Physics of extreme nuclei and extreme nuclear states

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IRL-NPA Kickoff Meeting

FRIB, MSU Dec. 11-13, 2023

Menu

- Threshold phenomena
- Global nuclear properties
- Connections to nuclear astrophysics – need for extrapolations
- Uncertainty quantification in nuclear theory

Fucus on collaborations withs CNRS (and CEA)

Open quantum systems
and
The limits of existence of atomic nuclei

Questions:

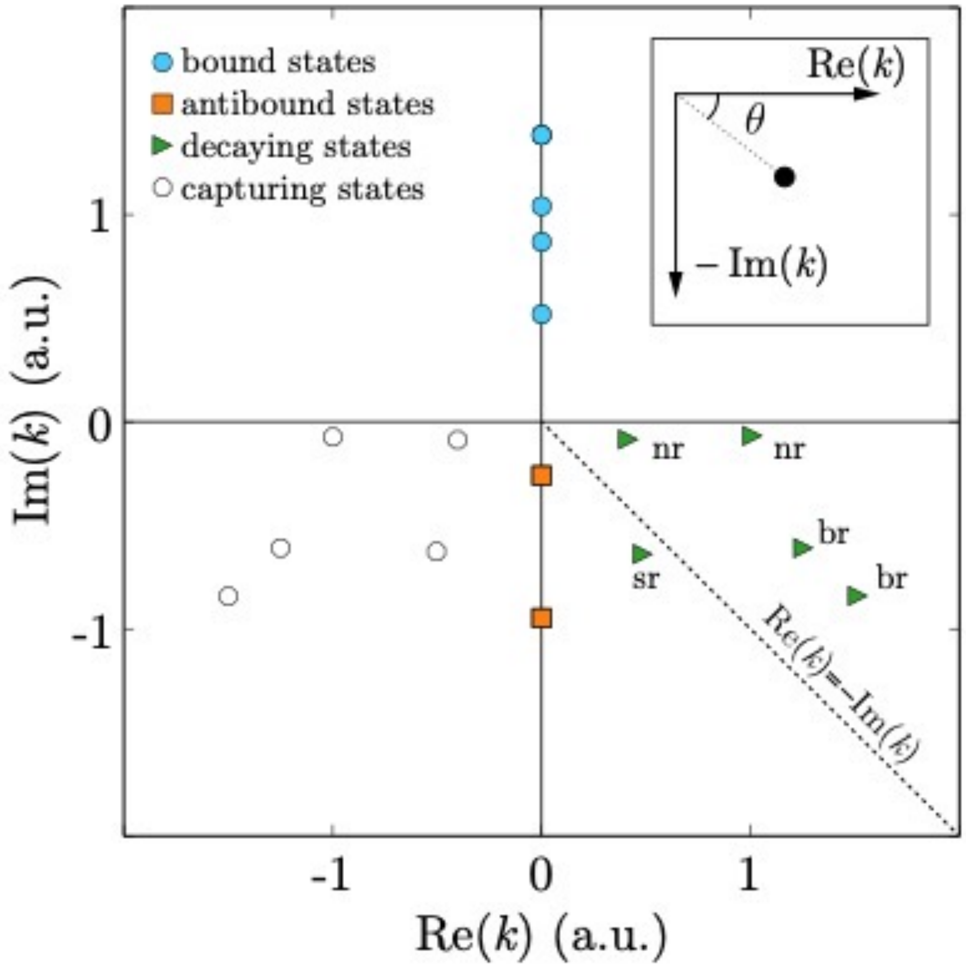
- *What is the nature of near-threshold states?*
- *At what point are states dissolved into the scattering continuum and should rather be called scattering features?*

Gamow Shell Model (2002): GANIL/ORNL/MSU

Strong existing collaboration

Threshold phenomena

$$\tilde{E} = E_r - i\Gamma/2$$



- Resonant states with Re(E)>0 and small Γ can be associated with narrow resonances (nr). Proton emitters in heavy nuclei belong to this class.
- Many prompt proton emitters in light nuclei are broad resonances (br)
- The antibound proton states do not exist because of the Coulomb force.
- The subthreshold resonant states lie on the second Riemann energy sheet. They have Re(E) < 0 and $\Gamma \geq 0$.
- Low-momentum threshold resonant states result in the low-energy cross-section enhancement. These poles should be viewed as *scattering features* rather than physical states of the system.

Near-threshold clustering: many examples!

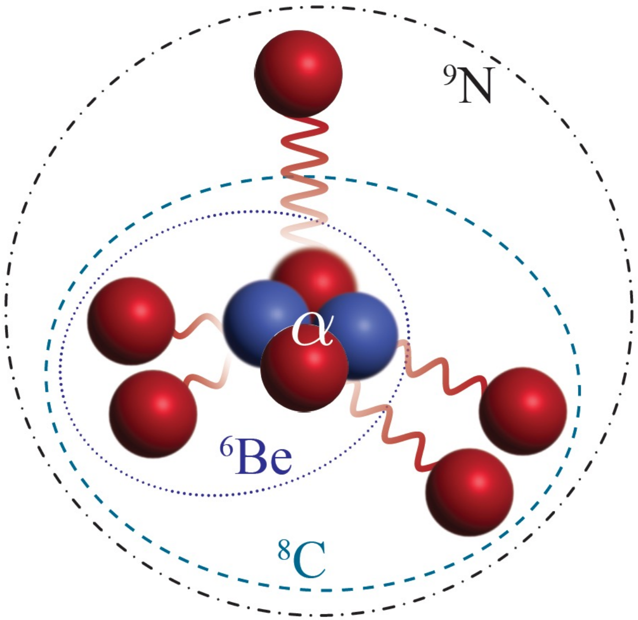
Featured in Physics | Editors' Suggestion

