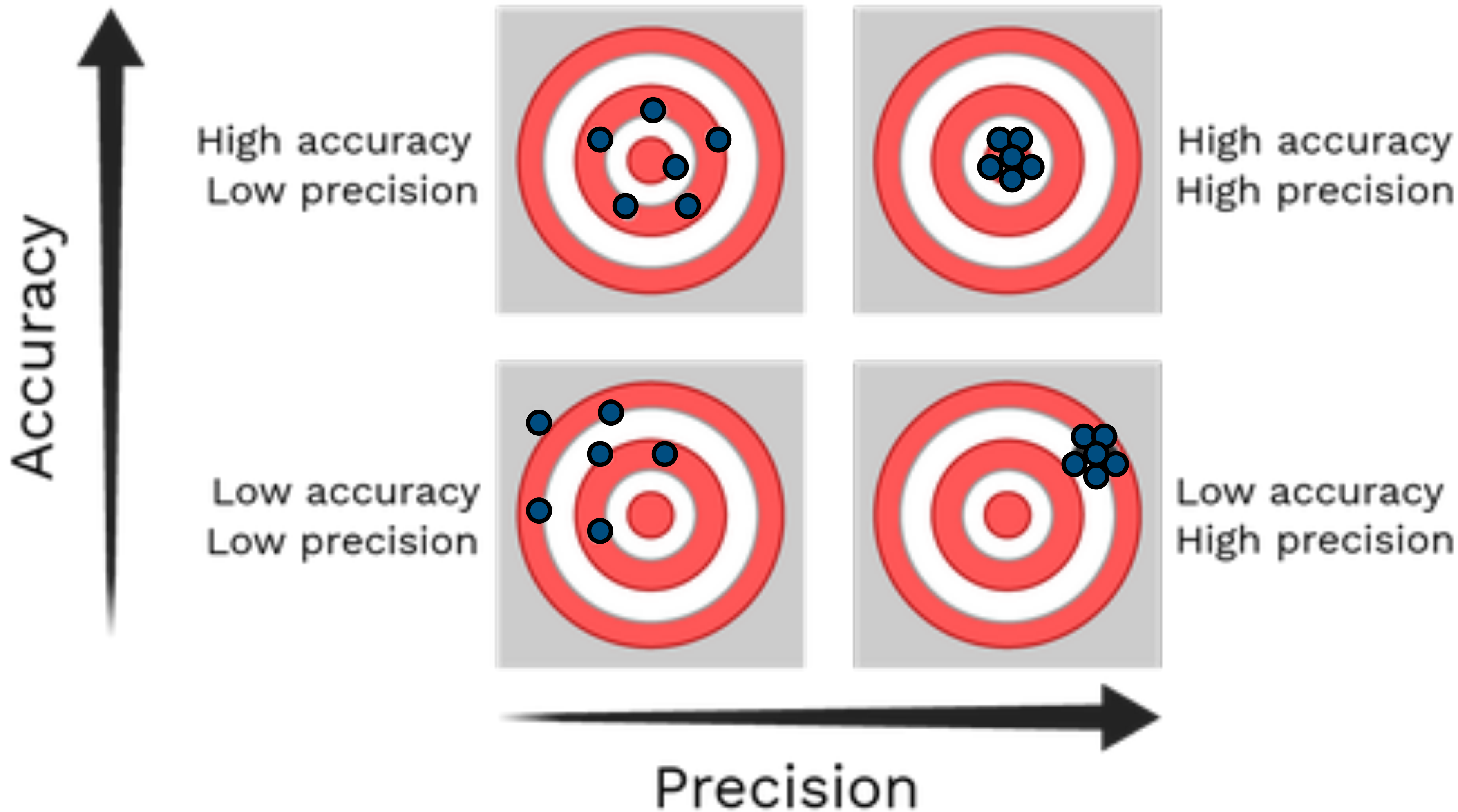

Precision nuclear theory

Christian Forssén
Chalmers University of Technology

14th International Spring Seminar on Nuclear Physics:
"*Cutting-edge developments in nuclear structure physics*" Ischia, May 19-23, 2025

Many thanks to my collaborators

CHALMERS UNIVERSITY OF TECHNOLOGY

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OAK RIDGE National Laboratory

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Durham University

Ian Vernon

UNIVERSITY OF NOTRE DAME

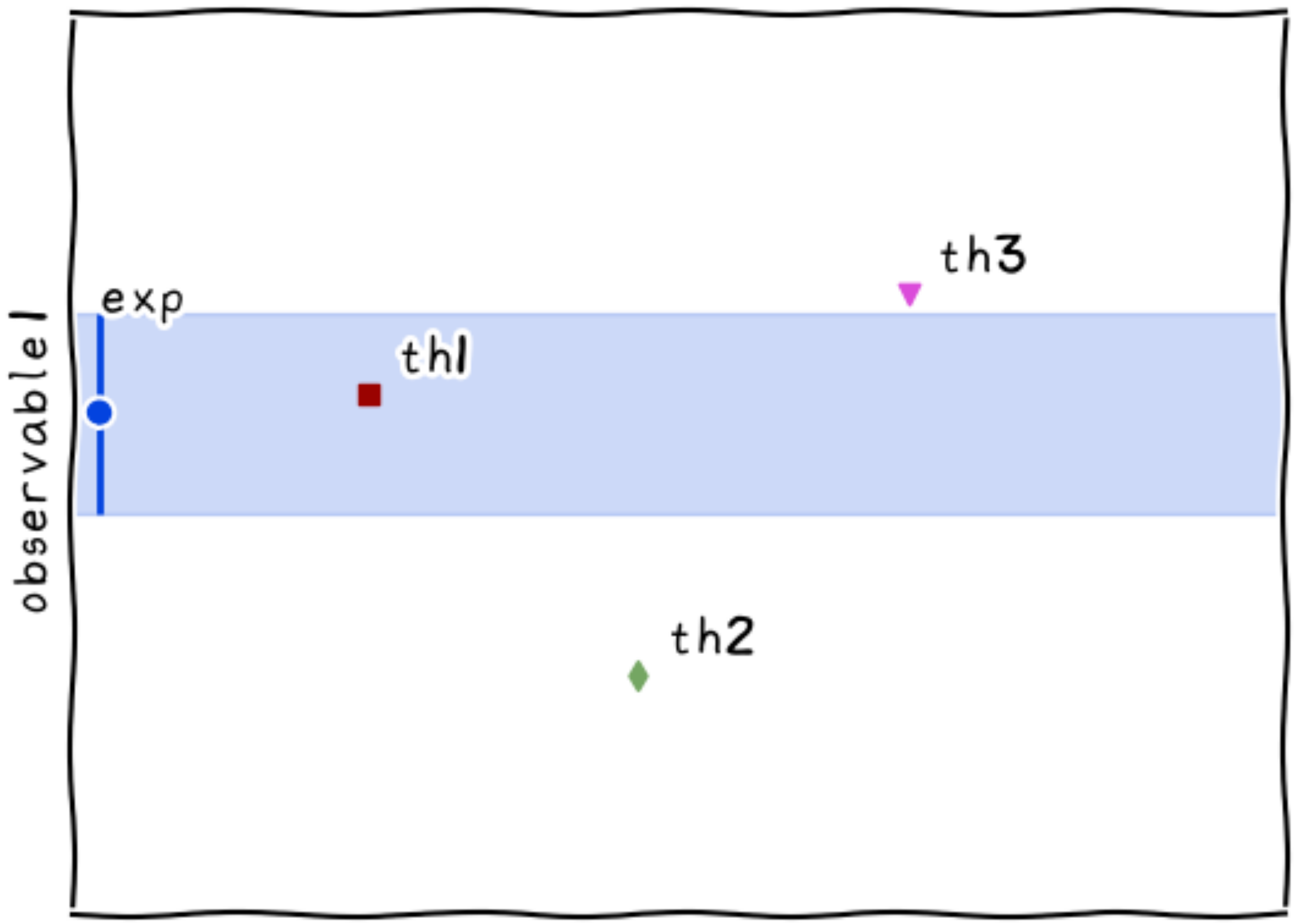
OHIO UNIVERSITY

Baishan Hu (A&M Texas), Takayuki Miyagi (Tsukuba), Ragnar Stroberg (Notre Dame), Weiguang Jiang (Mainz)

THE OHIO STATE UNIVERSITY

Dick Furnstahl (OSU), Daniel Phillips (OU)

