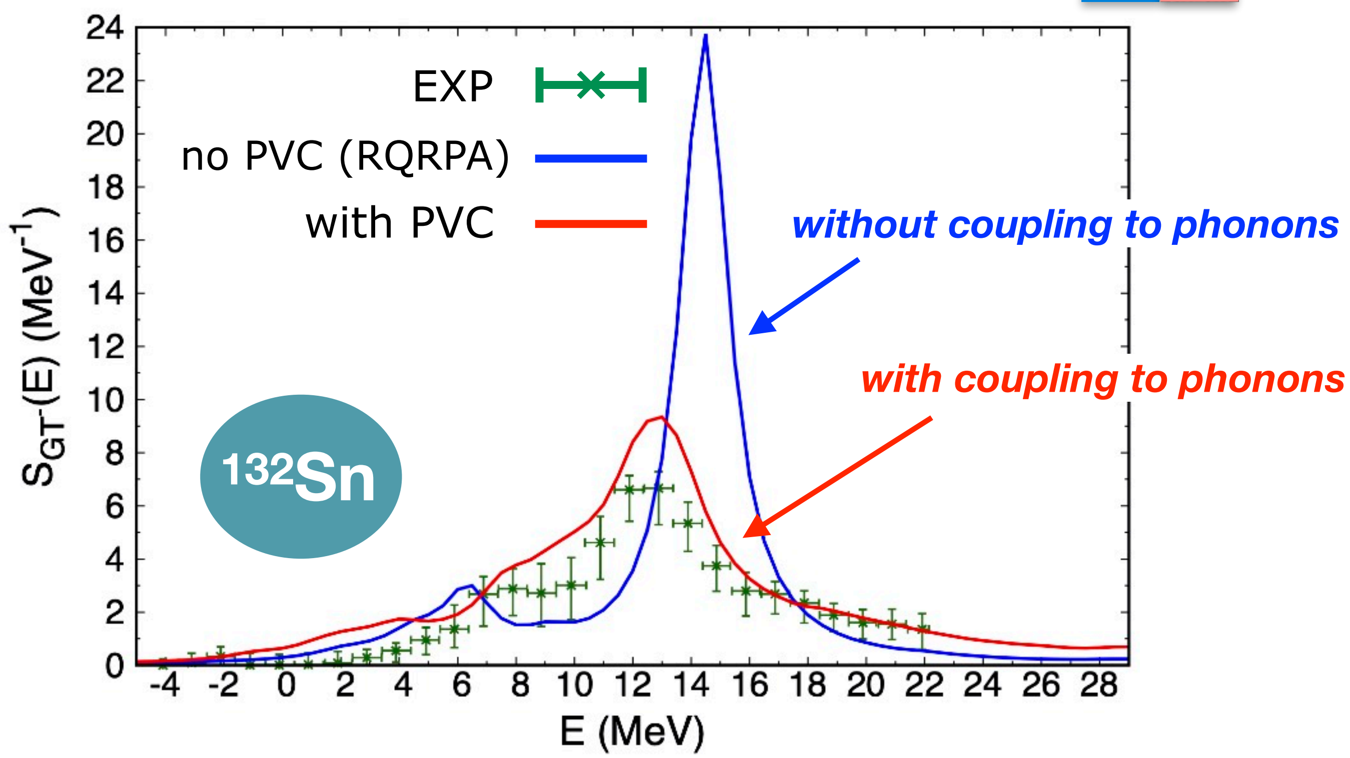
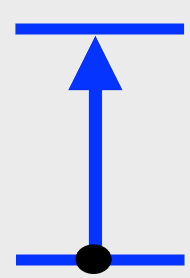
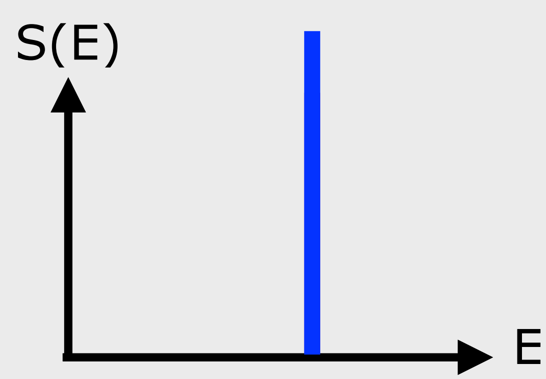