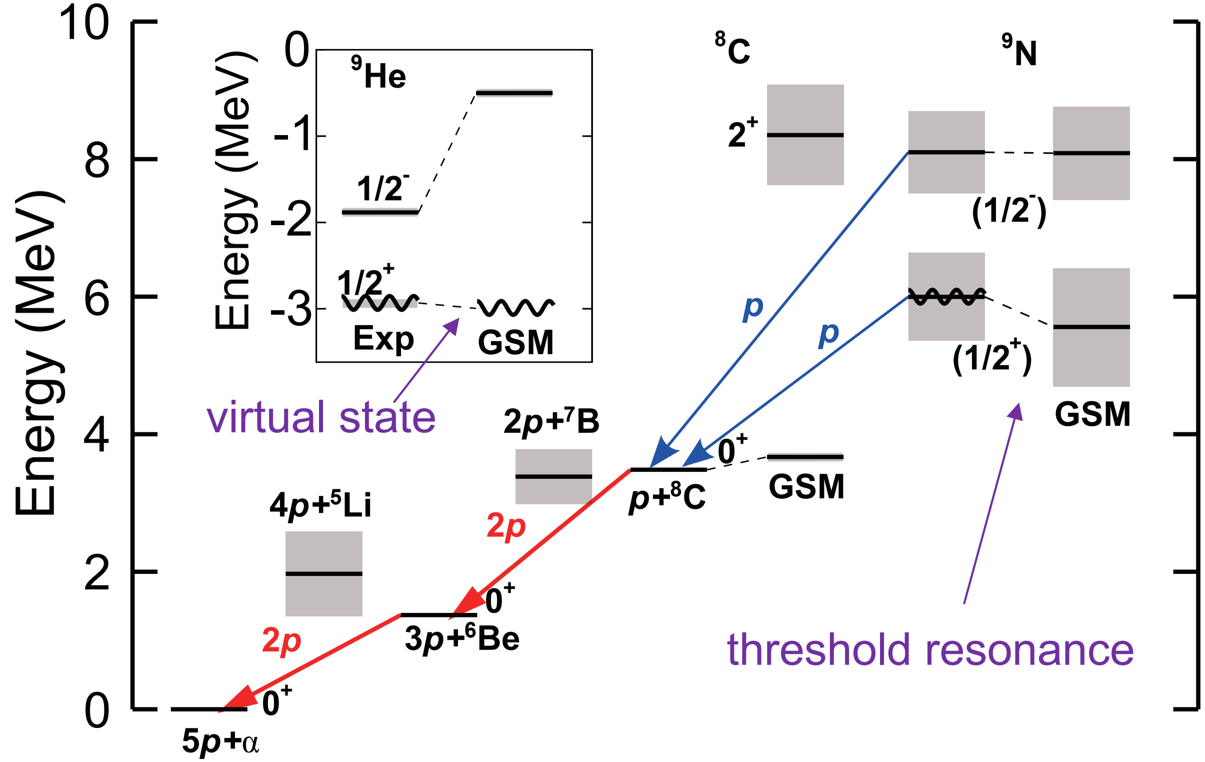
Strong Evidence for ^{9}N and the Limits of Existence of Atomic Nuclei

R. J. Charity, J. Wylie, S. M. Wang, T. B. Webb, K. W. Brown, G. Cerizza, Z. Chajecki, J. M. Elson, J. Estee, D. E. M. Hoff, S. A. Kuvin, W. G. Lynch, J. Manfredi, N. Michel, D. G. McNeel, P. Morfouace, W. Nazarewicz, C. D. Pruitt, C. Santamaria, S. Sweany, J. Smith, L. G. Sobotka, M. B. Tsang, and A. H. Wuosmaa

Phys. Rev. Lett. **131**, 172501 – Published 27 October 2023

Physics See Focus story: Five Protons Spew Out of Extreme Nucleus





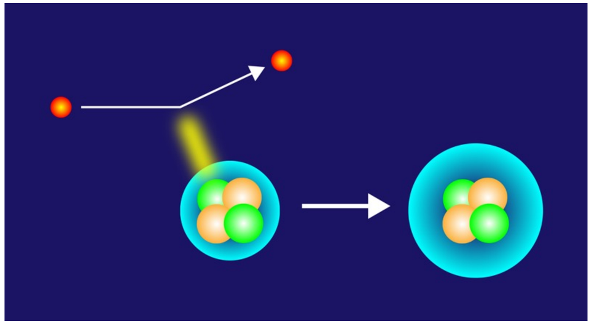
^{9}N: 5-proton emitter

Charity at al., Phys. Rev. Lett. 131, 172501 (2023)

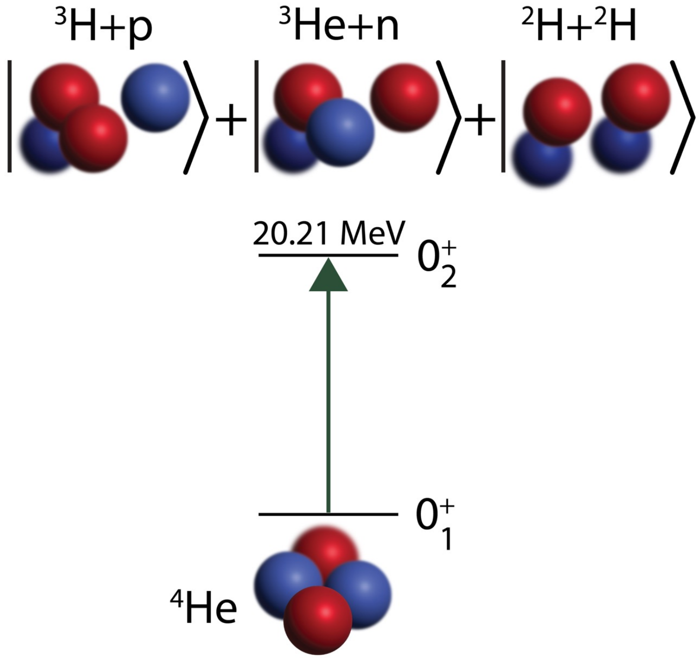
Coupled-channel no-core Gamow shell model description of the excited 0^+ state of the alpha particle, Michel, Płoszajczak, WN, Phys. Rev. Lett. 131, 242502 (2023)

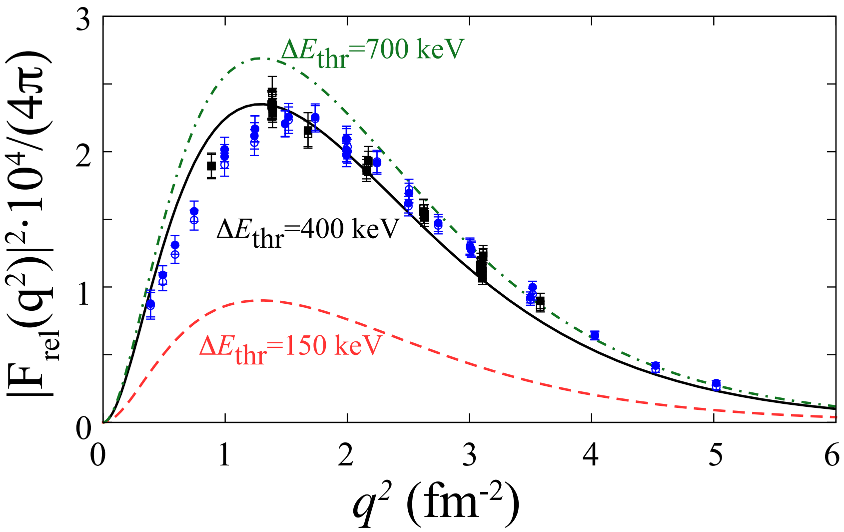
E(level) (keV)	XREF	J^π(level)	$T_{1/2}$(level)
0.0		0+	STABLE
20210	E GHI K	0+	0.50 MeV % p = 100
21010	H	0-	0.84 MeV % n = 24 % p = 76

Experiment: Monopole form factor Phys. Rev. Lett. 130, 152502 (2023)



S_p=19.8 MeV, S_n=20.6 MeV ⇒ open quantum system description needed!