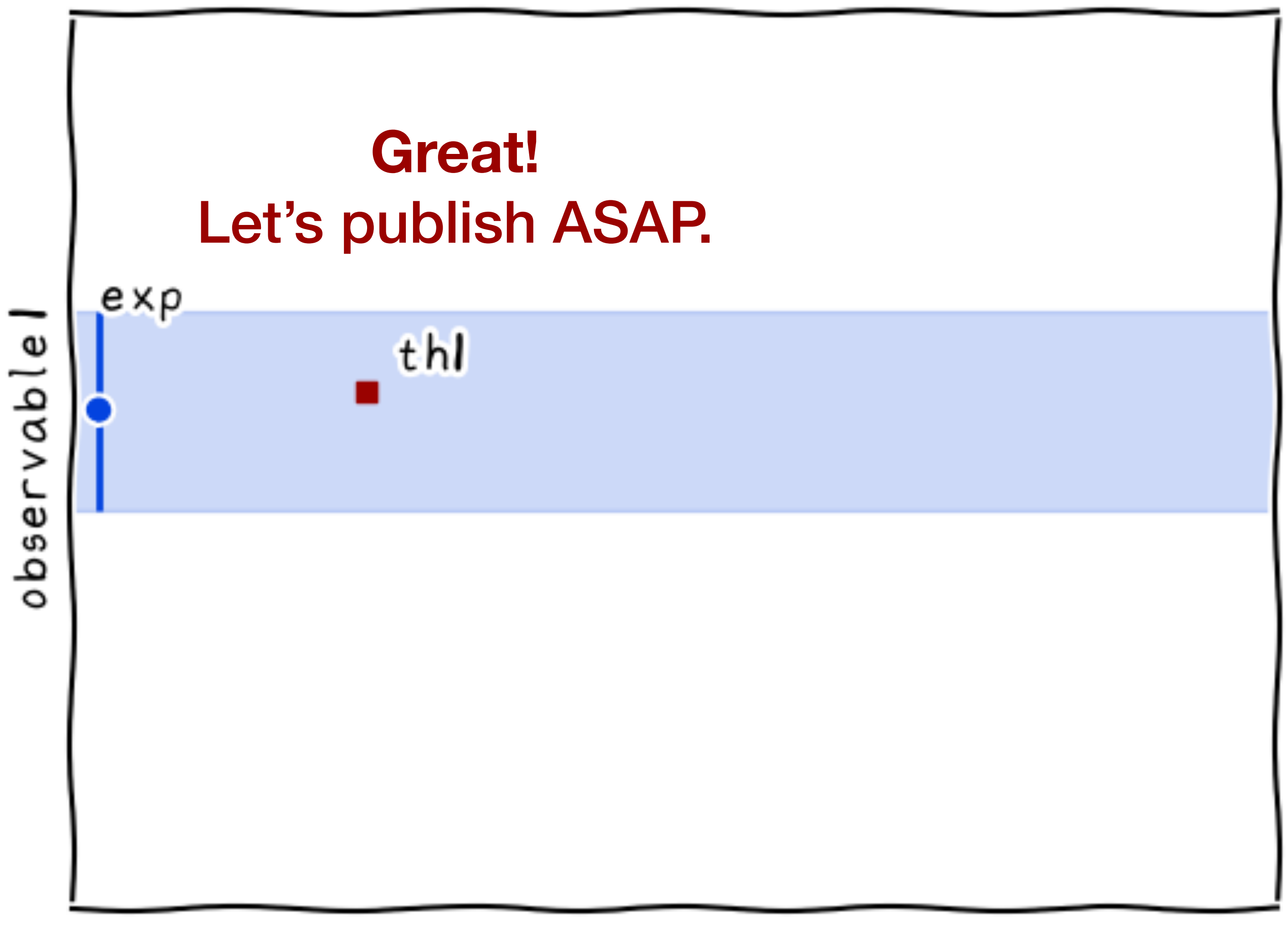
The importance of precision



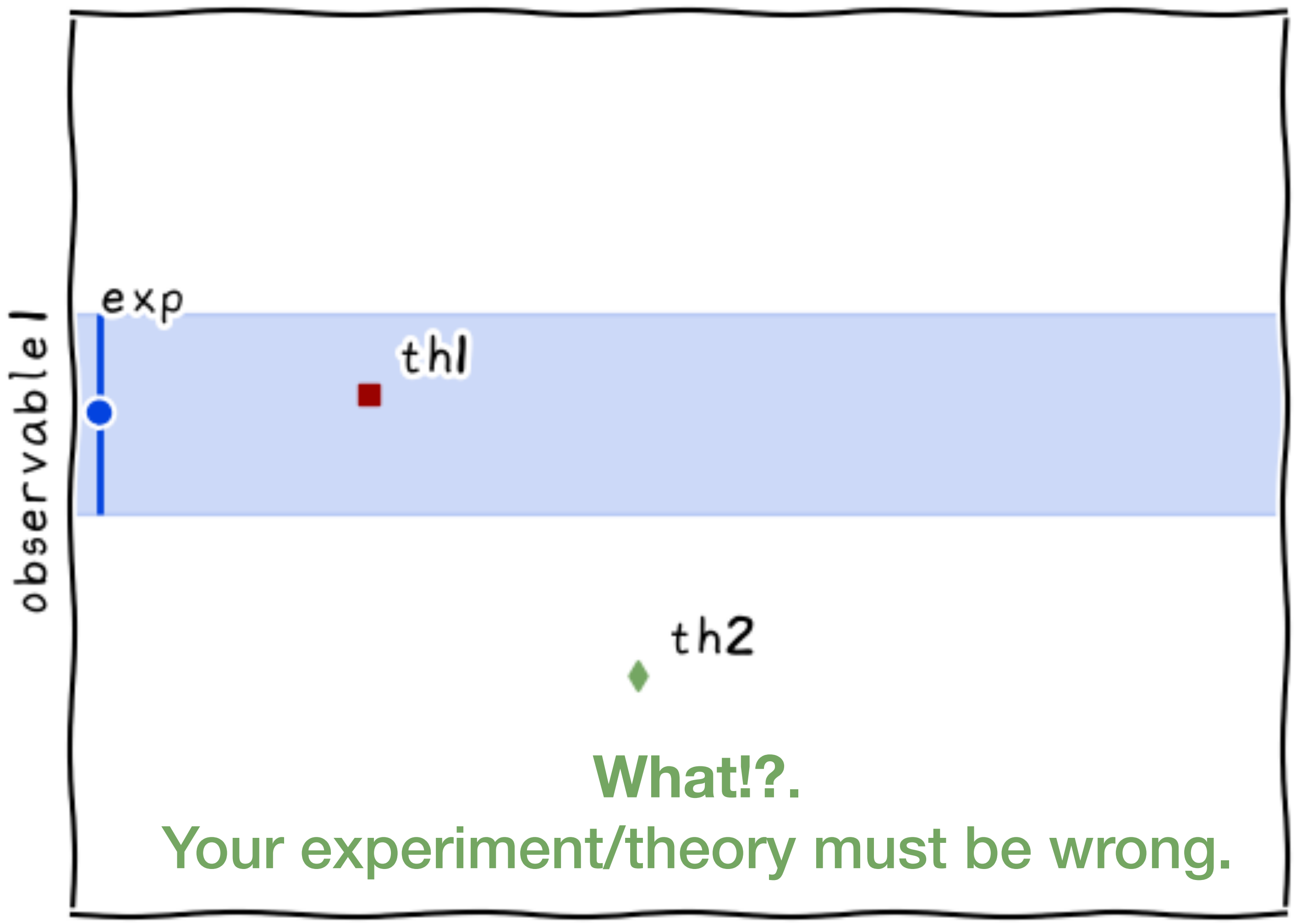
$$y_{\rm exp} + \delta y_{\rm exp} = y_{\rm th}(\boldsymbol{\alpha})$$