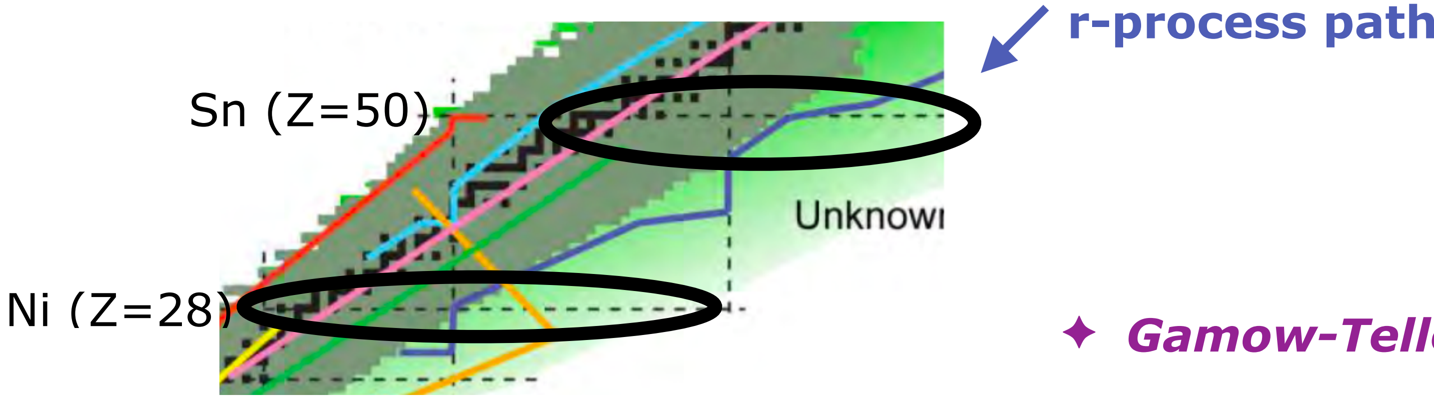


single-particle states



nuclear state

Gamow-Teller and β decay of nuclei near the r-process path



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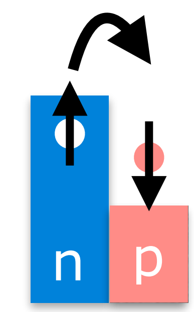
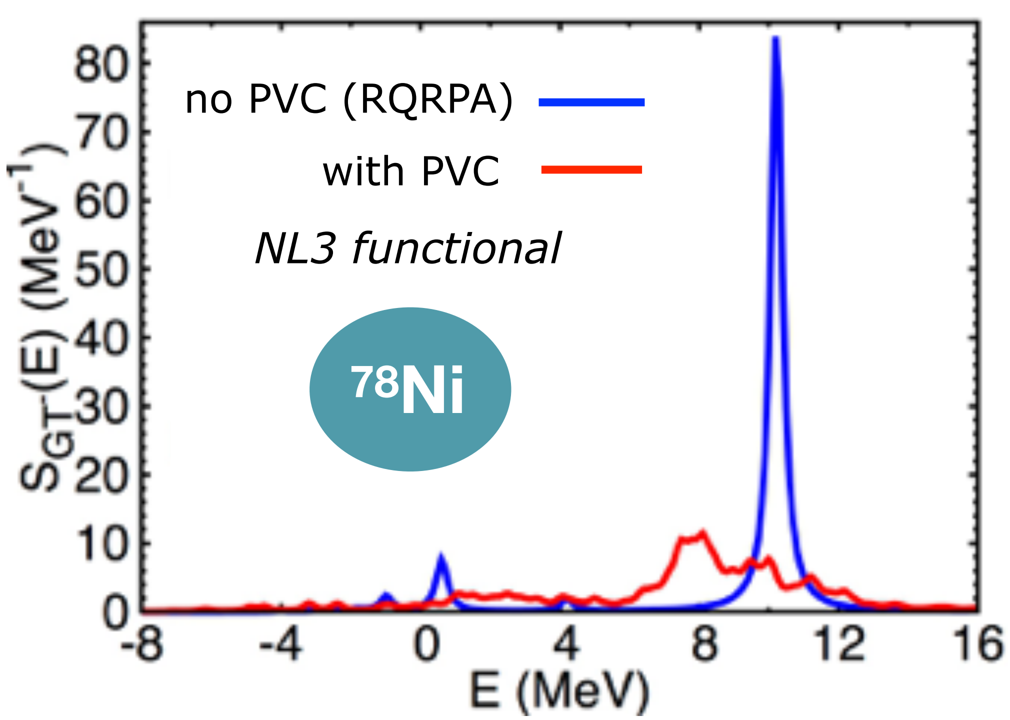
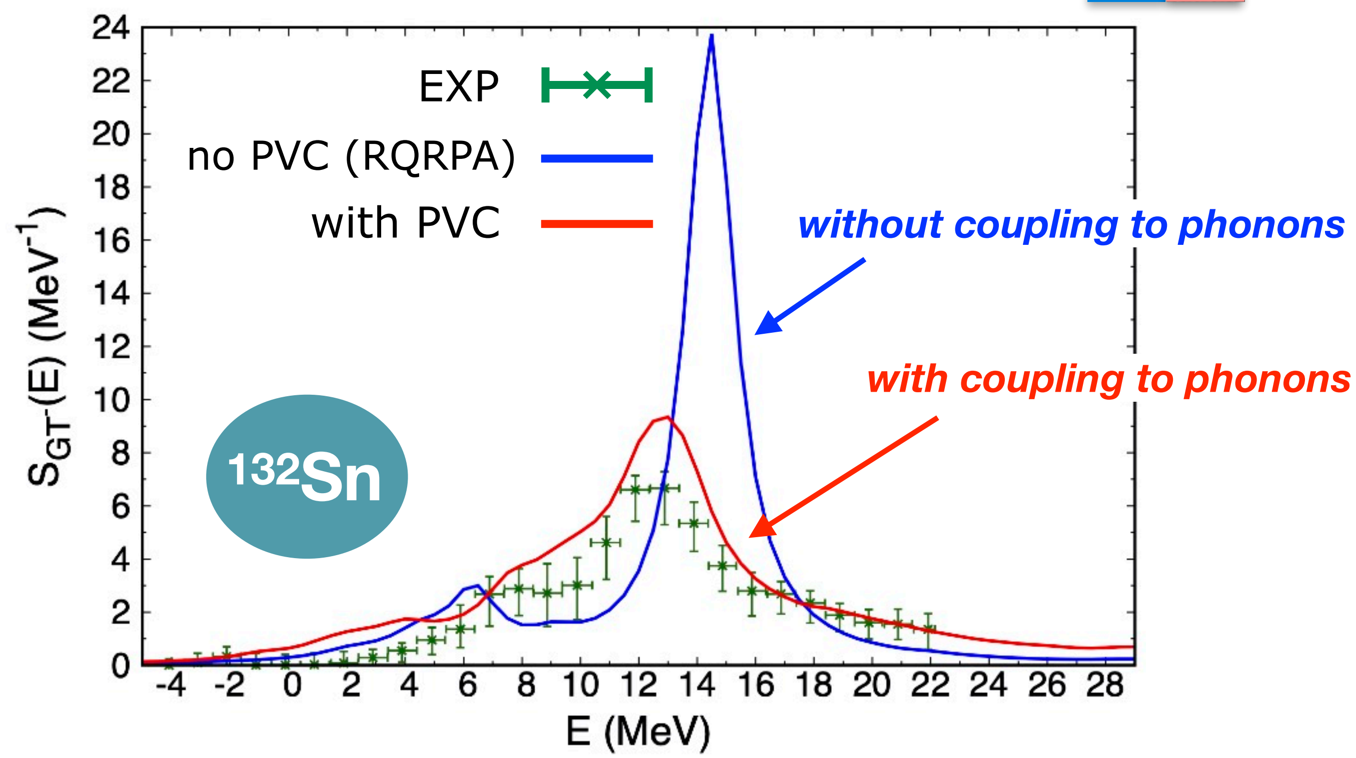
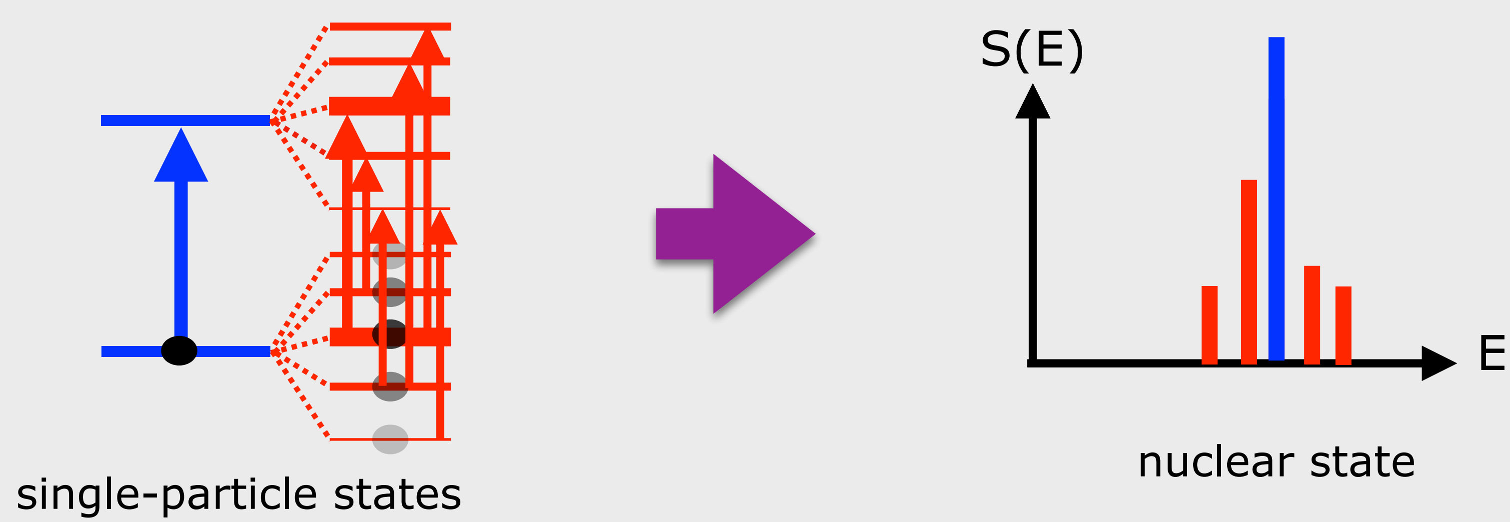