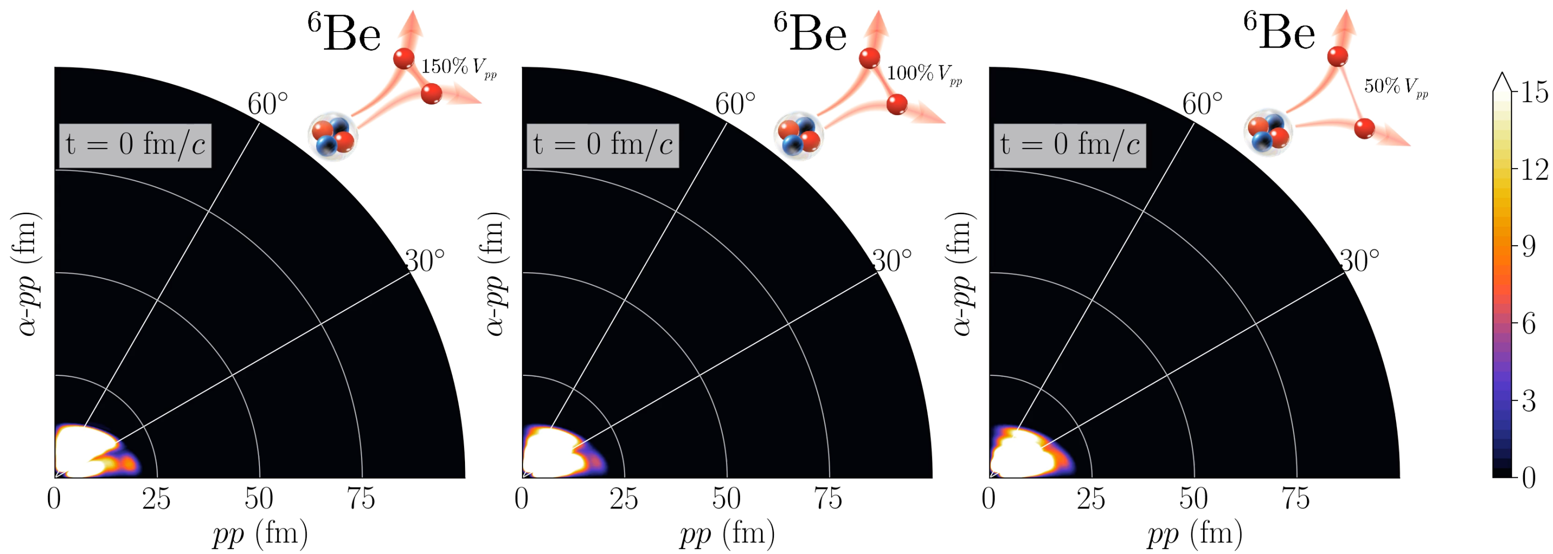


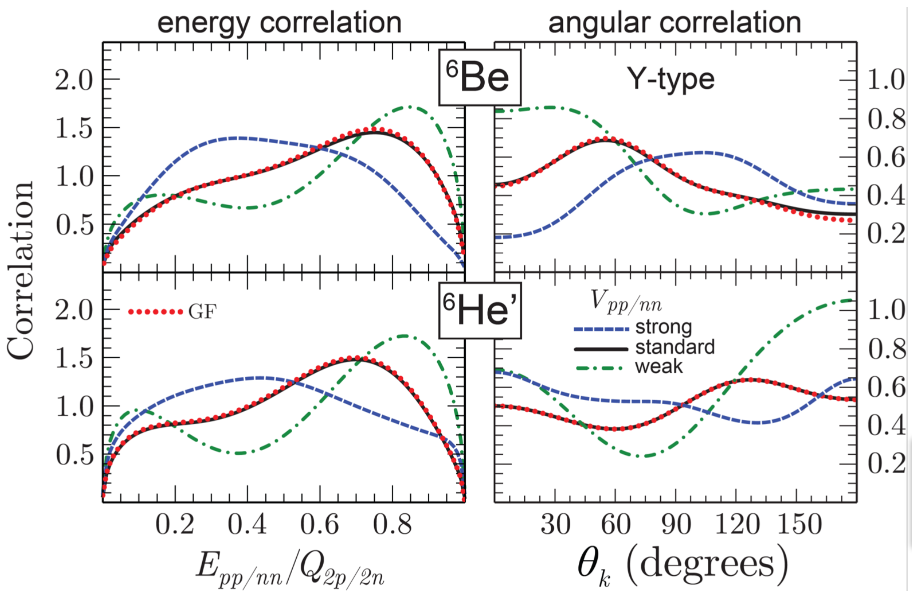
No puzzle for nuclear forces!

Correlation studies for 2-nucleon emission

Wang and WN, Phys. Rev. Lett. 126, 142501 (2021)

strong V_{pp} standard V_{pp} weak V_{pp}





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

Strong experimental effort in France

Global studies of nuclear properties
(nuclear structure and nuclear astrophysics)

- Nuclear density functional theory and its extensions (GCM, QRPA, TDDFT,…)
- Uncertainty quantification

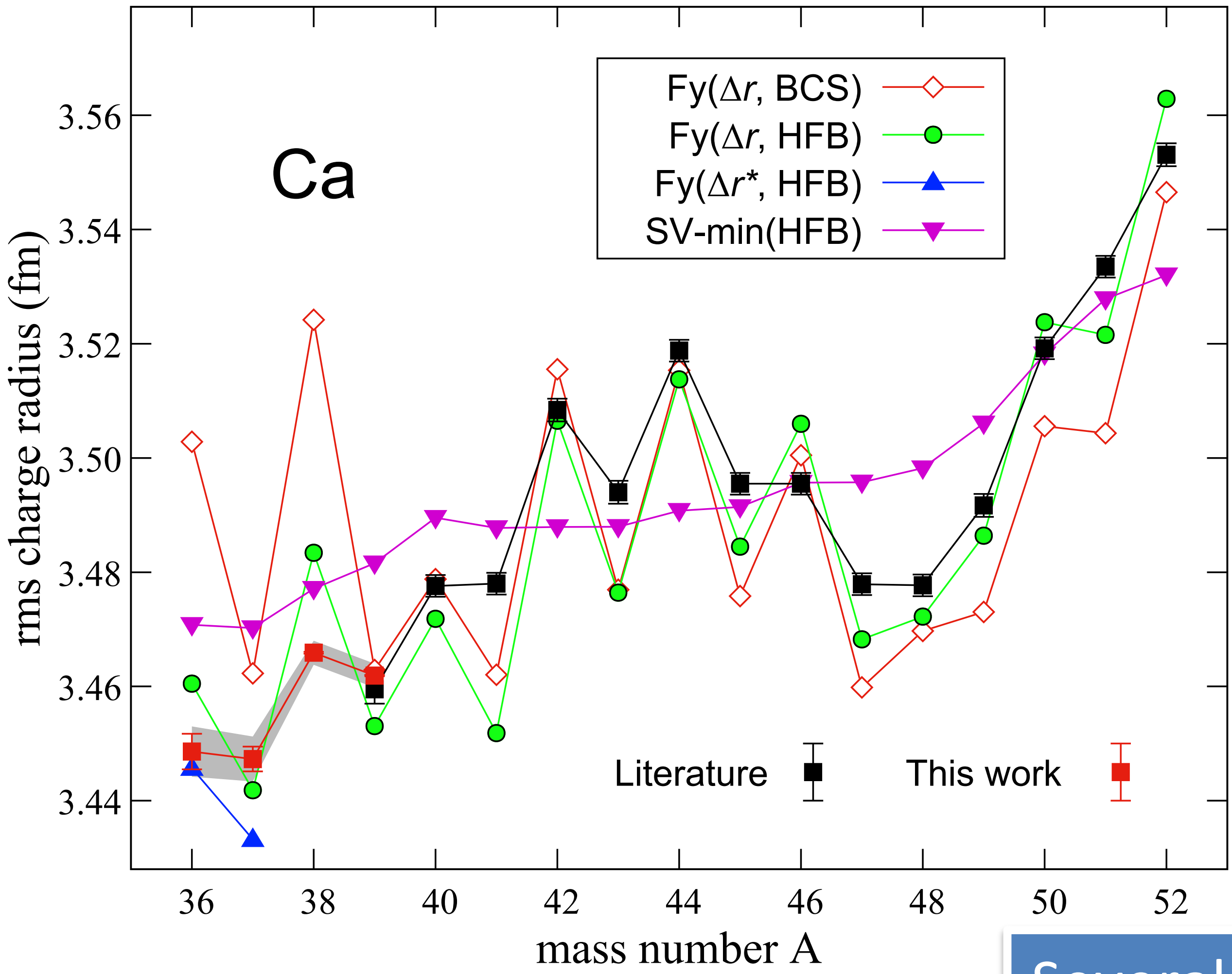
Questions:

- *What is the universal nuclear energy density functional?*
- *What are the global properties of yet-unknown isotopes?*
- *Quantitative description of large amplitude collective motion (fission and heavy-ion fusion)*

Several strong efforts in France
Sporadic collaborations

Quantitative predictions require many scientific-method loops

Charge radii of Ca isotopes in Fayans-DFT
Nat. Phys. 15, 432 (2019)



Understanding the charge radii data in the Ca chain took time and effort

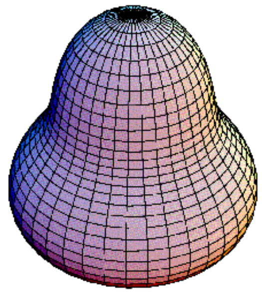
- Magnetic (spin-orbit) contribution to nuclear charge density
- New data on neutron- and proton-rich isotopes
- Dependence of pairing functional on the gradient of density
- HFB treatment of weakly-bound ^{36}Ca
- Calibration of the Fayans functional to differential radii

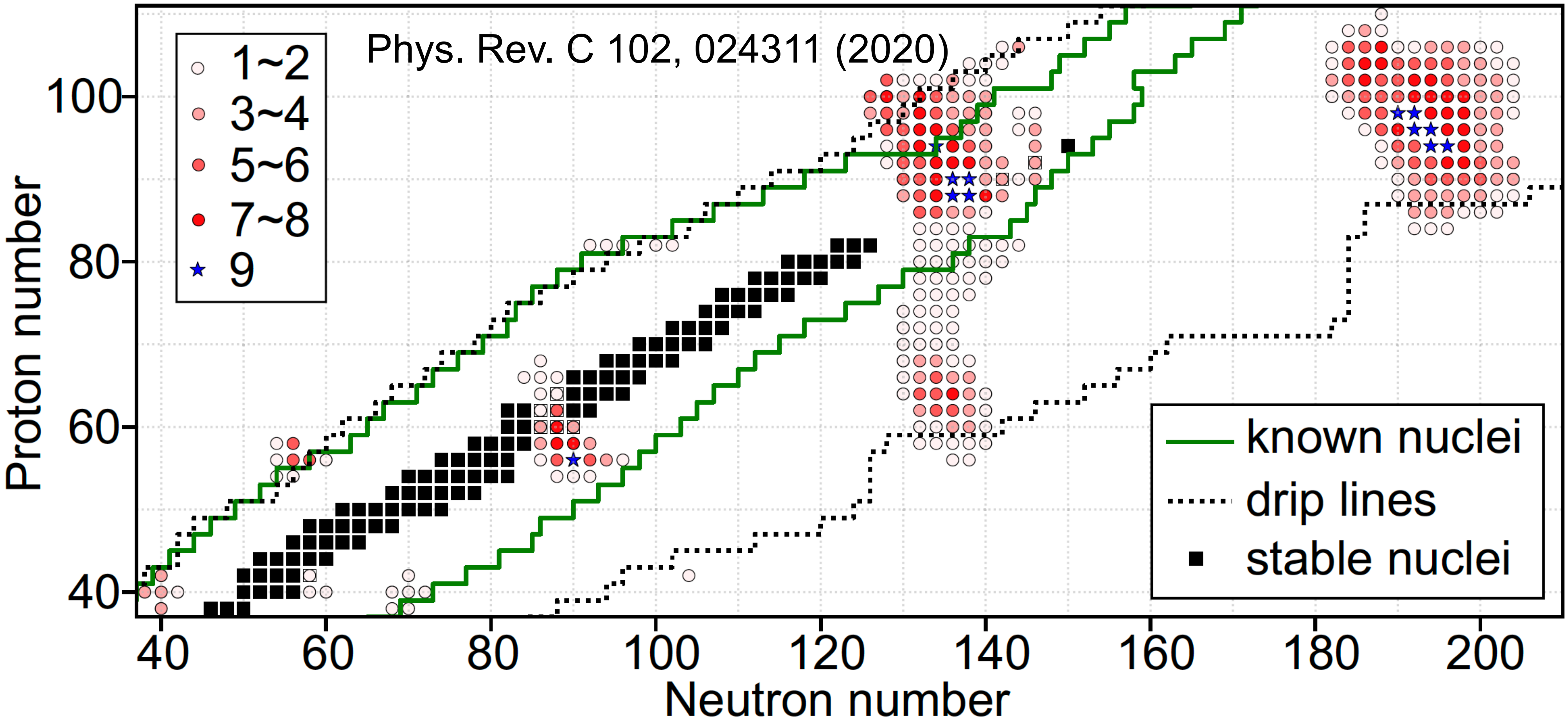
Several strong efforts in France

BSM searches in nuclei

Reflection-asymmetric nuclei and EDMs

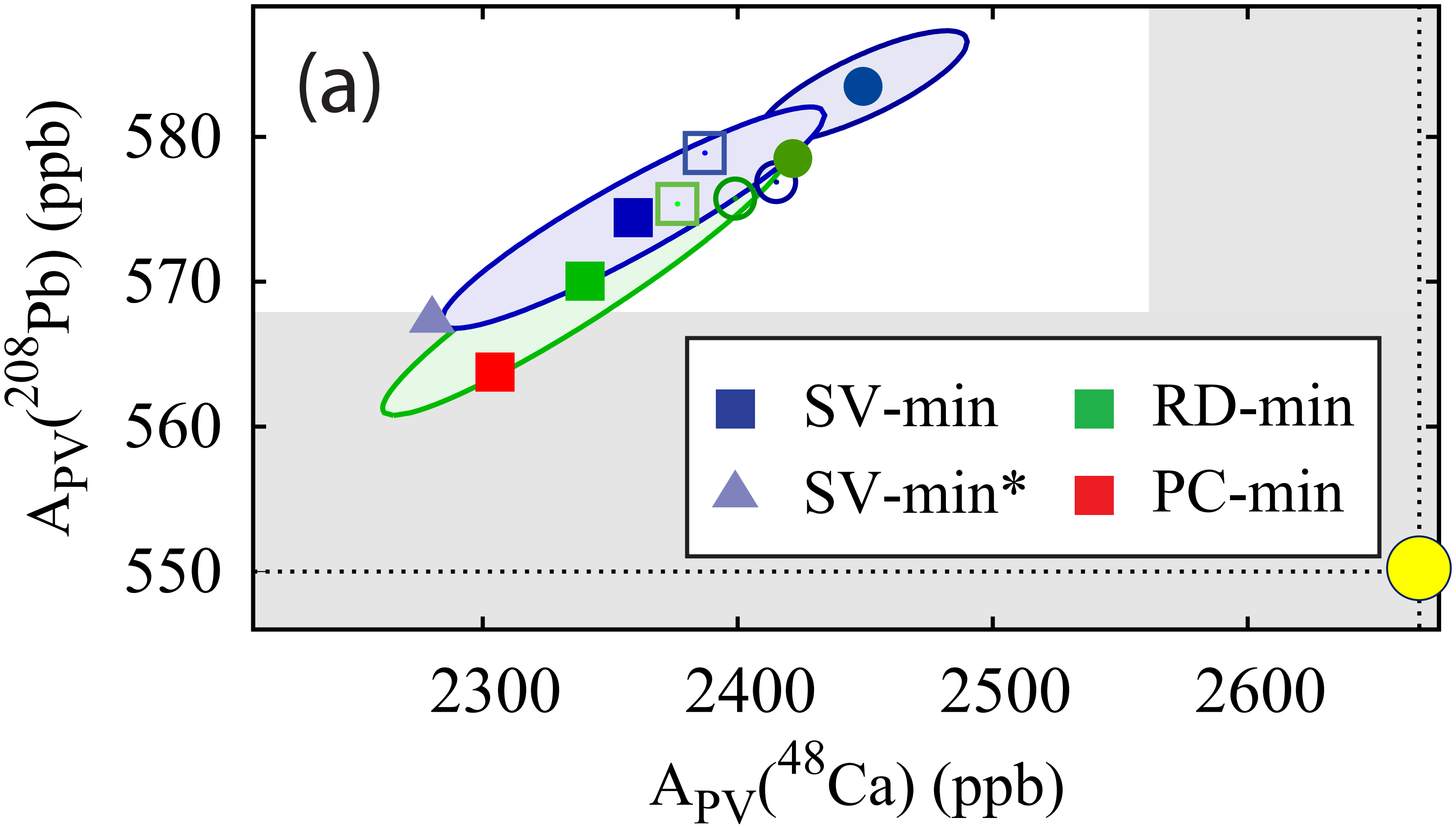
- Parity-doublet candidates
- Schiff moments





Isovector observables and symmetry energy

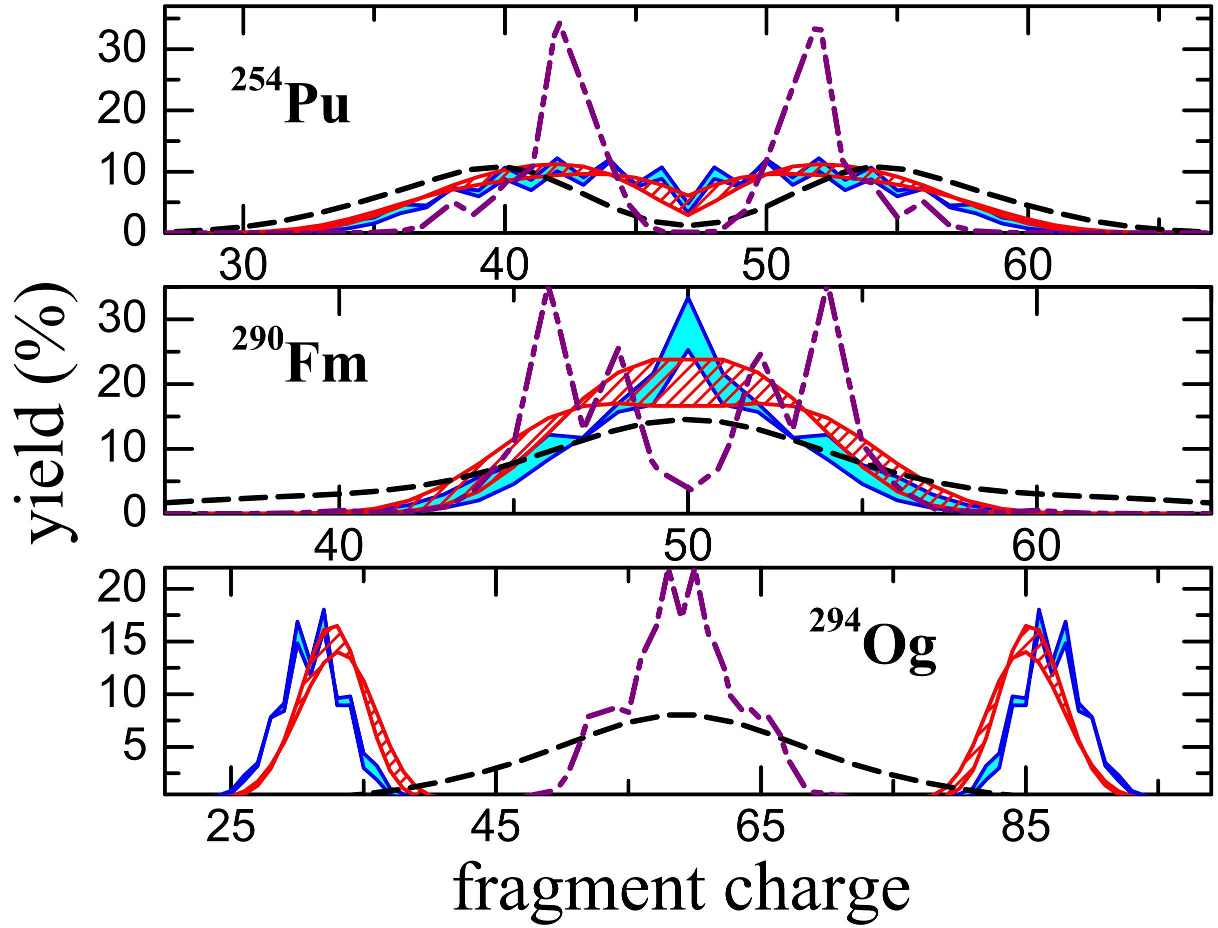
Reinhard, Roca-Maza WN, Phys. Rev. Lett. 127, 232501 (2021) and Phys. Rev. Lett. 129, 232501 (2022)



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

Challenge: r-process and fission

Phys. Rev. C 105, 014619 (2022)



Fragment charge distributions of ^{254}Pu,^{290}Fm, and ^{294}Og obtained in our work (blue bands) and predicted in previous work (red dashed bands). Predictions of Brownian shape-motion (Mumpower) and scission-point (Lemaître) models are shown by dashed and dash-dotted lines, respectively.