Credit W. Nazarewicz,
INTRANS 2024

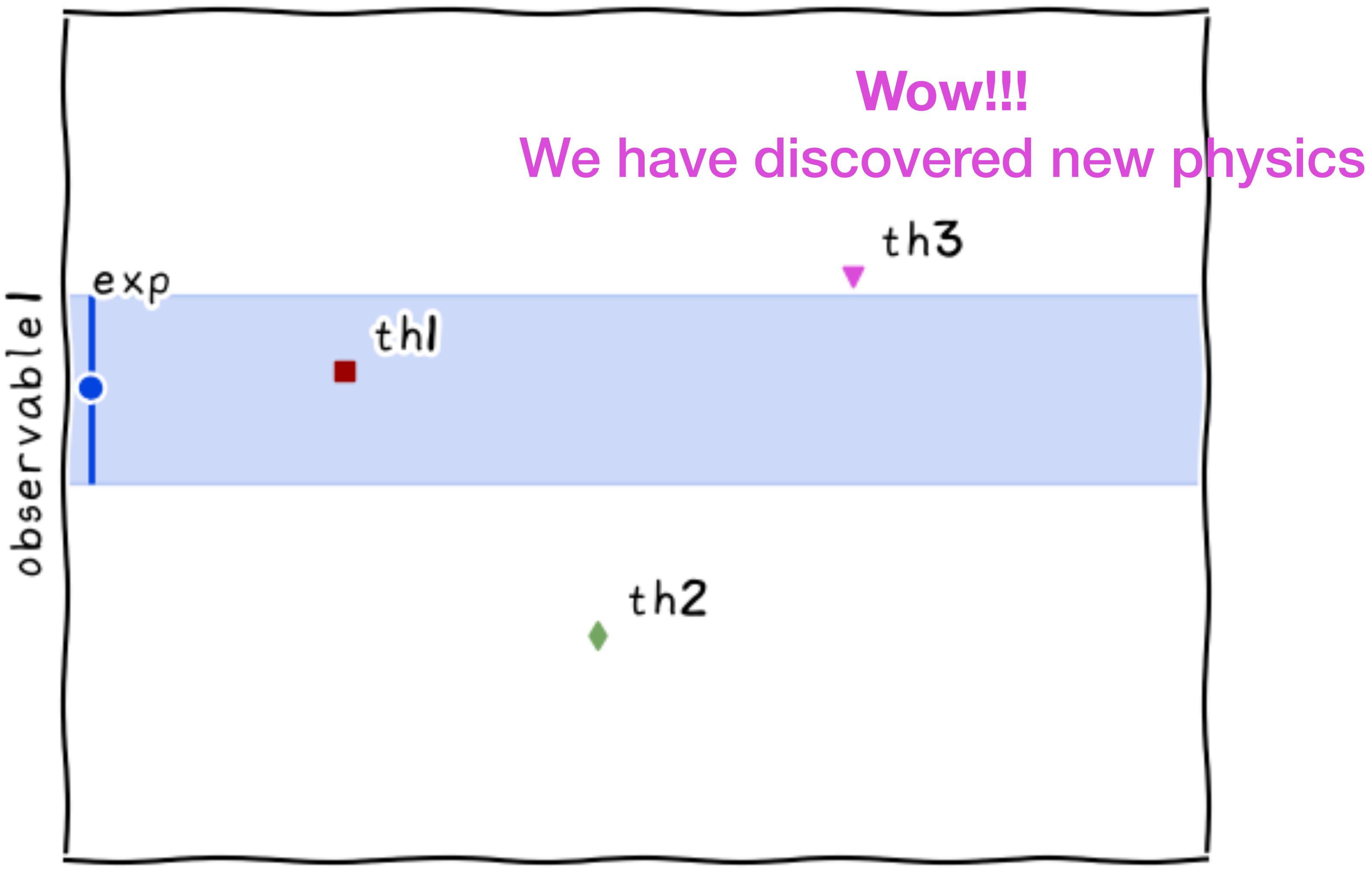
The importance of precision



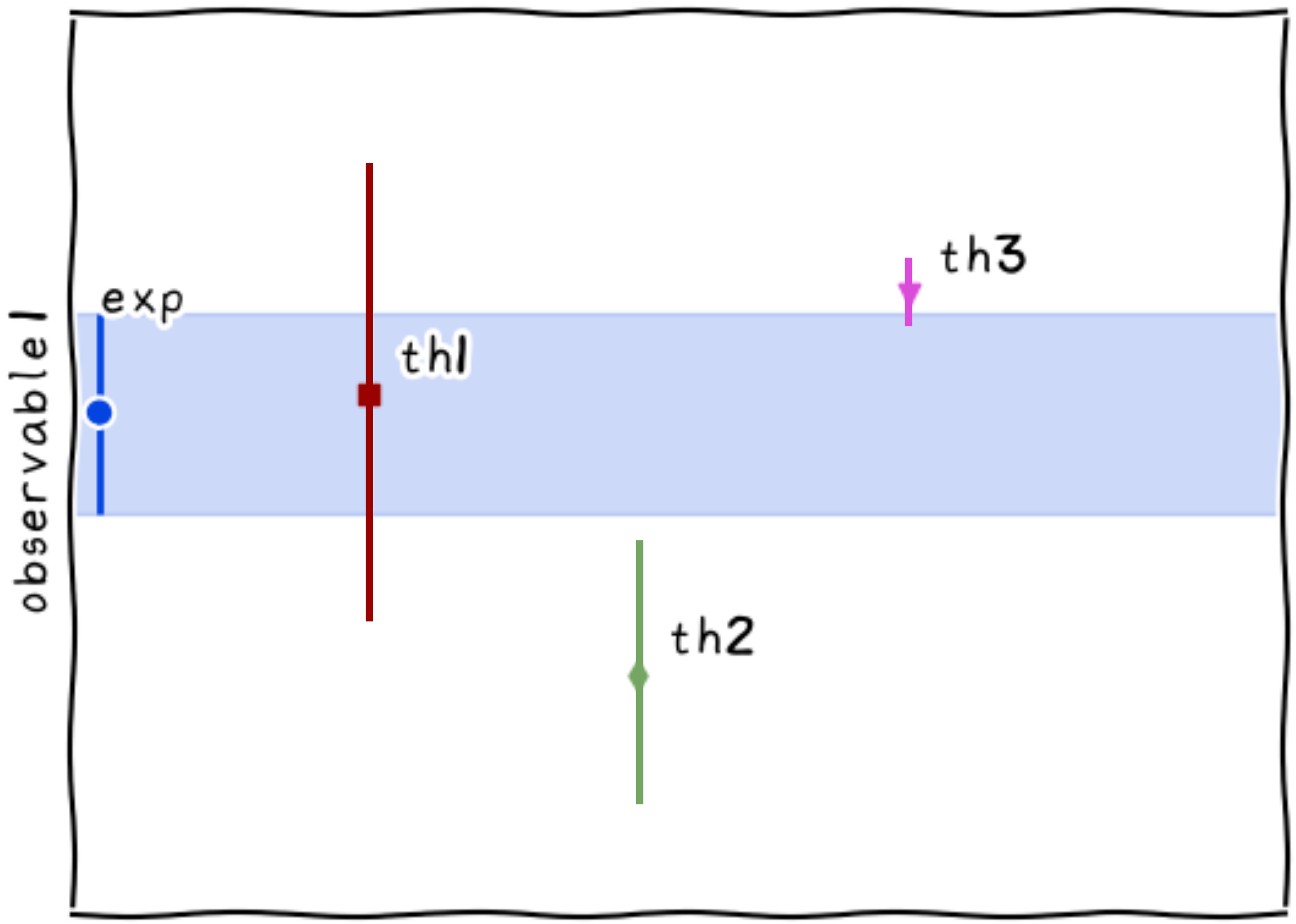
The importance of precision



The importance of precision



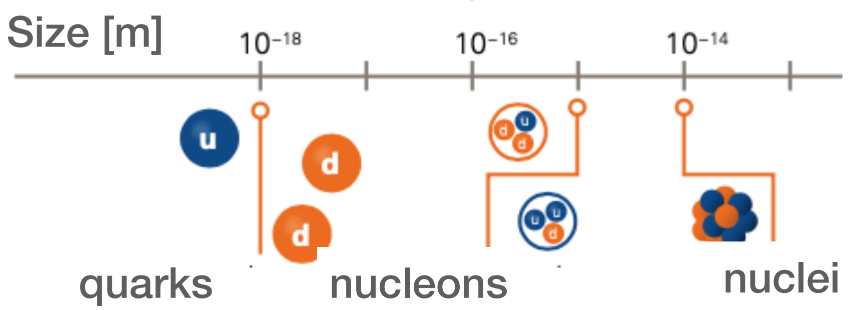
The importance of precision



$$y_{\text{exp}} + \delta y_{\text{exp}} = y_{\text{th}}(\boldsymbol{\alpha}) + \delta y_{\text{th}}$$

With complete uncertainty quantification this relation turns into a **statistical model**

Scientific goals in *ab initio* nuclear theory

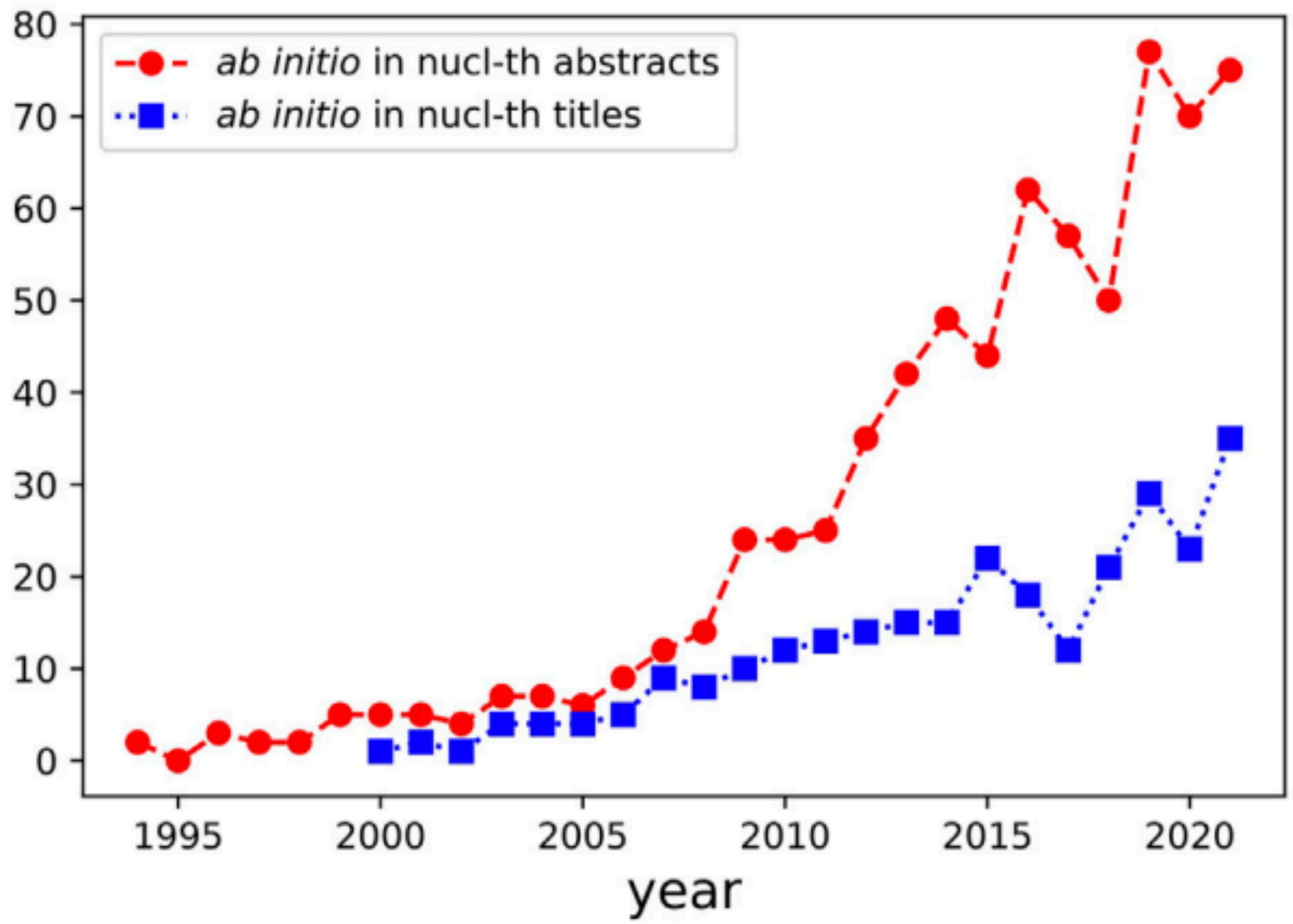


- Model the strong interaction at low-energy
  - At the most fundamental level, the strong interaction is described by Quantum Chromodynamics (QCD);
  - Atomic nuclei can presumably be described with relevant low-energy degrees of freedom—nucleons and pions—and residual interactions;
  - Effective field theories (EFTs) offer a systematic approach to this problem.
  - **Infer the parameters** (low-energy constants = LECs) of chiral EFT from low-energy observables such as NN scattering phase shifts, few-nucleon observables.

- Universal framework for few- and many-nucleon modeling
  - **Universal framework** for modeling of strongly-interacting many-nucleon systems.
  - Solve the many-nucleon problem with **controlled approximations.**

- Predictive power
  - **Linking** nuclear structure and observables to fundamental forces.
  - Reliably **predict** scientifically relevant nuclear observables.

Why *ab initio* is more like Gruyère than Champagne



Fine resolution scale

Predictive capability

Systematically improvable

We(*) interpret the *ab initio* method as a
“systemati

p… …imizing its
p… …tive capabilities.”

Ab initio ⇒
Inferential advantage—but not necessarily increased accuracy

Vibrant competitive marketplace

Trademark

(*)A. Ekström, cf, G.Hagen, G. R. Jansen, W.G. Jiang, and T. Papenbrock, Frontiers in Phys. (2023)

