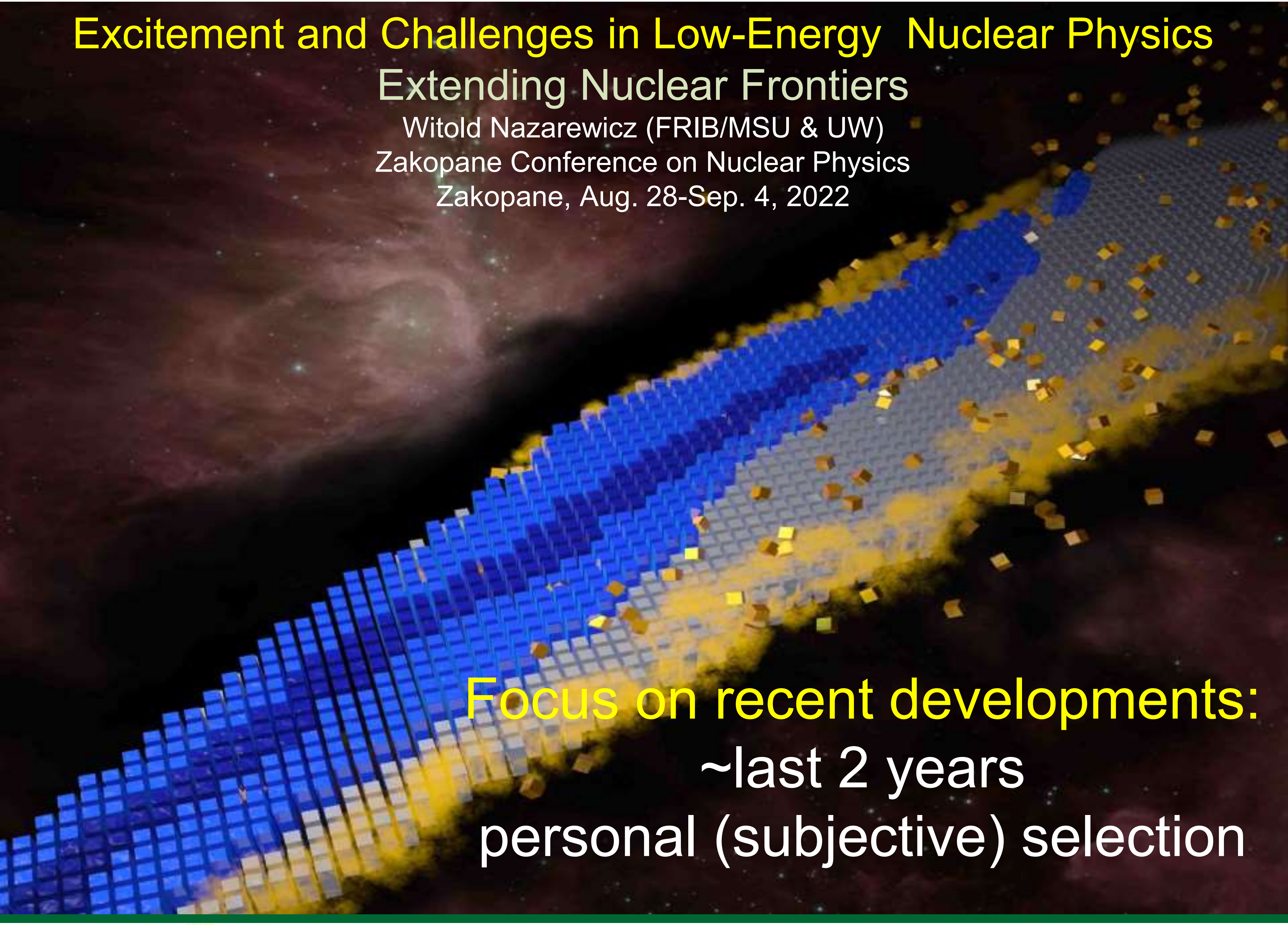


Excitement and Challenges in Low-Energy Nuclear Physics

Extending Nuclear Frontiers

Witold Nazarewicz (FRIB/MSU & UW)

Zakopane Conference on Nuclear Physics

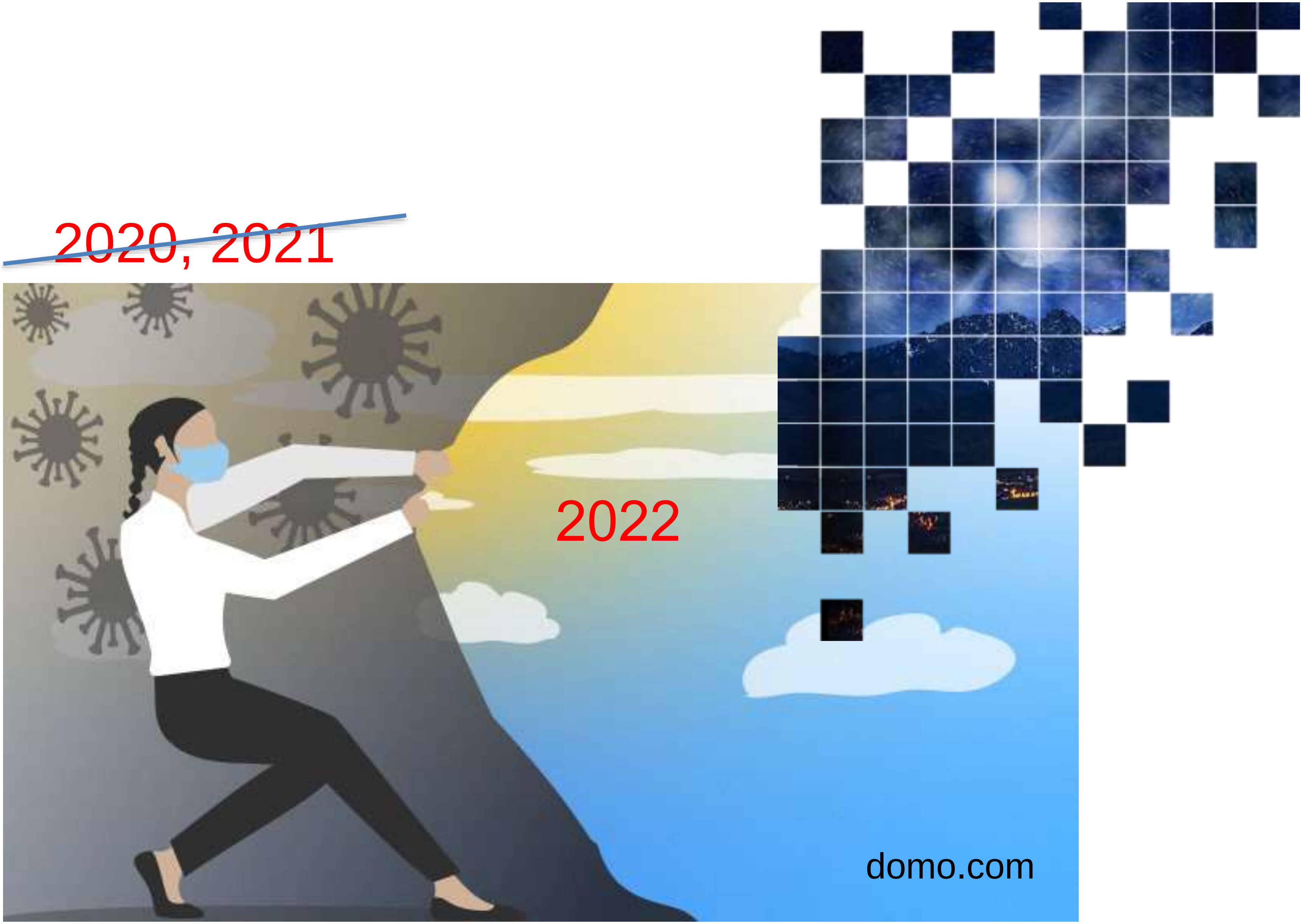
Zakopane, Aug. 28-Sep. 4, 2022

Focus on recent developments:

~last 2 years

personal (subjective) selection

~~2020, 2021~~

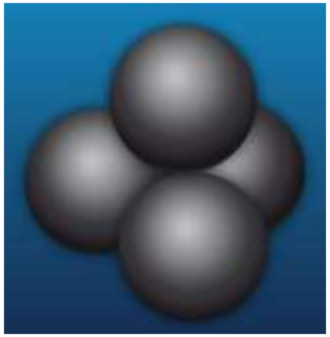


Extremes of the nuclear landscape

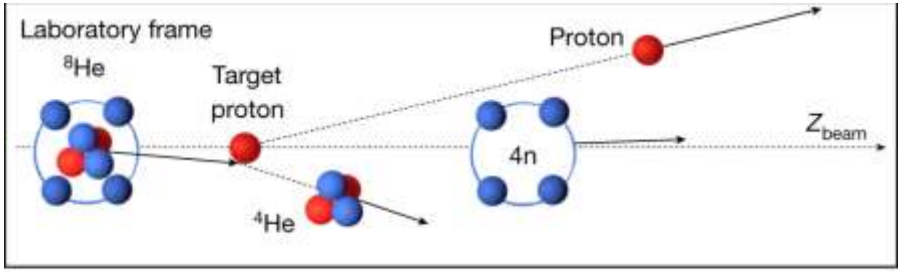
The average time it takes a nucleon to go across a light nucleus (A ≈ 10) and come back can be roughly estimated to be $T_{s.p.} \approx 1.3 \times 10^{-22}$ s (1.3 babysec), and it corresponds to the timescale needed to create the nuclear mean field. Consequently, broad scattering features with $T_{1/2} < T_{s.p.}$ (or $\Gamma > 3.5$ MeV for A ≈ 10) can hardly be interpreted in terms of nuclear states. There is no sharp borderline that separates *bona fide nuclear states* from *broad features* seen in scattering experiments, and this often results in interpretational difficulties.

Search for tetraneutron

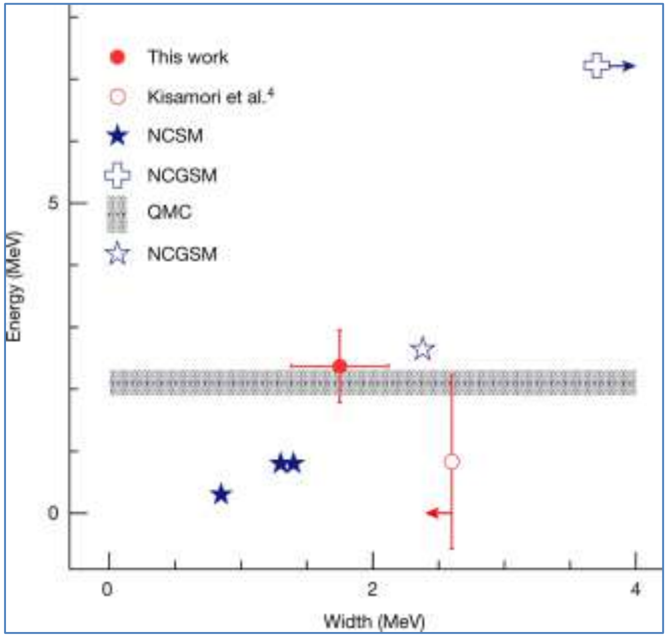
Is ^{4}n a part of the nuclear landscape?



?



Duer et al. Nature 606, 678 (2022)



“So, is the peak observed by Duer *et al.* a resonance? Our honest answer is that we are not convinced that it is — at least, not a resonance of an isolated four-neutron system. However, the work has generated data of high statistical significance on pure, or nearly pure, neutron systems that researchers must now try to understand using theory that models the full many-body problem.”

Sobotka and Piarulli, Nature 606, 656 (2022)

A tetraneutron resonance cannot exist:

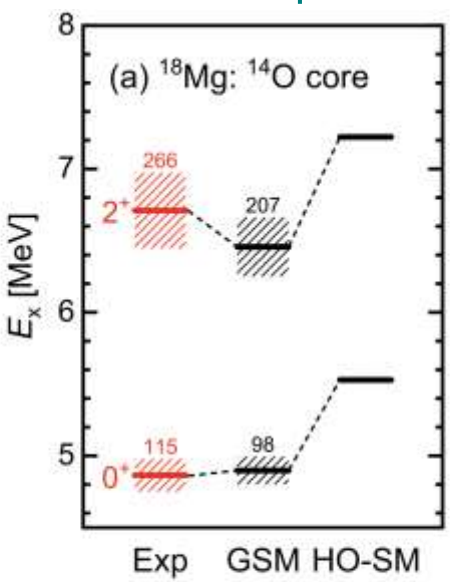
- Deltuva, Phys. Lett. B 782, 238–241 (2018)
- Higgins et al., Phys. Rev. Lett. 125, 052501 (2020)
- Lazauskas et al. arXiv 2207.07575 (2n+2n channel essential)

Extreme proton-unbound exotica

Four-Proton unbound ^{18}Mg

Jin et al. Phys. Rev. Lett. 127, 262502 (2021)

12p+8n

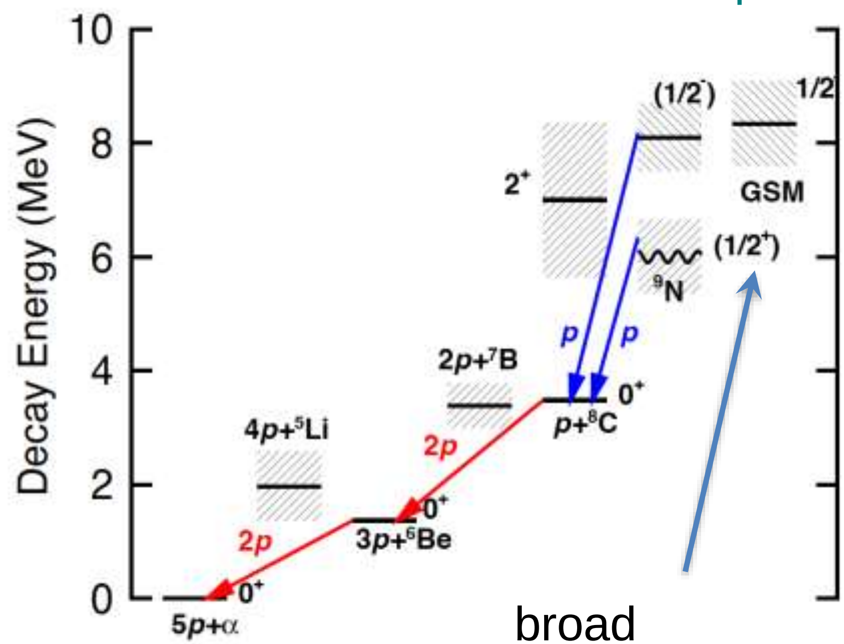


two sequential 2p decays

Structure of ^{8}C and ^{9}N

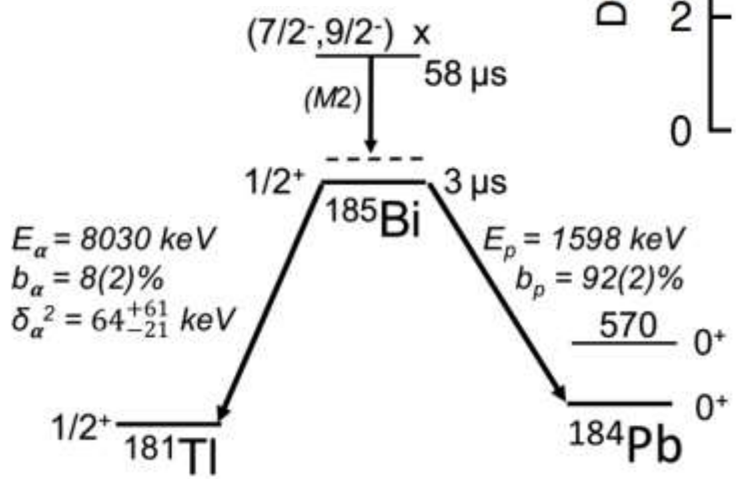
Charity et al. (2022)

7p+2n



broad resonant state

Heaviest proton emitter ^{185}Bi



Doherty et al., Phys. Rev. Lett. 127, 202501 (2021)

Does g.s. of ^{9}N (mirror to ^{9}He) belong to the nuclear landscape?