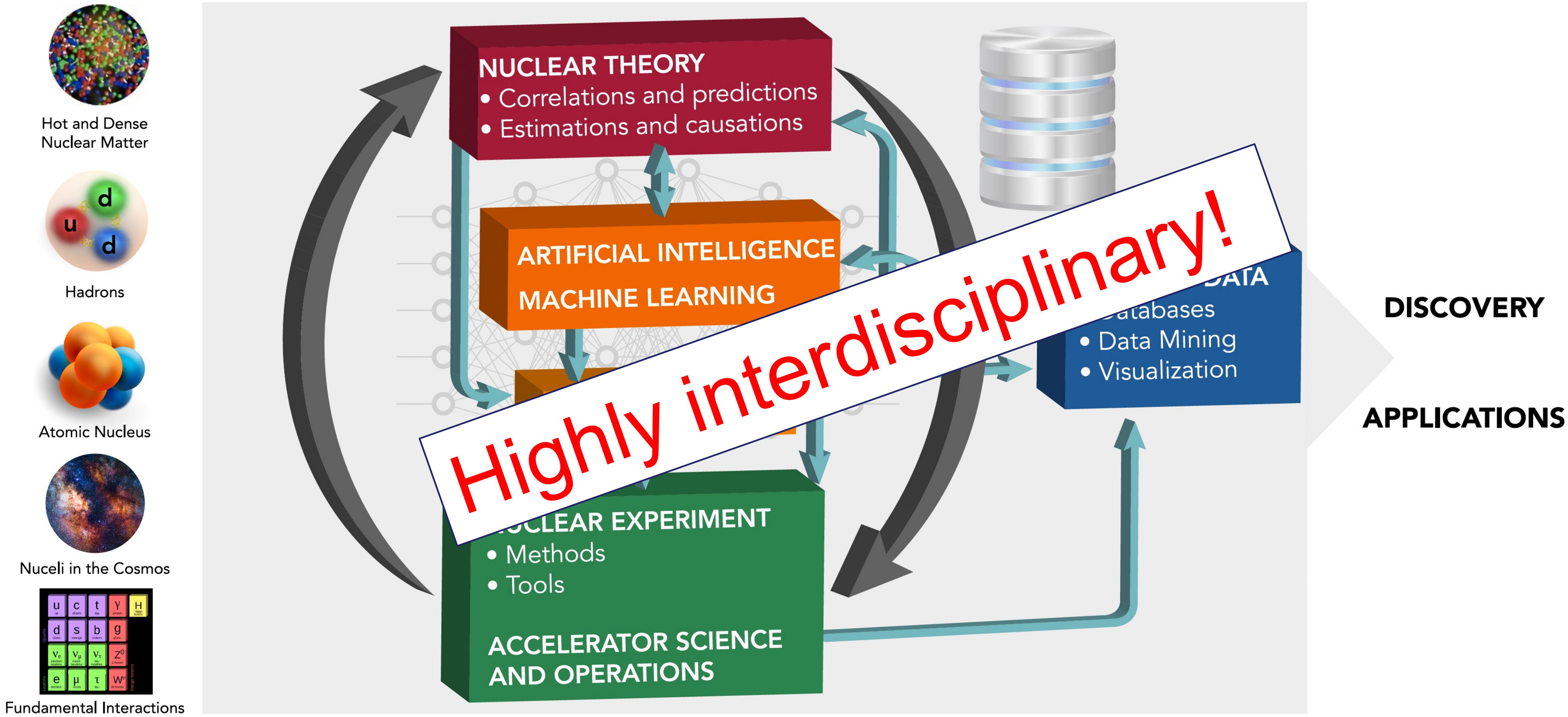
$^{294}\mathrm{Og} \rightarrow {}^{208}\mathrm{Pb} + {}^{86}\mathrm{Kr}_{50}$

Several strong efforts in France
Sporadic collaborations

Machine learning and nuclear theory: big picture

Artificial Intelligence and Machine Learning in Nuclear Physics
A. Boehnlein et al., Rev. Mod. Phys. Rev. Mod. Phys. 94, 031003 (2022)

Many examples can be found there!



Speeding-up the cycle of the scientific method through machine learning

Machine learning & low-energy nuclear theory: Why?

ML tools can help us to speed up the scientific method cycle and hence facilitate discoveries

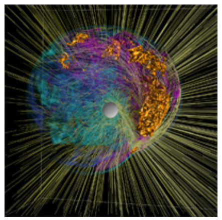
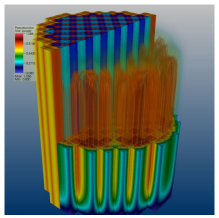
- Enabling fast emulation for big simulations
- Revealing the information content of measured observables w.r.t. theory
- Identifying crucial experimental data for better constraining theory
- Providing meaningful input to applications and planned measurements

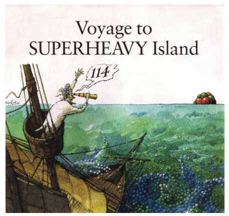
ML tools can help us to reveal the structure of our models