Reach of *ab initio* nuclear theory

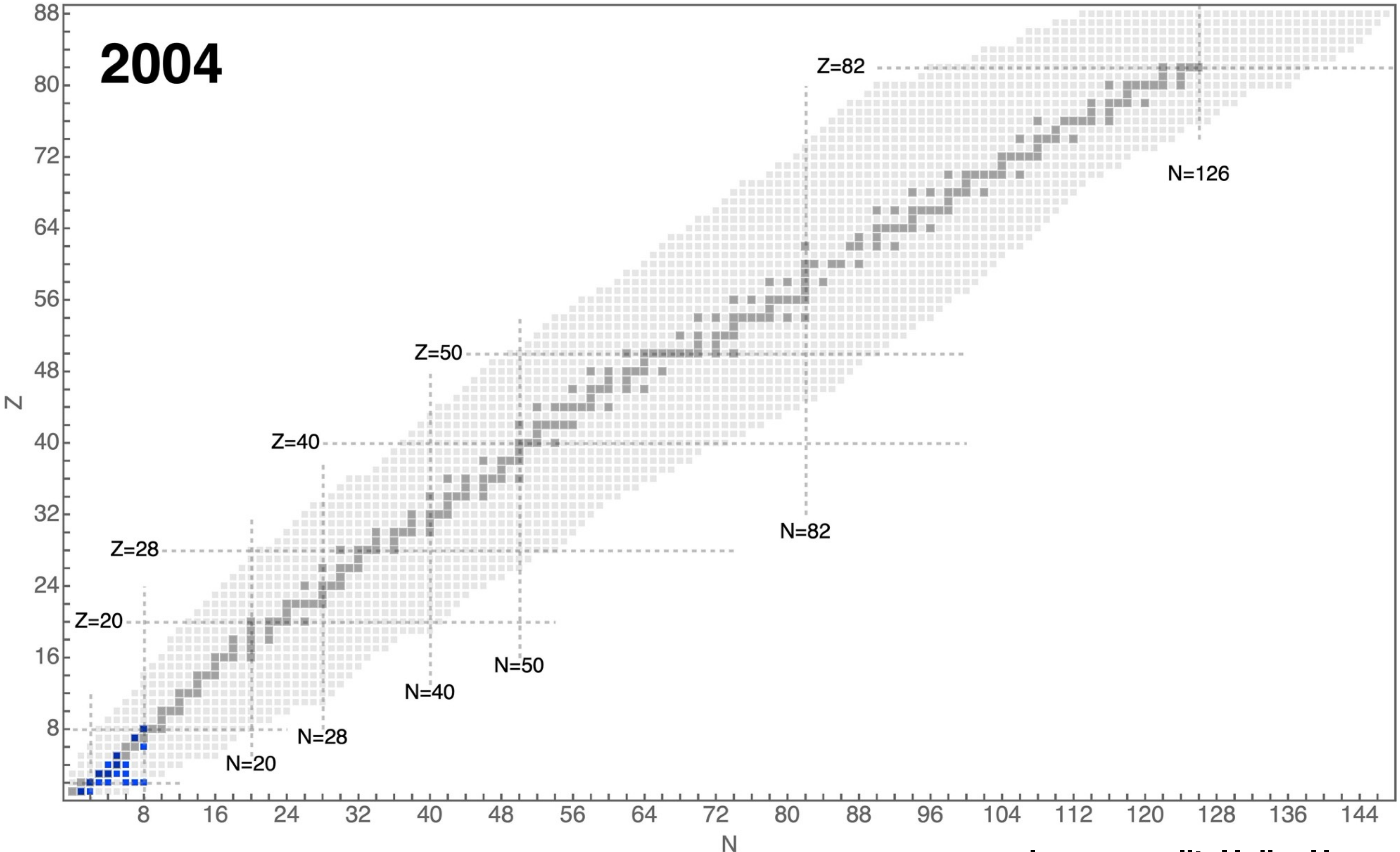
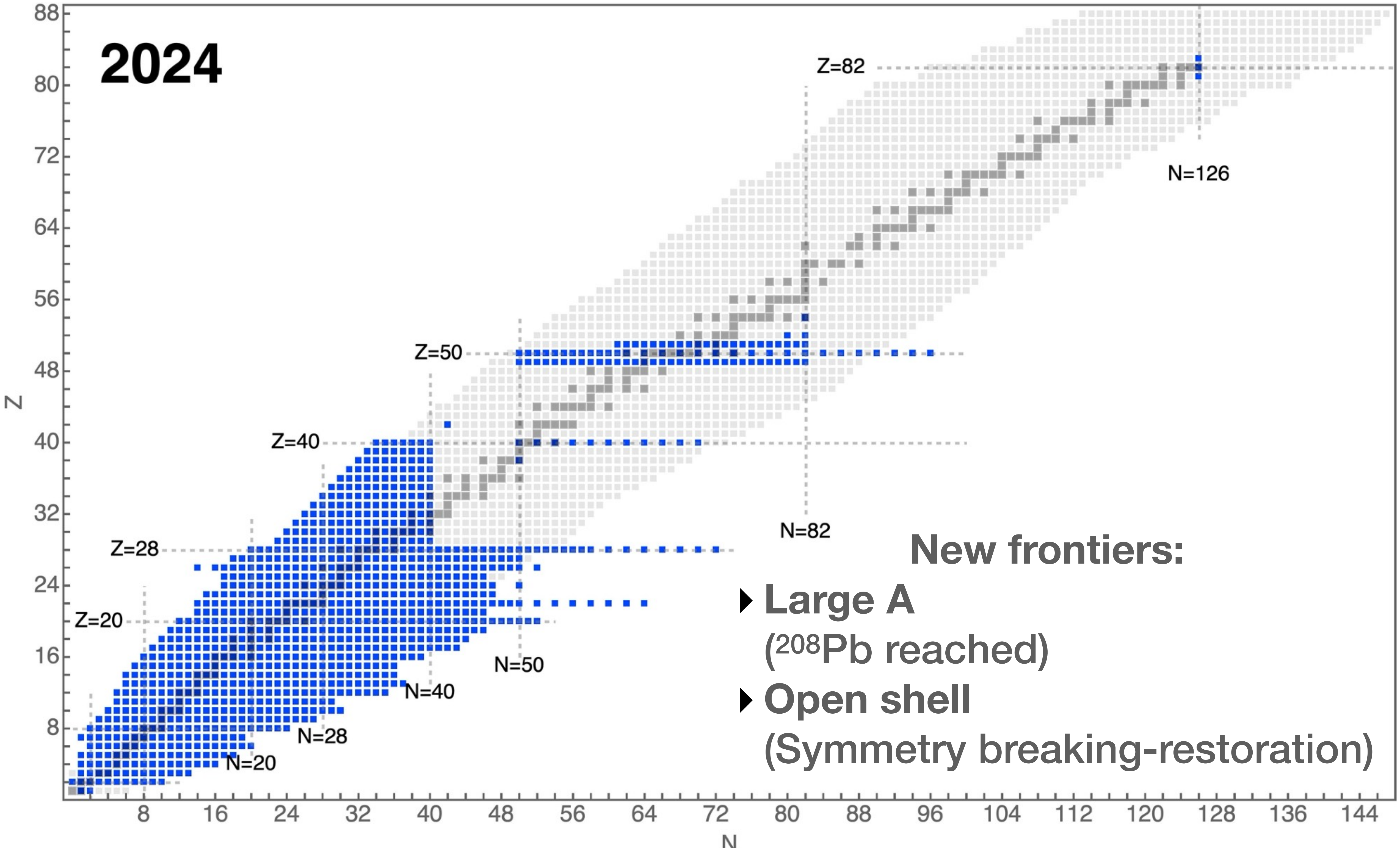


Image credit: Heiko Hergert

Reach of *ab initio* nuclear theory



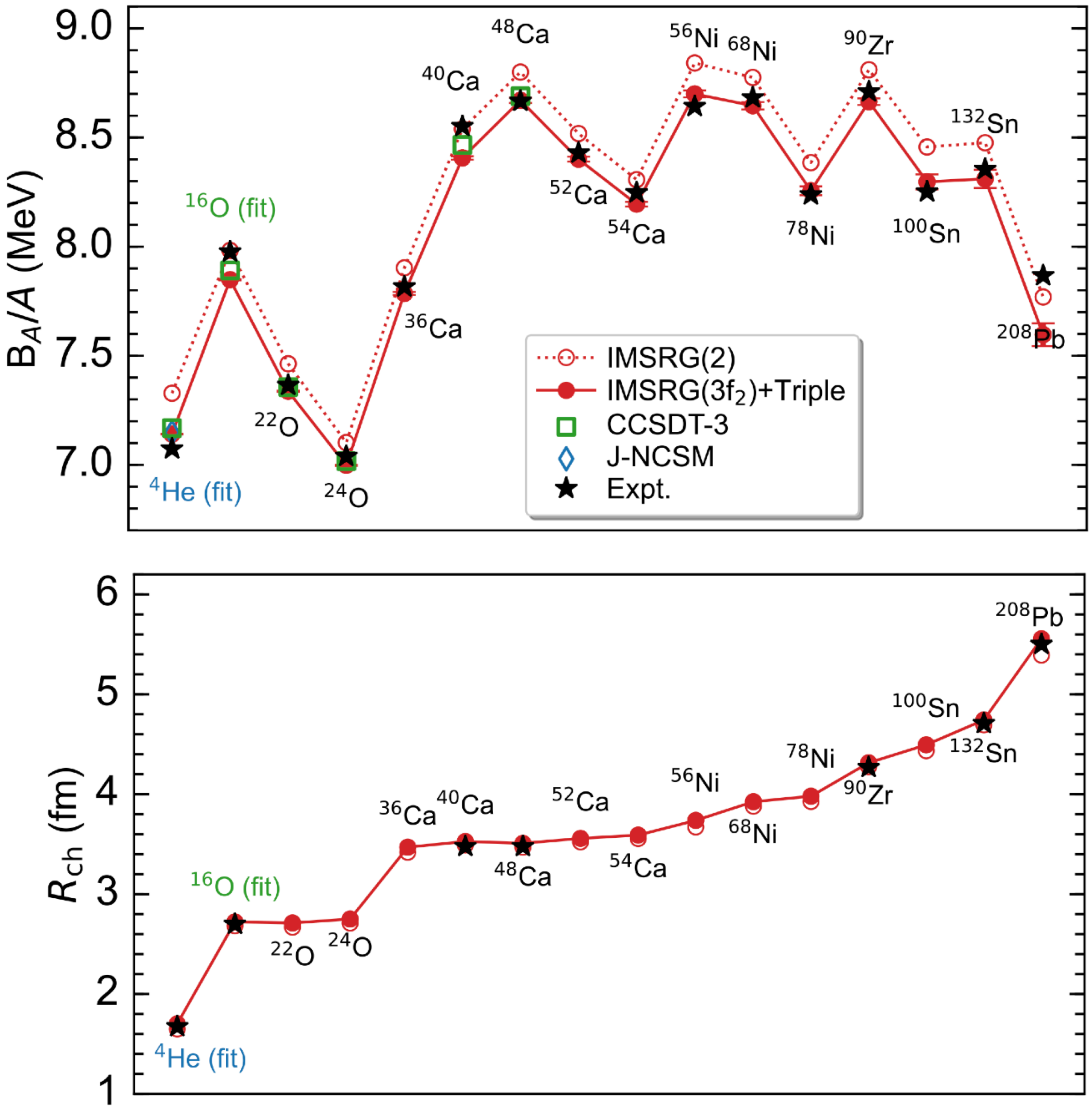
New frontiers:

- **Large A**
  (^{208}Pb reached)
- **Open shell**
  (Symmetry breaking-restoration)

Image credit: Heiko Hergert

Accuracy: N3LO$_{TX}$ (work in progress)

- Optimization includes NN observables, ^{4}He and ^{16}O energy and radius.
- Enabled by the use of fast & accurate emulators (reduced-order models)



Baishan Hu, Weiguang Jiang, A. Ekström, cf, G. Hagen. T. Papenbrock (2025) in prep.