✦ ***Gamow-Teller transition strength:***



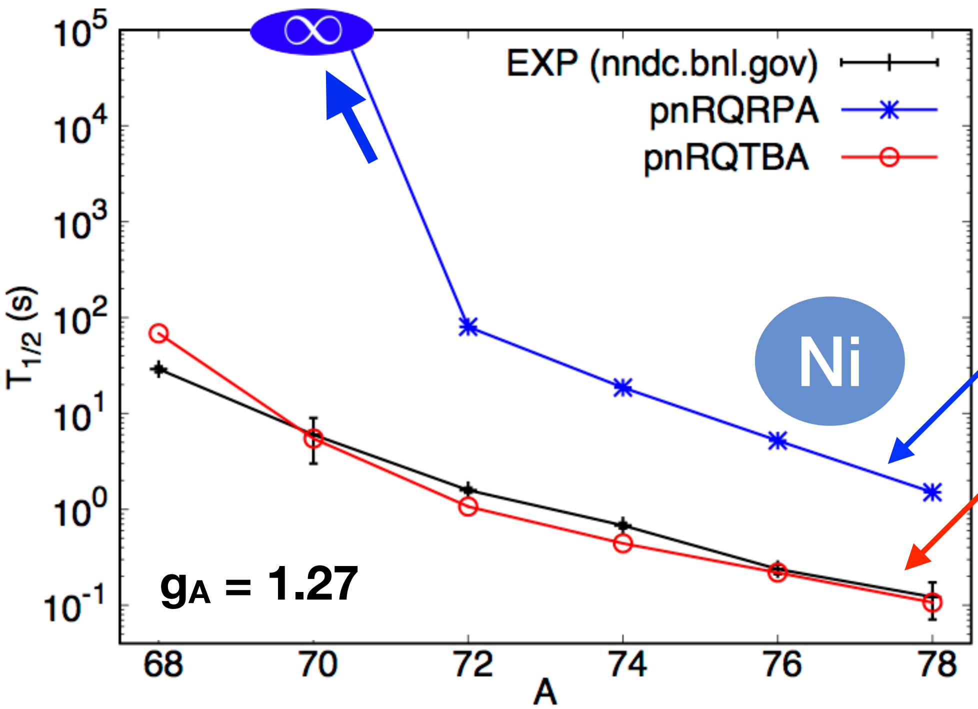




Gamow-Teller and β decay of nuclei near the r-process path

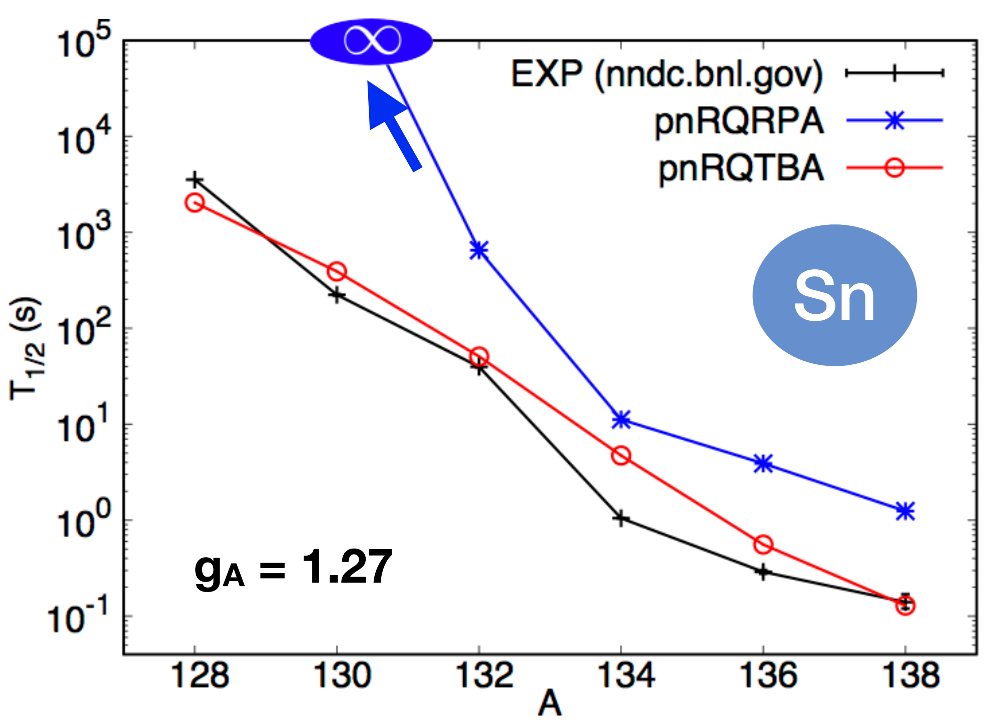
C. R. and E. Litvinova EPJA 52, 205 (2016) & AIP Conf. Proc. 1912, 020014 (2017).