Witkacy. Seismograph of the age of acceleration (National Museum, Warsaw)

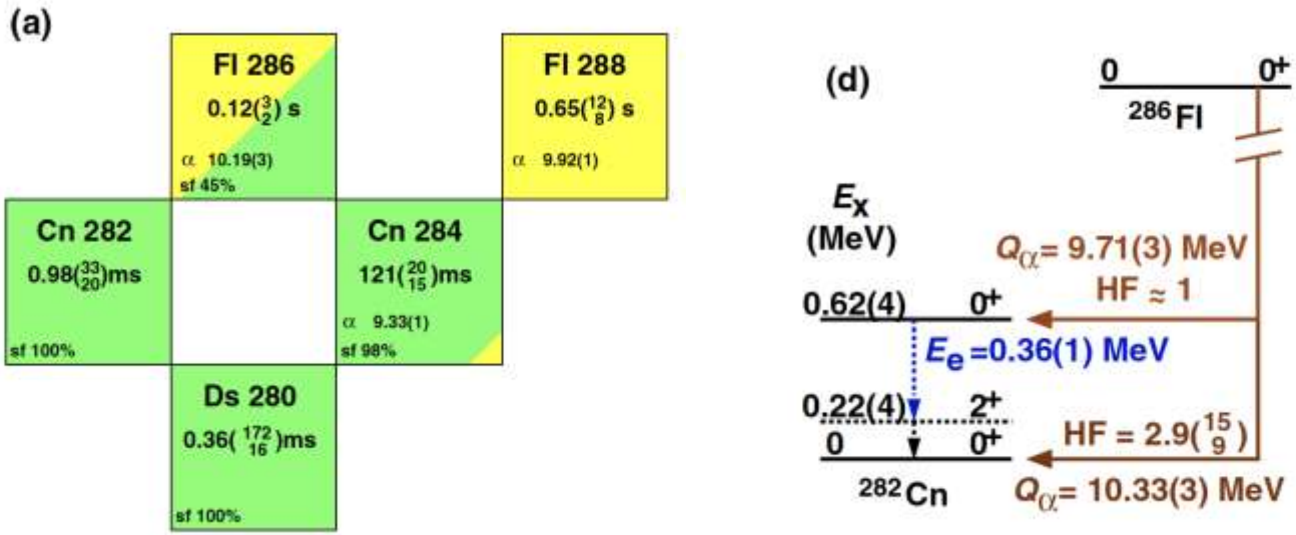
The comprehensive exhibition devoted to the work of Stanisław Ignacy Witkiewicz: a versatile artist, philosopher, writer, and keen critic of civilization.

Nitrogen, Phosphorus, and Arsenic, 1918

Muzeum Tatrzańskie

Spectroscopy along flerovium decay chains

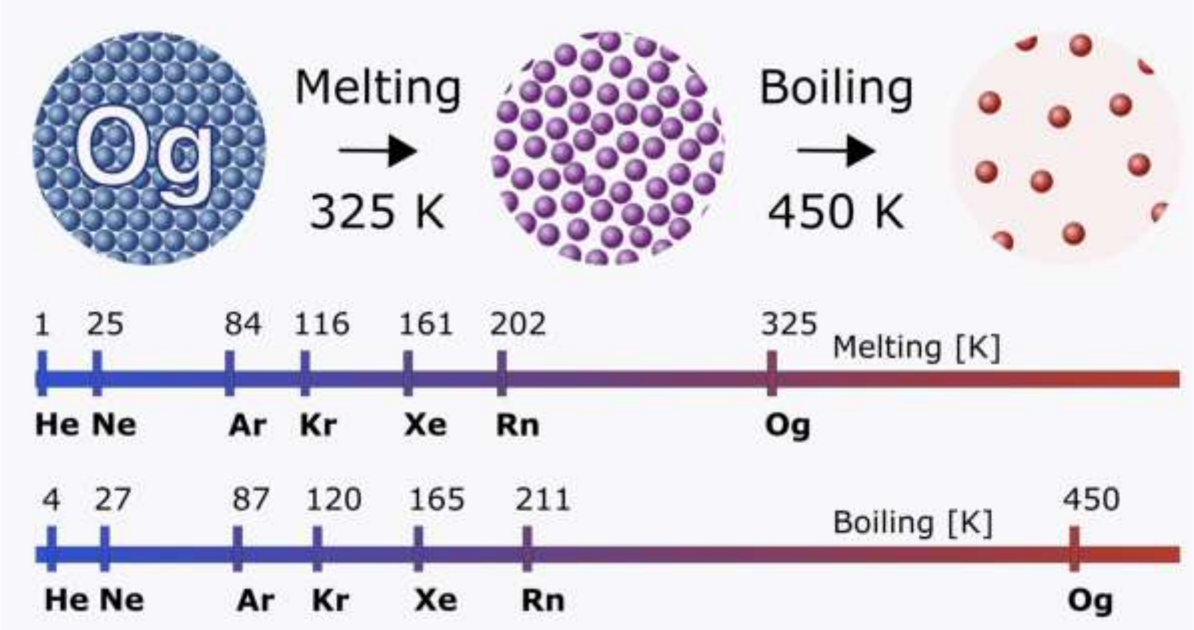
Såmark-Roth et al., Phys. Rev. Lett. 126, 032503 (2021)



- Spectroscopic quality spectra provide detailed insight into structure of nuclei around proton number Z=114: no pronounced Z=114 shell gap at N=174. (not surprising…)
- Discovery of the new isotope ^{280}Ds.
- An excited state observed in ^{282}Cn, marking the experimental reach of detailed spectroscopy of the heaviest elements.

The periodic table and the physics that drives it, Schwerdtfeger, Smits, and Pyykkö, Nature Reviews Chemistry 4, 359 (2020)

Smits et al., Angew. Chem. Int. (2020)

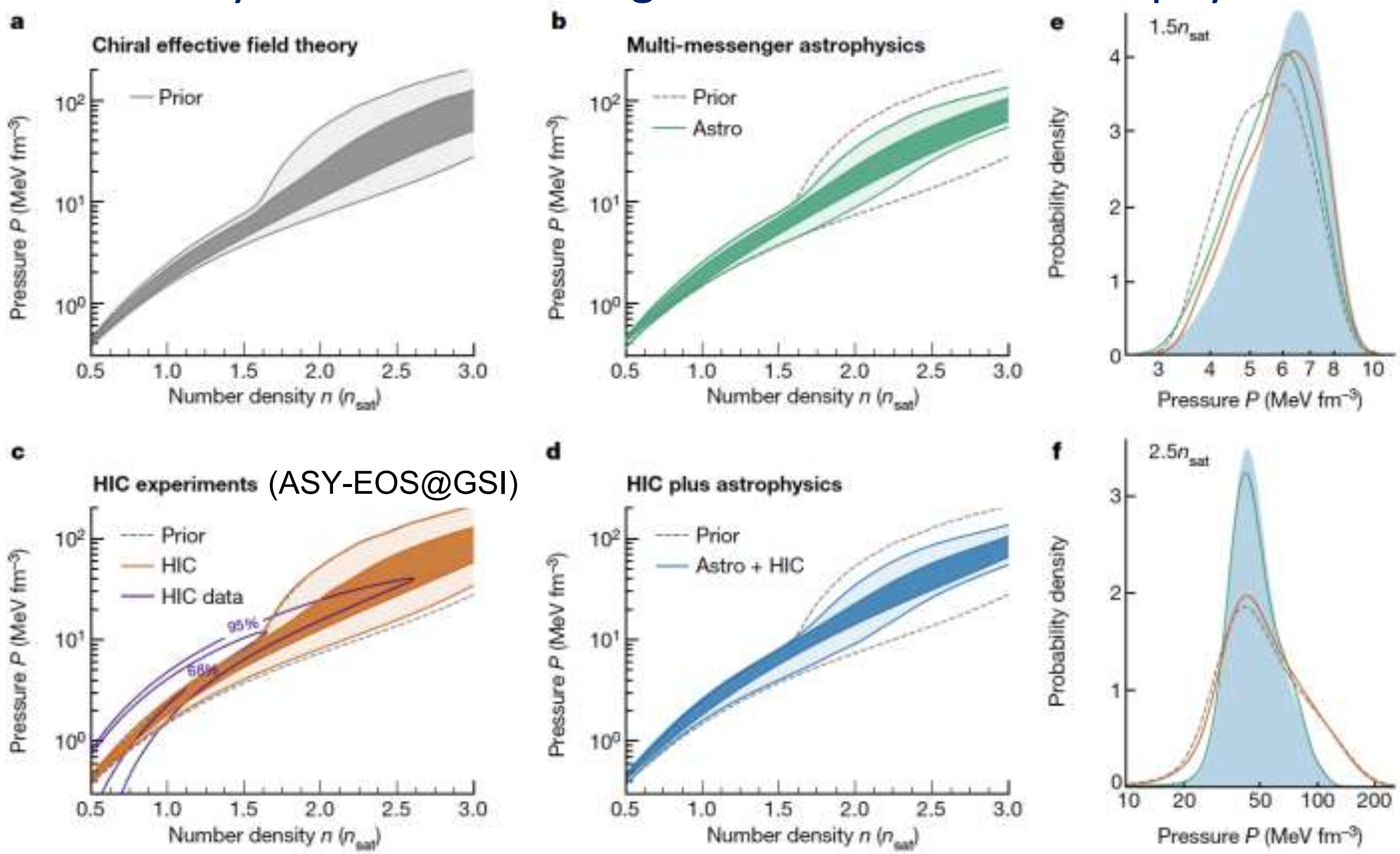


Two complementary state-of-the-art approaches reveal that Og is a solid at ambient conditions. With predicted melting and boiling points of 325K and 450K, is not particularly volatile. Og is calculated to be a semiconductor in room temperature.

Copernicium: A relativistic noble liquid: Mewes et al., Angew. Chem. Int. 58, 17964 (2019)

Equation of state of nuclear matter

Many studies combining nuclear data and astrophysical observations



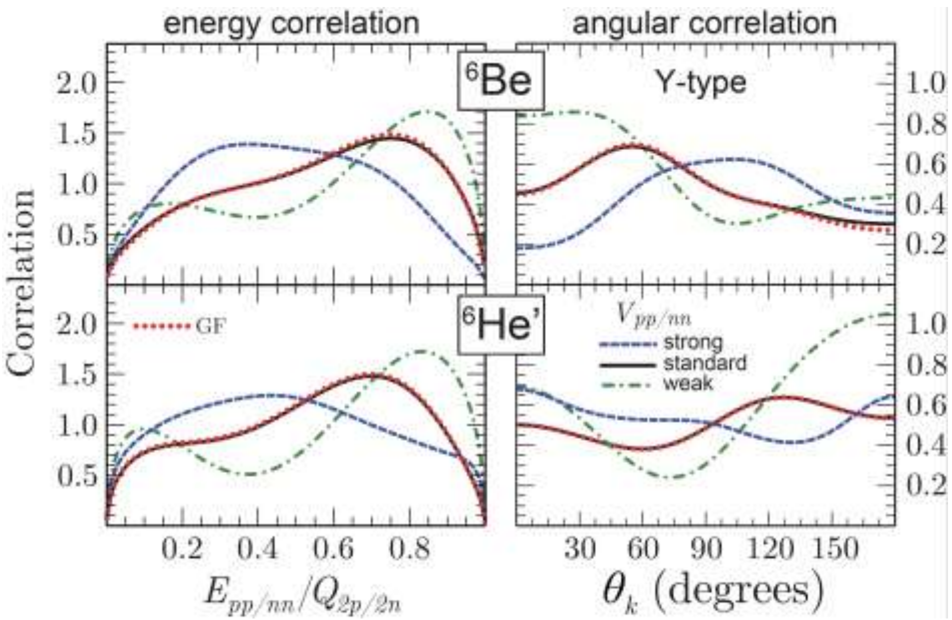
Huth et al. Nature 606, 276 (2022)

"At high temperatures and very large densities, quarks are expected to transition from being bound to a phase in which they can move freely. Such effects are relevant for neutron-star merger simulations, but they are not included in Huth and colleagues' study. This key question in nuclear astrophysics research is thus left unanswered — as is the role of other types of exotic nuclear matter. However, with the advent of new experimental data in nuclear and gravitational-wave physics, answers might finally be on the horizon." (Noronha, Nature 606, 258 (2022))

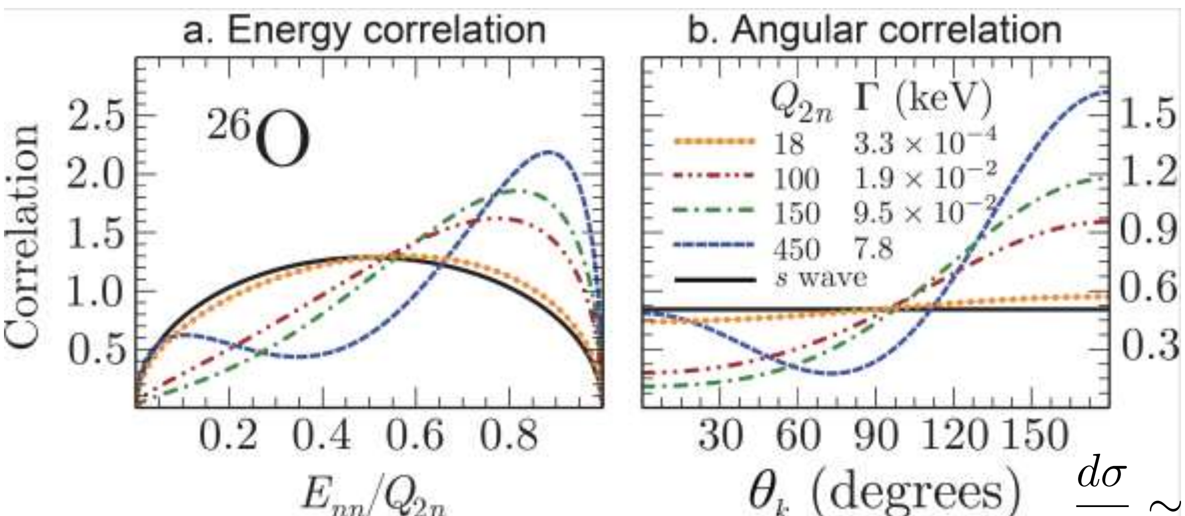
Open quantum systems

Two-nucleon correlations using real-time propagation

Wang et al. Phys. Rev. Lett. 126, 142501 (2021) and J. Phys. G (L) arXiv:2108.08007



- The energy and angular correlations in the Jacobi-Y angle between emitted nucleons strongly depend on the initial-state structure and final-state interactions.
- The correlations between emitted nucleons provide invaluable information on the dinucleon structure in the initial state!