From accuracy to precision in *ab initio* theory

- Model the strong interaction at low-energy
  - Effective field theories (EFTs) offer a systematic description of this physics.
  - Truncating your EFT implies an understanding of the importance of terms beyond the truncation order.
- Bayesian parameter estimation and model checking
  - The **inference** of EFT parameters using low-energy observables.
  - Also other parameters might be of interest. E.g.,
    - Can we infer the breakdown scale of the EFT?
    - Can we rigorously test the EFT model assumptions?
- Predictive power strongly linked to precision
  - **Predict** scientifically relevant nuclear observables with **quantified uncertainties.**

Learning from data via Bayesian statistics

- Model calibration via **Bayes' theorem**

Likelihood Prior

Posterior

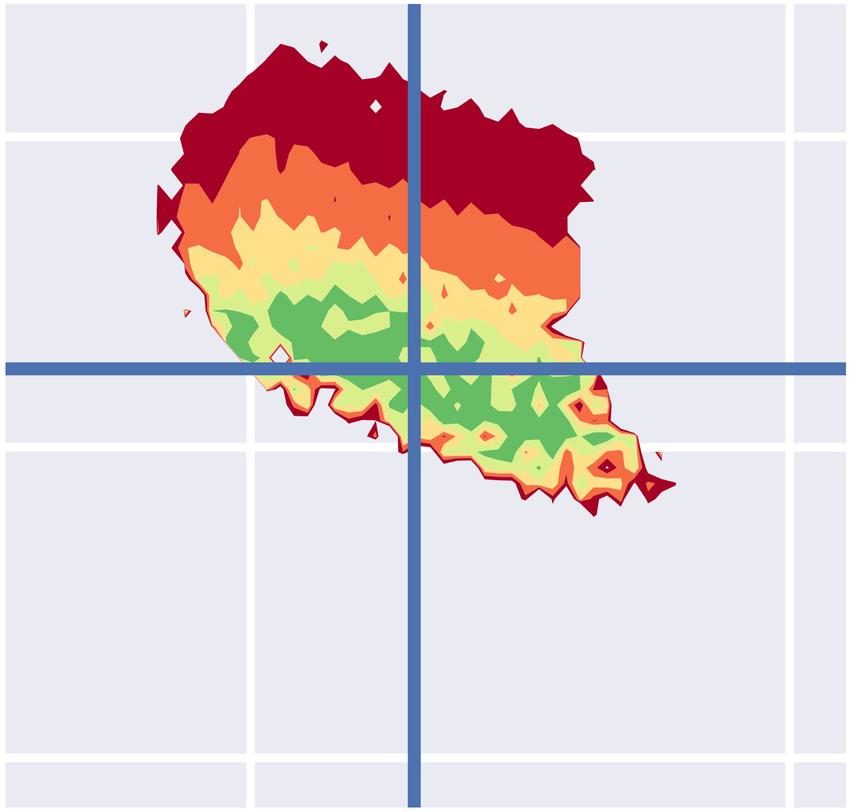
$$\mathrm{pr}(\boldsymbol{\alpha} \,|\, \mathscr{D}, I) = \frac{\mathrm{pr}(\mathscr{D} \,|\, \boldsymbol{\alpha}, I)\,\mathrm{pr}(\boldsymbol{\alpha} \,|\, I)}{\mathrm{pr}(\mathscr{D} \,|\, I)}$$

Marginal likelihood

  - **The prior encodes our knowledge about parameter values before analyzing the data**
  - **The likelihood is the probability of observing the data given a set of parameters**
  - **The marginal likelihood (or model evidence) provides normalization of the posterior.**
  - **The posterior is the inferred probability density for the parameters.**

- Statistical models (for *ab initio* predictions)

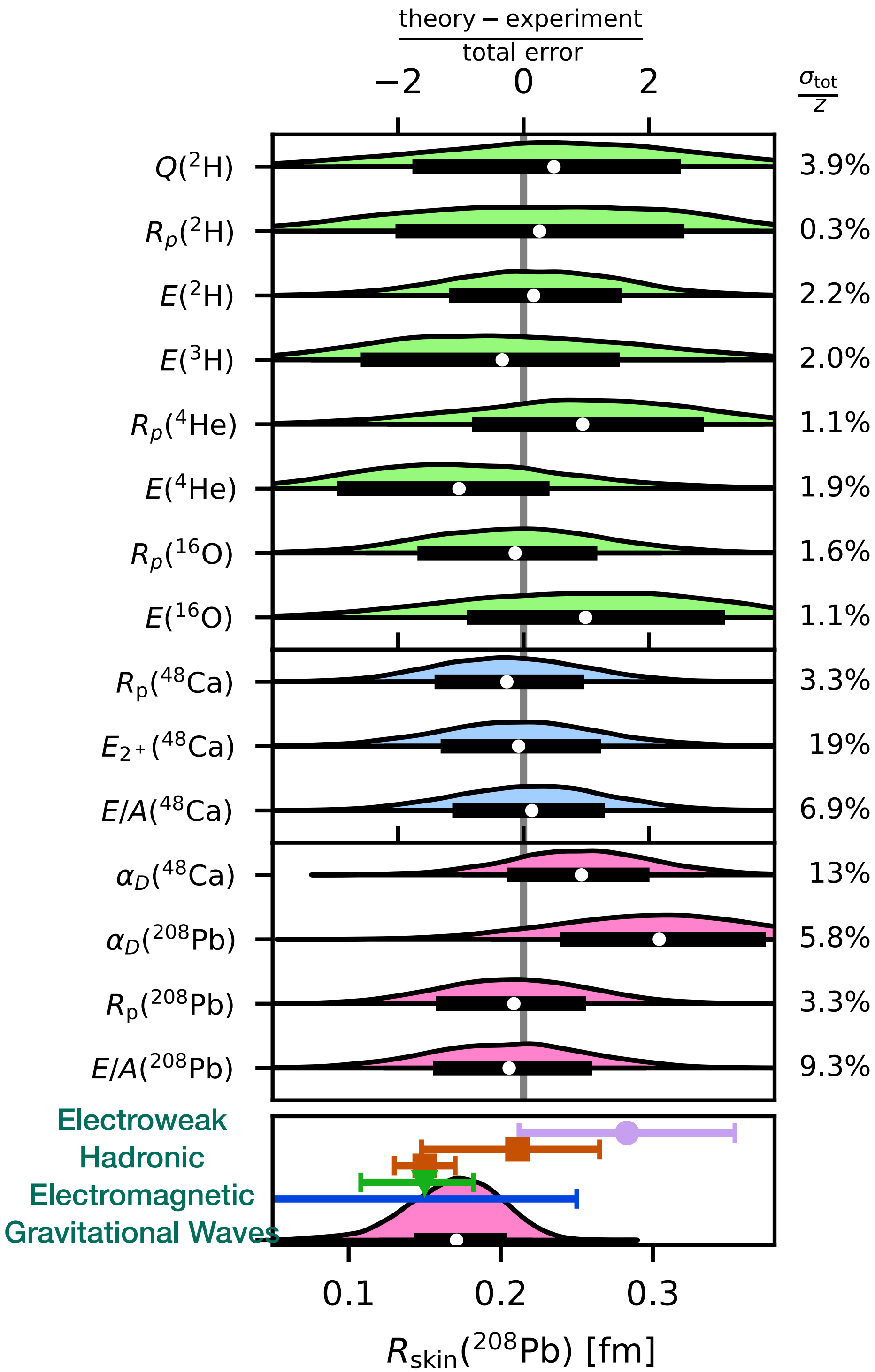
$$\boldsymbol{y}_{\mathrm{exp}} = \tilde{y}(\boldsymbol{\alpha}) + \delta\boldsymbol{y}_{\mathrm{EFT}} + \delta\boldsymbol{y}_{\mathrm{method}} + \delta\tilde{\boldsymbol{y}}_{\mathrm{em}} + \delta\boldsymbol{y}_{\mathrm{exp}}$$



The present: *ab initio* predictions with quantified uncertainties

Selected examples

Ab initio predictions link the skin of ^{208}Pb to nuclear forces



History Matching

We explore 10^9 different interaction parameterizations

Confronted with A=2-16 data + NN scattering information

Find 34 non-implausible interactions

Model calibration

Importance resampling

Model checking

Inspect ab initio model and error estimates

B. Hu et al (Nature Phys. 2022)

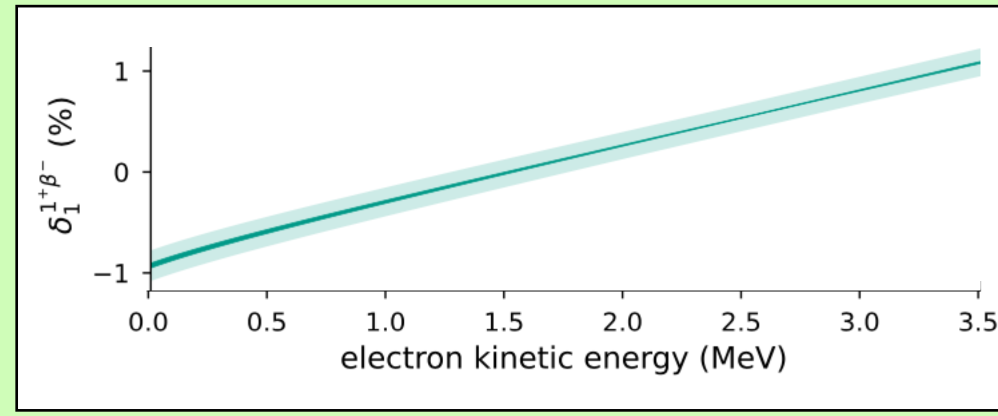
<u>Prediction</u>: small skin thickness 0.14-0.20 fm in mild (1.5 sigma) tension with PREX results.

Physics predictions with (complex) precision models

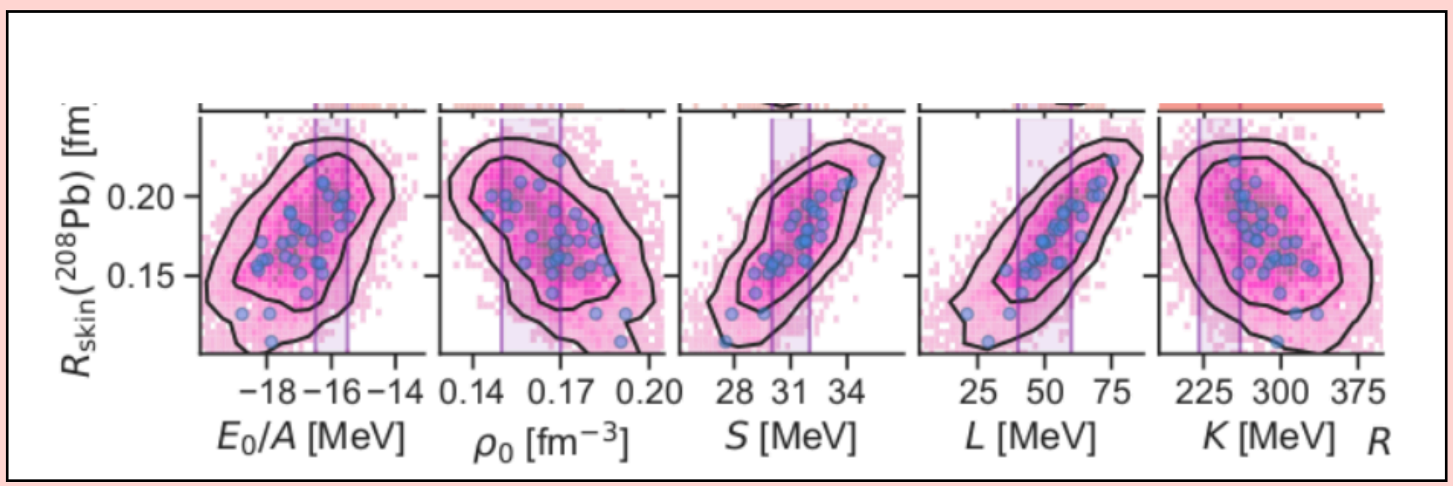
Searches for BSM physics via high-precision beta decay

