Calculating β Decay for the r Process

J. Engel

with

M. Mustonen, T. Shafer

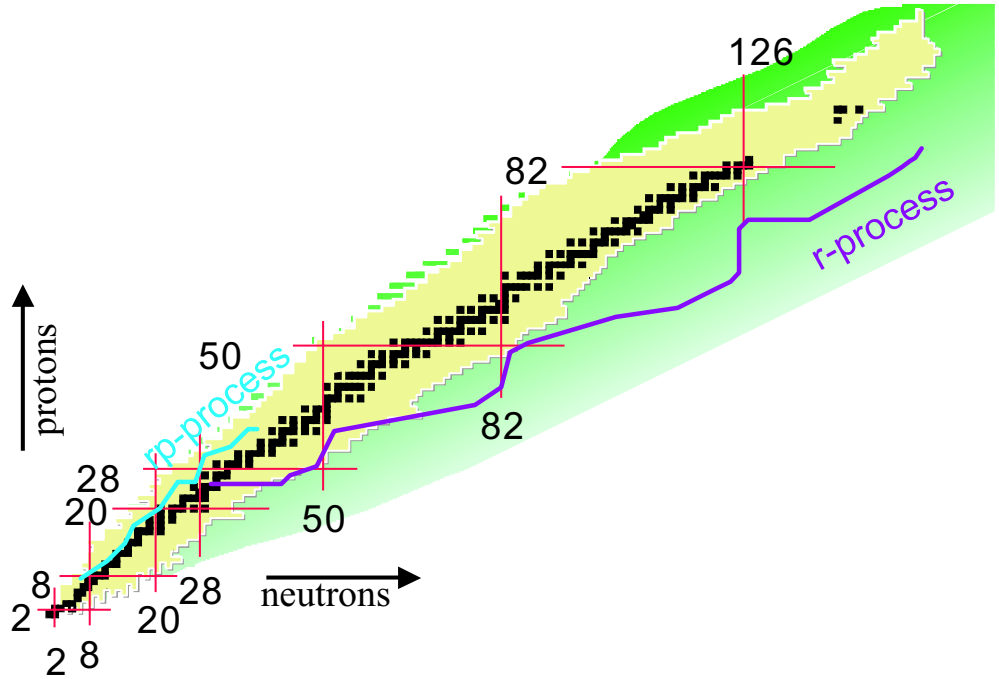
C. Fröhlich, G. McLaughlin, M. Mumpower, R. Surman

Nuclear Structure 2016
Knoxville, Tennessee, USA July 24-29

July 27, 2016

Nuclear Landscape

To locate the site(s) of the *r* process, need reaction rates and properties in very neutron-rich nuclei.



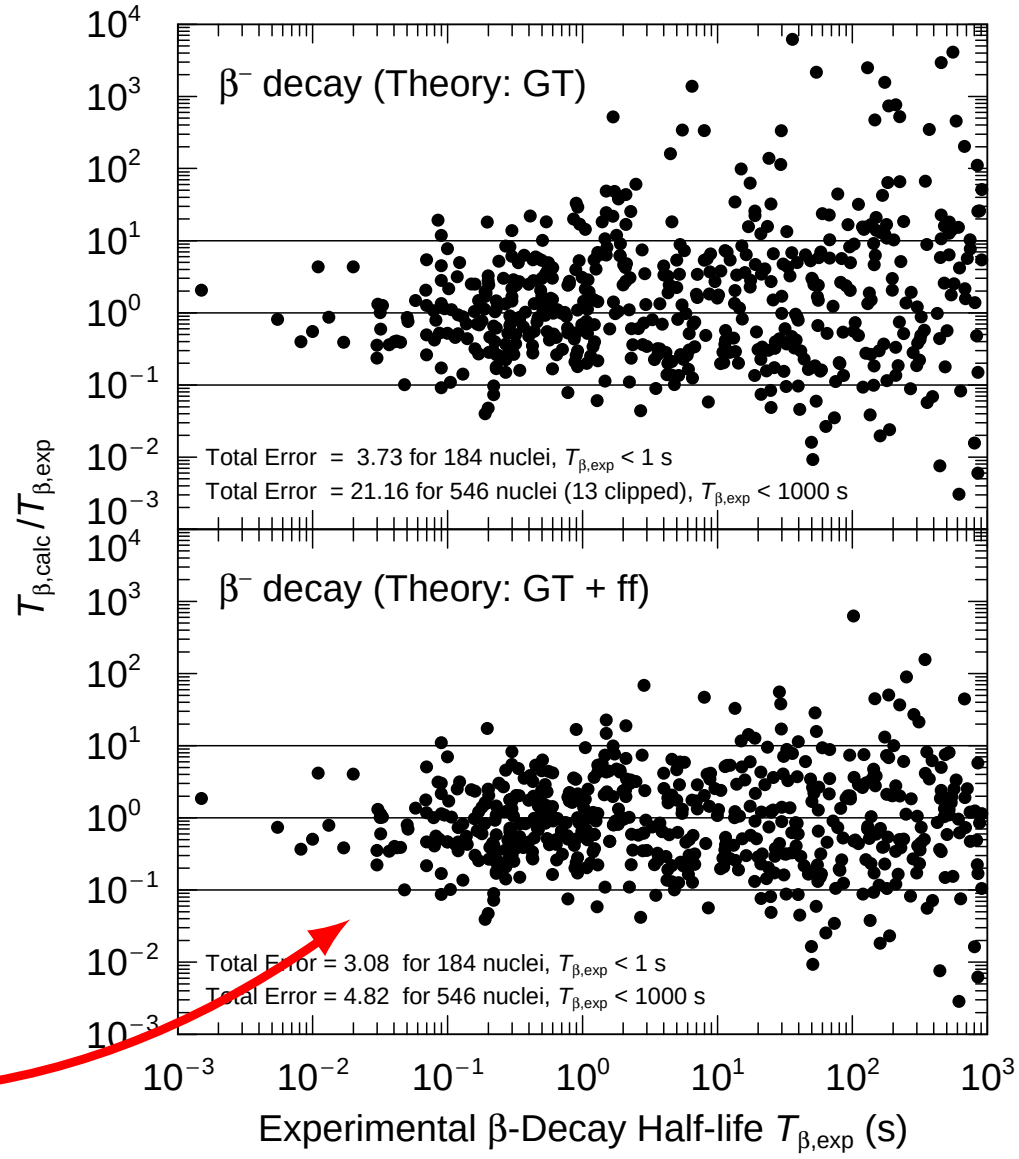
β decay particularly important. Increases *Z* throughout the *r* process, and competition with neutron capture during freeze-out can have large effect on abundances.

What's Usually Used for β Decay in Simulations

Old but Still in Some Ways Unsurpassed Technology

- Masses through finite-range droplet model with shell corrections.
- QRPA with simple space-independent interaction.
- First forbidden decay added in crude way in 2003. Shortens half lives.

Möller, Pfeiffer, Kratz (2003)



Modern Alternative: Skyrme Density-Functional Theory

Started as zero-range effective potential, treated in mean-field theory.

Later re-framed as density functional, which can then be extended:

$$\mathcal{E} = \int d^3r \left(\underbrace{\mathcal{H}_{\text{even}} + \mathcal{H}_{\text{odd}}}_{\mathcal{H}_{\text{Skyrme}}} + \mathcal{H}_{\text{kin.}} + \mathcal{H}_{\text{em}} \right)$$

$\mathcal{H}_{\text{odd}}$ has no effect in mean-field description of time-reversal even states (e.g. ground states), but large effect in β decay.

Contains eight terms that depend on spin density, current density, spin-kinetic density, tensor-kinetic density.

QRPA

QRPA done properly is time-dependent mean-field theory with small harmonic perturbation by β-decay transition operator.

Matrix elements of operator between the initial state and final excited states obtained from response of nucleus.

QRPA of Möller et al. is simplified.

No fully self-consistent mean-field calculation to start.

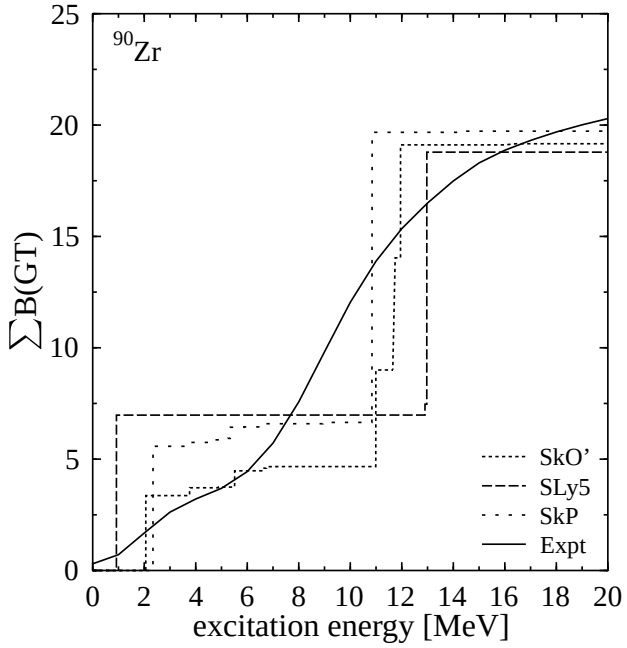
Nucleon-nucleon interaction (schematic) is used only in QRPA part of calculation.

Several groups have tried to do better.

Initial Skyrme Application: Spherical QRPA

Example: late-90's calculation, in nuclei near "waiting points;" no forbidden decay.