✦ *Beta-decay half-lives:*

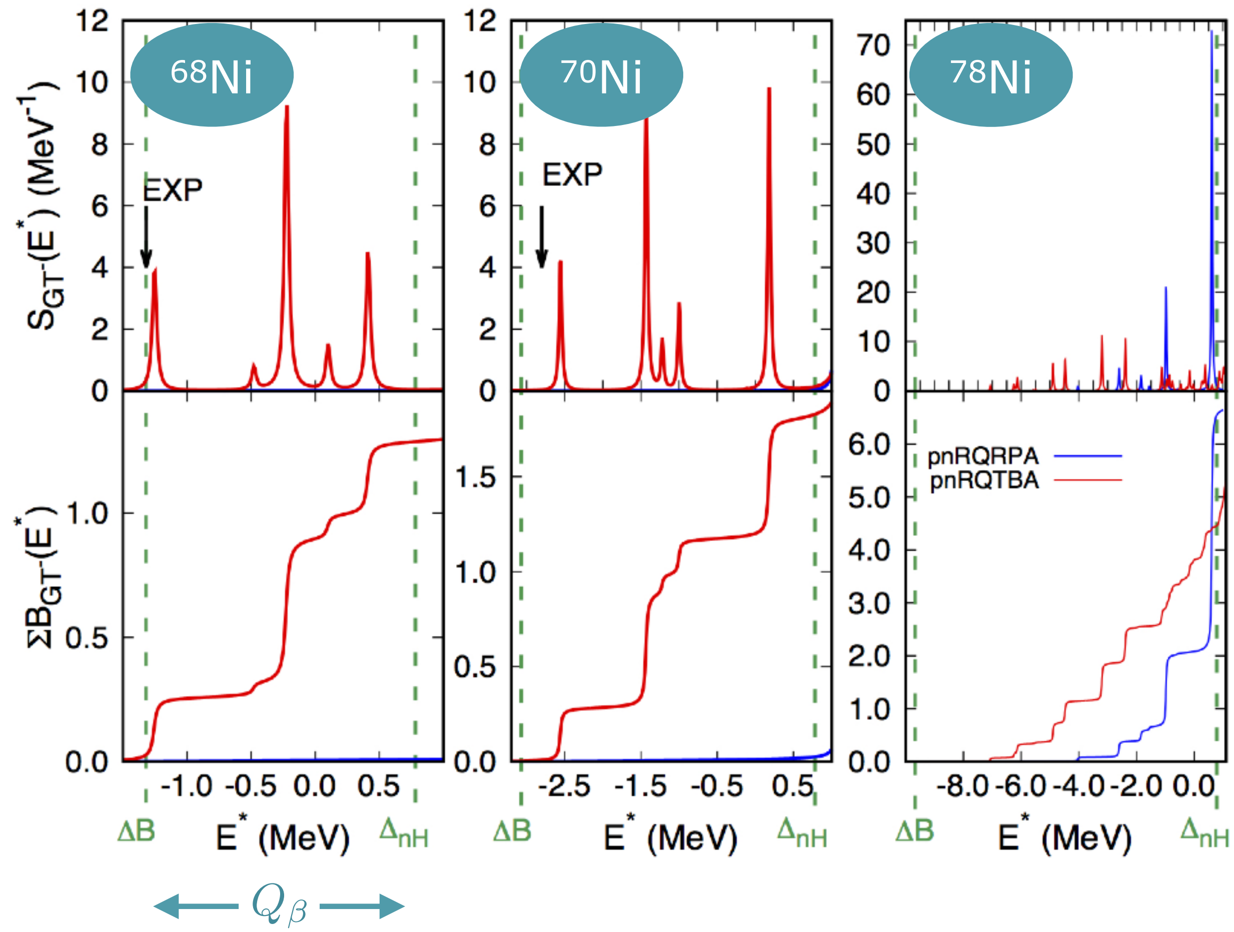


without coupling to phonons

with coupling to phonons



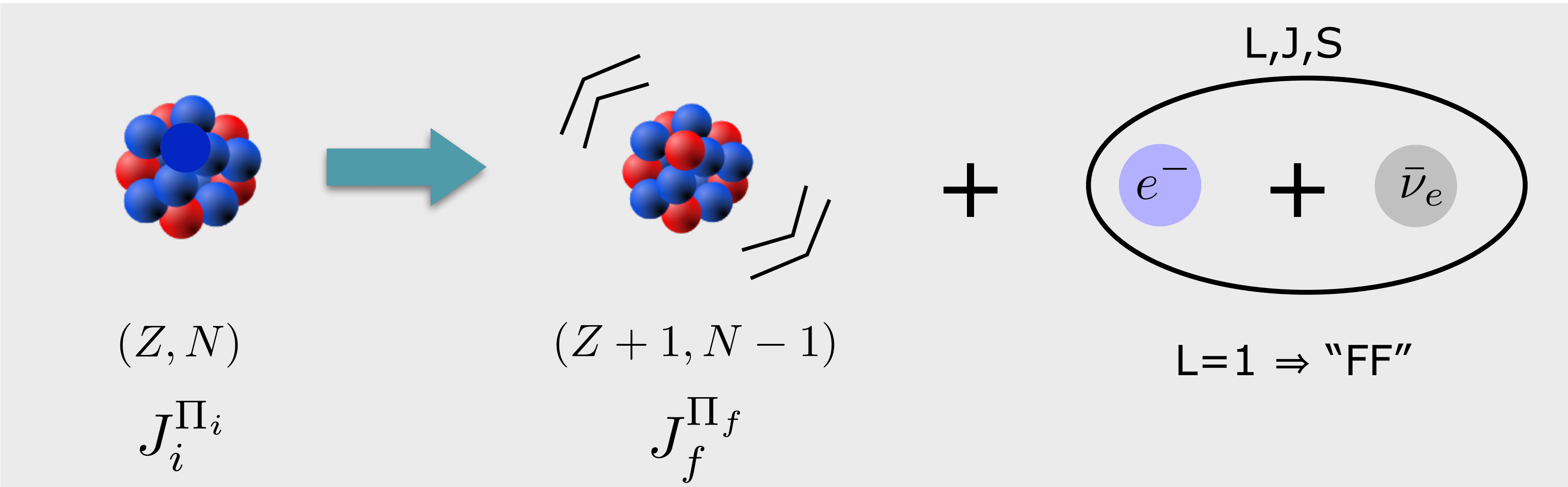
✦ *Low-energy strength:*

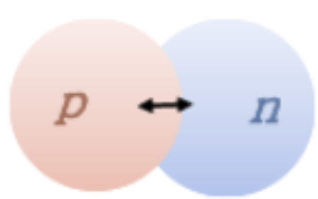


Large improvement of the β-decay half-lives **without extra parameter**

β decay of nuclei near the r-process path

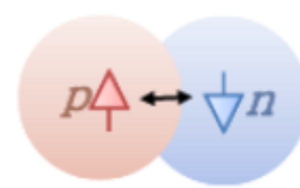
First forbidden (FF) transitions: $\Pi_i \neq \Pi_f$





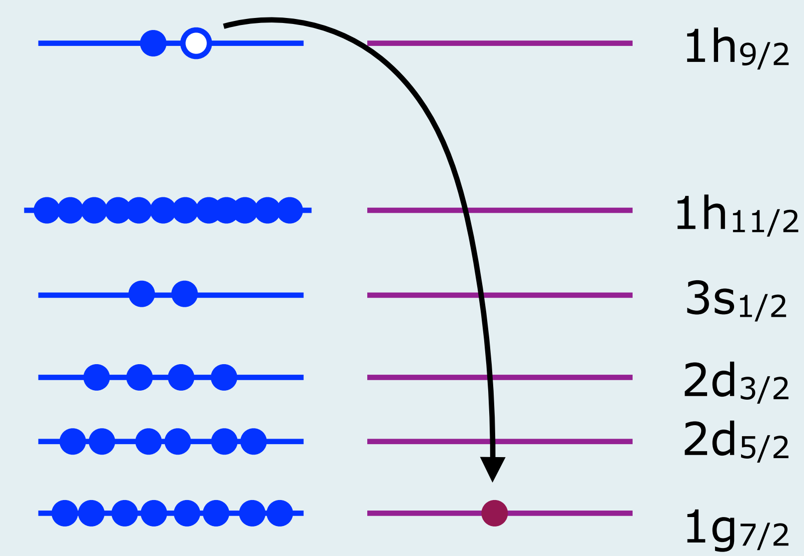
L=1 , S=0, J=1

dipole modes



L=1 , S=1, J=0,1,2

spin dipole modes



transitions between opposite-parity shells

+ ***relativistic contributions***

(connect the large and small components of the Dirac spinor)

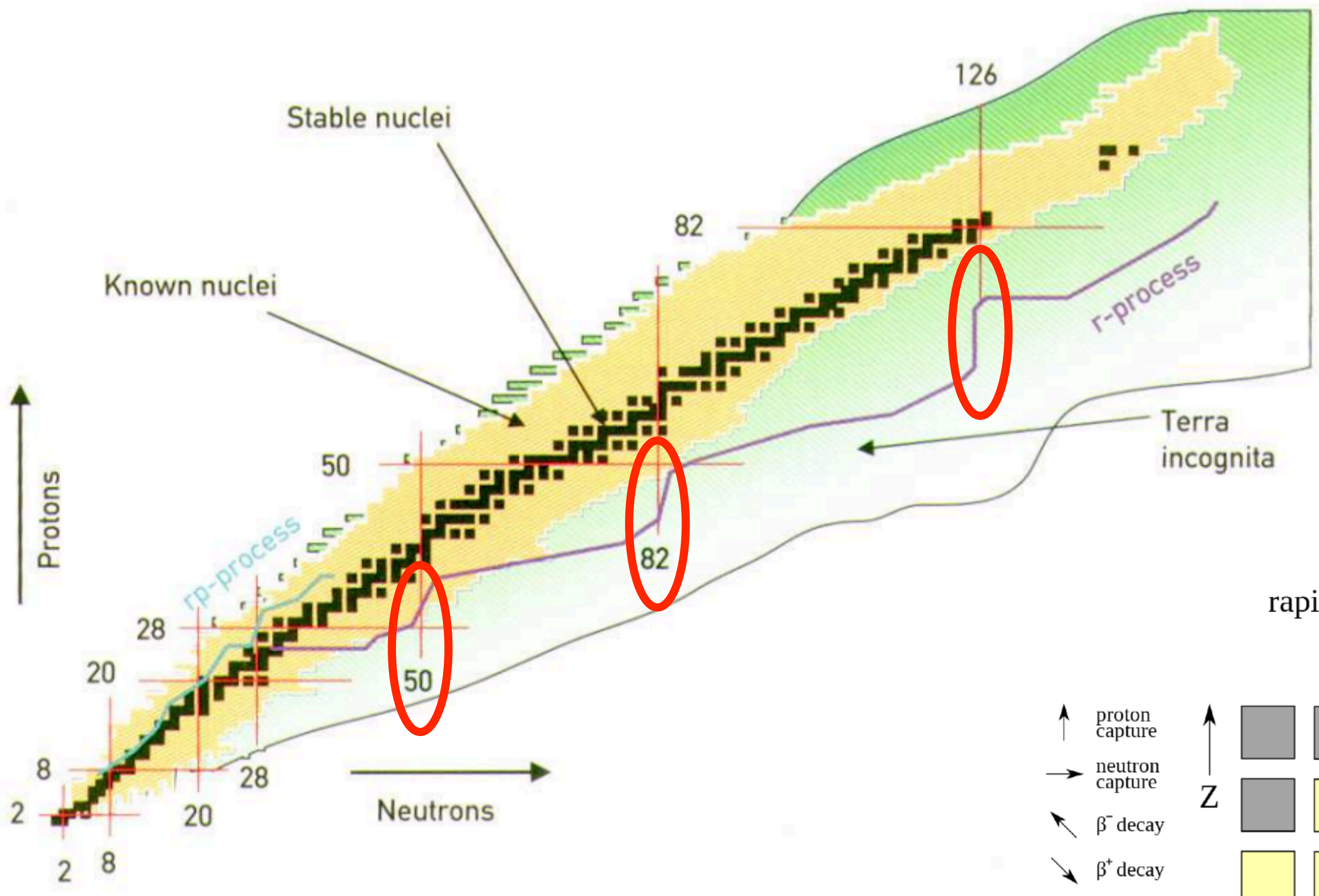
J=0: $\mathcal{O}_{RA} \propto \gamma_5 \tau_-$

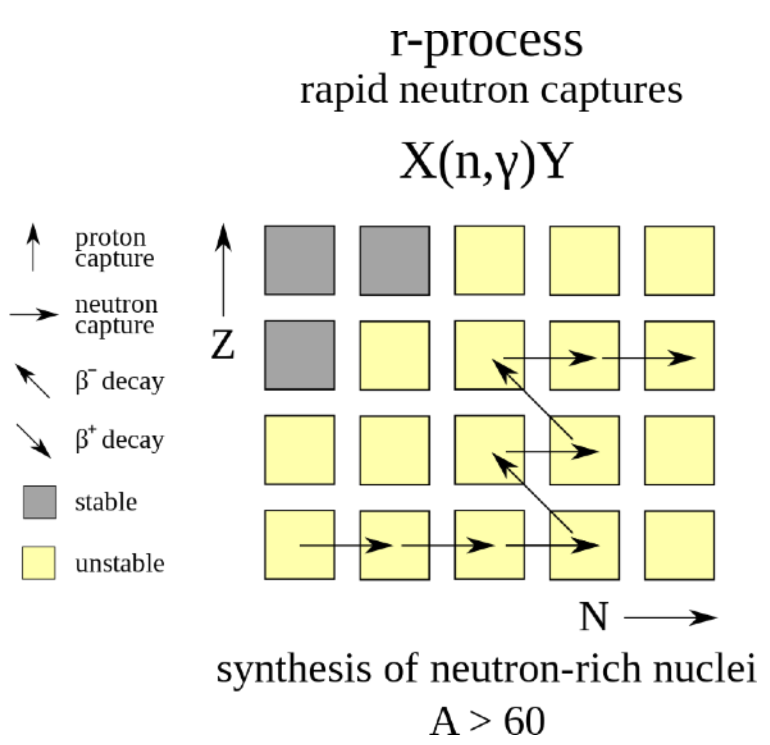
J=1: $\mathcal{O}_{RV} \propto \boldsymbol{\alpha} \tau_-$

β decay of nuclei near the r-process path

CR, G. Martínez-Pinedo, in prep.

