What holds the nucleus together?

In the past quarter century physicists have devoted a huge amount of experimentation and mental labor to this problem – probably more man-hours than have been given to any other scientific question in the history of mankind. [. . .]

The glue that holds the nucleus together must be a kind of force utterly different from any we yet know.

HANS A. BETHE: “What holds the nucleus together?”,
Scientific American **189** (1953), no. 2, p. 58

What Is Modern *Ab Initio* Low-Energy Nuclear Theory, And What Are Its Goals? – A Bias-Free Review!!

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THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

1. The Goals of Modern Nuclear Physics
2. Chiral Effective Field Theory
3. Some Achievements and Targets
4. A Few Issues I Need To Understand Better for Lasers: $\omega \lesssim 100\ \text{MeV}$

How to root Nuclear Physics in QCD?
Which constituents rule nucleons and nuclei at low energies?
How do nuclei react to external fields?
How does that serve our understanding?
How to plan effective experiments & test theory?

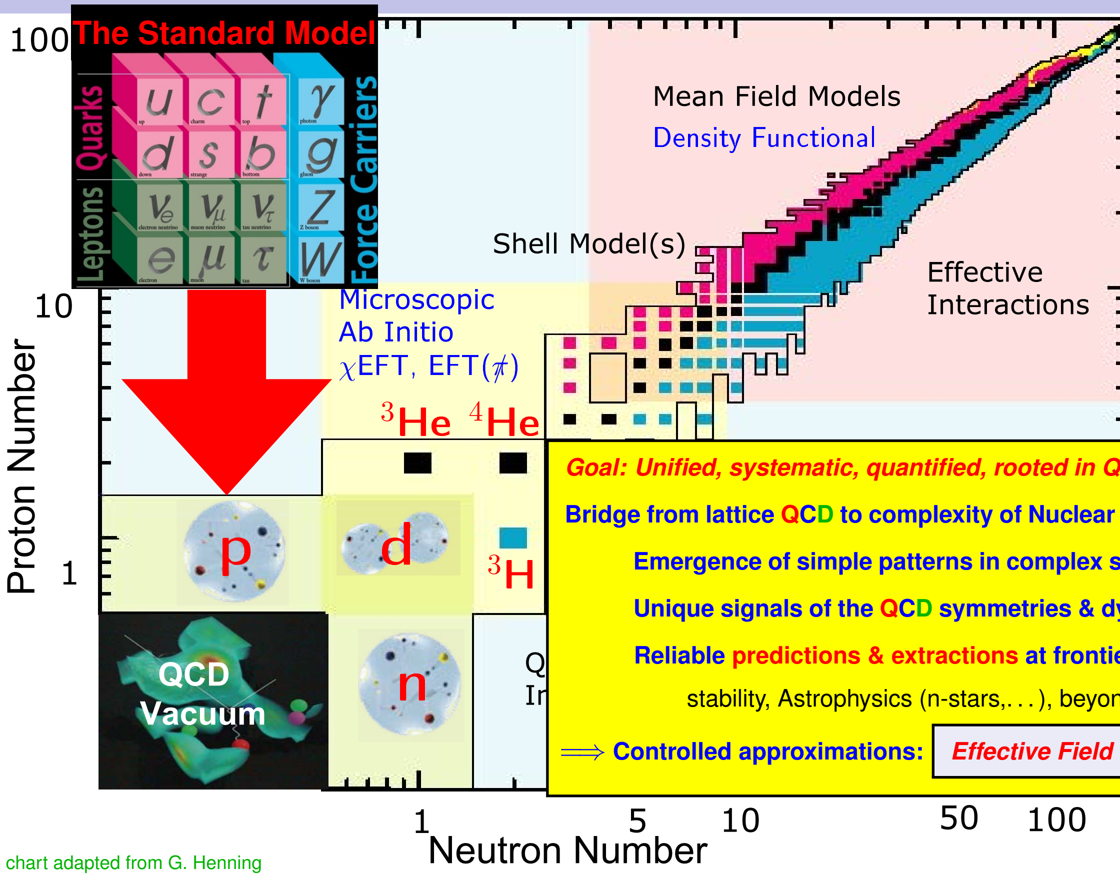
Office of Science
U.S. DEPARTMENT OF ENERGY

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

Community Effort – see US and NuPECC Long Range Plans.
Unrepresentative examples of interest to me.

1. The Goals of Modern Nuclear Physics

Nuclear/Hadronic Long-Range Plans: NSAC 2023, NAS 2012
NuPECC 2024, OECD 2008, STFC-NPA (UK) 2009



Goal: Unified, systematic, quantified, rooted in QCD.