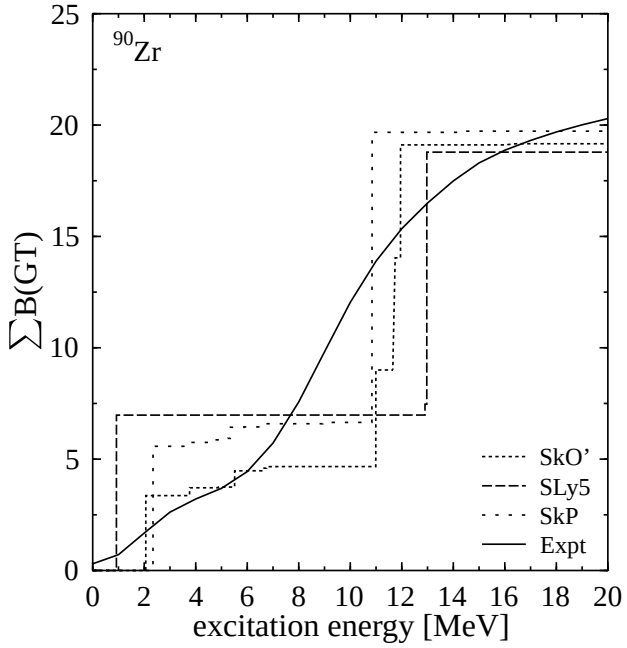
Chose functional SkO′ because did best with GT distributions.



Initial Skyrme Application: Spherical QRPA

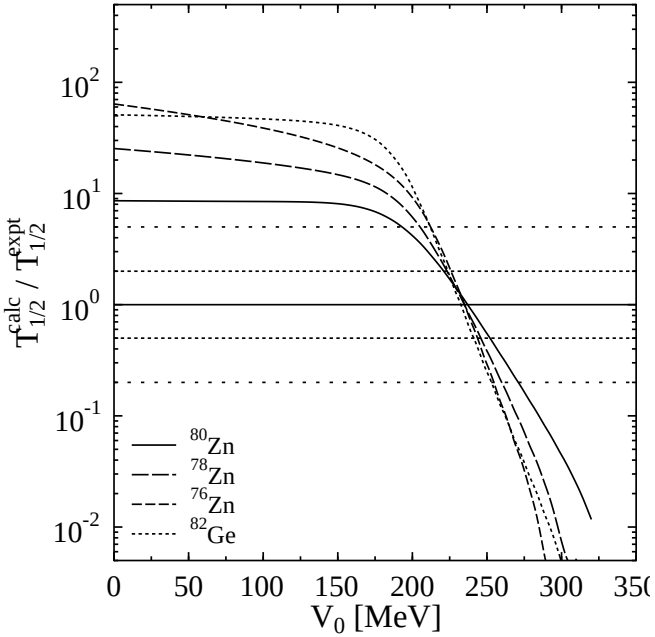
Example: late-90's calculation, in nuclei near "waiting points;" no forbidden decay.

Chose functional SkO′ because did best with GT distributions.



One free parameter: strength of isoscalar pairing (zero in schematic QRPA.)

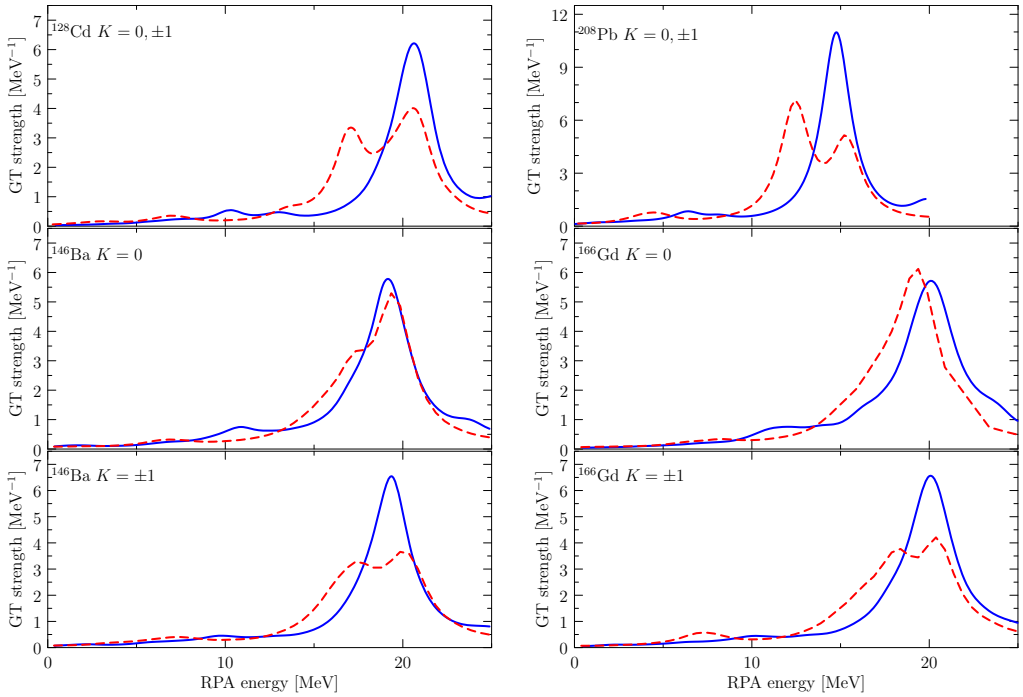
Adjusted in each of the three peak regions to reproduce measured lifetimes.



New: Fast Skyrme QRPA in Deformed Nuclei

Finite-Amplitude Method (Nakatsukasa et al.)

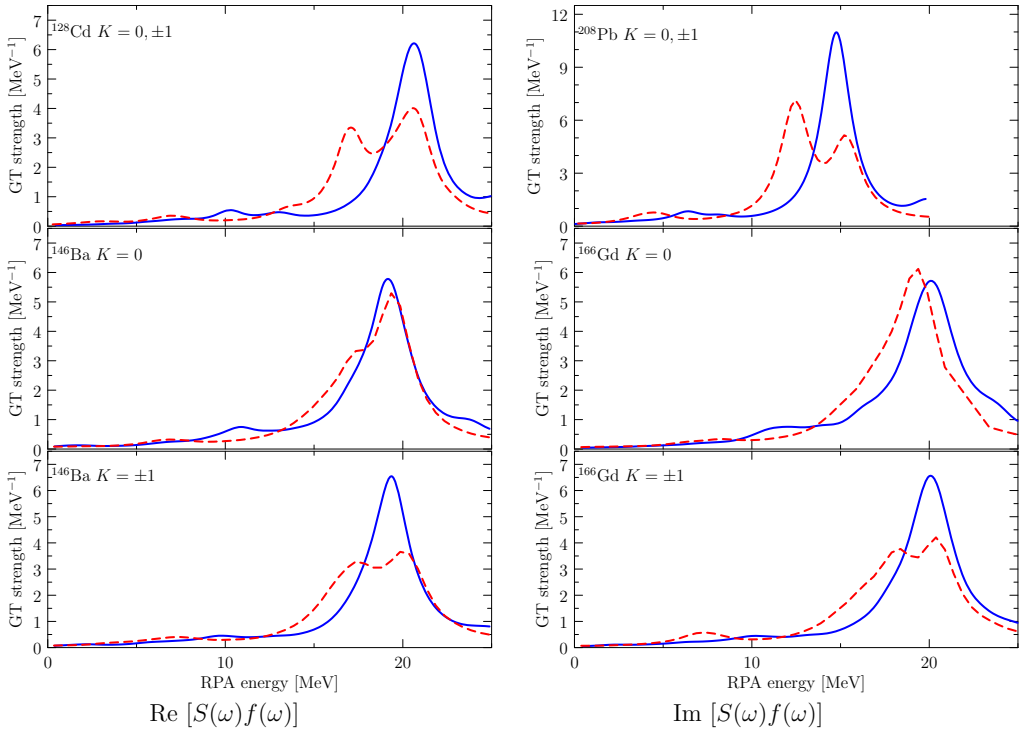
Strength functions computed directly, in orders of magnitude less time than with matrix QRPA.



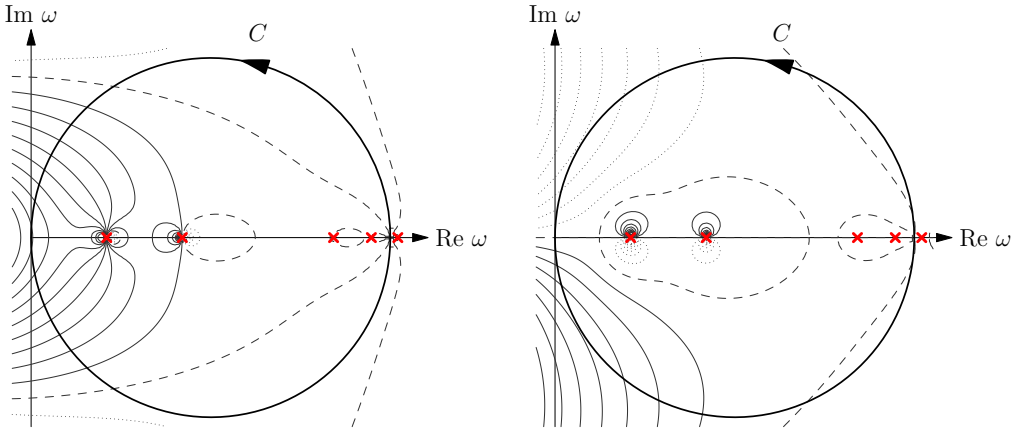
New: Fast Skyrme QRPA in Deformed Nuclei

Finite-Amplitude Method (Nakatsukasa et al.)

Strength functions computed directly, in orders of magnitude less time than with matrix QRPA.



Beta-decay rates obtained by integrating strength with phase-space weighting function in contour around excited states below threshold.