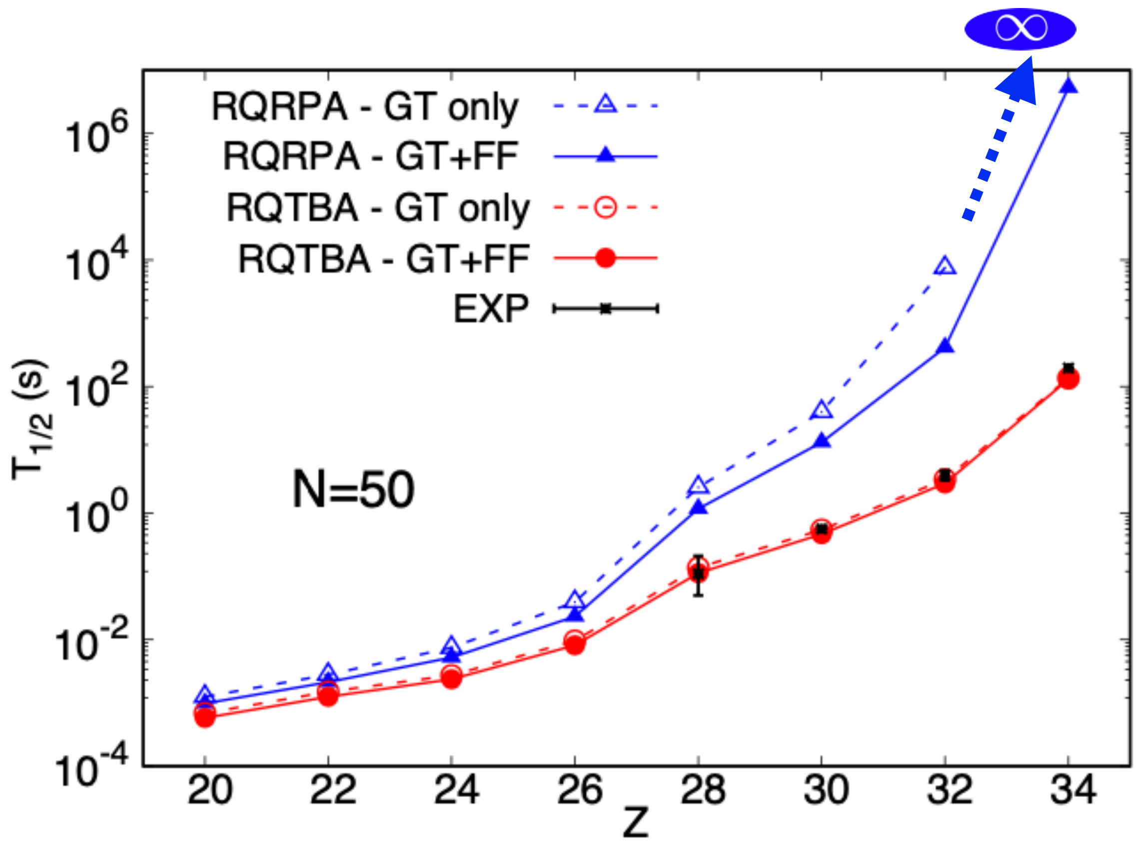
β-decay of isotonic chains N=50, N=82, N=126 & N=184 including first-forbidden transitions