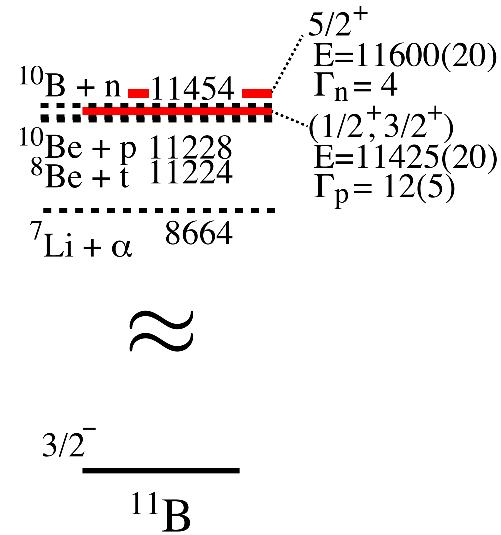


universal phase-space limit:

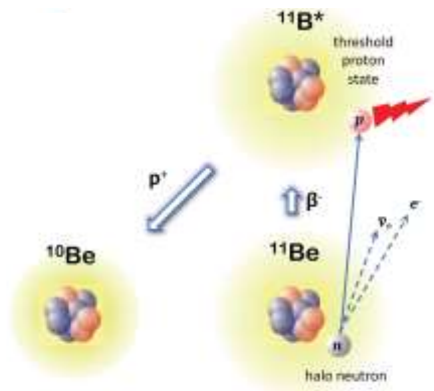
$$\frac{d\sigma}{d\varepsilon} \sim \sqrt{\varepsilon(1-\varepsilon)} \quad \text{with} \quad \varepsilon = E_{nn}/Q_{2n}$$

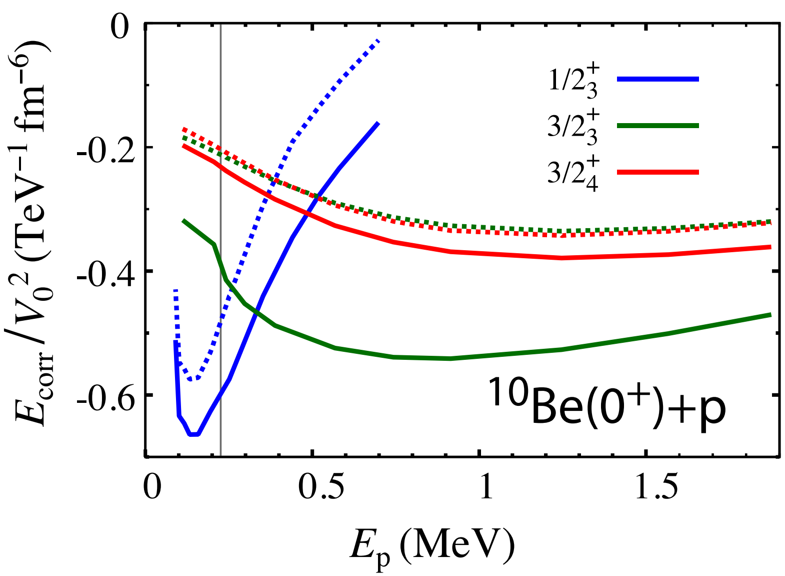
Near-Threshold Proton-Emitting Resonance in ^{11}B

Experiment: Ayyad et al., Phys. Rev. Lett. 123, 082501 (2019); Ayyad et al., Phys. Rev. Lett. 129, 012501 (2022); Lopez-Saavedra et al., Phys. Rev. Lett. 129, 012502 (2022)



β^--delayed proton decay of a neutron-rich nucleus! (predicted 2001-2013)





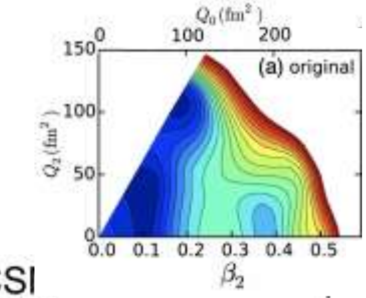
Theory (SMEC): Okołowicz et al., Phys. Rev. Lett. 124, 042502 (2020); arXiv:2112.05622; (SM) Volya, Europhys. Lett. 130, 12001 (2020); (ab-initio) Atkinson et al., Phys. Rev. C 105, 054316 (2022).

Astro relevance: Sieverding et al., Phys. Rev. C 106, 015803 (2022).

b_r(□−□),Γ_p(1/2+), and EM transitions in ^{11}B consistently described but tension between b_r(□−□)) and Γ_p(1/2+) and b_r(□−p)

Complex nuclei

Shape coexistence in ^{64}Ni



Mărginean et al., Phys. Rev. Lett. 125, 102502 (2020)
79 co-authors from 25 institutions!

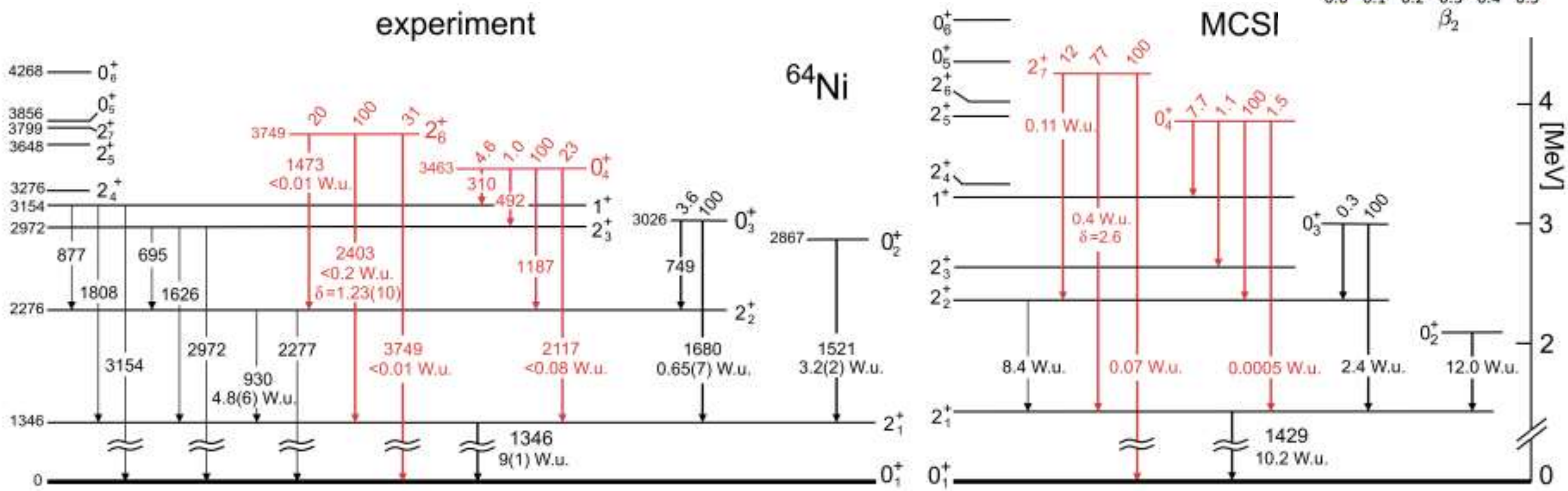


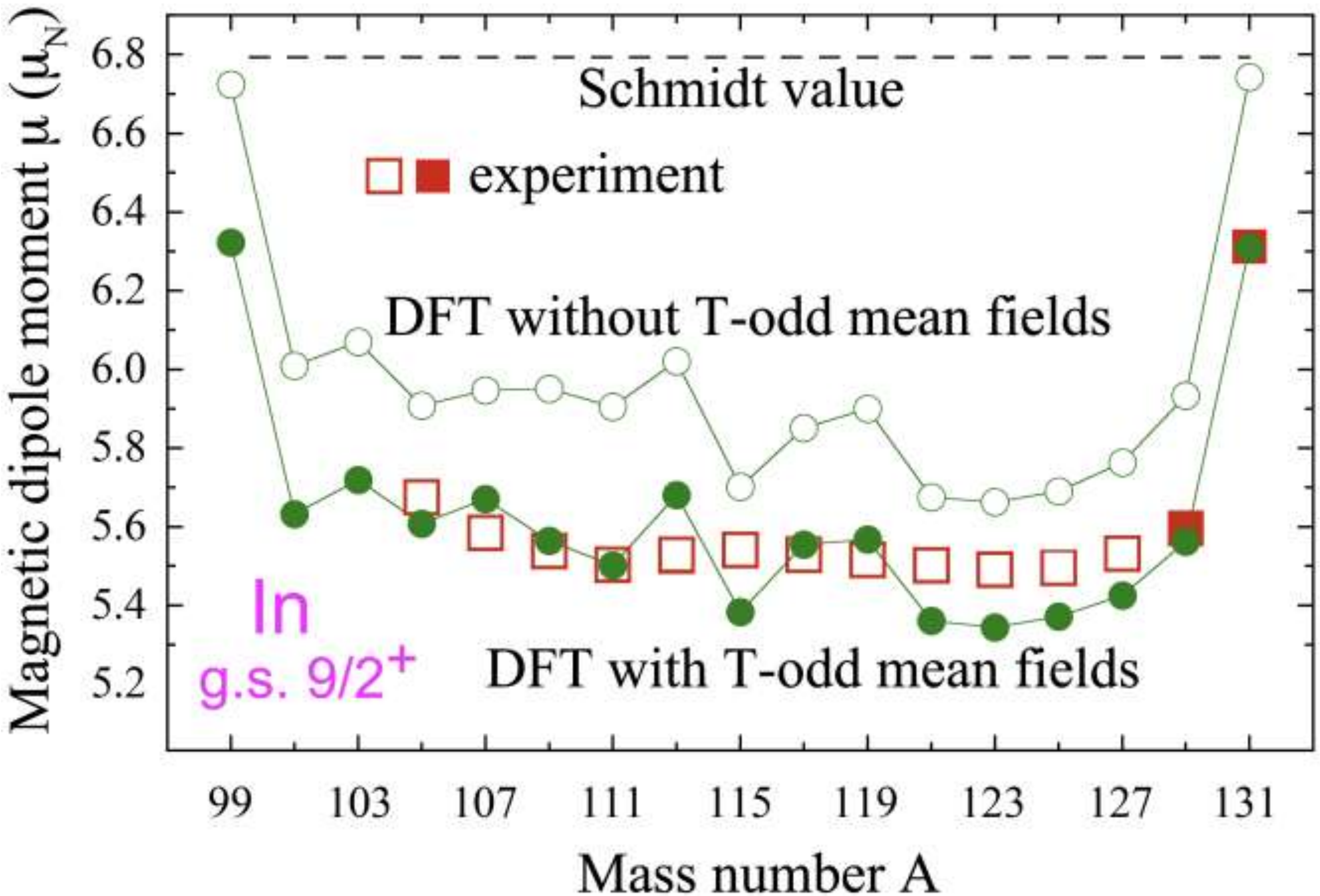
FIG. 3. Data (left) and MCSM calculations (right) for ^{64}Ni level properties derived in this work. Transition strengths are from CE, branchings and mixing ratios from neutron capture. In red, decays from prolate structures.

To achieve the required experimental sensitivity, four experiments, i.e., transfer reactions, neutron capture, Coulomb excitation, and nuclear resonance fluorescence, had to be carried out at the IFIN-HH Tandem Laboratory (Bucharest, Romania), the Institut Laue-Langevin (ILL, Grenoble, France), the Argonne National Laboratory (ANL, Argonne, U.S.), and the Triangle Universities Nuclear Laboratory (TUNL, Duke University, U.S.), respectively. + Theory

Nuclear moments

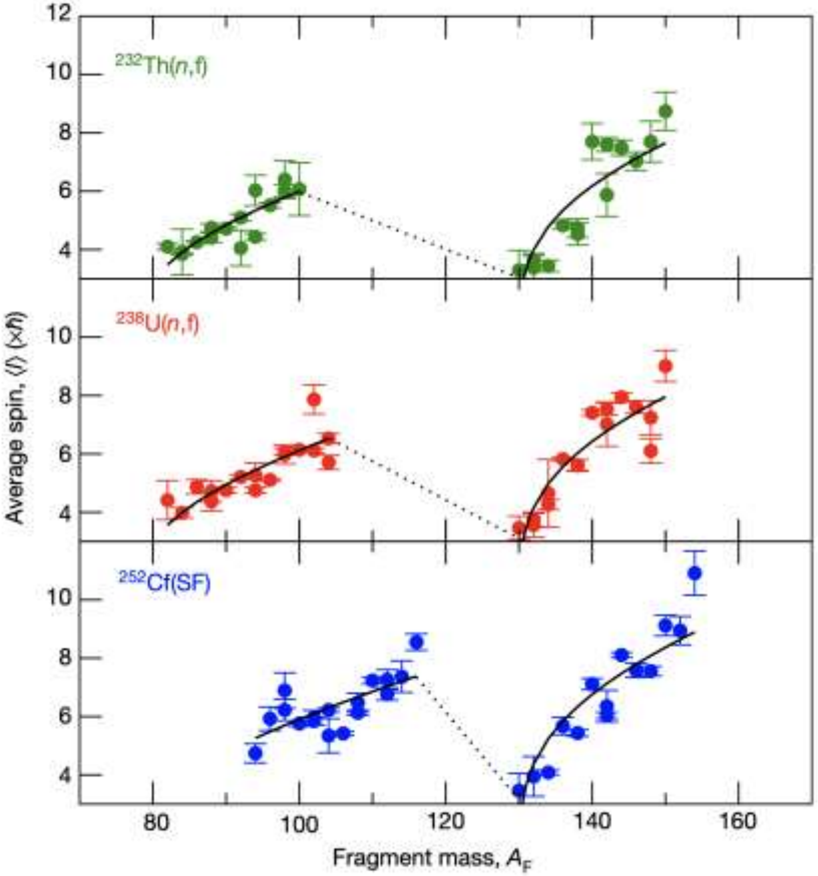
Precision laser spectroscopy measurements

Vernon et al. Nature 607, 260 (2022)



No effective g-factors needed in (no core) DFT calculations!