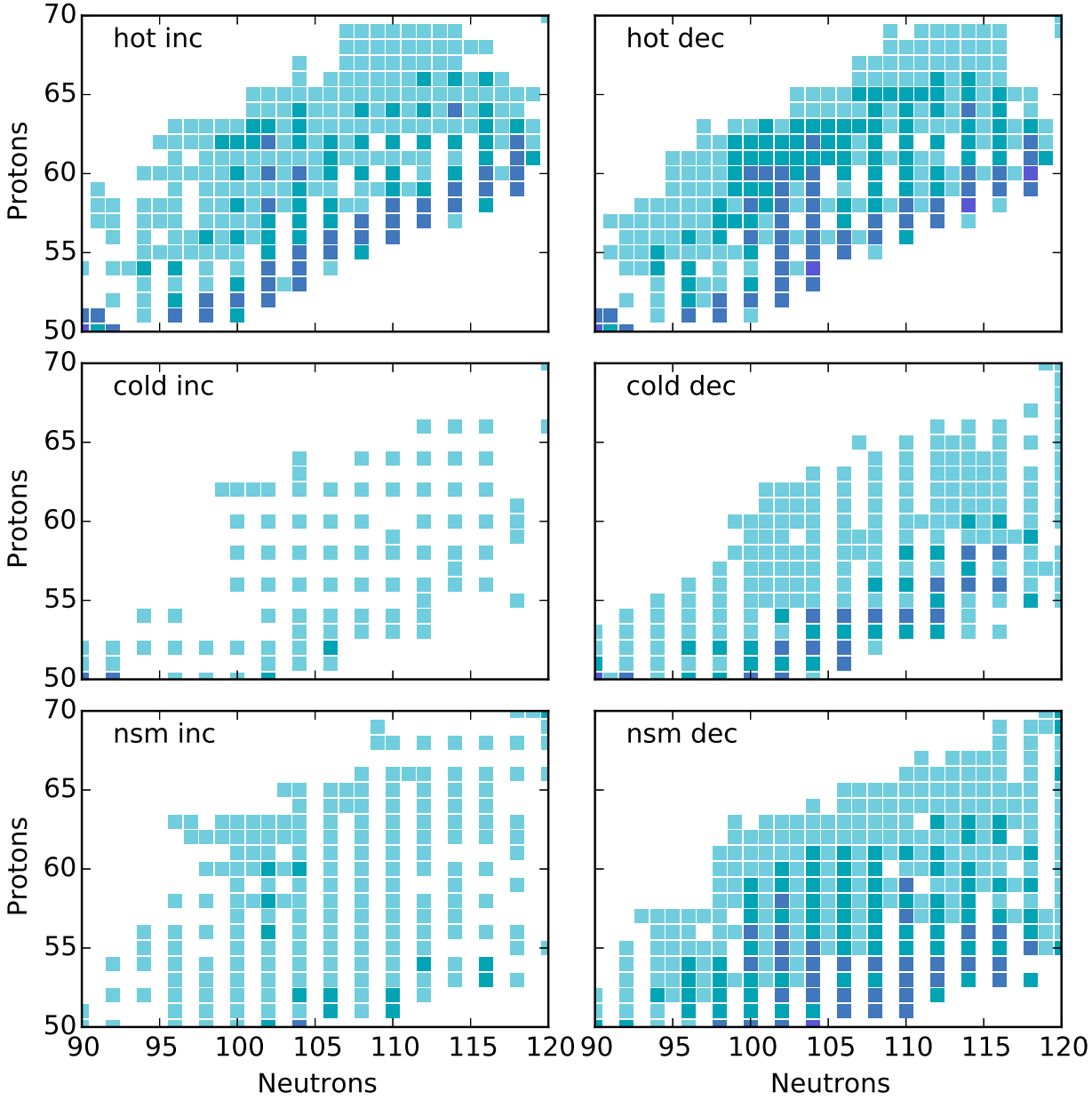
Two Projects Described Here

1. Local focus on rare-earth region, consequences of new rates for rare-earth "bump."

2. Global calculation, attempt at comprehensive fit of relevant part of Skyrme functional.

Sensitivity Studies

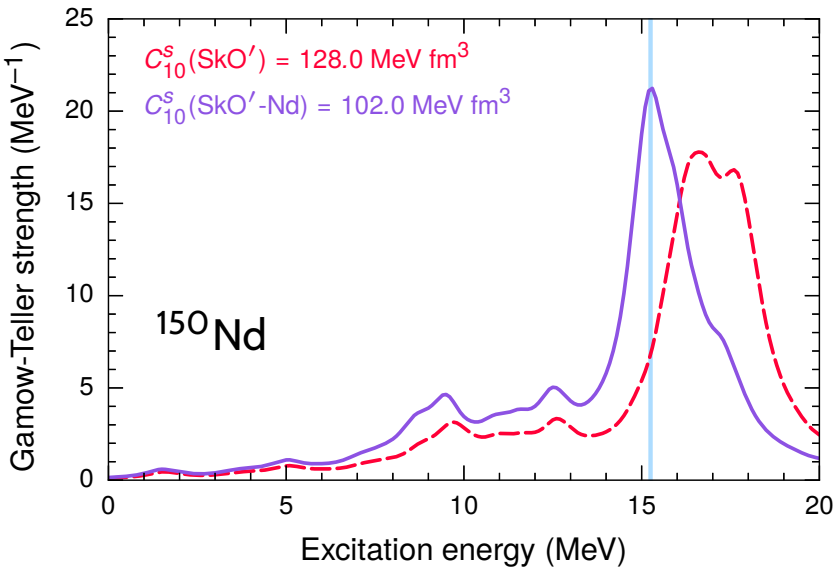
For Rare-Earth Peak:



Rare-Earth Region

Local fit of two parameters: strengths of spin-isospin force and proton-neutron isoscalar pairing force, with several functionals.

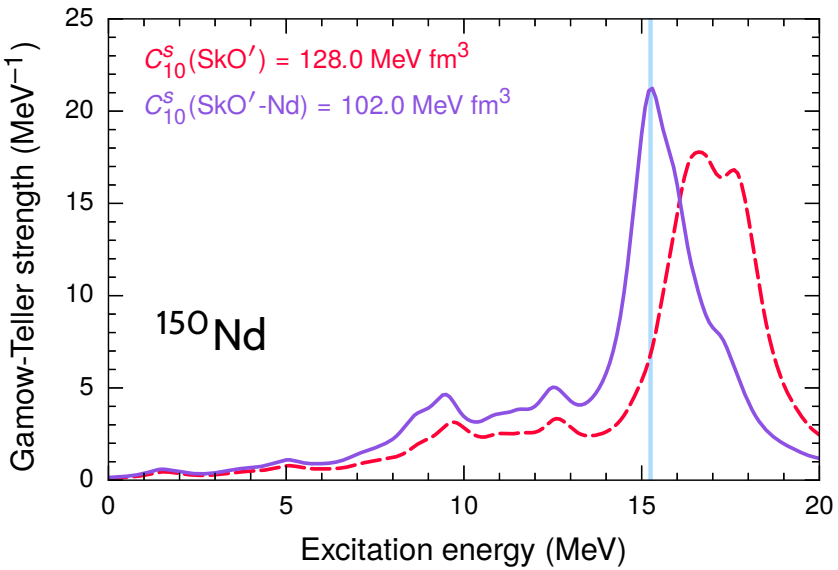
Adjusting spin-isospin force



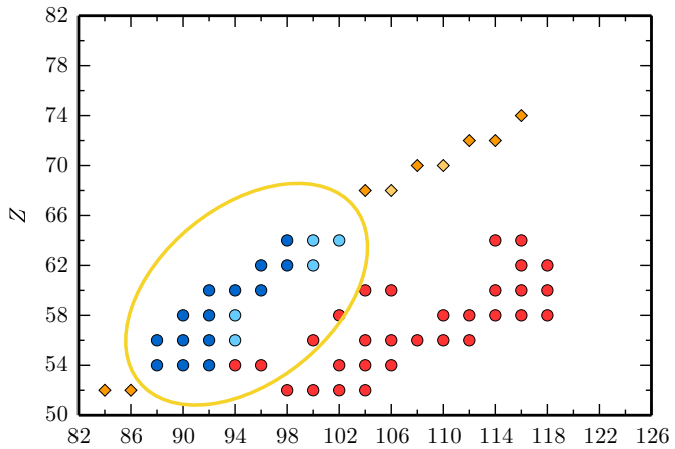
Rare-Earth Region

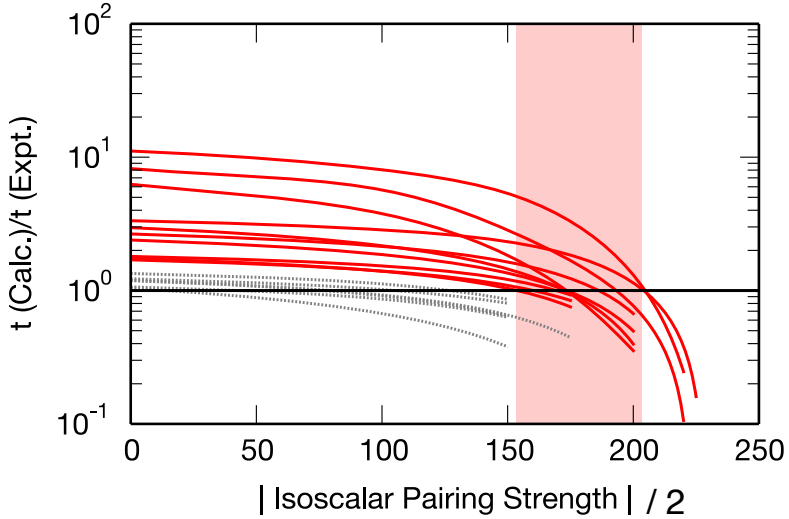
Local fit of two parameters: strengths of spin-isospin force and proton-neutron isoscalar pairing force, with several functionals.