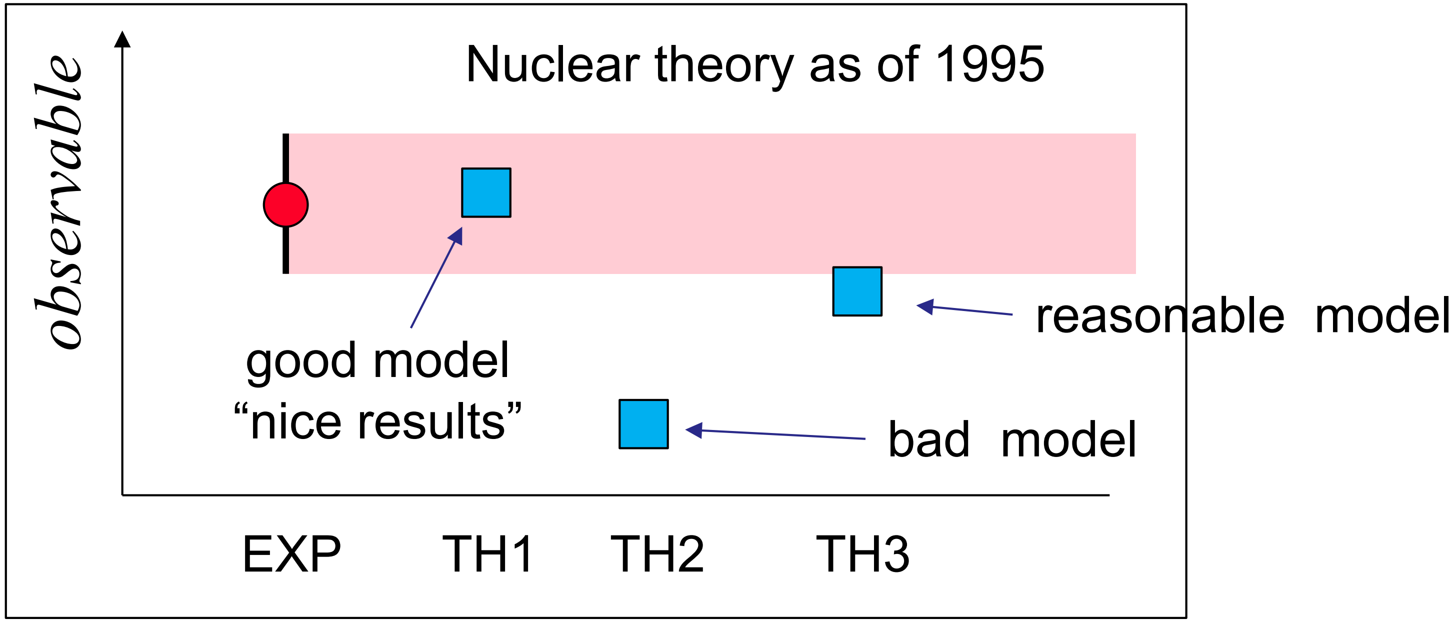
- Parameter estimation with heterogeneous/multi-scale datasets
- Model reduction

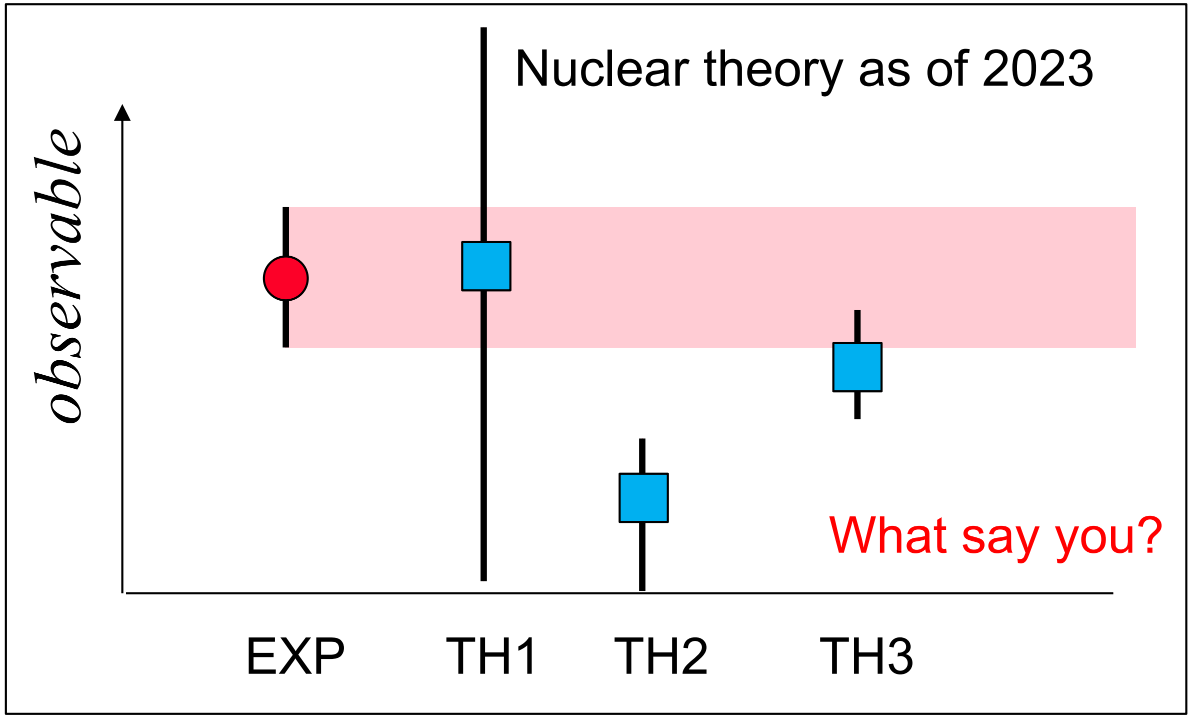
ML tools can help us to provide predictive capability

- Theoretical results often involve ultraviolet and infrared extrapolations due to Hilbert-space truncations
- Uncertainty quantification essential
- Theoretical models are often applied to entirely new nuclear systems and conditions that are not accessible to experiment