- Importance of polarization effects
- Other examples include quadupole charges, isospin mixing

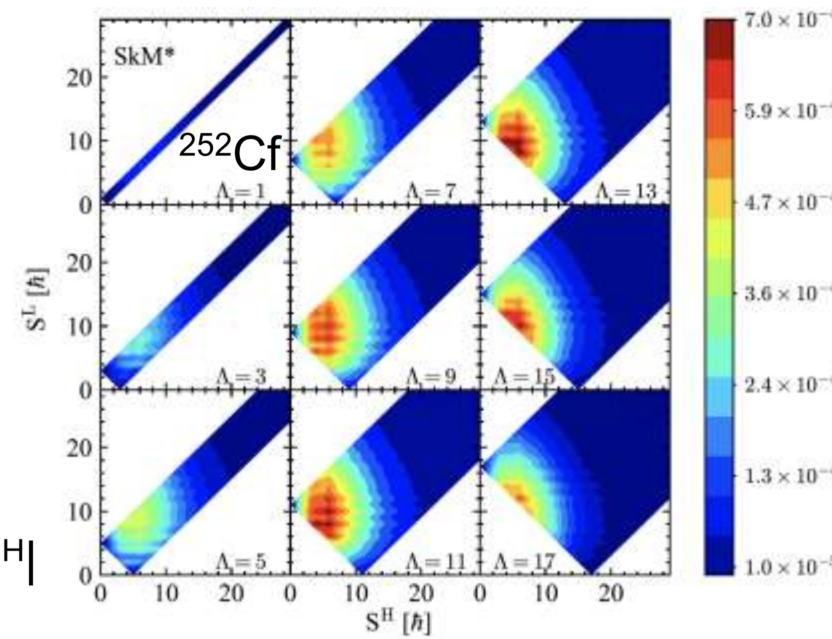


Angular momentum of fission fragments

Wilson et al., Nature 590, 566 (2021)

No notable dependence of fragment spin on the mass or charge of the partner nucleus. Does it indicate the uncorrelated post-scission nature of the spin mechanism?

Statistical model FREYA: Randrup and Vogt, Phys. Rev. Lett. 127, 062502 (2021)



Nuclear Fission with TDDFT

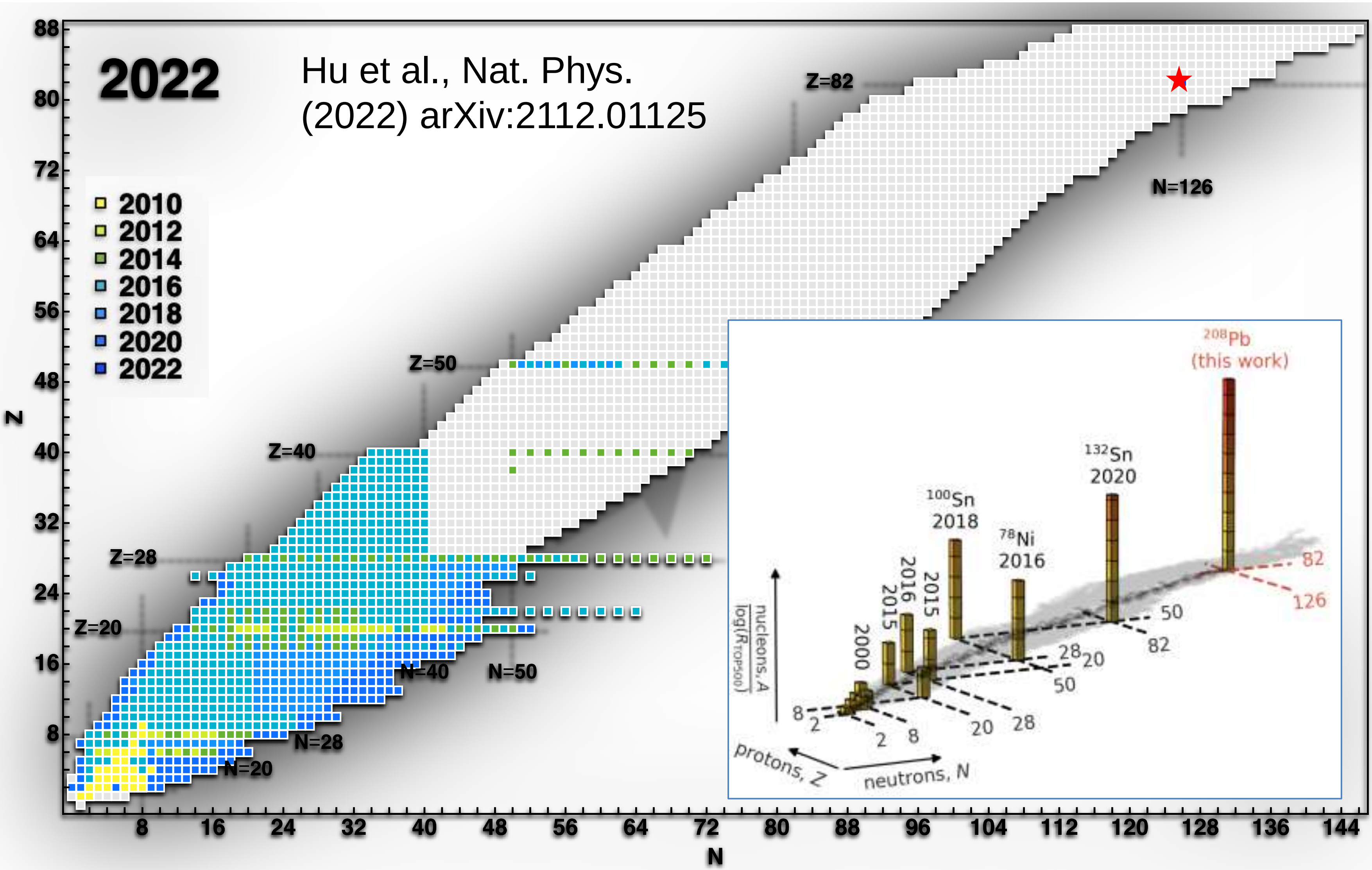
Bulgac et al. Phys. Rev. Lett. 128, 022501 (2022)

$$\boldsymbol{S}^L + \boldsymbol{S}^H + \boldsymbol{\Lambda} = 0$$

Probability distribution $P(\Lambda; S^L; S^H)$. distribution vanishes outside the region $|S^L - S^H| \leq \Lambda \leq |S^L + S^H|$ marked white

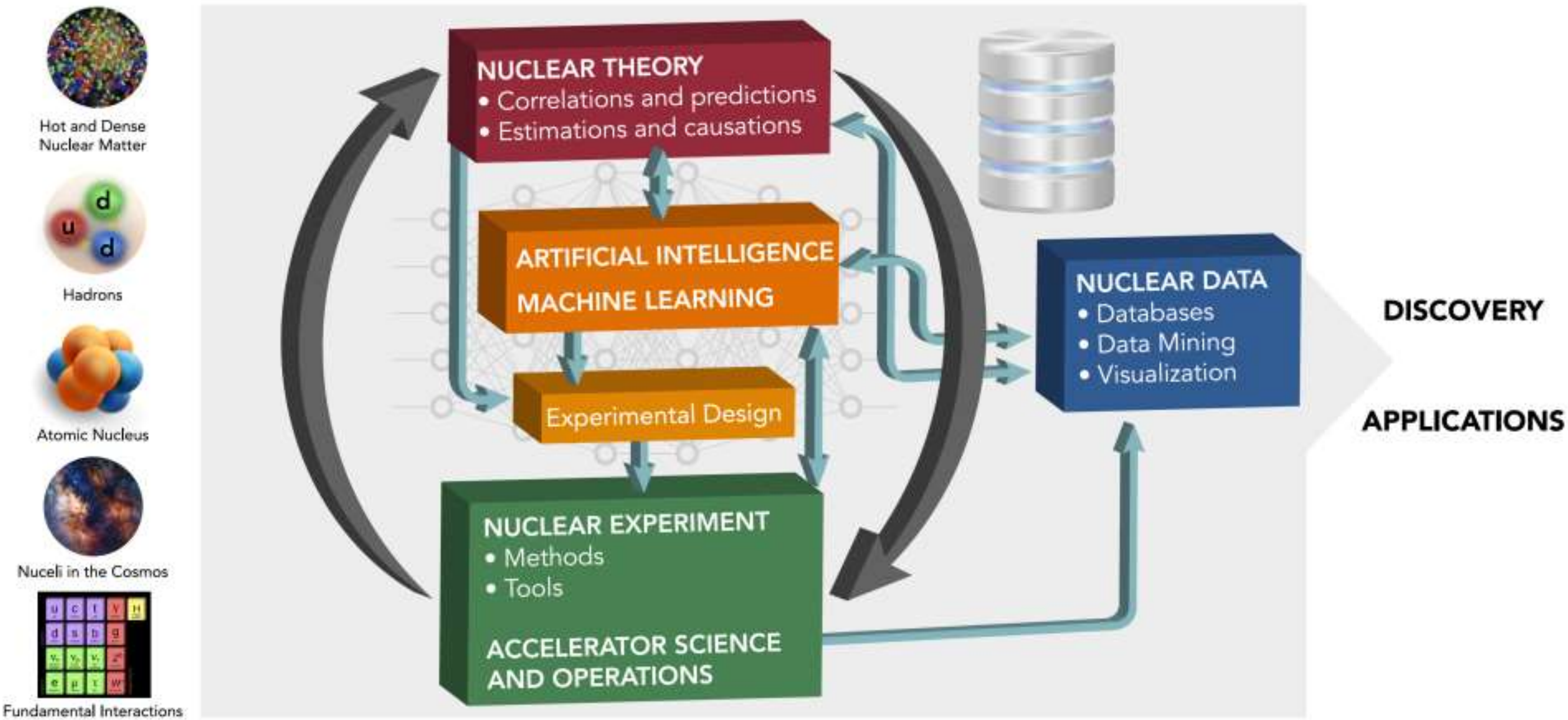
High performance Computing
Machine Learning

How to solve the nuclear many-body problem precisely?



Nuclei from NN+NNN interactions: CC and IM-SRG

Machine learning in nuclear physics

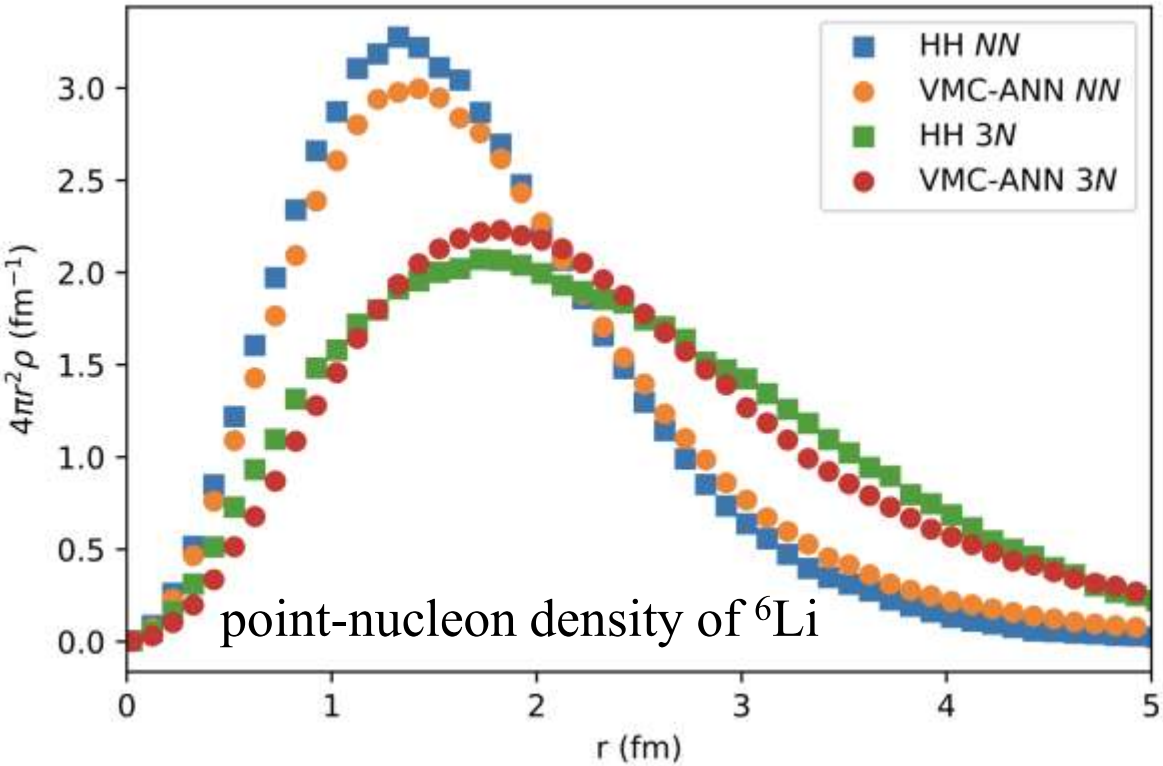


A. Boehnlein et al., Rev. Mod. Phys. in press; arXiv:2112.02309

ML helps speeding-up the cycle of the scientific method

Variational Monte Carlo calculations of A ≤ 6 nuclei Artificial Neural Networks: Adams et al., Phys. Rev. Lett. 127, 022502 (2021); Gnech et al. Few Body Systems 63, 7 (2022)