Adjusting spin-isospin force



Adjusting isoscalar pairing

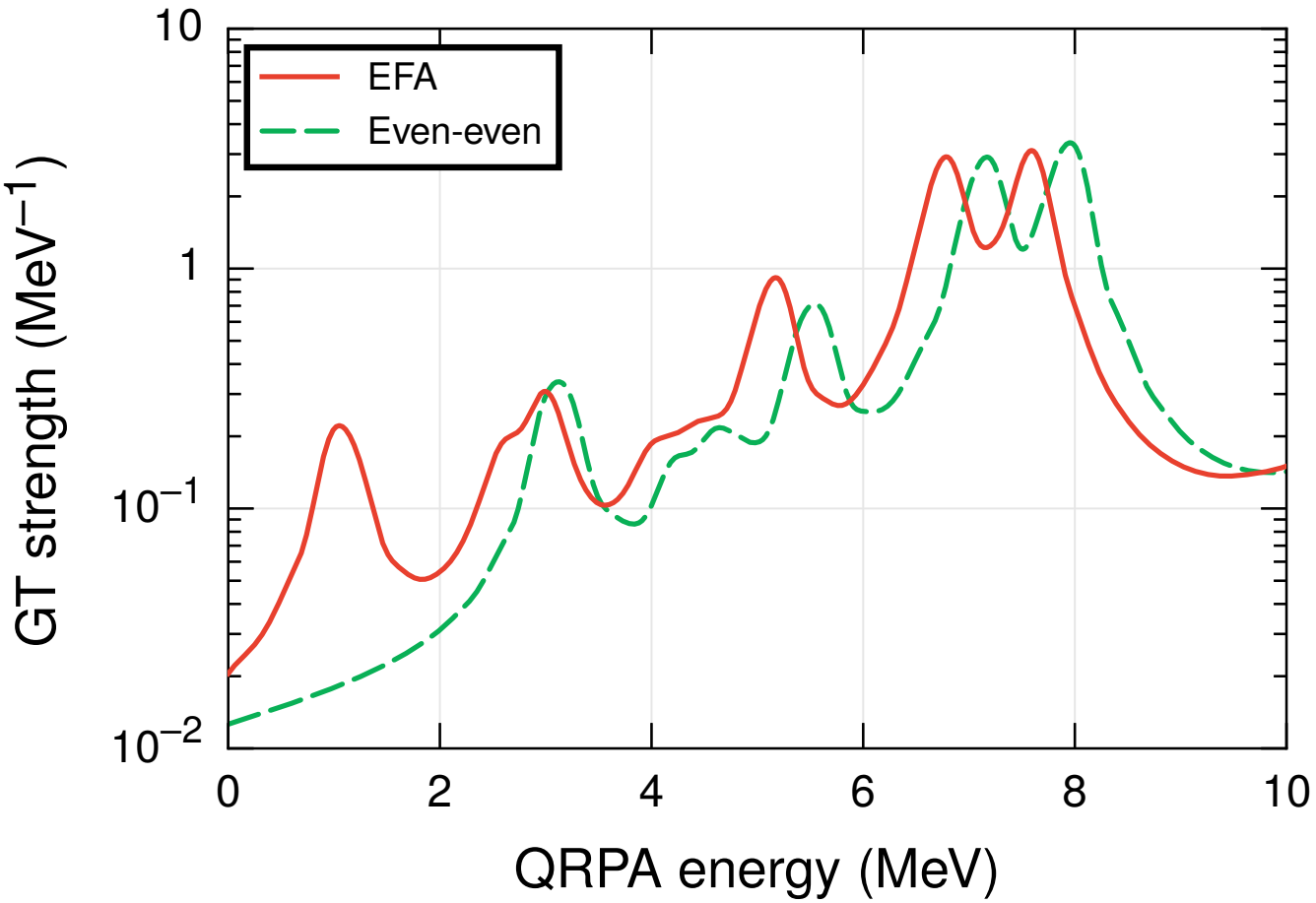




Odd Nuclei

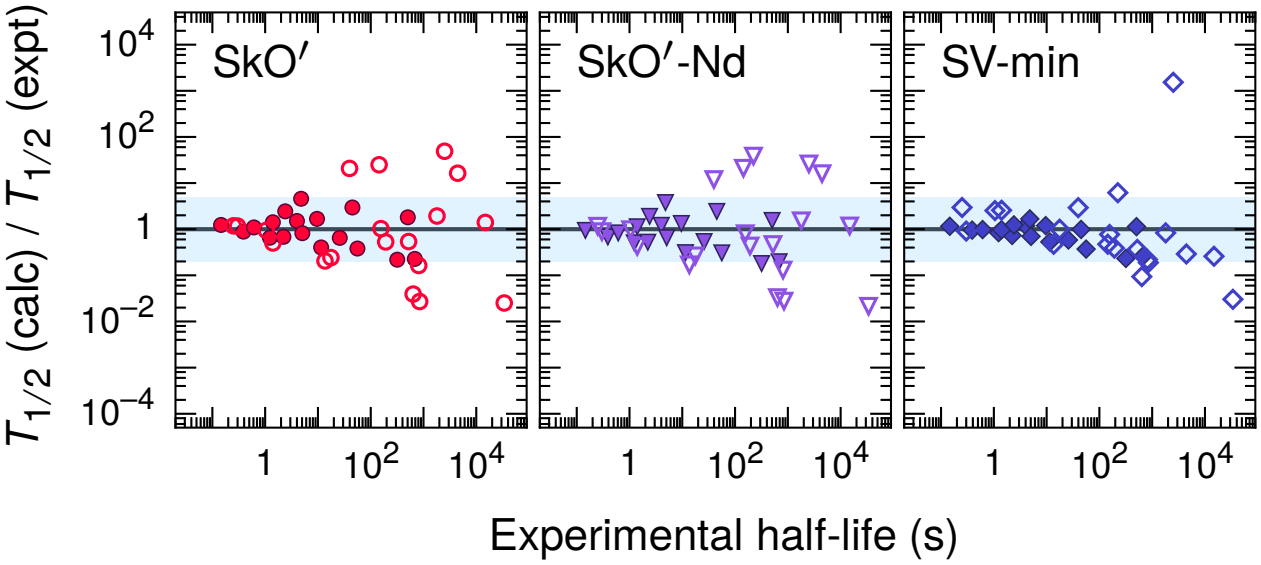
$J \neq 0$, degenerate ground state

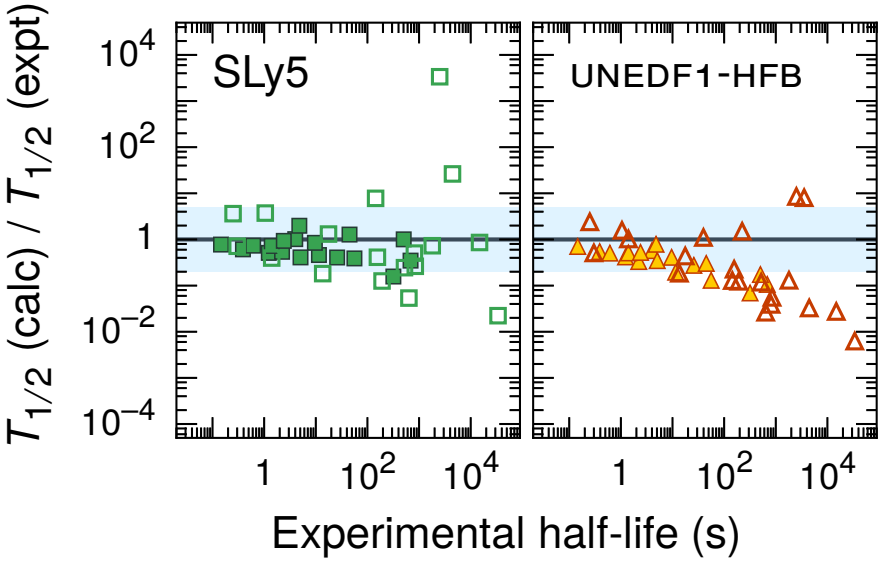
Treat degeneracy as ensemble of state and angular-momentum-flipped partner (equal filling approximation).