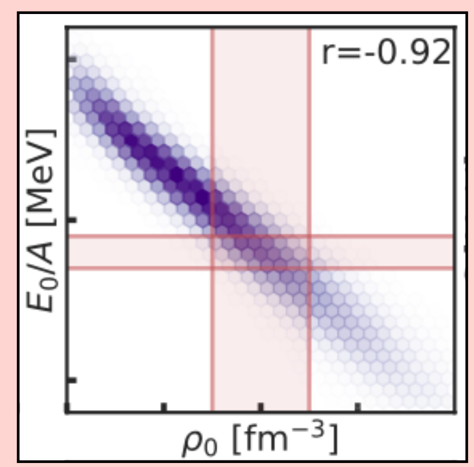
$$\frac{d\omega^{1^+\beta^-}}{dE\,\frac{d\Omega_k}{4\pi}\,\frac{d\Omega_\nu}{4\pi}} = \frac{4}{\pi^2}\left(E_0 - E\right)^2 kEF^-(Z_f,E)\,C_{\rm corr}\left|\langle\|\hat{L}_1^A\|\rangle\right|^2$$
$$\times 3\left(1+\delta_1^{1^+\beta^-}\right)\left[1 + a_{\beta\nu}^{1^+\beta^-}\vec{\beta}\cdot\hat{\nu} + b_{\rm F}^{1^+\beta^-}\frac{m_e}{E}\right],$$

A. Glick-Magid et al.,
Phys. Lett. B 832 (2022) 137259



Nuclear matter modelling



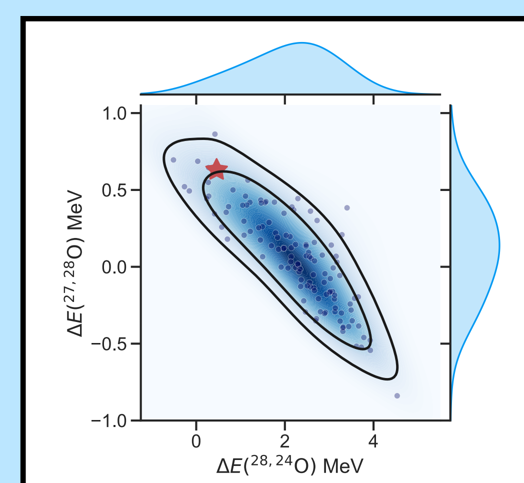


W. Jiang et al., PRC 109 (2024) L061302

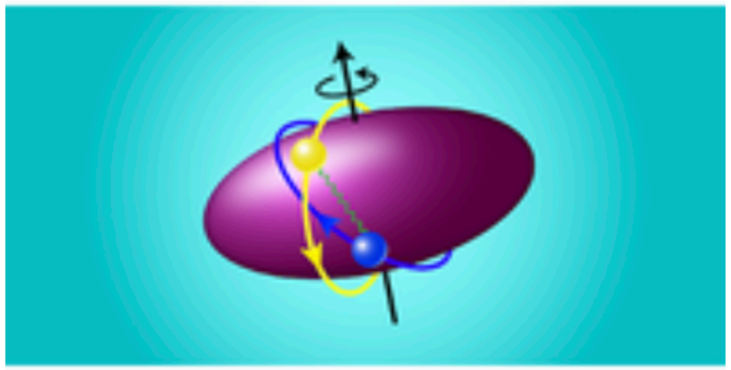
B. Hu et al., Nature Phys, 18 (2022) 1196,

Predictive modelling of rare isotopes such as heavy oxygen isotopes

Y. Kondo et al.,
Nature 620, (2023), 965



Ab initio predictions of deformed nuclei

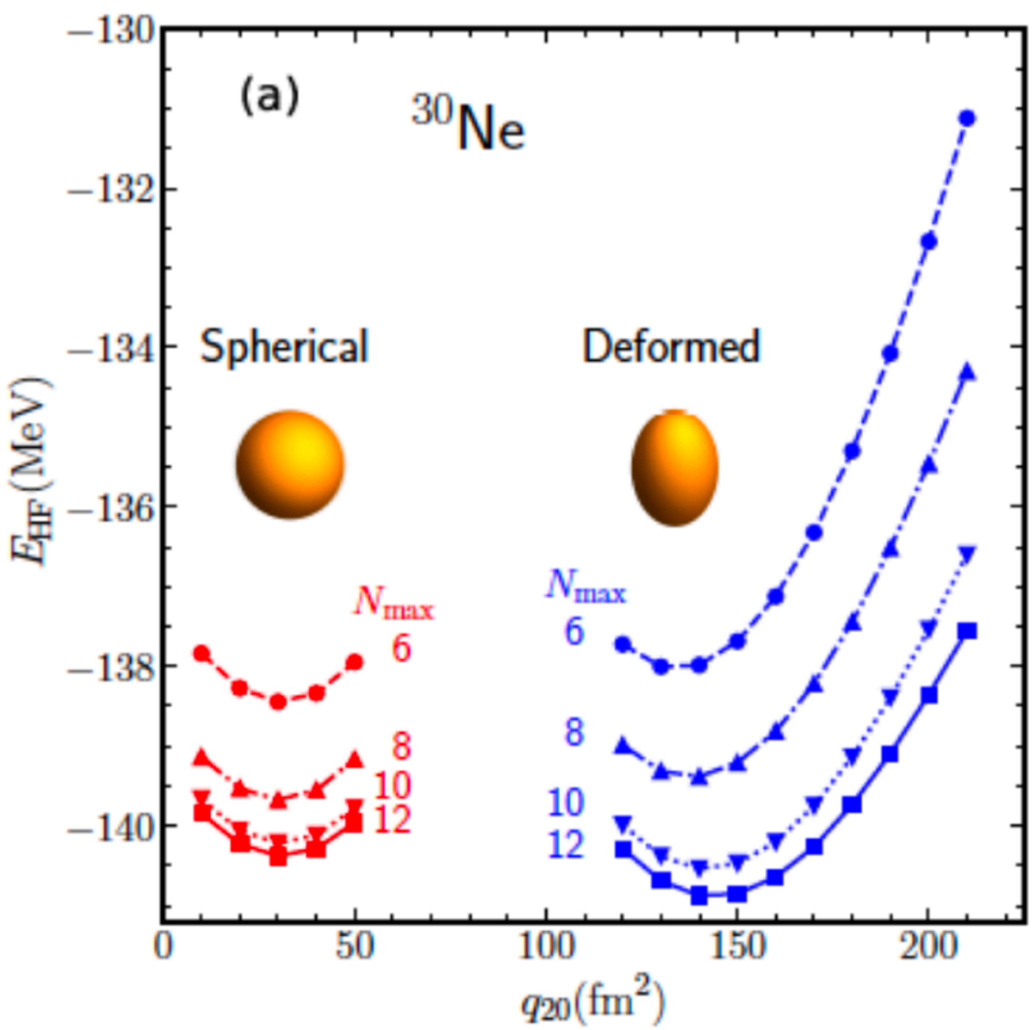


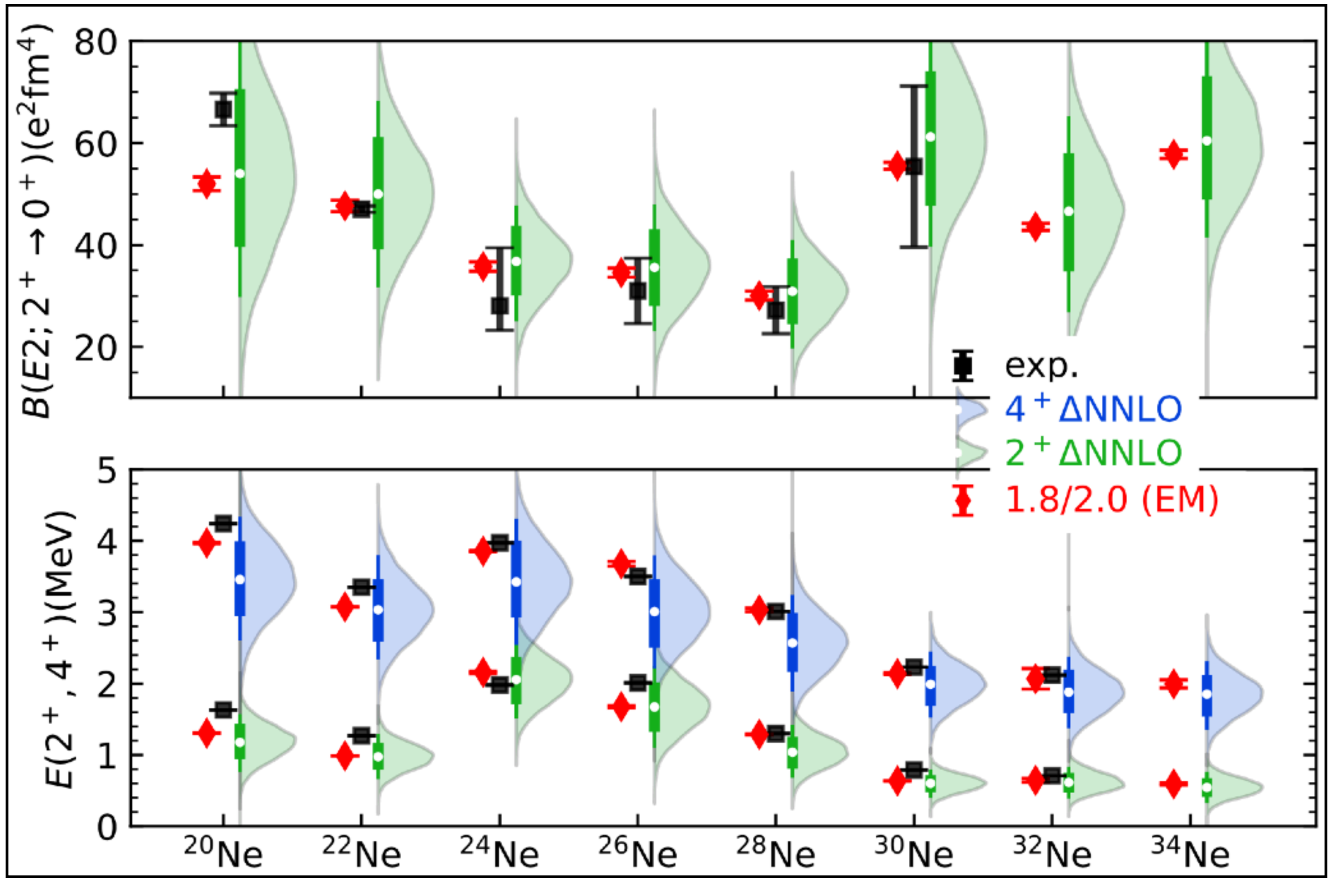
FEATURED IN PHYSICS

Multiscale Physics of Atomic Nuclei from First Principles

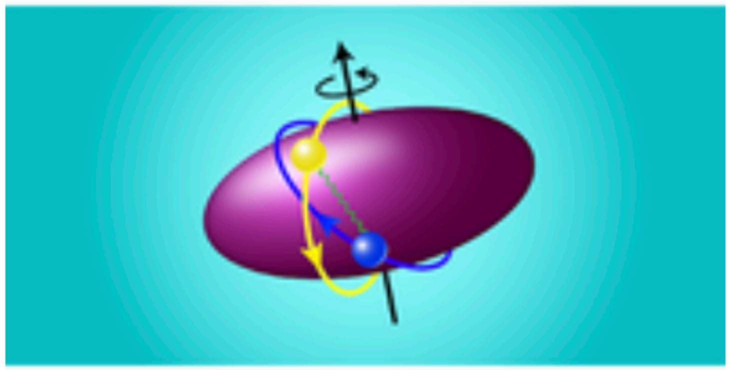
Z. H. Sun, A. Ekström, C. Forssén, G. Hagen, G. R. Jansen, and T. Papenbrock