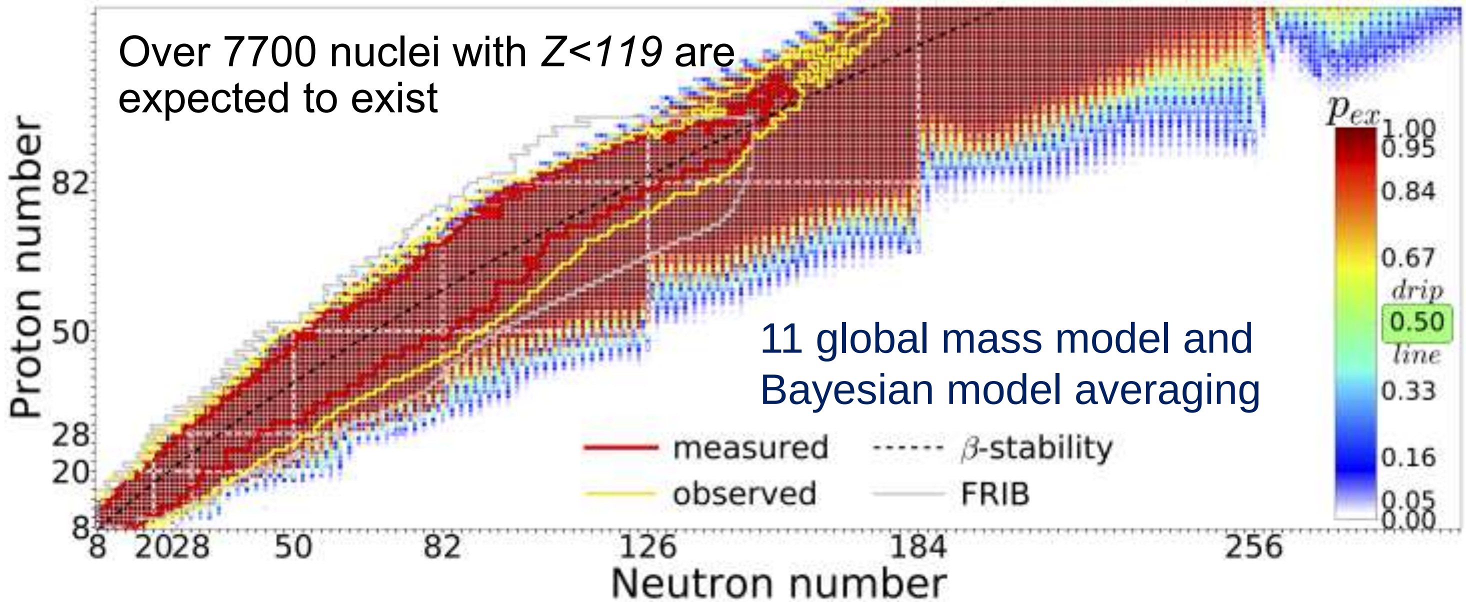
Leading order pionless EFT NN+NNN Hamiltonian

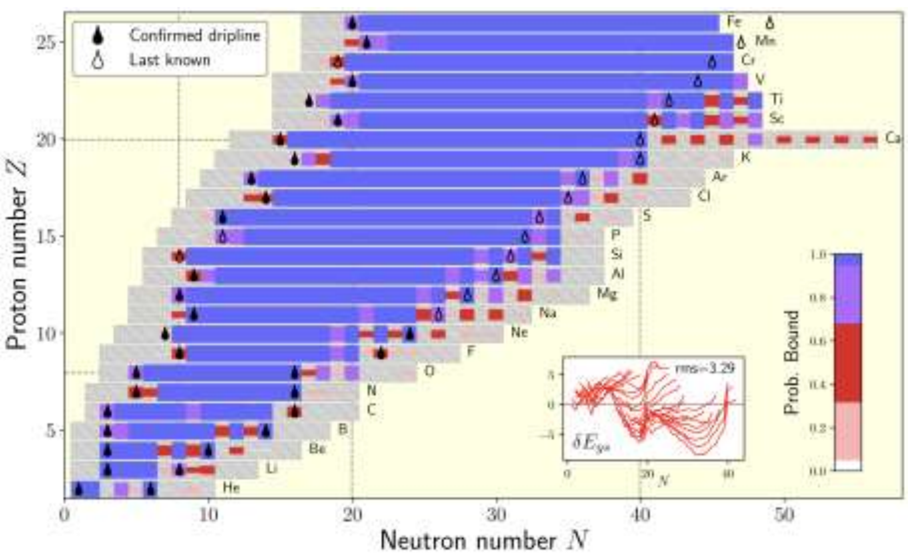


- VMC+ANN scaling for NN+3N is A^6; HH scaling is factorial
- Hidden-nucleon, neural-network ansatz arXiv: 2206.1002 very promising

Quantified limits of the nuclear landscape

Neufcourt et al. Phys. Rev. C 101, 044307 (2020)





Ab Initio Limits of Atomic Nuclei

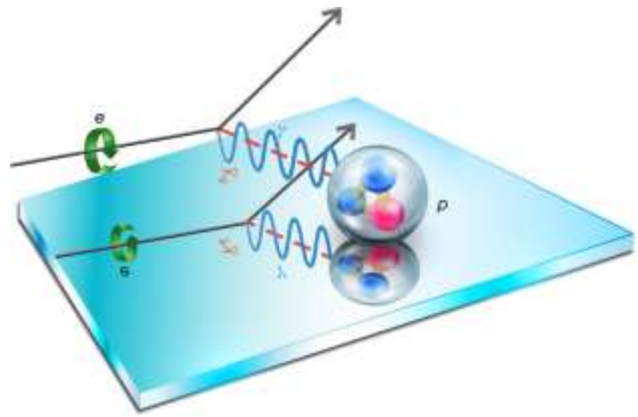
Stroberg et al., Phys. Rev. Lett. 126, 022501 (2021)

- IMSRG with EM 1.8/2.0
- properties of nearly 700 isotopes between helium and iron

Electroweak sector

PREX-2 and CREX completed!

$$A_{\rm PV}(Q^2) = \frac{d\sigma_R/d\Omega - d\sigma_L/d\Omega}{d\sigma_R/d\Omega + d\sigma_L/d\Omega}$$

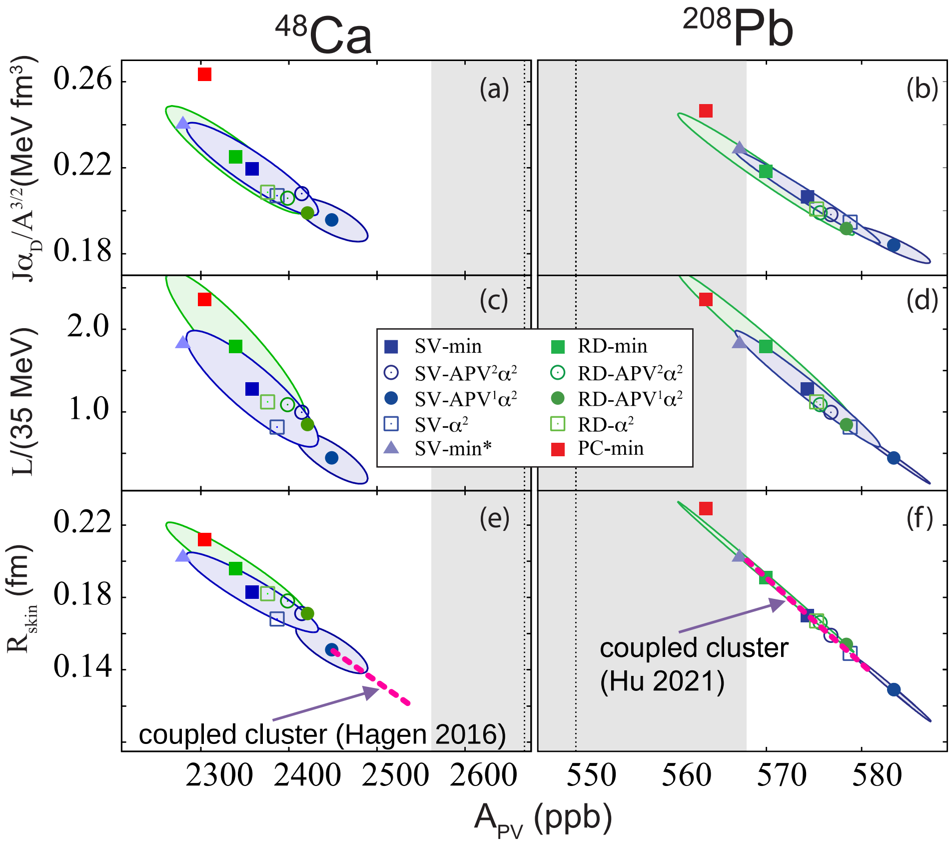


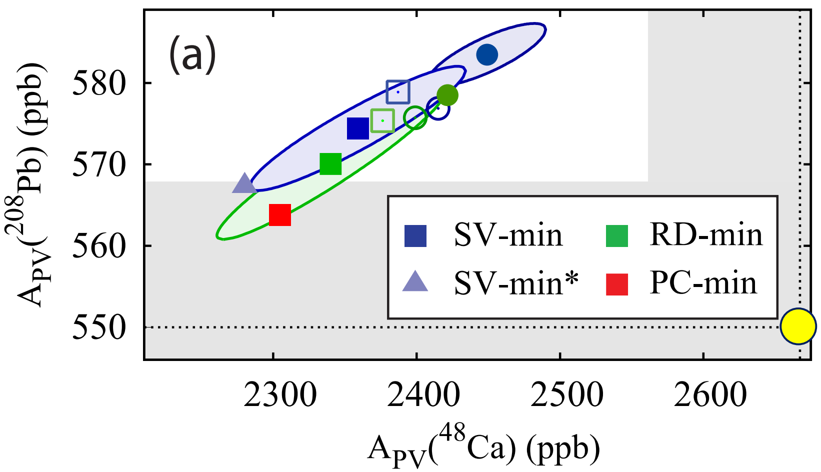
- Adhikari et al., Phys. Rev. Lett. 126, 172502 (2021) measured A_{PV} for ^{208}Pb at a single kinematic condition (transferred momentum q=0.3978/fm):
  A_{PV} =550 ± 16 (stat) ± 8 (syst)
- Adhikari et al., Phys. Rev. Lett. 129, 042501 (2022) measured A_{PV} for ^{48}Ca at a single kinematic condition (transferred momentum q=0.8733/fm):
  A_{PV}=2668 ± 106 (stat) ± 40 (syst)

$$A_{\rm PV}(Q^2) \approx \frac{G_F Q^2 |Q^{(W)}_{N,Z}|}{4\sqrt{2}\,\pi\alpha Z}\,\frac{F_W(q)}{F_C(q)}$$

$$A_{\rm PV} \xrightarrow{\mathcal{M}} F_W(q) \xrightarrow{\mathcal{M}} R_{\rm skin}, J, L$$

Reinhard, Roca-Maza, et al.: Phys. Rev. Lett. 127, 232501 (2021) and arXiv:2206.03134





A tension between the A_{pv} data and global nuclear EDFs

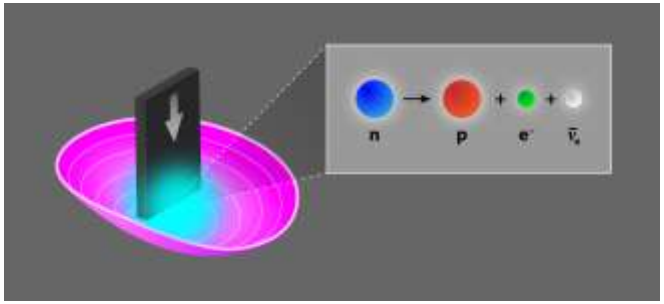
or

The values of CREX and PREX-2 are not mutually compatible considering the current theory

Until the tension between theory and experiment, or between the two measurements, is resolved, one should exercise extreme caution when interpreting the A_{pv} values in the context of neutron skins or nuclear symmetry energy.

Improved Neutron Lifetime Measurement with UCNτ

Gonzalez et al. Phys. Rev. Lett. 127, 162501 (2021)



An improved version of a "bottle" experiment

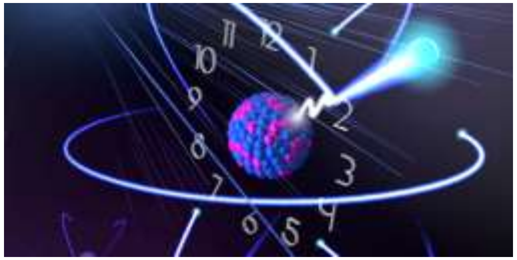
T_n=877.75 (0.28) s

Important for first-row CKM unitarity tests!