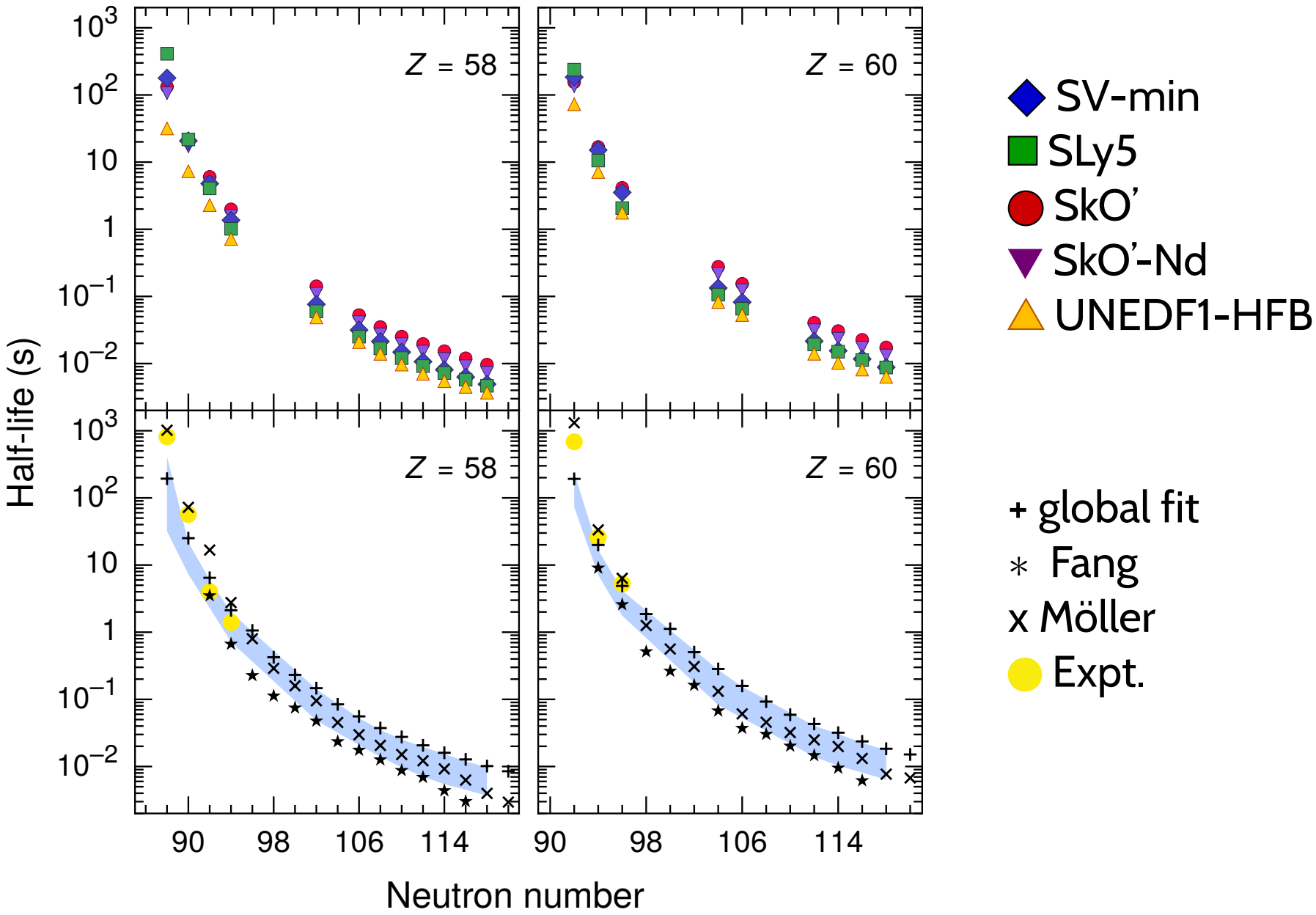
How Do We Do?

Open symbols mean "used in fit"

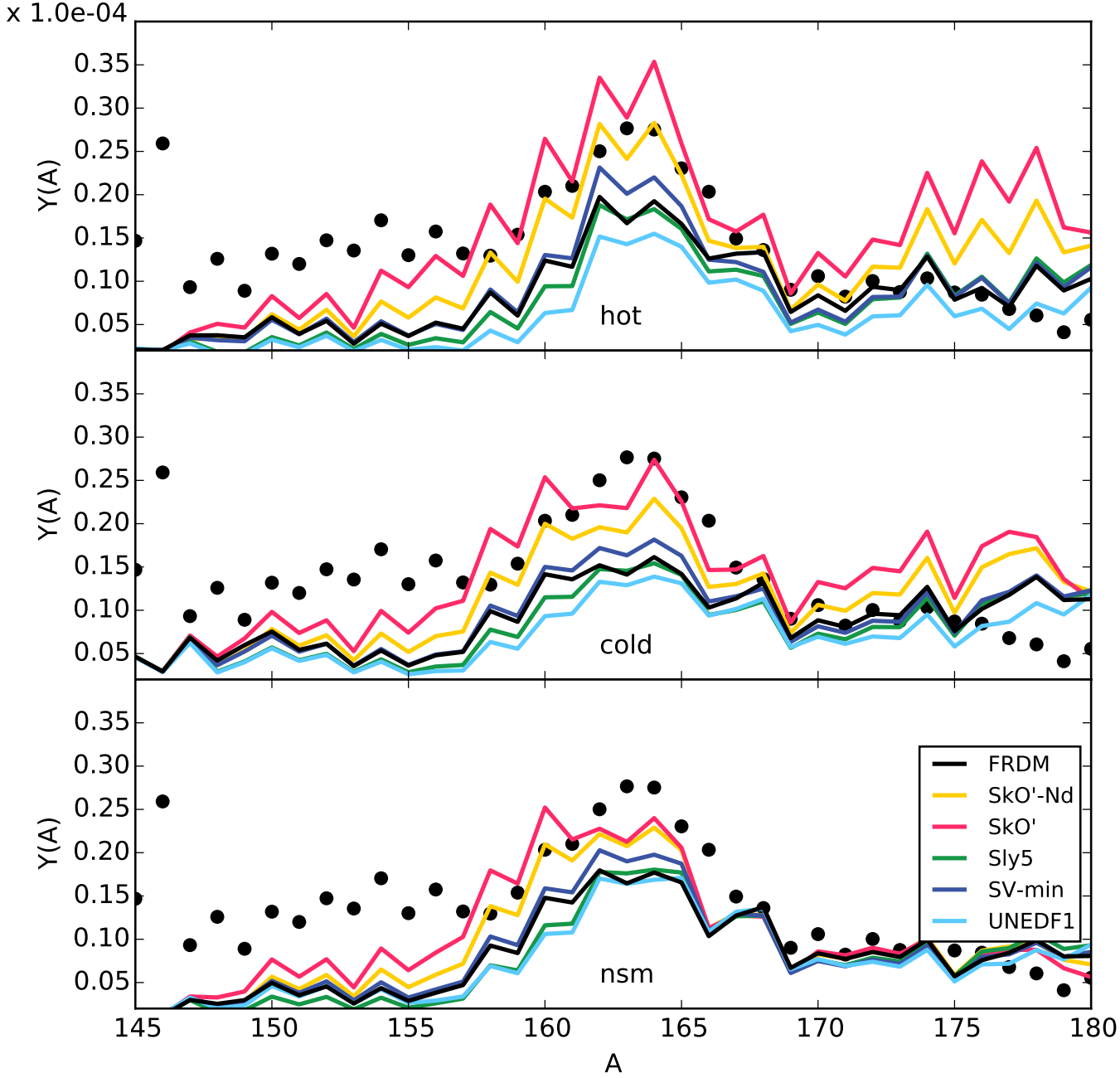




Predicted Half Lives



What's the Effect?



Fast QRPA Allows Global Skyrme Fit

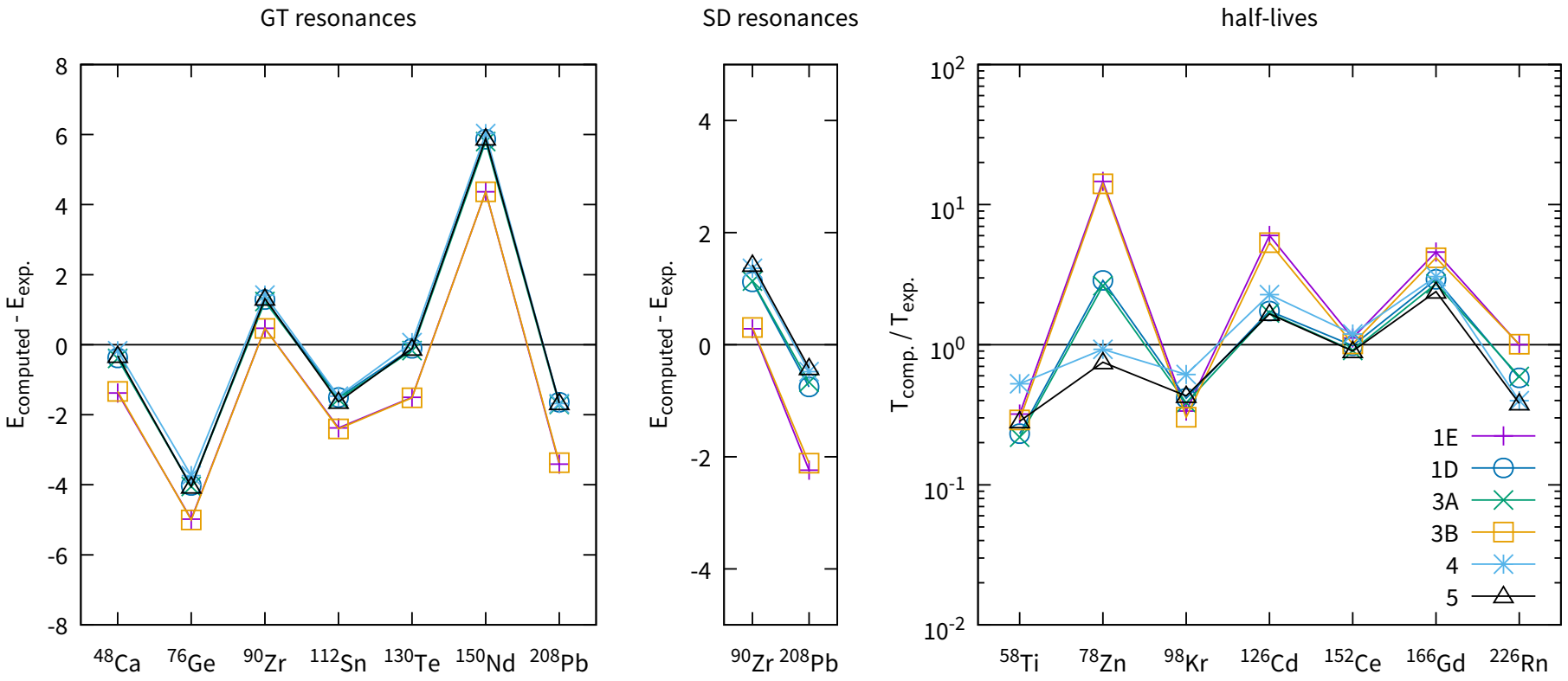
Fit to 7 GT resonance energies, 2 spin-dipole resonance energies, 7 β-decay rates in selected spherical and well-deformed nuclei from light to heavy.