Phys. Rev. X **15**, 011028 (2025)





Ab initio predictions of deformed nuclei



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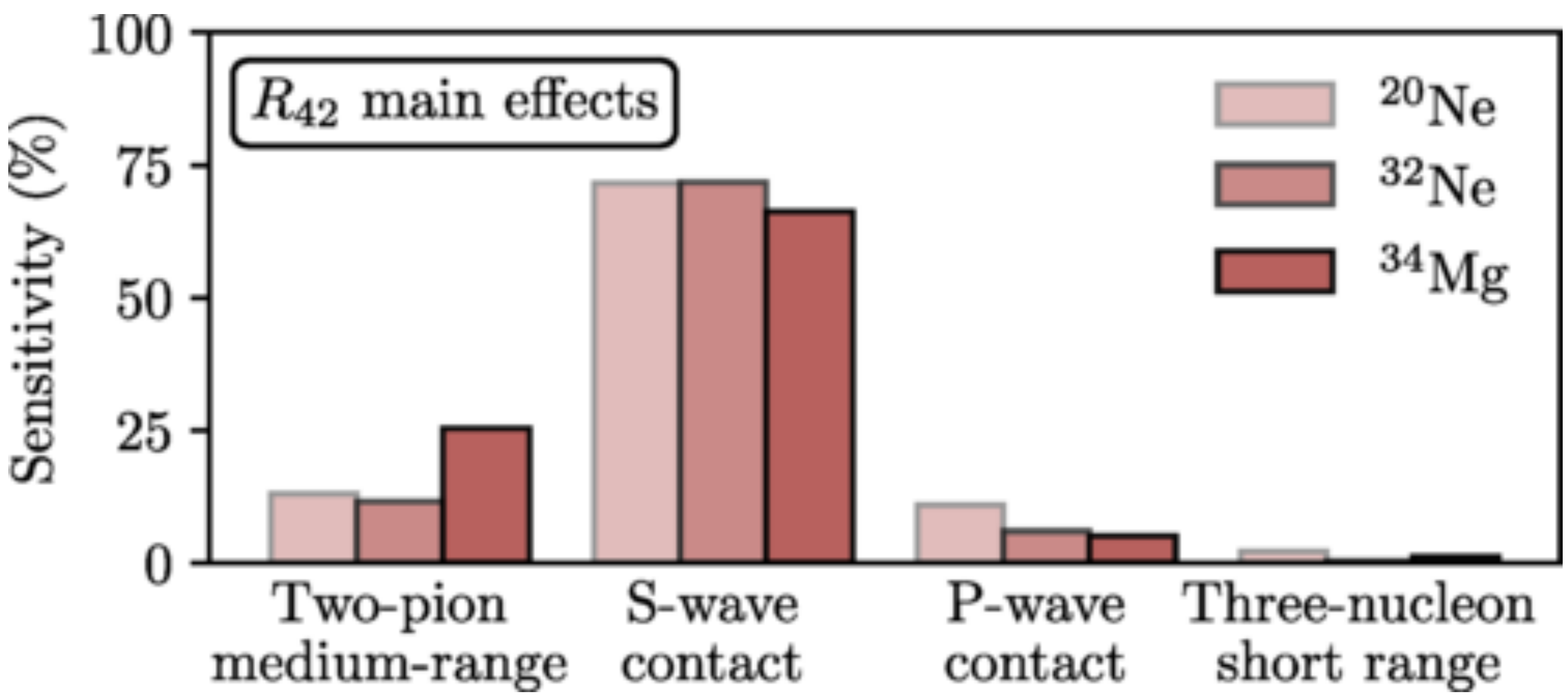


Global Sensitivity Analysis of R_{42}

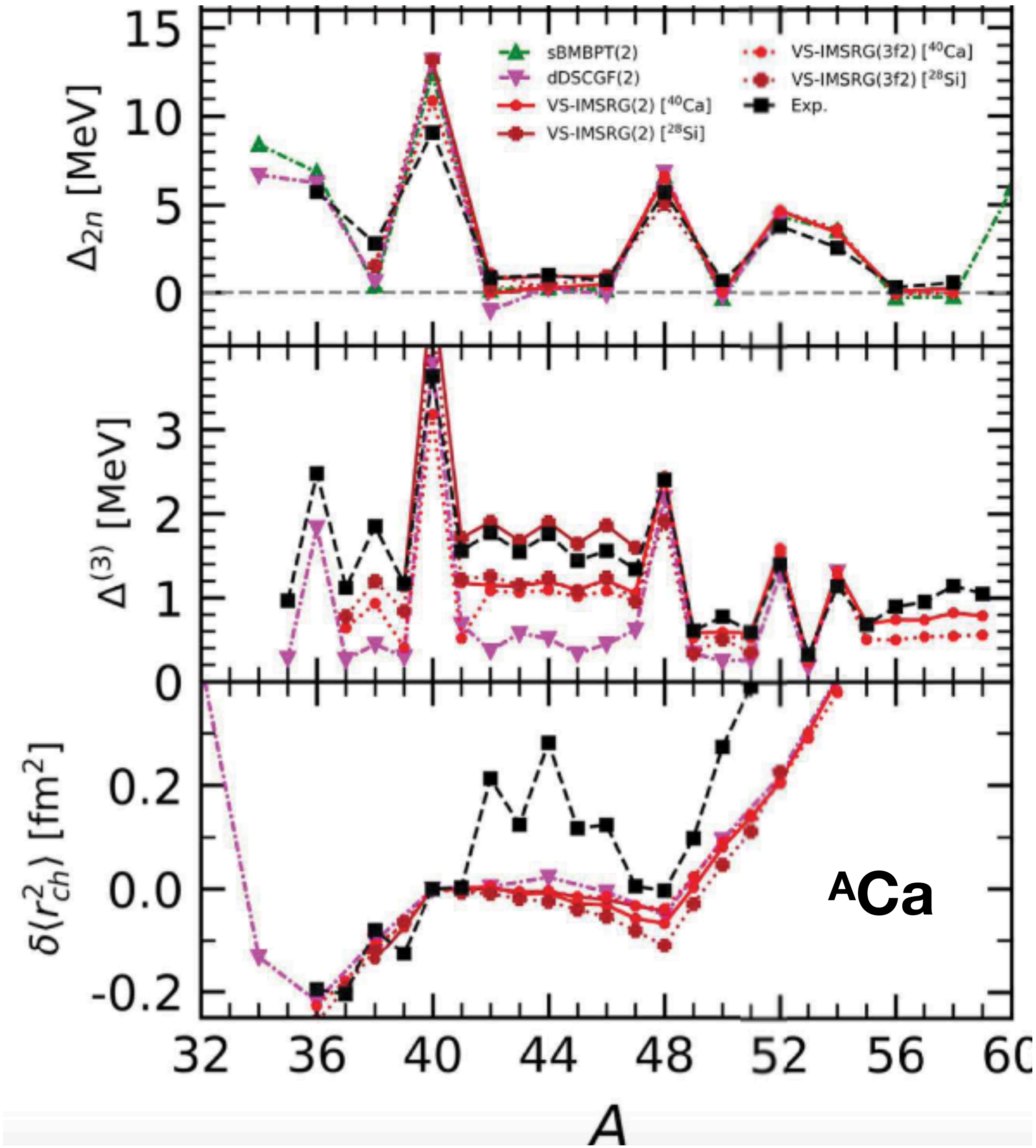
Nuclear radii in Ca isotopes: pairing / superfluidity

Ab initio computations based on chiral EFT interactions fail to reproduce the parabolic radius trend in the Ca isotopes— where is the pairing?
- missing correlations
- interaction