...but beam experiments yield a value for neutron lifetime about 8 s longer than that indicated by bottle experiments

Measurement of the ^{229}Th Isomer Energy with Microcalorimeter

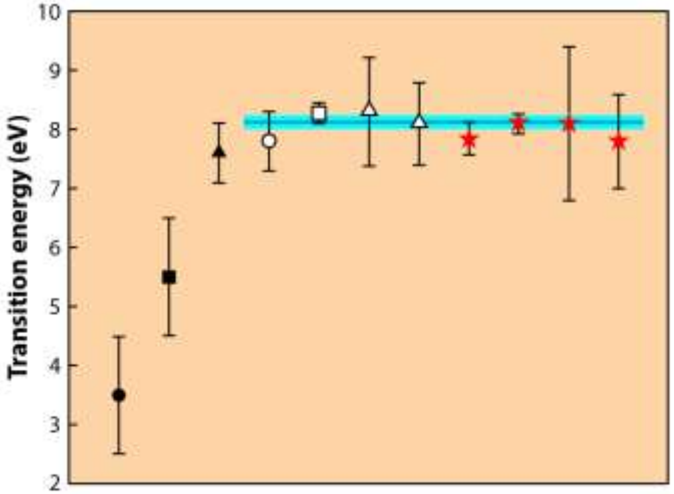
Sikorsky et al., Phys. Rev. Lett. **125**, 142503 (2020)



- Optical clock of very high accuracy
- New physics tests

E*=8.10(17) eV

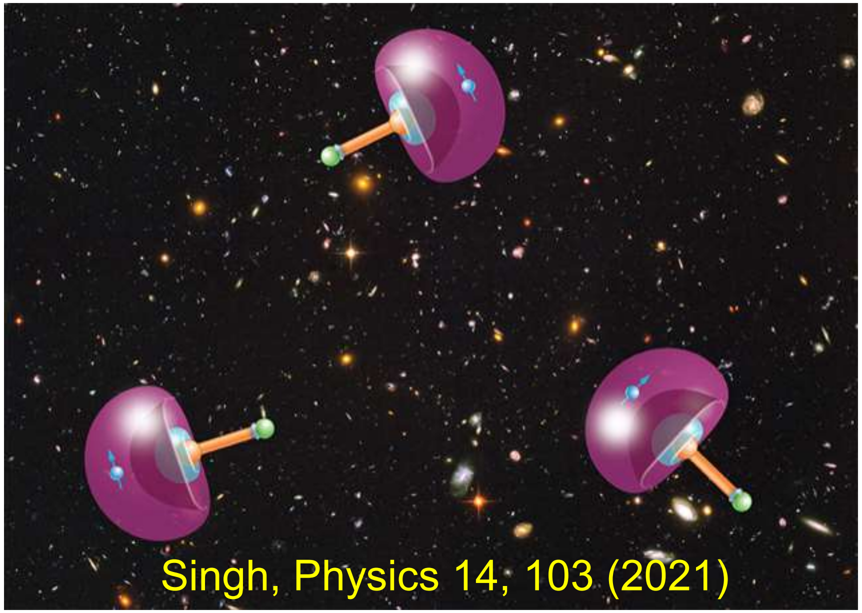
From low-energy γ-ray spectrum produced in the α decay of ^{233}U



Fundamental physics research with radioactive molecules

RaF

Garcia-Ruiz et al., Nature 581, 396 (2020)
Udrescu et al., Phys. Rev. Lett. 127, 033001 (2021)

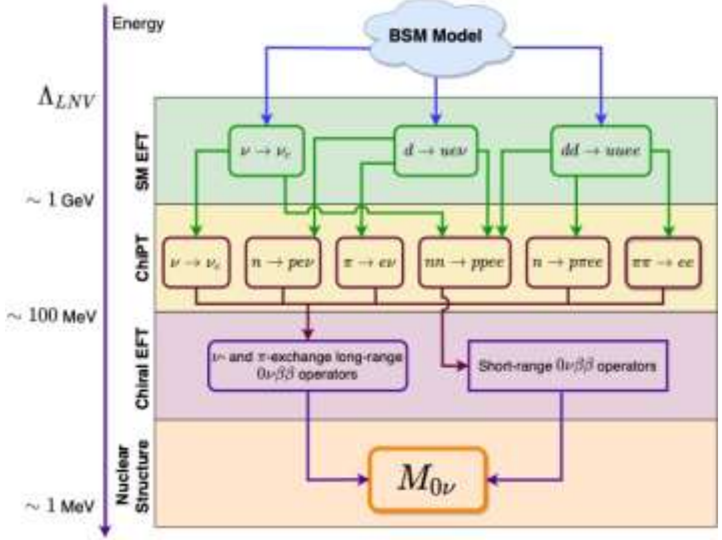


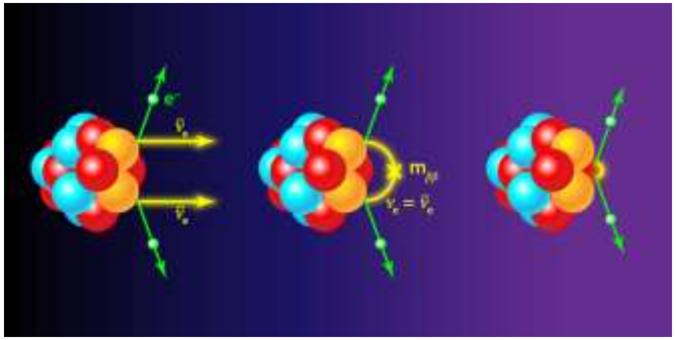
Singh, Physics 14, 103 (2021)

Studying certain radioactive nuclei within polar molecules, such as the radium nuclei in radium monofluoride, is a promising approach for understanding fundamental symmetry violations

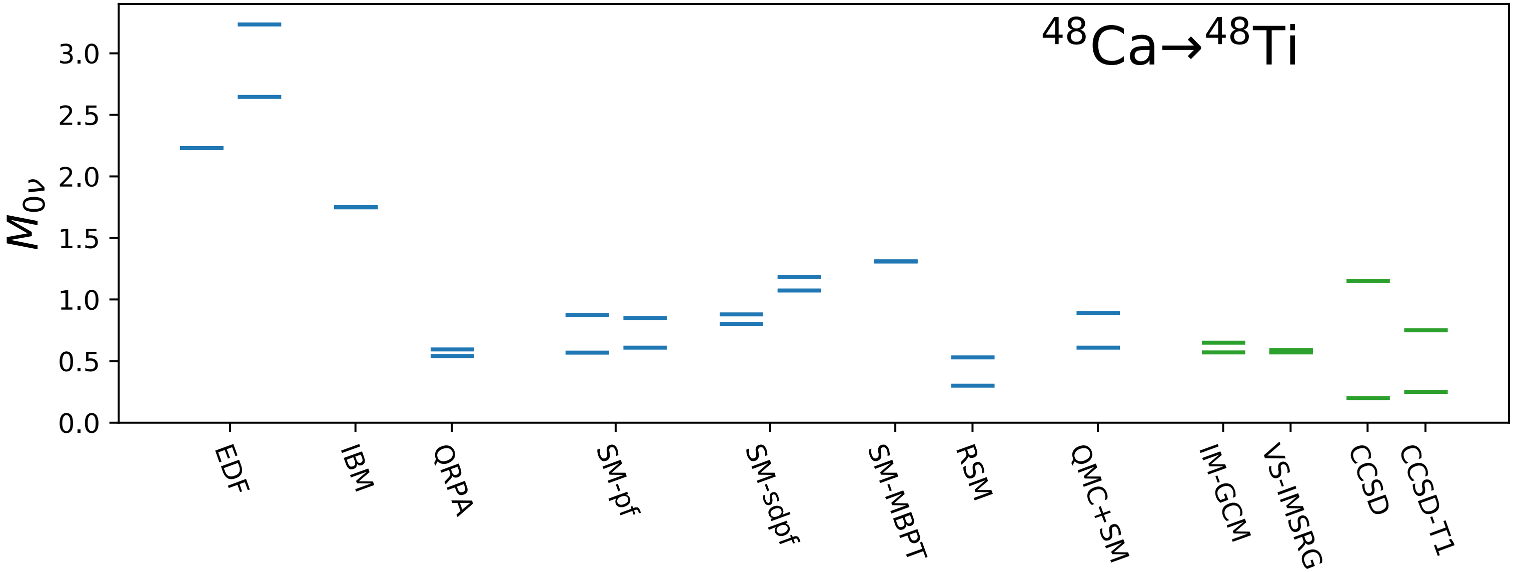
- Extremely large electric fields within the molecule
- Atomic EDM measurements in molecules containing reflection-asymmetric nuclei

Neutrinoless double beta decay





A "tower of theories" leading to the computation of the nuclear matrix elements $M_{0\nu}$ that control the rate of $0\nu\beta\beta$ decay



Novario et al., Phys. Rev. Lett. 126, 182502 (2021)

The road to calculations of $M_{0\nu}$ with uncertainty quantification that accounts for all limitations of the nuclear-physics calculation, see arXiv:2207.01085


LIVE
BREAKING
NEWS

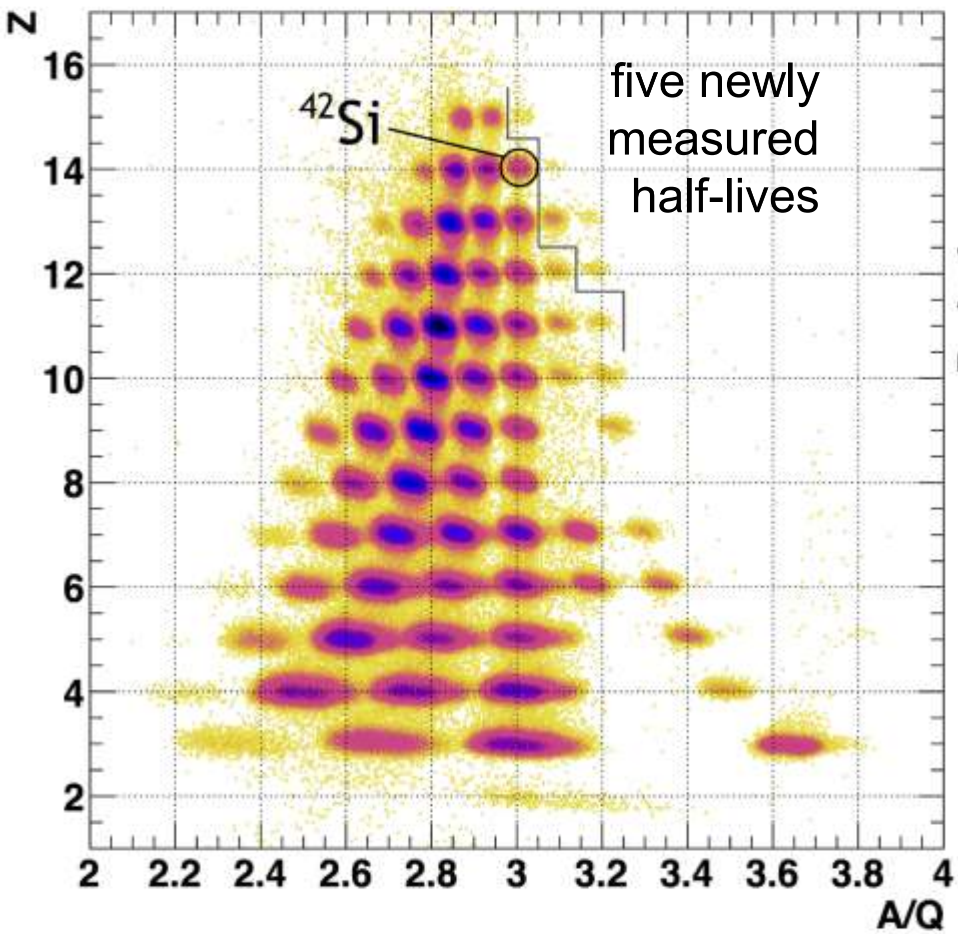

PROSPECT

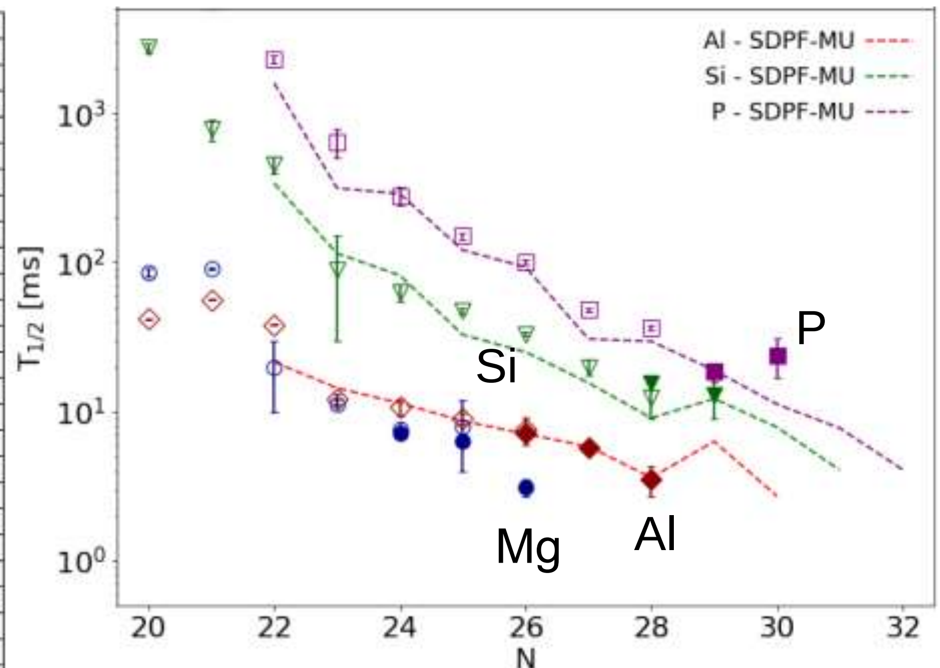
Facility for Rare Isotope Beams has been launched!

Crawford et al., https://frib.msu.edu/news/2022/first-experiment.html

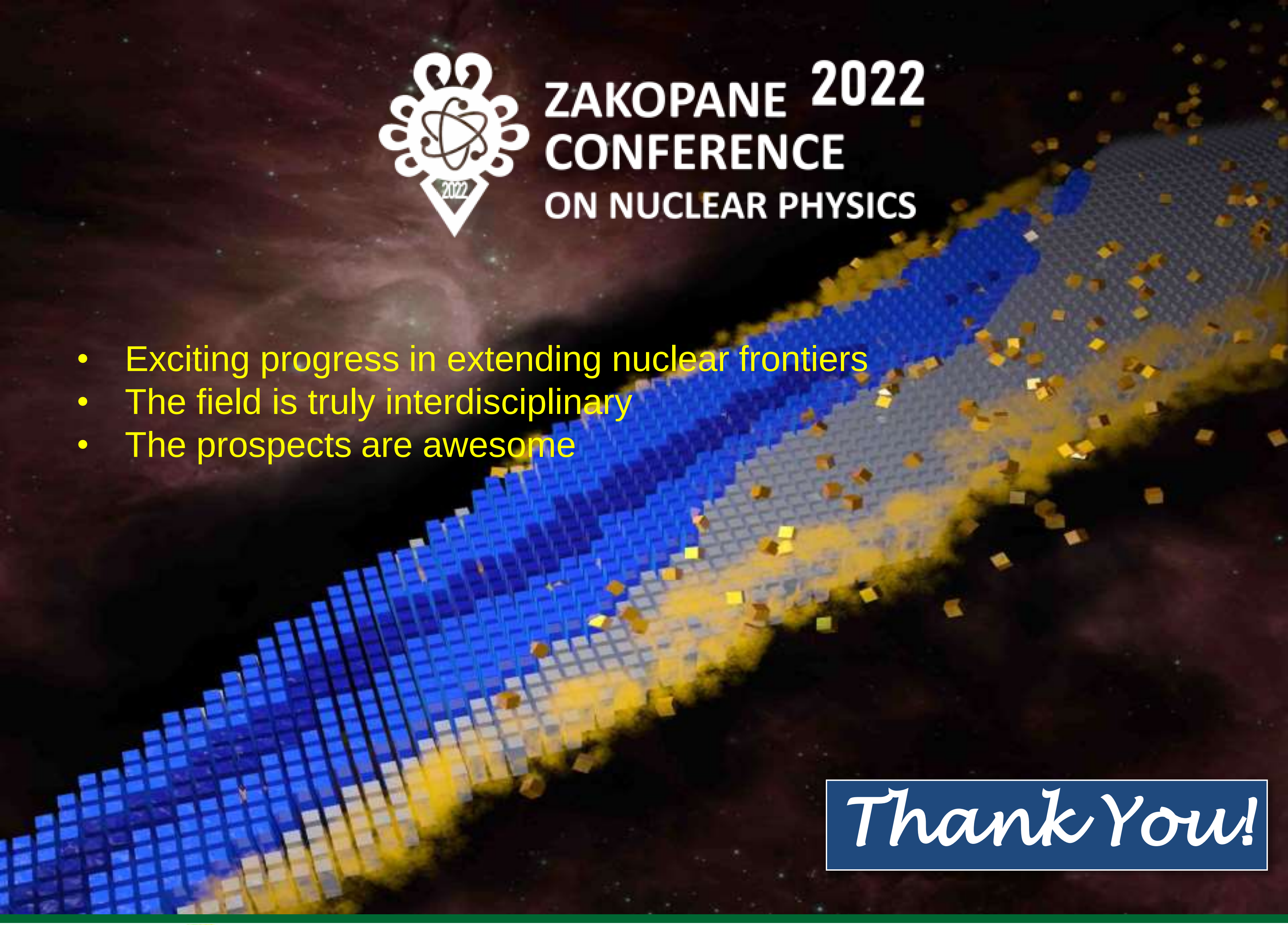
FRIB Decay Station initiator: ORNL ,UTK, MSU, ANL

https://fds.ornl.gov/initiator/





- The erosion of the Z=14 sub-shell closure in Si at N=28 confirmed
- Reduction in the ^{38}Mg half-life