Fast QRPA Allows Global Skyrme Fit

Fit to 7 GT resonance energies, 2 spin-dipole resonance energies, 7 β-decay rates in selected spherical and well-deformed nuclei from light to heavy.

1. Initial two-parameter fit (spin-isospin, isoscalar pairing interactions)
2. Four-parameter fit (add terms with kinetic spin density, kinetic tensor density)
3. Adjust three additional terms with current density and divergence of spin density on top of four-parameter fit

Tried Lots of Combinations of Data/Parameters…

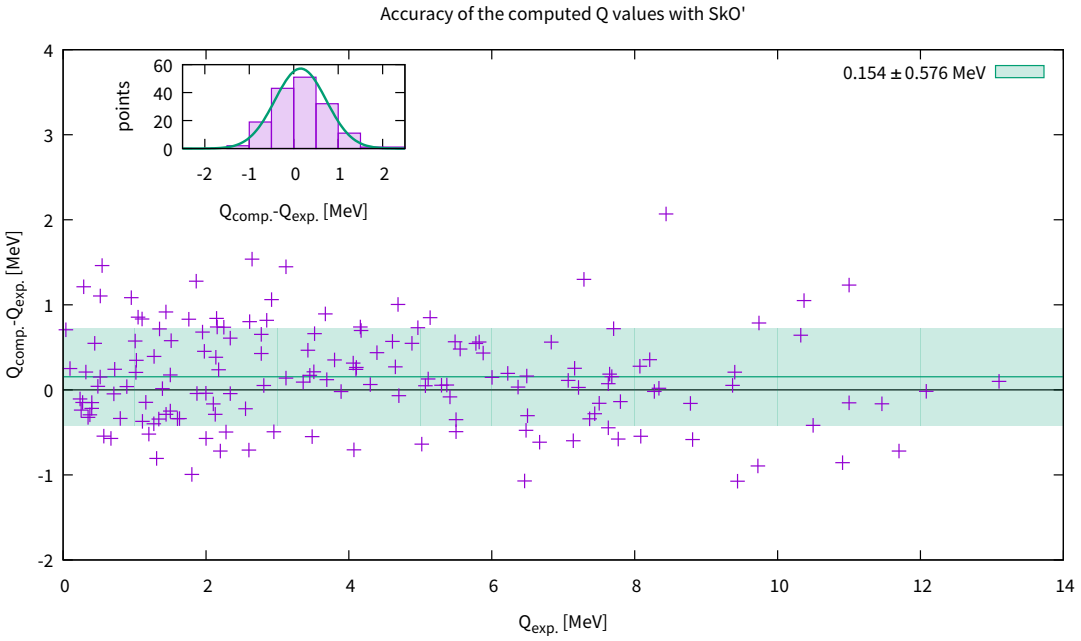


All SkO'

1E = Experimental *Q* values, 2 parameters
3A = Computed *Q* values, 4 parameters
4 = Start with 3A, 3 more parameters

1D = Computed *Q* values, 2 parameters
3A = Experimental *Q* values, 4 parameters
5 = Computed *Q* values, three more parameters

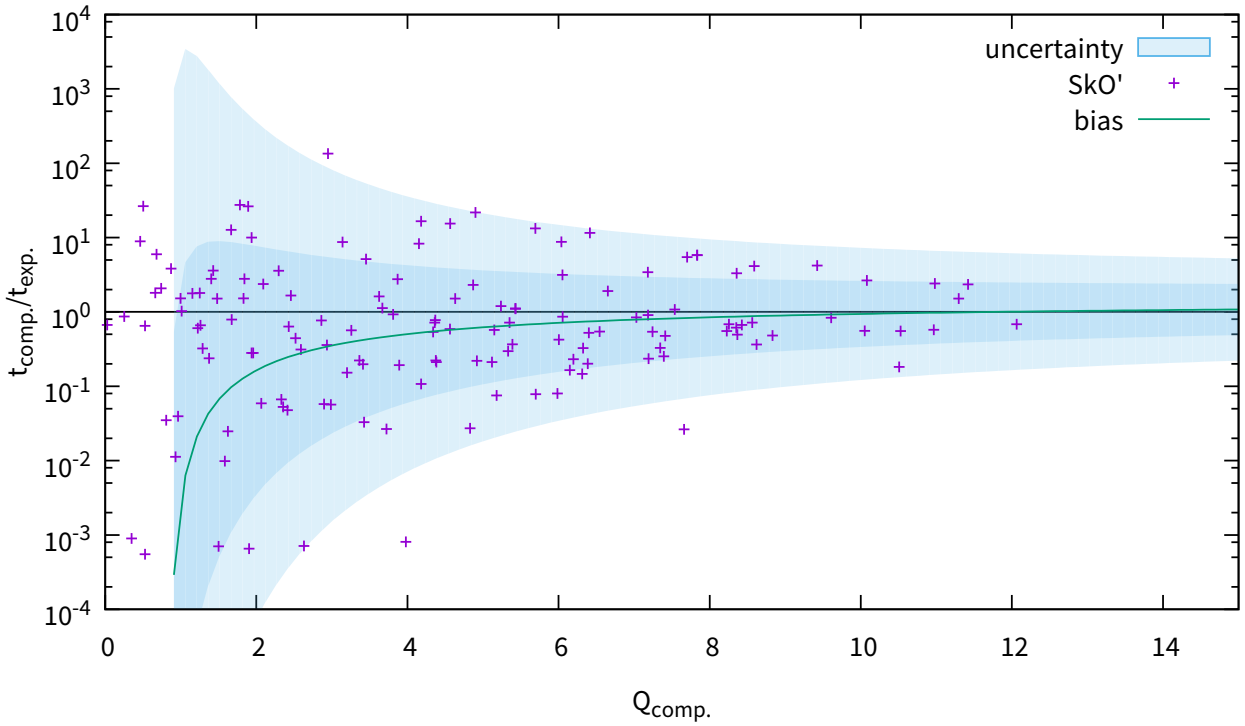
Initial Step: Two Parameters Again



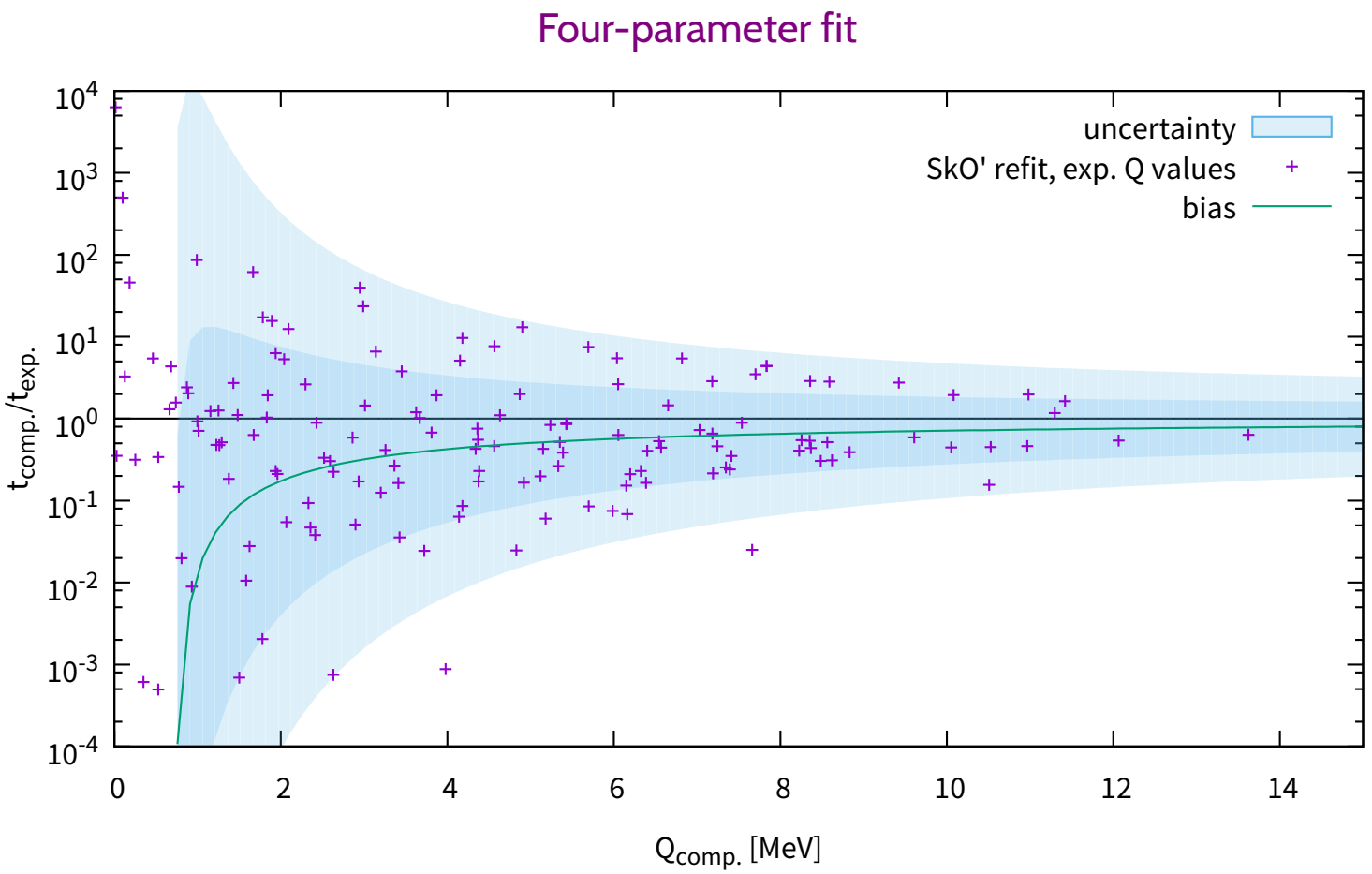
Q values not given perfectly, and β rate roughly $\propto Q^5$.