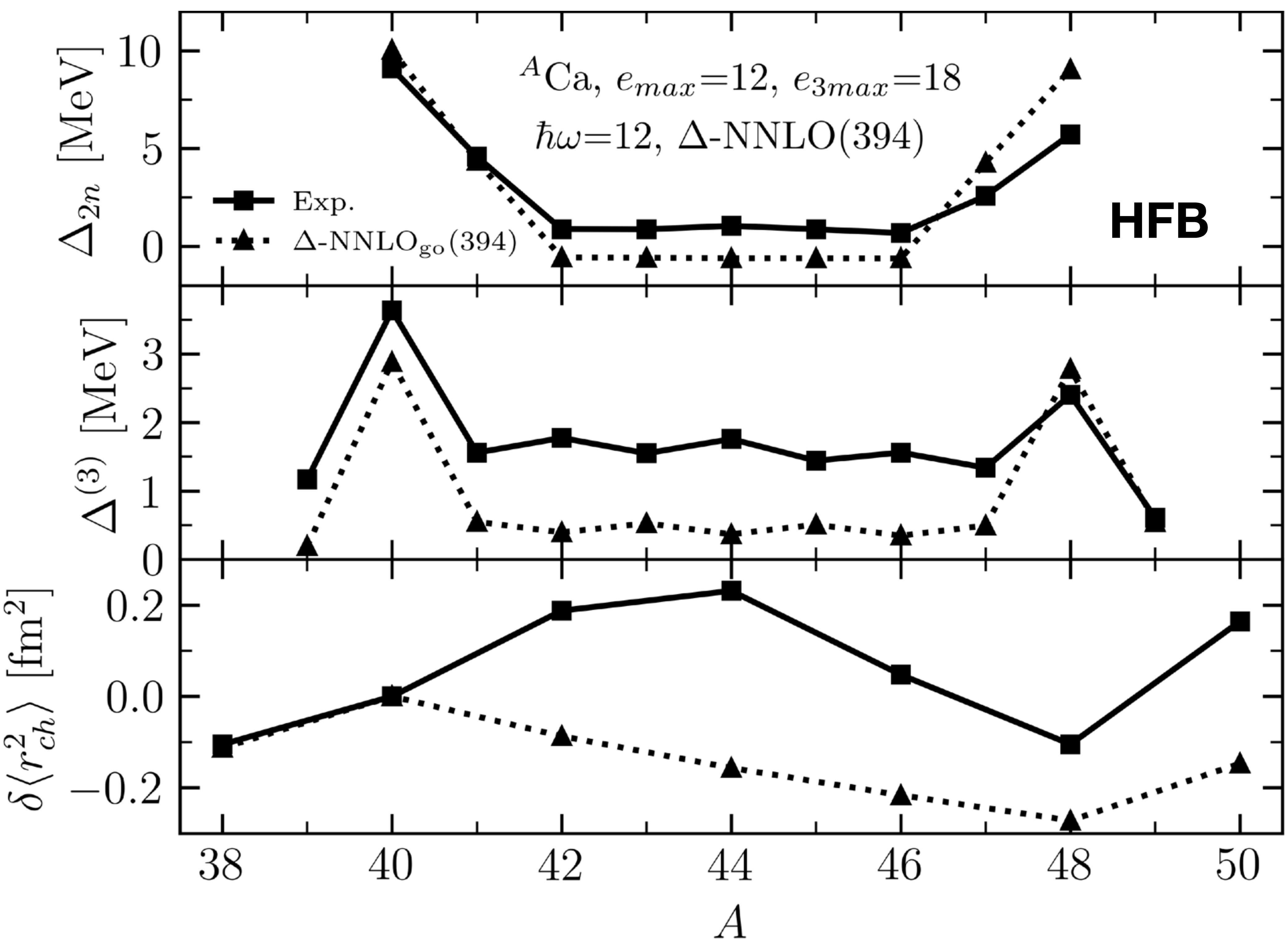
A. Scalesi et al.,
Eur. Phys. J. A 60 (2024) 209

A. Scalesi et al.,
unpublished (2025)

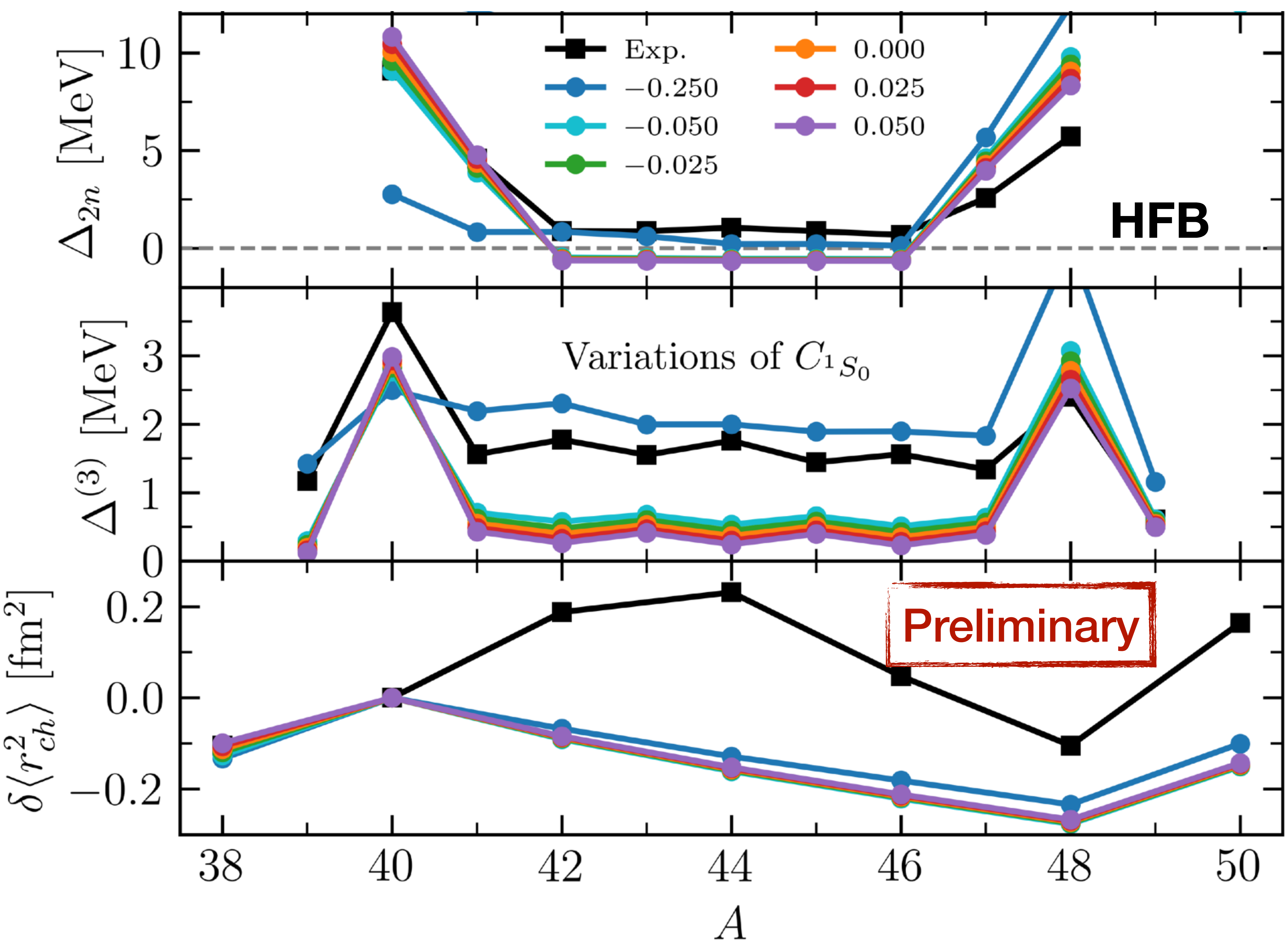
See Alberto's talk this afternoon



Nuclear radii in Ca isotopes: pairing



Ab initio predictions of deformed nuclei



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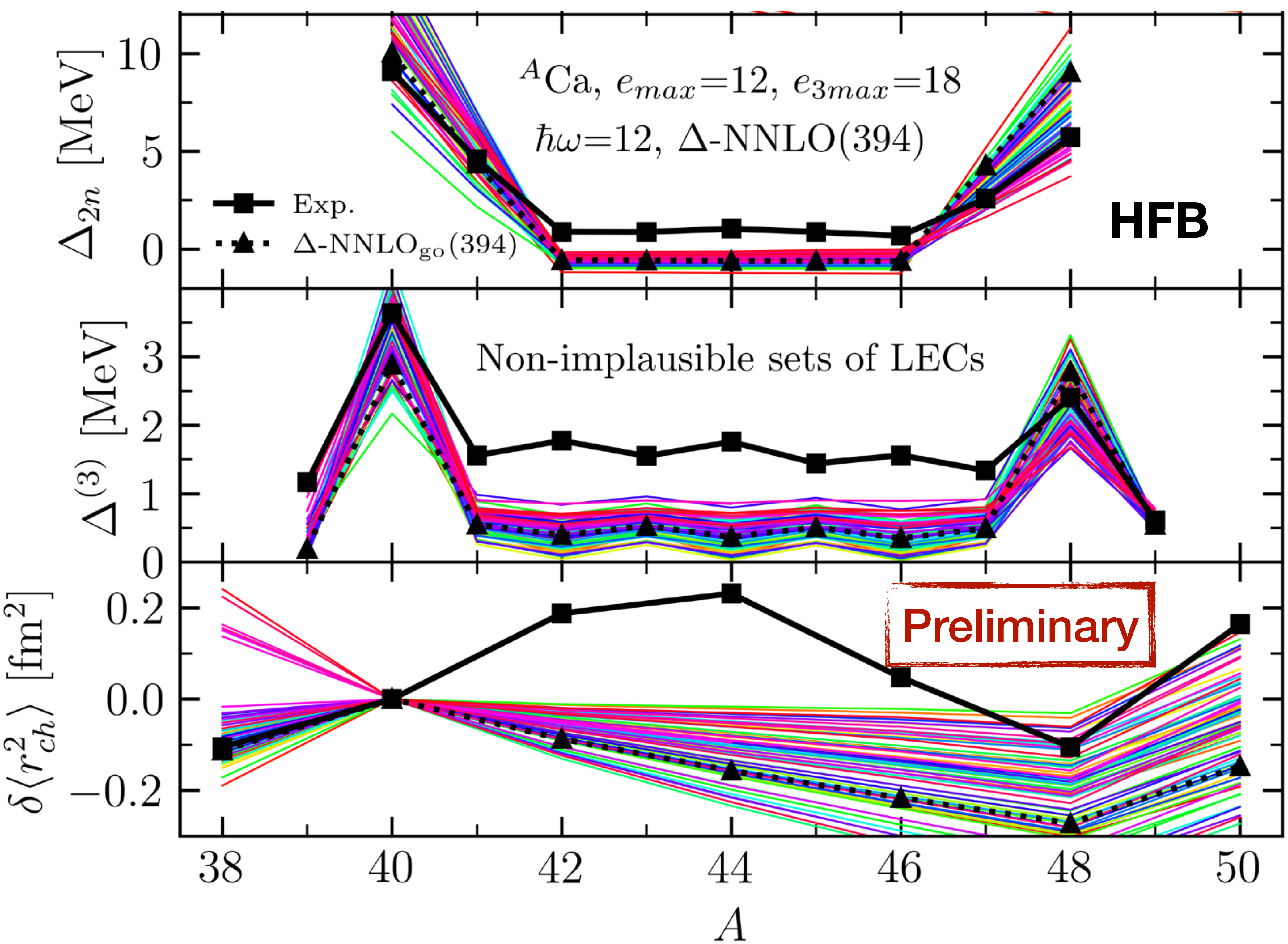

Summary and future

- *The concept of **tension in science** relies on statements of uncertainties*
- It is natural to strive for **accuracy** in theoretical modeling; but actual predictive power is more associated with quantified **precision.**
- Ab initio methods + χEFT + Bayesian statistical methods in combination with fast & accurate emulators is enabling **precision nuclear theory.**
- **Future frontiers of ab initio nuclear structure theory:**
  - Symmetry-breaking and restoration schemes for open-shell / deformed nuclei (see Alberto Scalesi's talk this afternoon)
  - Efficient handling of many-body forces for converging heavy (A>200) nuclear systems.
  - Predict scientifically relevant nuclear structure observables across the nuclear chart with quantified uncertainties (e.g. nuclear beta decay observables for BSM searches; ^{225}Ra PT-violating electric dipole moment)