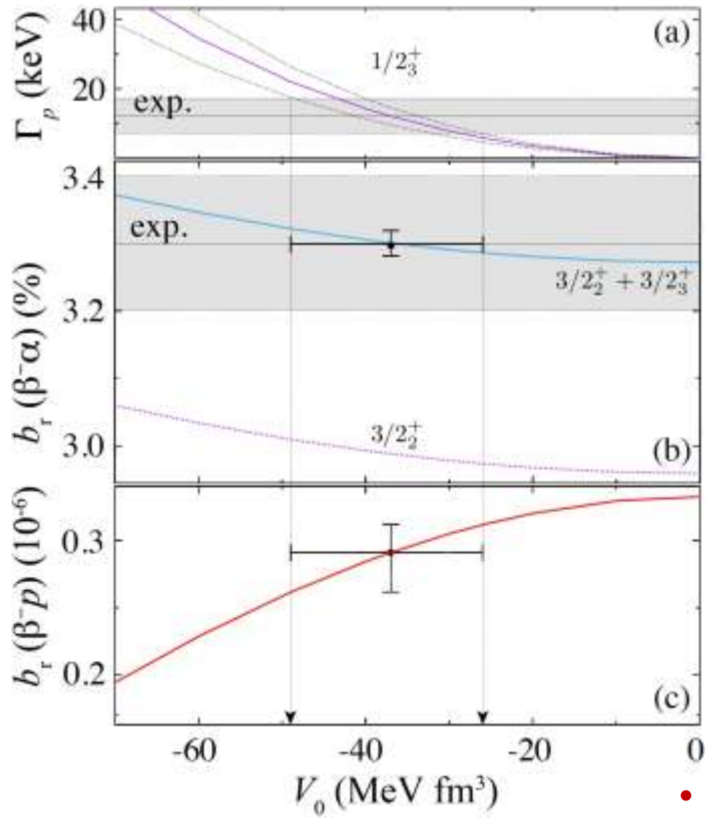

ZAKOPANE 2022
CONFERENCE
ON NUCLEAR PHYSICS
• Exciting progress in extending nuclear frontiers
• The field is truly interdisciplinary
• The prospects are awesome
Thank You!

Backup

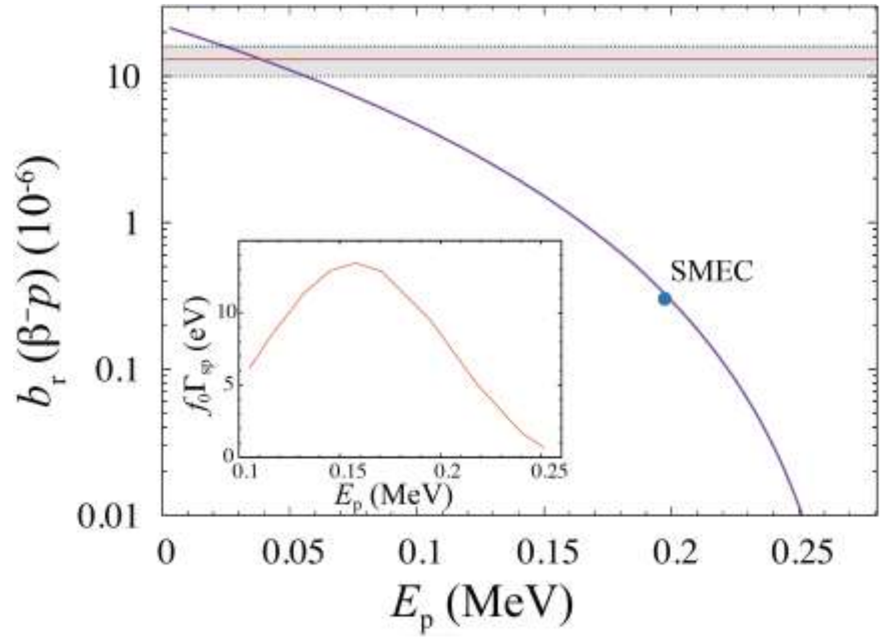
□−p and □−□ decay of the 11Be neutron halo ground state

Okołowicz et al., arXiv:2112.05622: SMEC analysis

See also Volya, Europhys. Lett. 130, 12001 (2020)



b_r(®–〈),Γ_p(1/2+), and EM transitions in 11B consistently described.



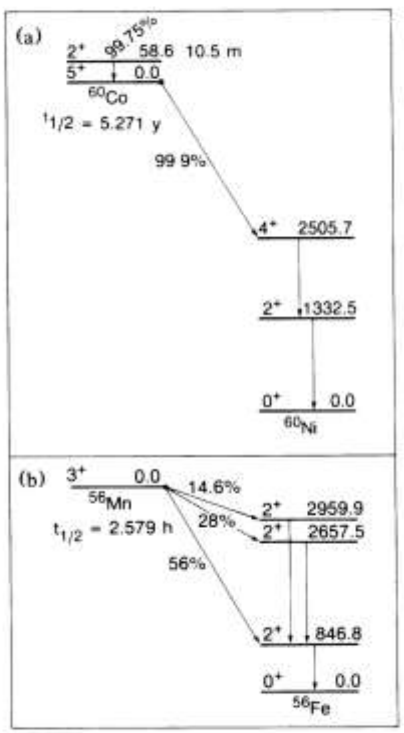
Tension between b_r(®–〈)) and Γ_p(1/2+) and b_r(®–p)

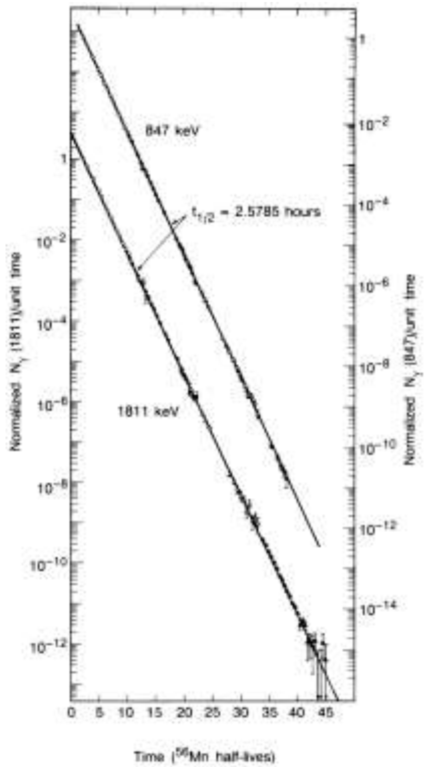
- Evidence of a near-threshold resonance in 11B, Ayyad et al., PRL 129, 012501 (2022) and Lopez-Saavedra et al., PRL129, 012502 (2022)
- Astro relevance: Sieverding et al., Phys. Rev. C 106, 015803 (2022)
- Ab initio: Atkinson et al., Phys. Rev. C 105, 054316 (2022)

The Decay law at long times

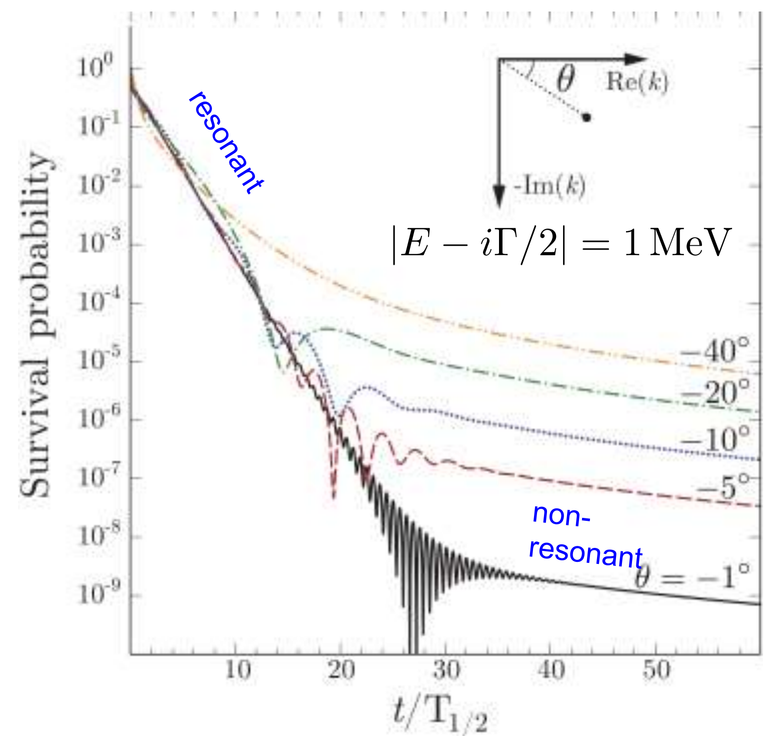
Fonda et al., Rep. Prog. Phys. 41 587 (1978)
Muga et al., Ann. Phys. 252, 336 356 (1996)
Peshkin et al., Europhys. Lett. 107, 40001 (2014)

E. Norman et al., PRL 60, 2246 (1988) [60Co and 56Mn] and Phys. Lett. B 357, 521 (1995) [40K]



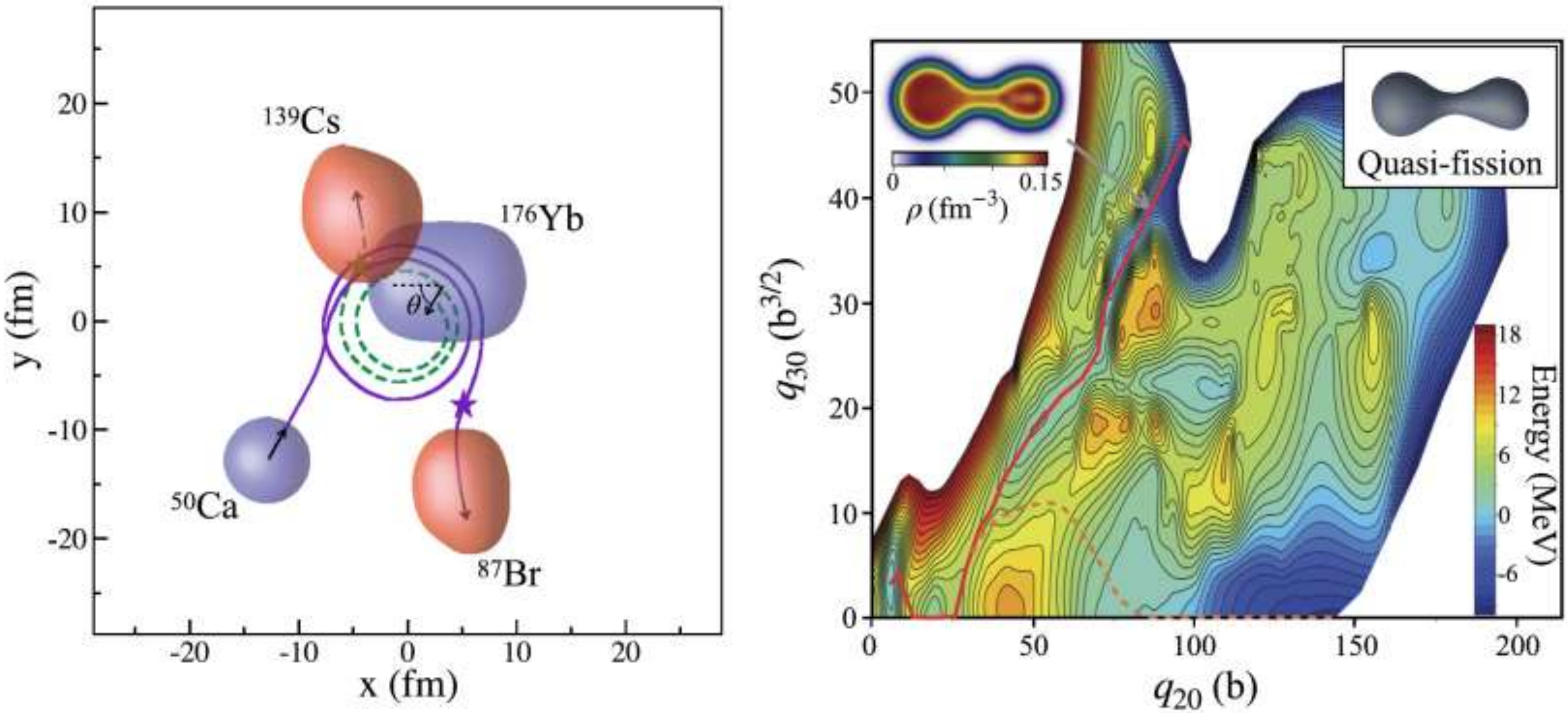


S.M. Wang et al., in preparation



Comparison of fission and quasi-fission modes with TDDFT

Simenel et al. Phys. Lett. B 822, 136648 (2021)



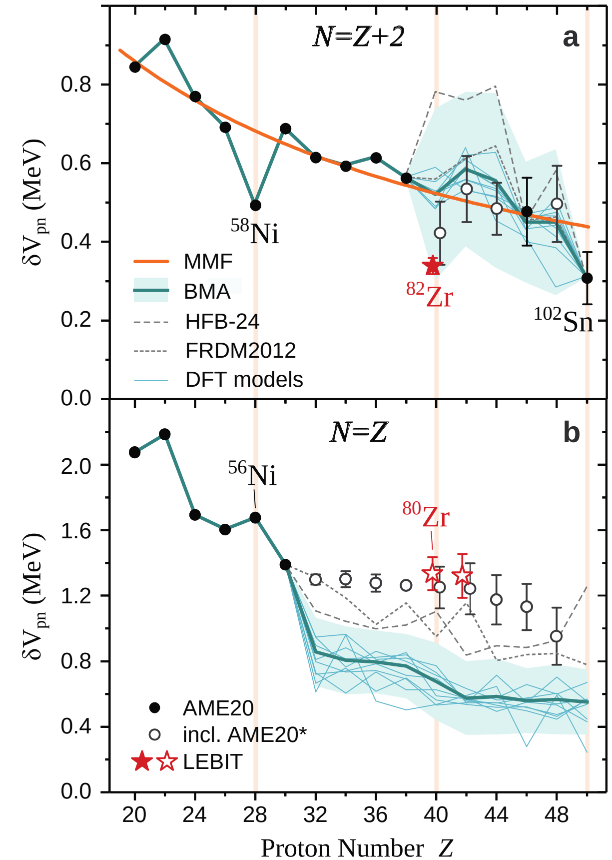
Shell effects affect quasi-fission reactions occurring in heavy-ion collisions. Systematic time-dependent Hartree-Fock simulations of ^{50}Ca+^{176}Yb collisions show that the mass equilibration between the fragments in quasi-fission is stopped when they reach similar properties to those in the asymmetric fission mode of the ^{226}Th compound nucleus. Similar shell effects are then expected to determine the final repartition of nucleons between the nascent fragments in both mechanisms.