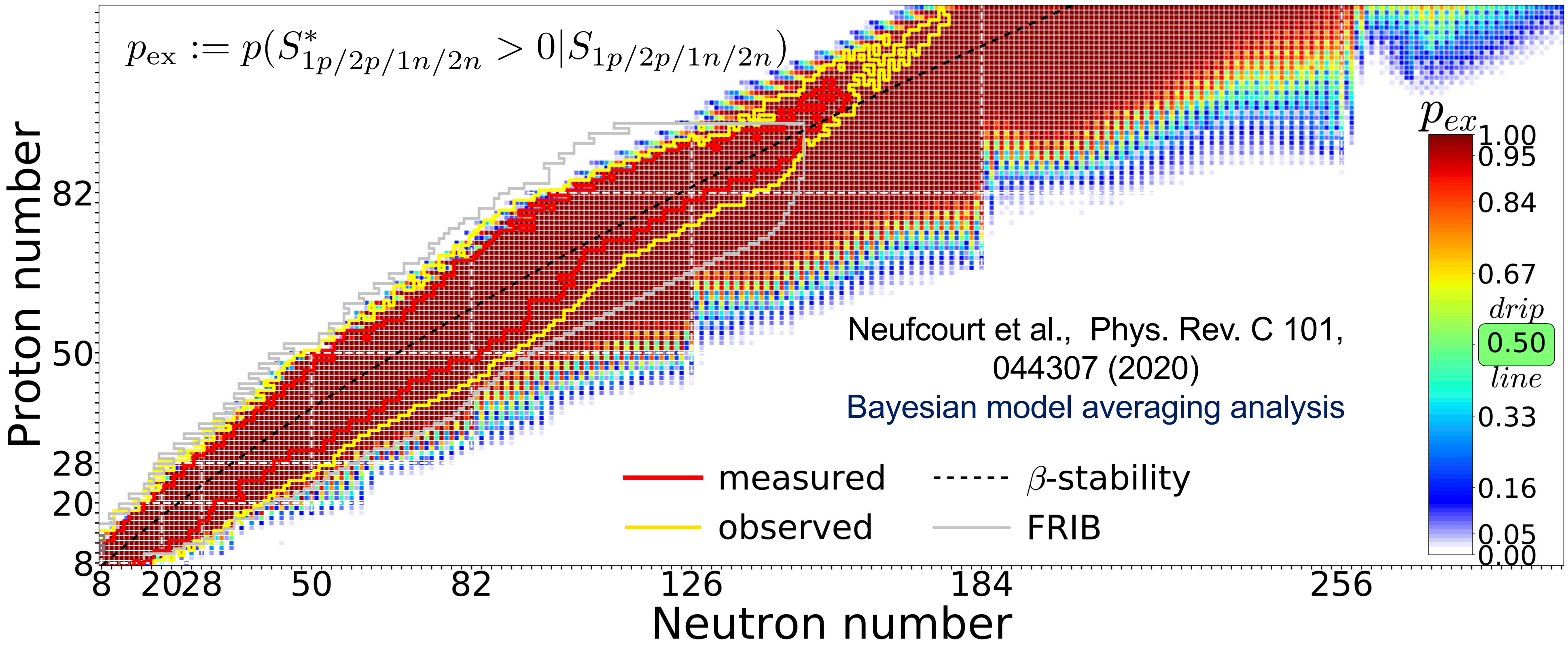






Nuclear theory as of 1995
observable
good model
“nice results”
reasonable model
bad model
EXP
TH1
TH2
TH3


Nuclear theory as of 2023
observable
What say you?
EXP
TH1
TH2
TH3

Nuclear landscape and particle drip lines



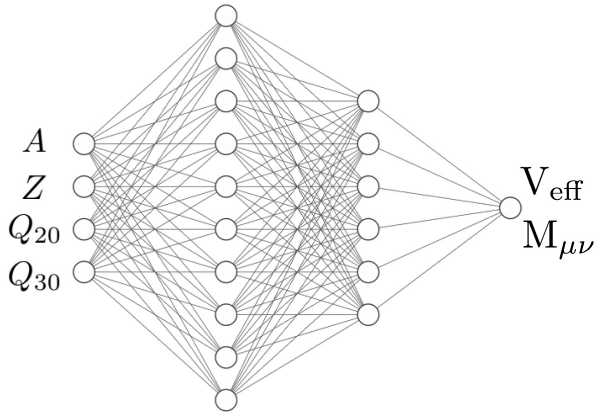
NEW: **Local Bayesian Dirichlet mixing of imperfect models**

Vojtech Kejzlar, Léo Neufcourt & Witold Nazarewicz

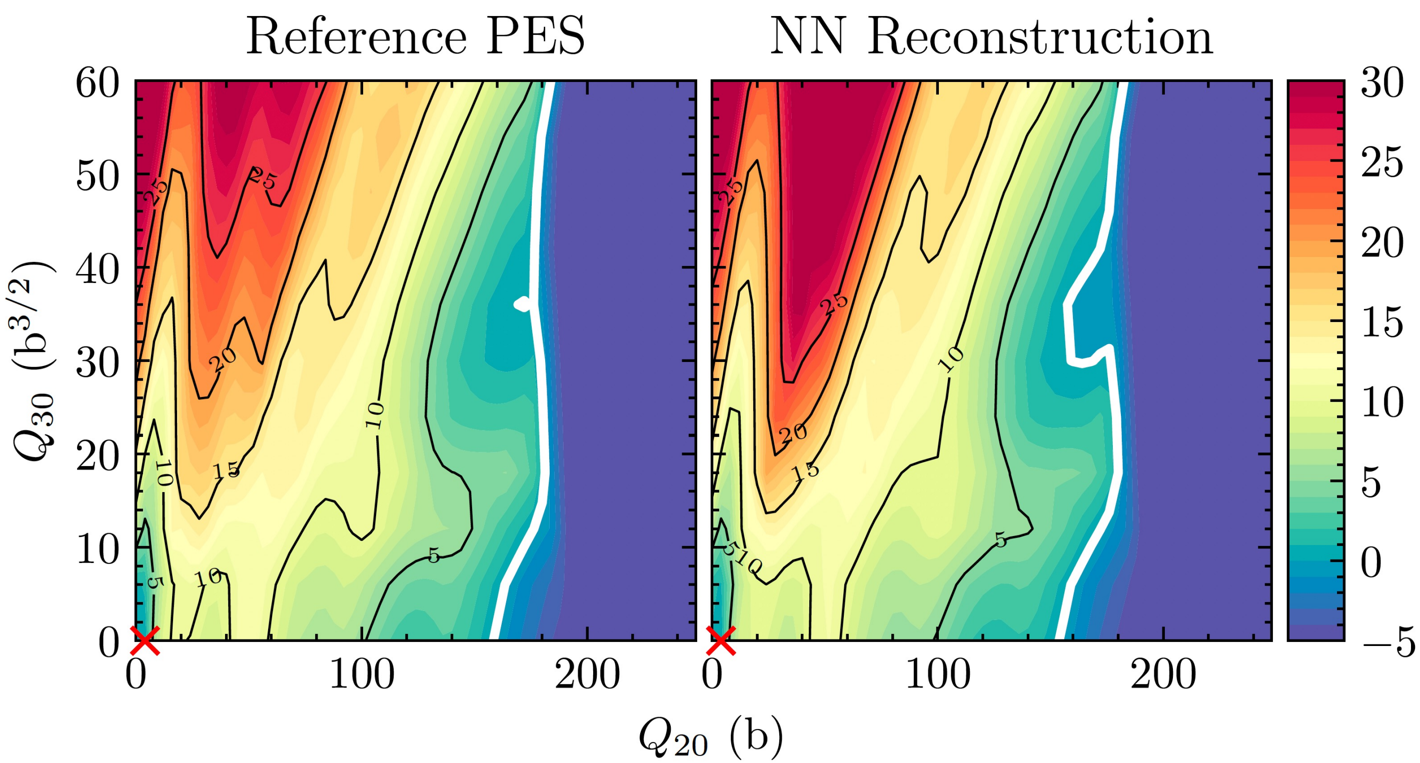
Scientific Reports **13**, Article number: 19600 (2023) | Cite this article

Neural Network Emulation of Spontaneous Fission (D. Lay, E. Flynn et al. arXiv:2310.01608)

Goal: Emulate PES and collective inertia across the nuclear chart using committee of neural networks, similar to Lasseri et. al., Phys. Rev. Lett. 124, 162502 (2020)



^{280}Cm



Many areas for expansion of (IRL-NPA) collaborations!

- Open quantum systems
- Nuclear density functional theory and its extensions
  - EDF development, calibration
- Small amplitude collective motion (EM strength, beta decay)
- Large amplitude collective motion (fission and heavy-ion fusion)
  - Dissipative dynamics
  - Time dependent approaches
- Uncertainty quantification
- Machine learning applications
  - Emulators
  - Bayesian machine learning