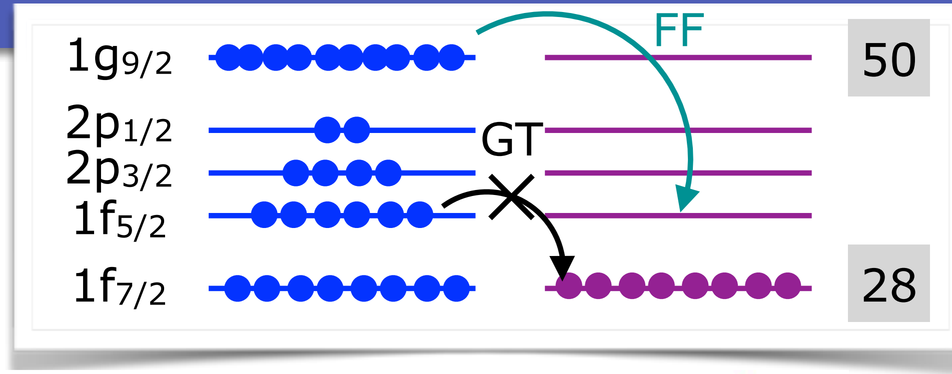


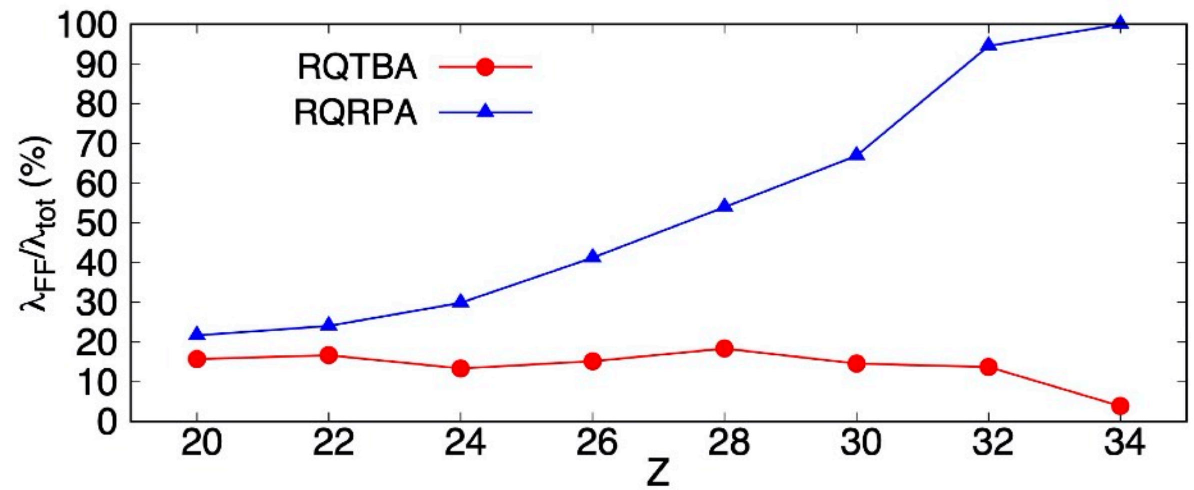


β decay of nuclei near the r-process path

★β-decay of isotonic chain N=50

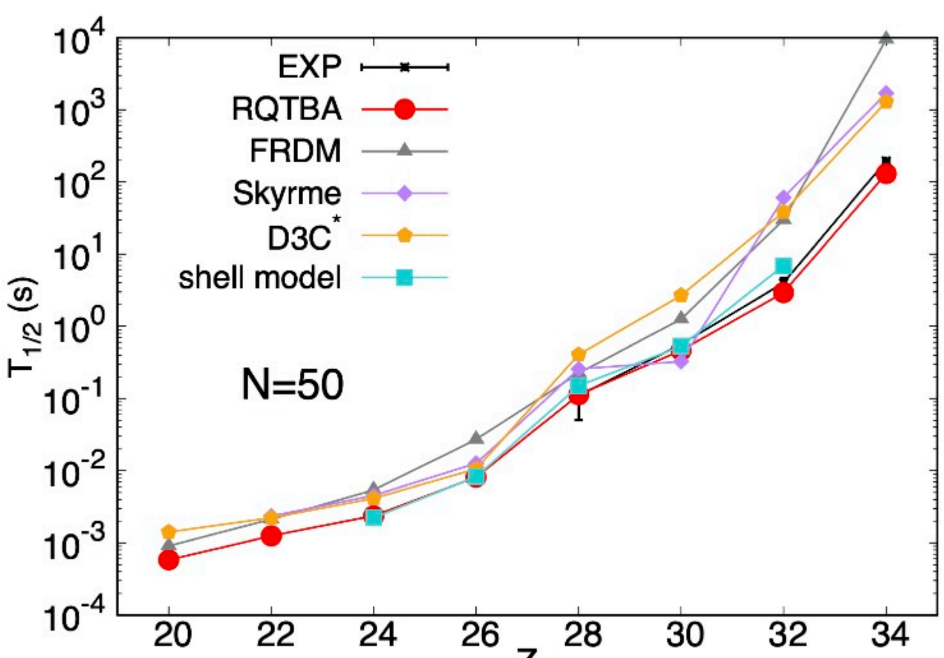


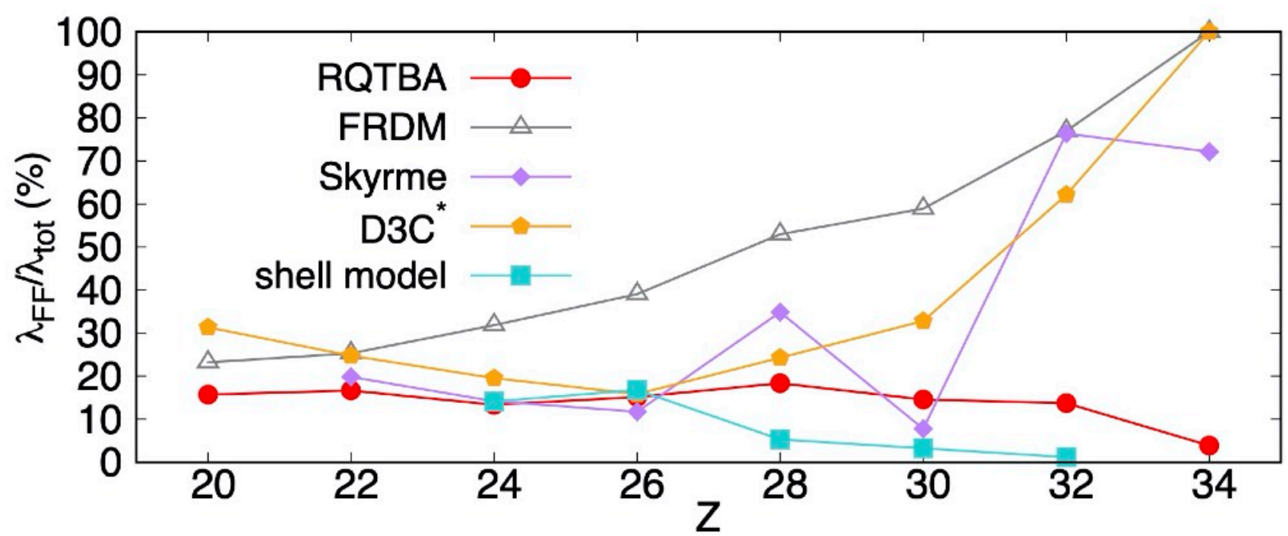




- *The low-energy GT transition is blocked for Z≥28.*
- *In RQRPA, other GT transitions are near the Q value.*
- *With correlations, they are lowered in energy due to fragmentation.*

Comparison to other approaches:



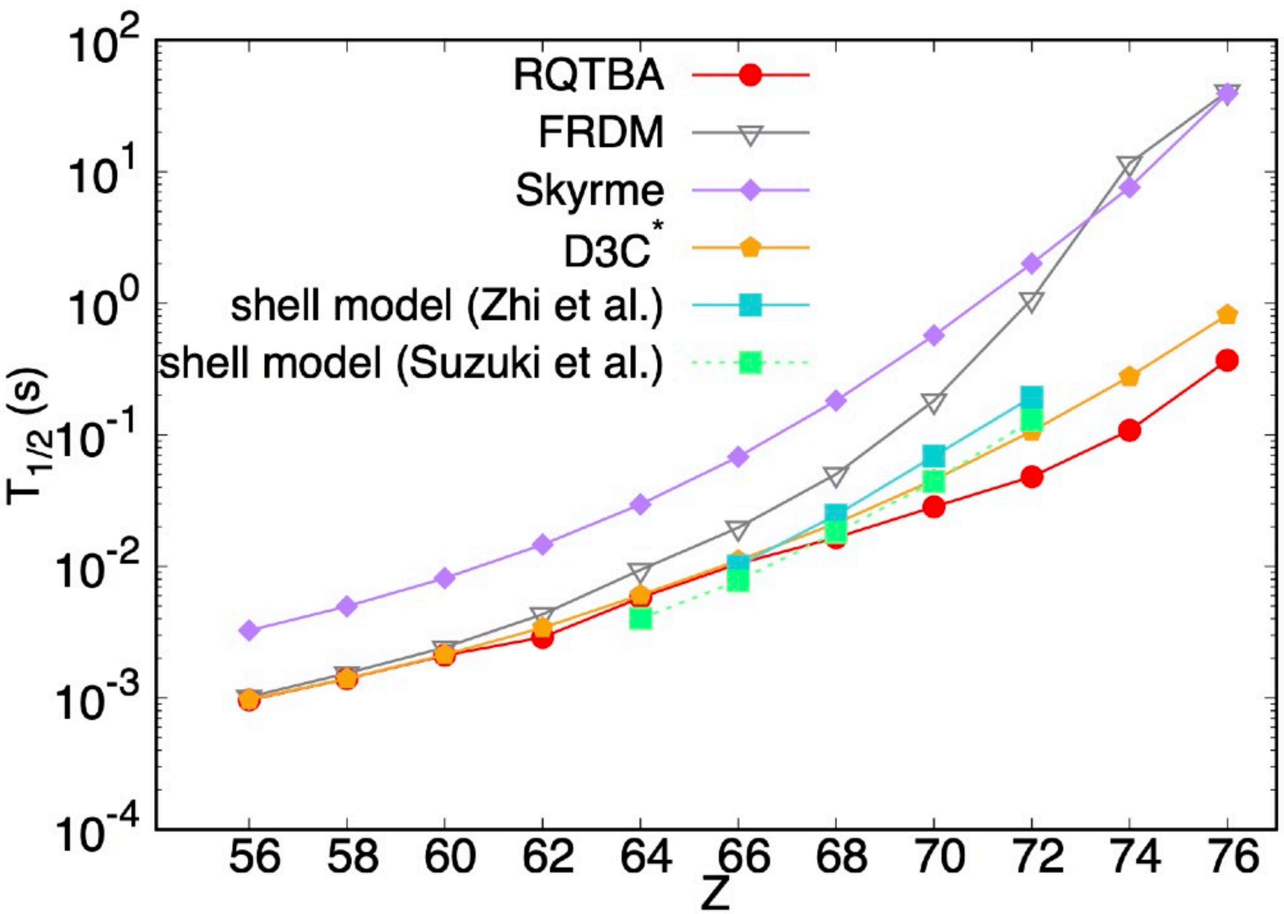


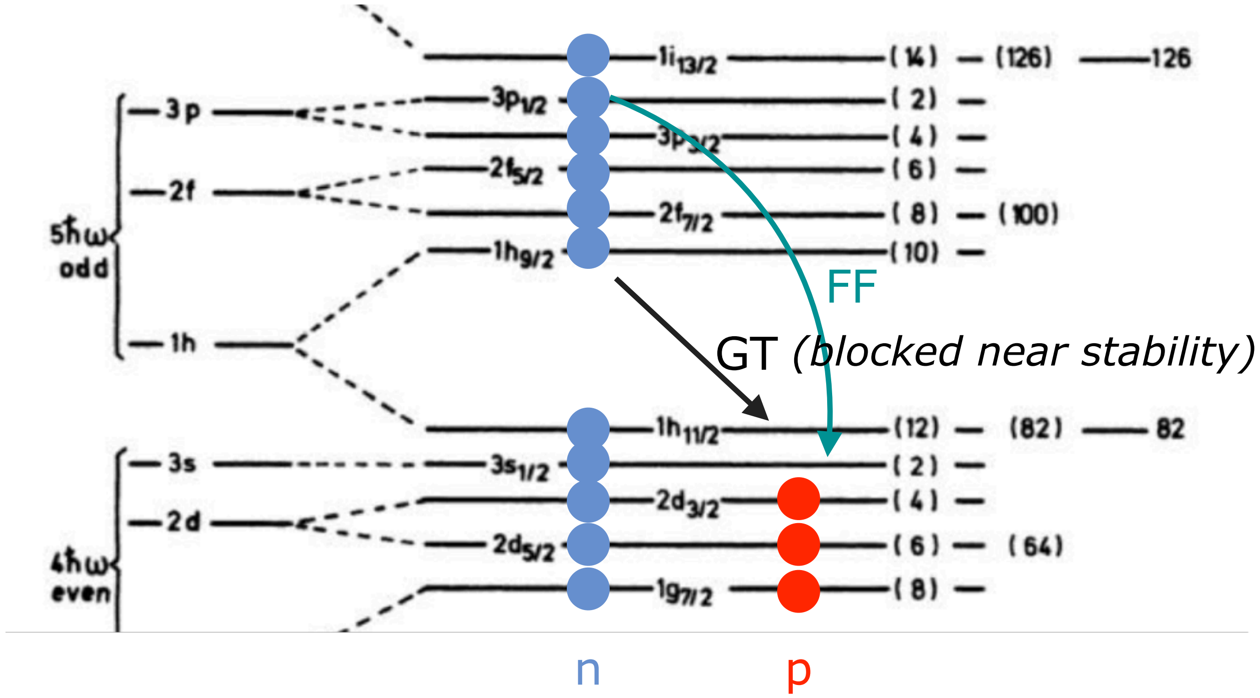
CR, G. Martínez-Pinedo, in prep.

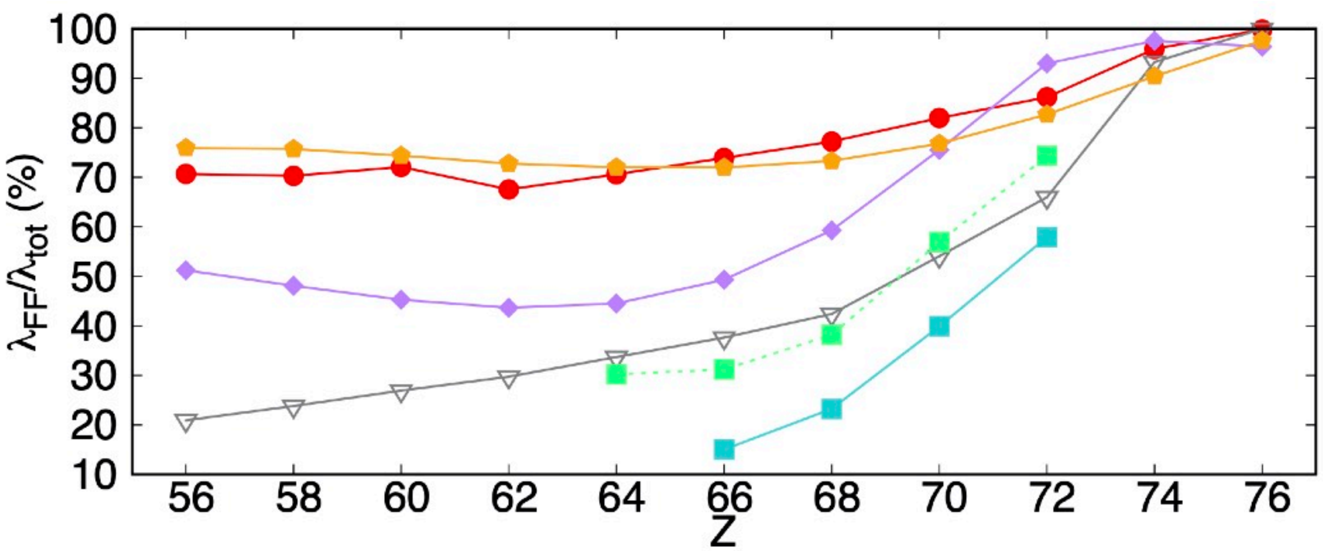
β decay of nuclei near the r-process path

★ **β-decay of isotonic chain N=126**

Comparison to other approaches:





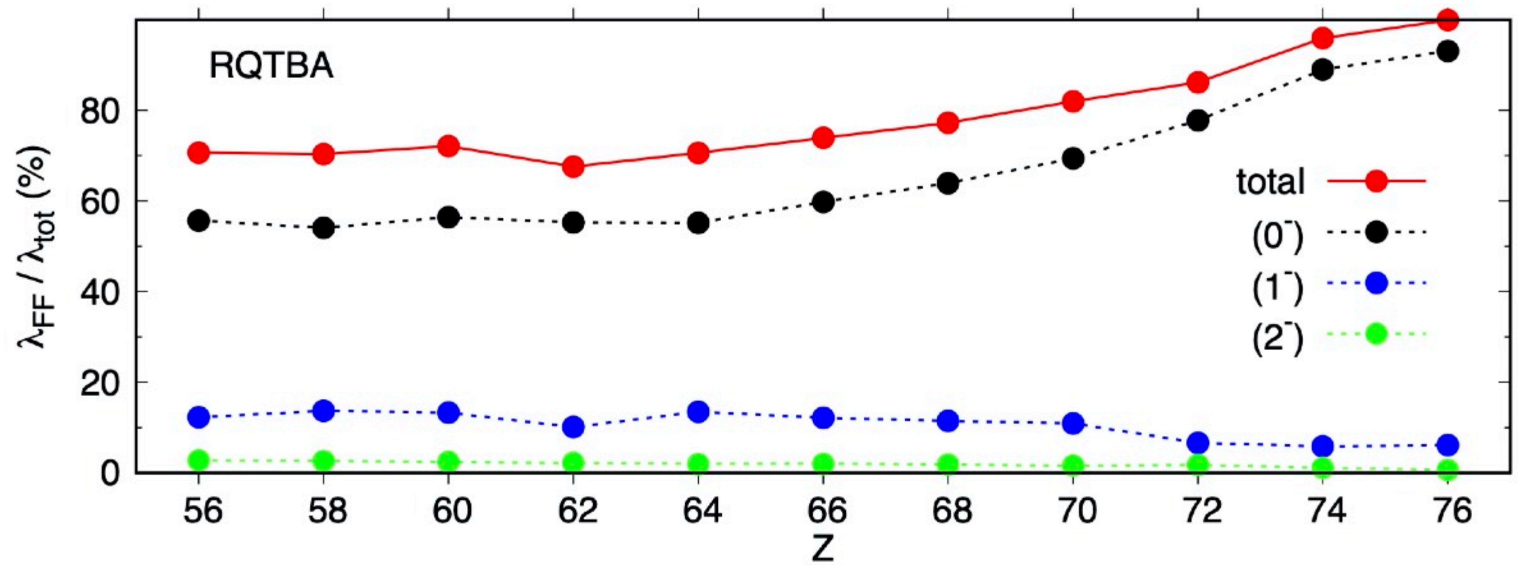


→ no agreement on the contribution of FF transitions far from stability

CR, G. Martínez-Pinedo, in prep.