Lightweight self-conjugate nucleus ^{80}Zr

A. Hamaker et al., Nature Physics 17, 1408 (2021)

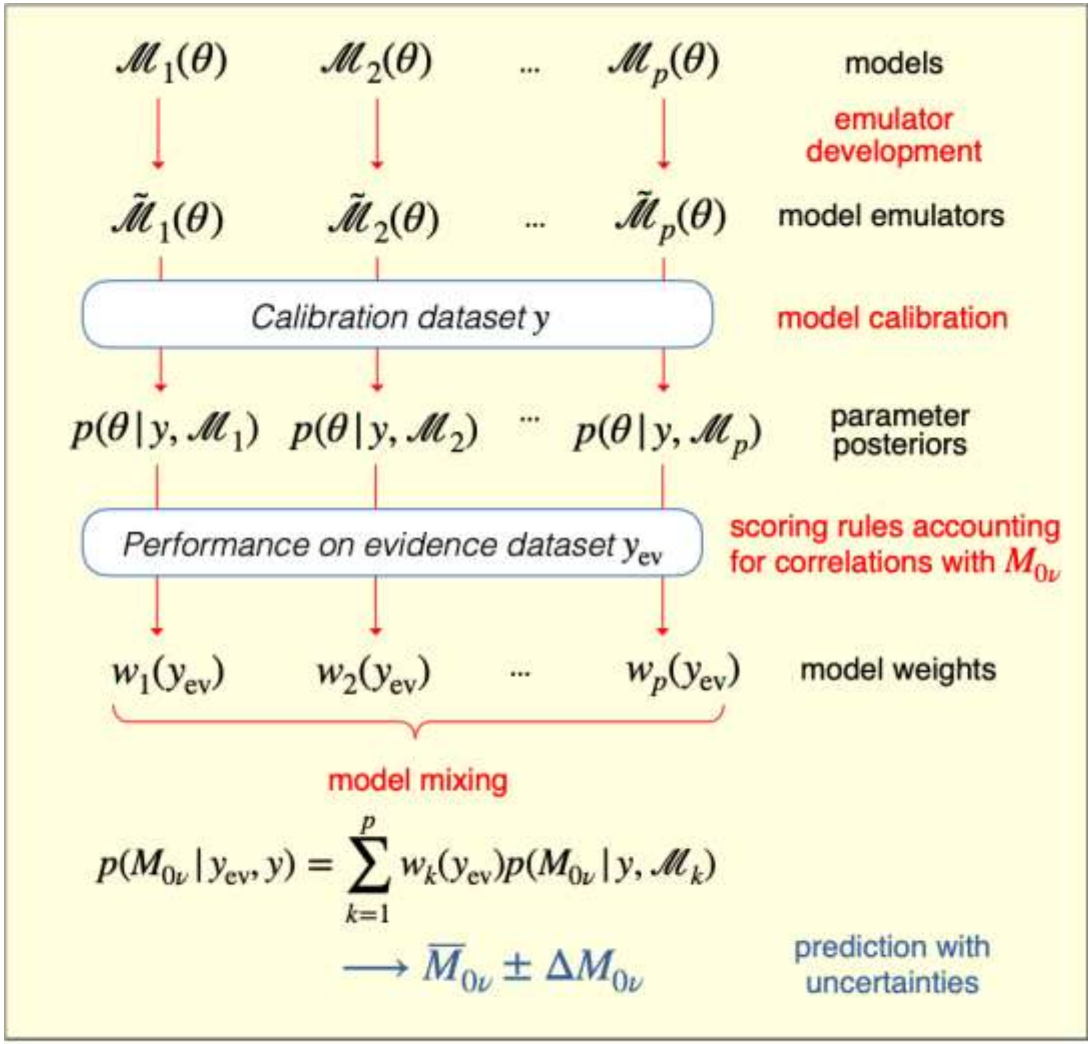
Isotope	Ion	Ion ref.	$\bar{R}$	Mass excess	AME20[23]	Difference
^{80}Zr	^{80}Zr^{16}O$^+$	^{85}Rb$^+$	1.129,829,01 (99)	−55,128 (80)	−54,760 (300)[a]	−370 (310)
^{81}Zr	^{81}Zr^{2+}	^{41}K$^+$	0.987,971,08 (13)	−57,556 (10)	−57,524 (92)	−32 (93)
^{82}Zr	^{82}Zr^{16}O$^+$	^{87}Rb$^+$	1.126,770,338 (31)	−63,618.6 (2.5)	−63,614.1 (1.6)	−4.5 (3.0)
^{83}Zr	^{83}Zr^{2+}	^{41}K$^+$	1.012,274,829,7 (85)	−65,916.33 (65)	−65,911.7 (6.4)	−4.7 (6.5)

A statistical Bayesian model mixing analysis employing several global nuclear mass models was used to interpret the observed mass anomaly. According to theory, the observed effect can be attributed to the deformed shell closure at N=Z=40 and the large Wigner energy.



"When compared with the mass measurements, the authors find a discrepancy between theory and experiment with a significance of more than one standard deviation. This represents a clear challenge for current theoretical models, and thus this work proves that it is not sufficient to perform better adjustment of a functional in order to better describe the data, but that new physics should be explored, for example the competition between deformation effects, isospin breaking effects and proton–neutron pairing."

A. Pastore , Nature Physics 17, 1283 (2021) News & Views



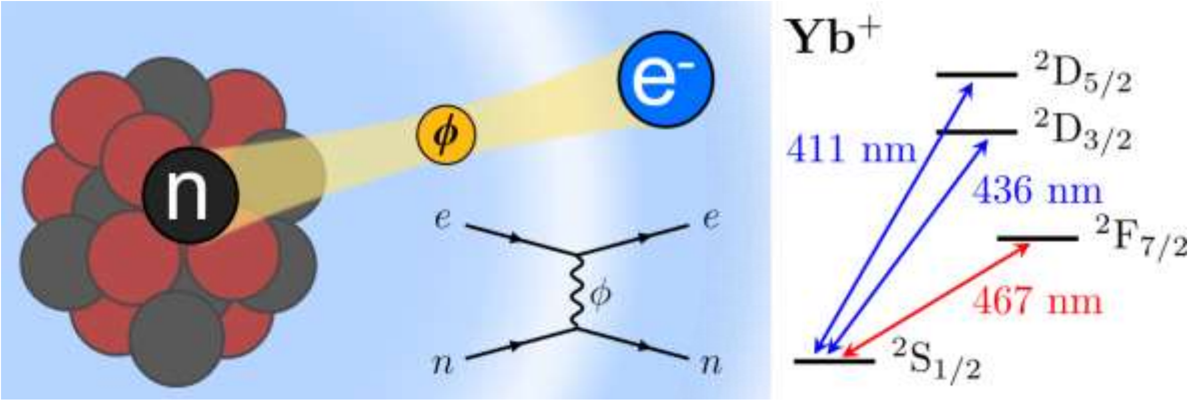
- Repeat for all nuclei of $0\nu\beta\beta$ interest
- Repeat with calibration dataset refined for $0\nu\beta\beta$

The road to calculations of $M_{0\nu}$ with uncertainty quantification that accounts for all limitations of the nuclear-physics calculation

Evidence of two-source King plot nonlinearity in spectroscopic search for new boson

Hur et al., Phys. Rev. Lett. 128, 163201 (2022)

The new forces mediated by unknown dark-matter particles may slightly disturb the structure of atoms.



Measurement of highly forbidden $^2S_{1/2} \rightarrow {}^2F_{7/2}$ octupole transition of trapped ^{168,170,172,174,176}Yb ions

$$\nu_\gamma^{AA'} = F_\gamma \delta\langle r^2\rangle^{AA'} + K_\gamma \mu^{AA'} + G_\gamma^{(4)} \delta\langle r^4\rangle^{AA'} + G_\gamma^{(2)} [\delta\langle r^2\rangle^2]^{AA'} + \upsilon_{ne} D_\gamma a^{AA'} + \cdots$$

The careful analysis, involving advanced atomic theory and nuclear theory, combined with other recent results, suggests that the observed deviations *primarily originate from nuclear effects* related to charge radii and shape deformations.

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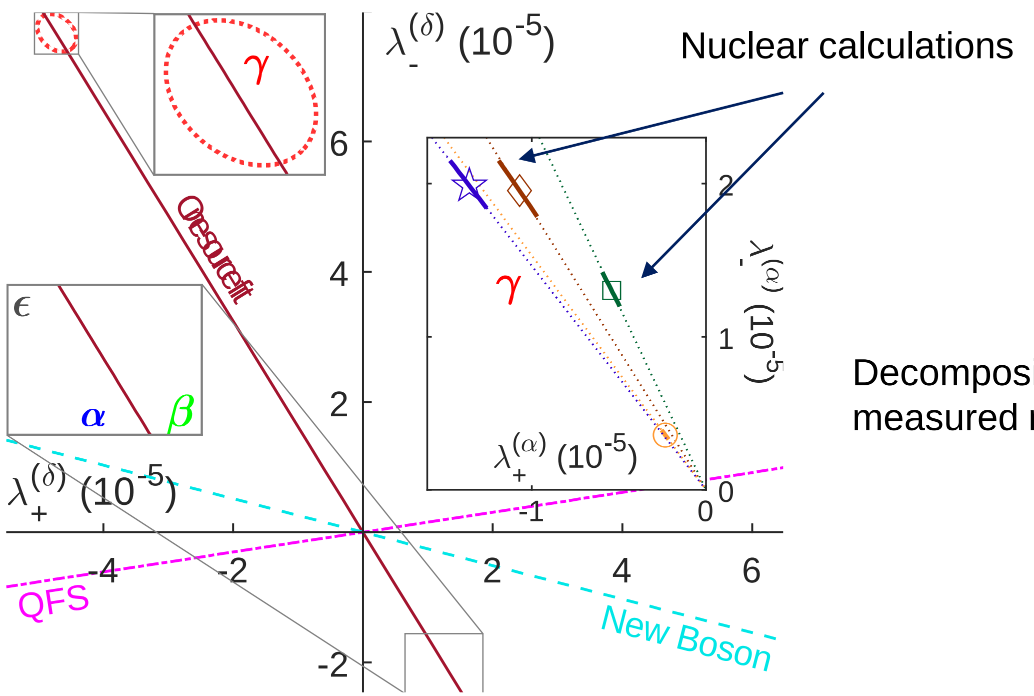
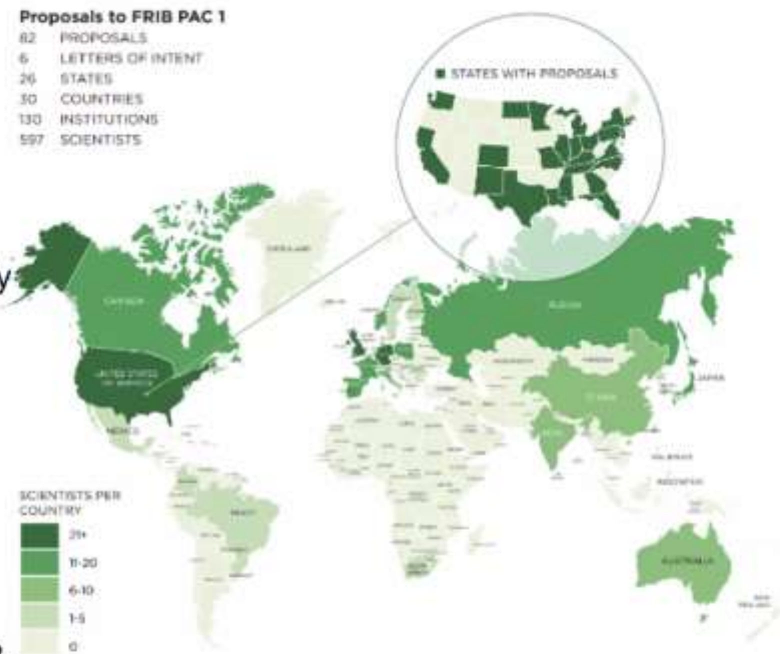


Decomposition of the measured nonlinearity

Started Delivering on PAC-1 Experiments, PAC-2 will be in March 2023

- August 2021: FRIB Program Advisory Committee (PAC1) reviews, ranks proposals PAC-recommended experiments represent
  - 34 out of 82 experiments proposed
  - 401 out of 597 scientists
  - 4,122 hours out of 12,412 facility-use hours
  - 25 out of 30 countries
  - 88 institutions
  - 15 of 17 National Academies benchmarks for FRIB
  - 31 of 34 approved experiments outside MSU (91%)
- May 2022: First user experiments
  - May-June: Two user experiments concluded successfully
  - July-August: Third user experiment
- October 2022: Second call for proposals
  - Proposal preparation workshop later in 2022
  - Early January - submission
- 1-3 March 2023: Second FRIB PAC meeting
  - Fast, stopped, reaccelerated, and ReA standalone (unique science)
  - Considerations: Scientific merit, workforce training, DEIB, status of PAC1 experiment for spokespersons' groups



FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

T. Glasmacher, August 2022 LECM, Slide 4