Adjusted only spin-isospin interaction and isoscalar pairing.

Uncertainty decreases with increasing *Q*.

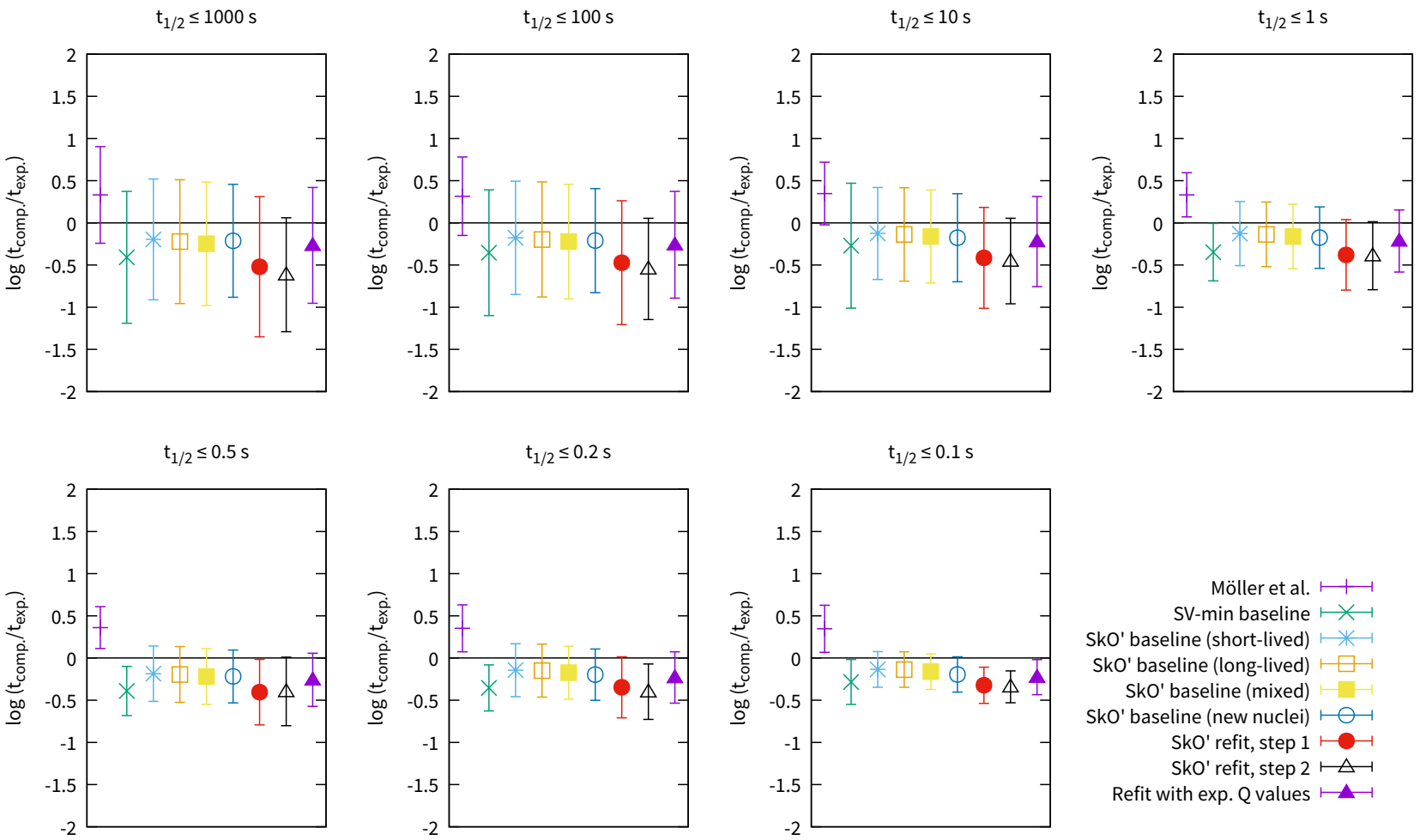


More Parameters



Not significantly better than restricted two-parameter fit.

Summary of Fitting



Meh.... Not doing as well as we had hoped.

Is the QRPA near its limits? We think so.

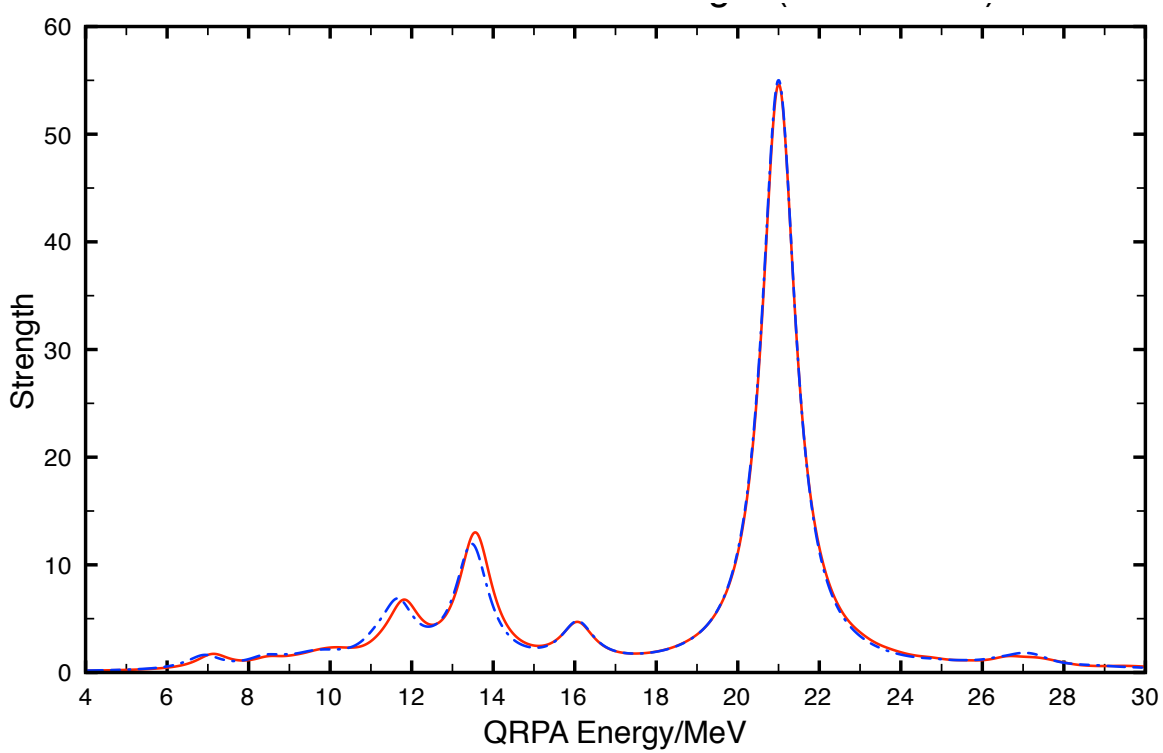
But We Really Care About High-*Q*/Fast Decays

- These are the most important for the *r* process.

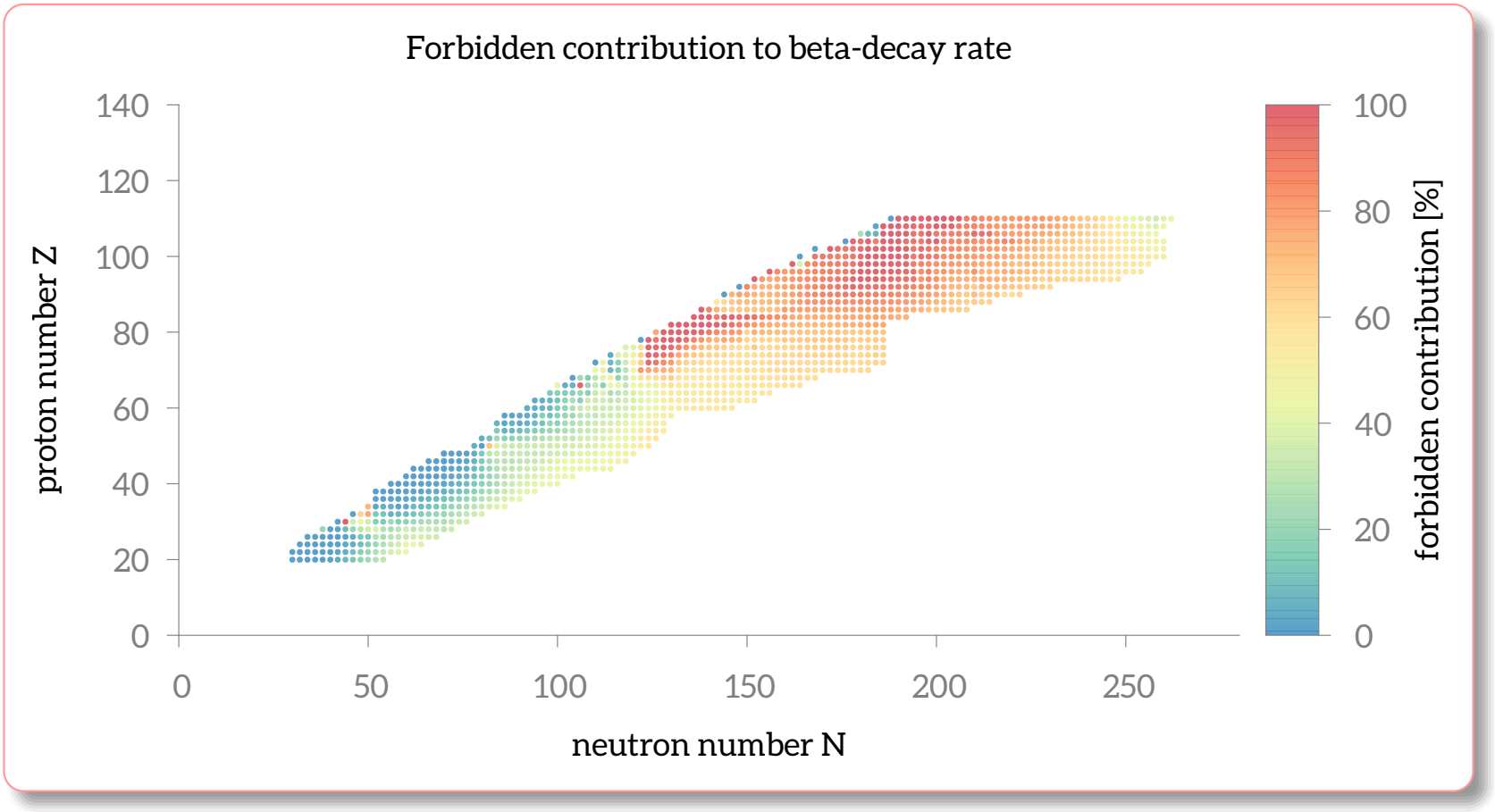
But We Really Care About High-Q/Fast Decays