β decay of nuclei near the r-process path

→ Contributions of the first-forbidden components:

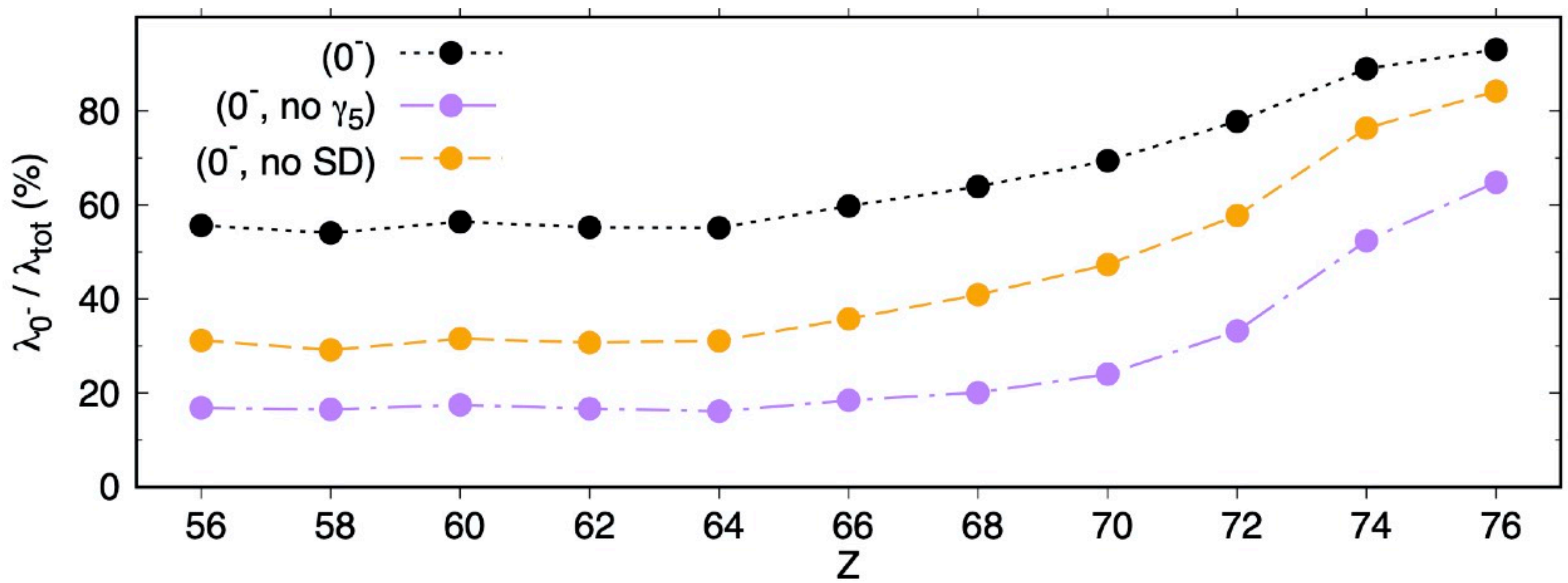


⇒ The decay occurs dominantly via 0^- FF transitions

✳ *spin-dipole (SD) modes*

$$\mathcal{O}_{SA} \propto (\boldsymbol{\sigma}.\boldsymbol{r})\ \tau_-$$

L=1 , S=1, J=0



✳ relativistic contributions

$$\mathcal{O}_{RA} \propto \gamma_5 \tau_-$$

⇒ Relativistic effects appear to be the most important

CR, G. Martínez-Pinedo, in prep.

Outline

★ *Introduction:*

goals and challenges in low-energy nuclear structure theory
β decay calculations for the r process: current status

★ *Towards a universal and precise description of nuclei within Relativistic Nuclear Field Theory*

Method: from mesons to nucleons and emergent collective phenomena
Application to β decay of r-process nuclei

★ *Conclusion and future plans*

Conclusion and future plans

★ The particle-vibration coupling captures the relevant correlations in mid-mass to (super-)heavy nuclei

★ Such correlations are necessary for a correct description of both

- the very low-energy strength ⇛ crucial for accurate weak-interaction rates
- the overall distribution to high excitation energy ⇛ needed to tackle the quenching problem of the Gamow-Teller strength in charge-exchange experiments

★ The role of FF transitions in beta-decay of heavy r-process nuclei should be clarified (upcoming FAIR experiments will be crucial)

★ In progress: Extensions to deformation -> Ph.D. thesis of Diana Alvear Terrero (GSI)

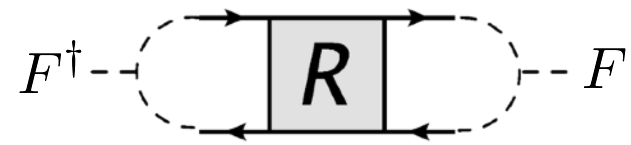
⇒ to perform global calculations of β-decay rates

Thank you!

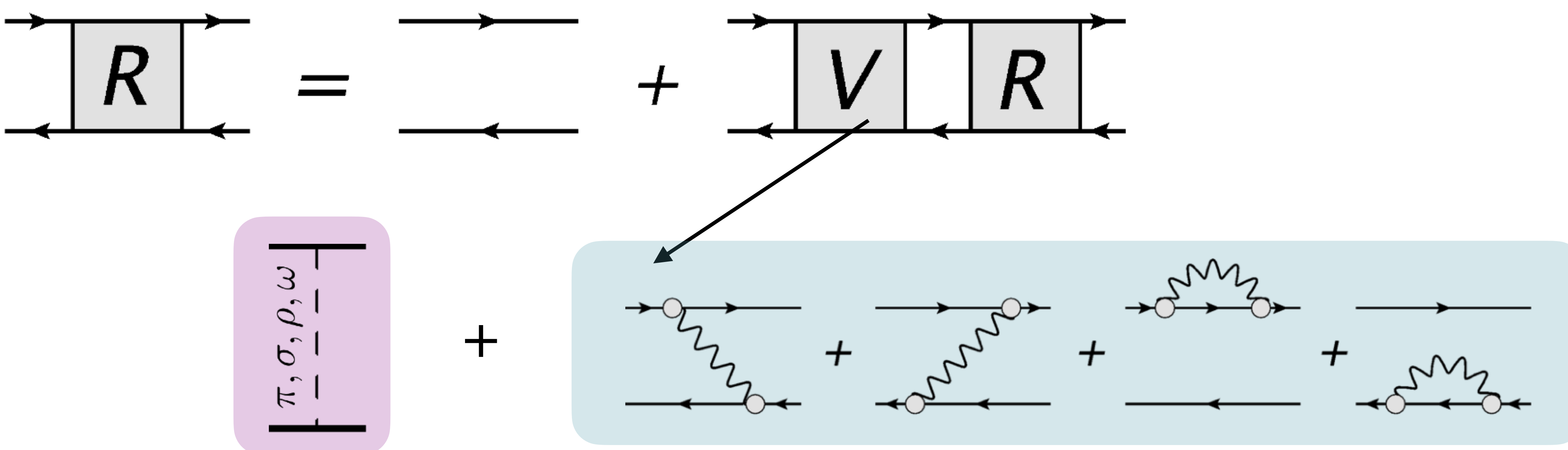
BACKUP SLIDES

Nuclear response in RNFT

★ *Transition strength distribution:* $S(E) =$

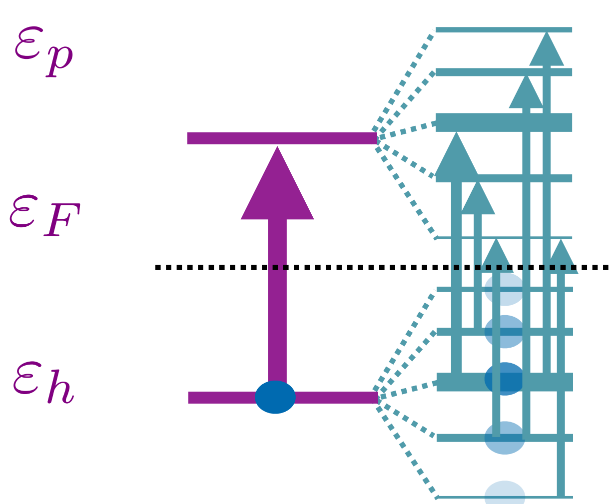


R= Response function
describes the propagation of two correlated nucleons in the nucleus

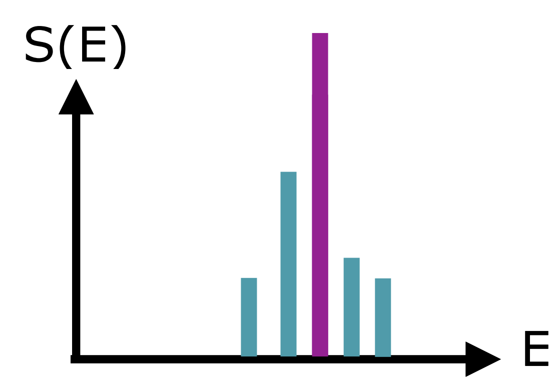


meson exchange

phonon exchange



Single-particle states



many-body states:

$1p - 1h \otimes 1\ \text{phonon}$

configurations

Relativistic Random Phase Approximation (RRPA)

+

particle-vibration coupling (PVC)