- These are the most important for the *r* process.
- And they are easier to predict:

$$\frac{(\Delta E + \delta)^5}{(\Delta E)^5} = 1 + 4\frac{\delta}{\Delta E} + \ldots$$



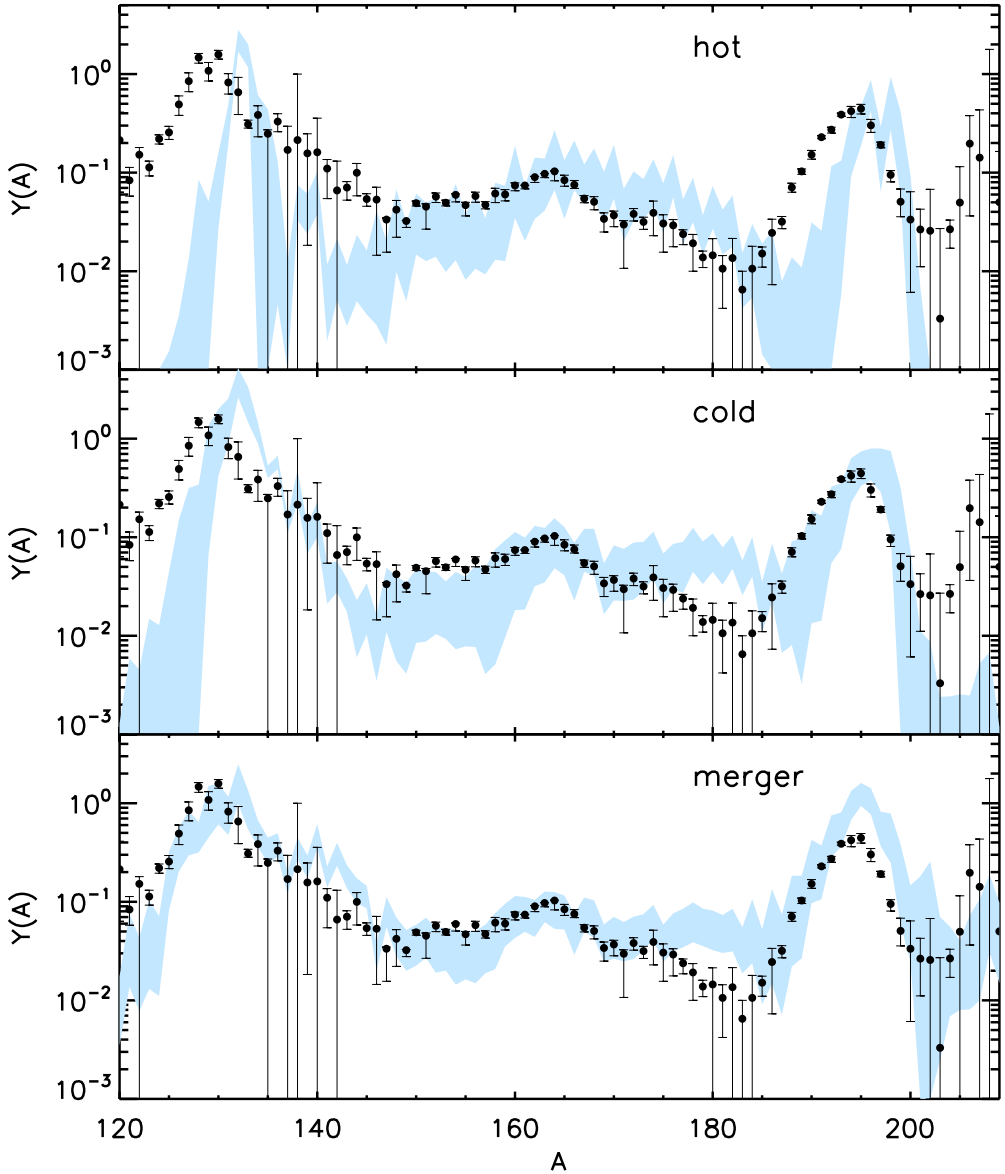
Role of Forbidden Decay



Message: the neutron-rich nuclei usually have significant contributions from both allowed and forbidden operators.

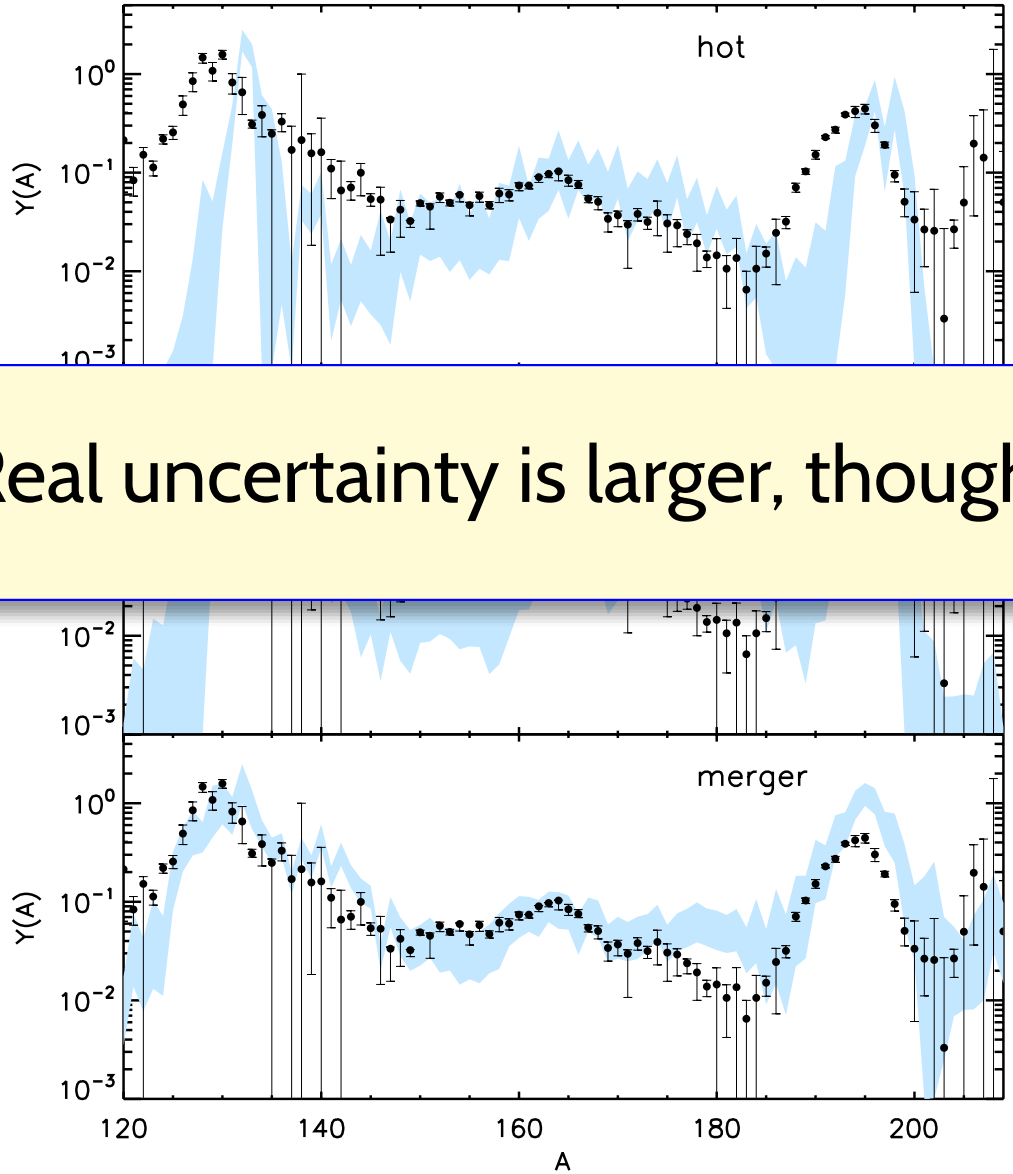
What's at Stake Here?

Significance of Factor-of-Two Uncertainty



What's at Stake Here?

Significance of Factor-of-Two Uncertainty



Real uncertainty is larger, though.

Finally…

Need to go beyond QRPA. With density functionals some conceptual problems arise but they are solvable.

See, e.g., work of E. Litvinova, V. Tselyaev, D. Gambacurta, M. Grasso, etc.

Finally…

Need to go beyond QRPA. With density functionals some conceptual problems arise but they are solvable.

See, e.g., work of E. Litvinova, V. Tselyaev, D. Gambacurta, M. Grasso, etc.

The End

Thanks for your kind attention.