Bridge from lattice QCD to complexity of Nuclear Physics:

Emergence of simple patterns in complex systems?

Unique signals of the QCD symmetries & dynamics;

Reliable predictions & extractions at frontiers:

stability, Astrophysics (n-stars,. . .), beyond-SM,. . .

$\Longrightarrow$ **Controlled approximations:** ***Effective Field Theories***

chart adapted from G. Henning

PHYSICAL REVIEW A **83**, 040001 (2011)

Editorial: Uncertainty Estimates

The purpose of this Editorial is to discuss the importance of including uncertainty estimates in papers involving theoretical calculations of physical quantities.

It is not unusual for manuscripts on theoretical work to be submitted without uncertainty estimates for numerical results. In contrast, papers presenting the results of laboratory measurements would usually not be considered acceptable for publication
The question is to what extent can the same high standards be applied to papers reporting the results of theoretical calculations. It is all too often the case that the numerical results are presented without uncertainty estimates. Authors sometimes say that it is difficult to arrive at error estimates. Should this be considered an adequate reason for omitting them? In order to answer this question, we need to consider the goals and objectives of the theoretical (or computational) work being done. Theoretical papers

accuracy. However, the same is true for the uncertainties in experimental data. The aim is to estimate the uncertainty, not to state the exact amount of the error or provide a rigorous bound.

There are many cases where it is indeed not practical to give a meaningful error estimate for a theoretical calculation; for example, in scattering processes involving complex systems. The comparison with experiment itself provides a test of our theoretical understanding. However, there is a broad class of papers where estimates of theoretical uncertainties can and should be made. Papers presenting the results of theoretical calculations are expected to include uncertainty estimates for the calculations whenever practicable, and especially under the following circumstances:

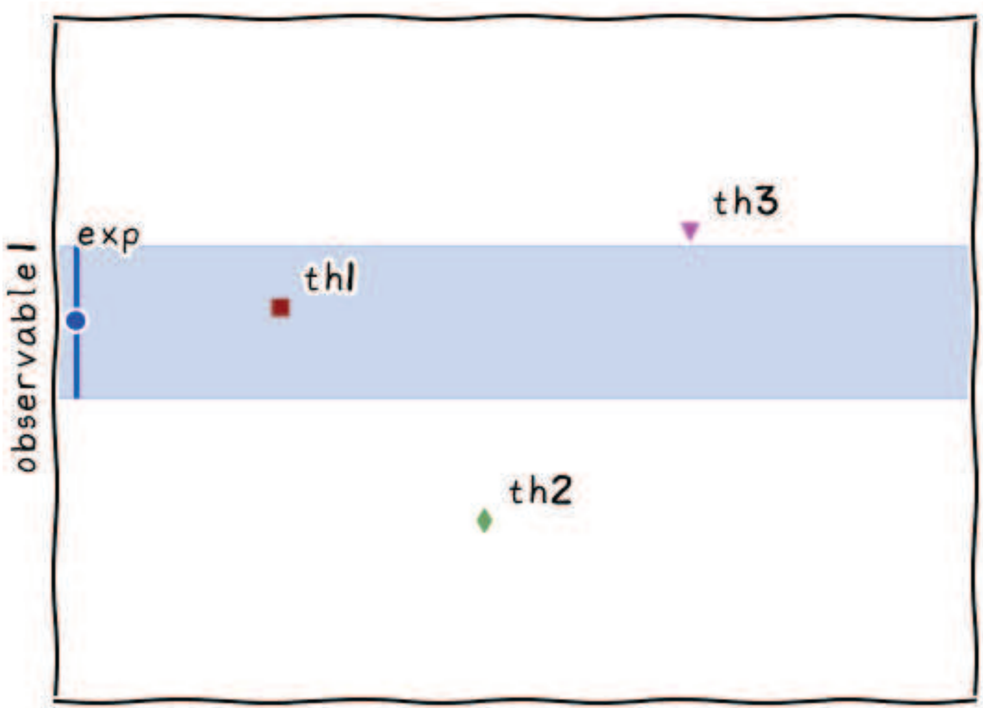
1. If the authors claim high accuracy, or improvements on the accuracy of previous work.
2. If the primary motivation for the paper is to make comparisons with present or future high precision experimental measurements.
3. If the primary motivation is to provide interpolations or extrapolations of known experimental measurements.

Scientific Method: Quantitative results with corridor of theoretical uncertainties for *falsifiable predictions*.

Need procedure which is established, economical, reproducible: room to argue about “error on the error”.

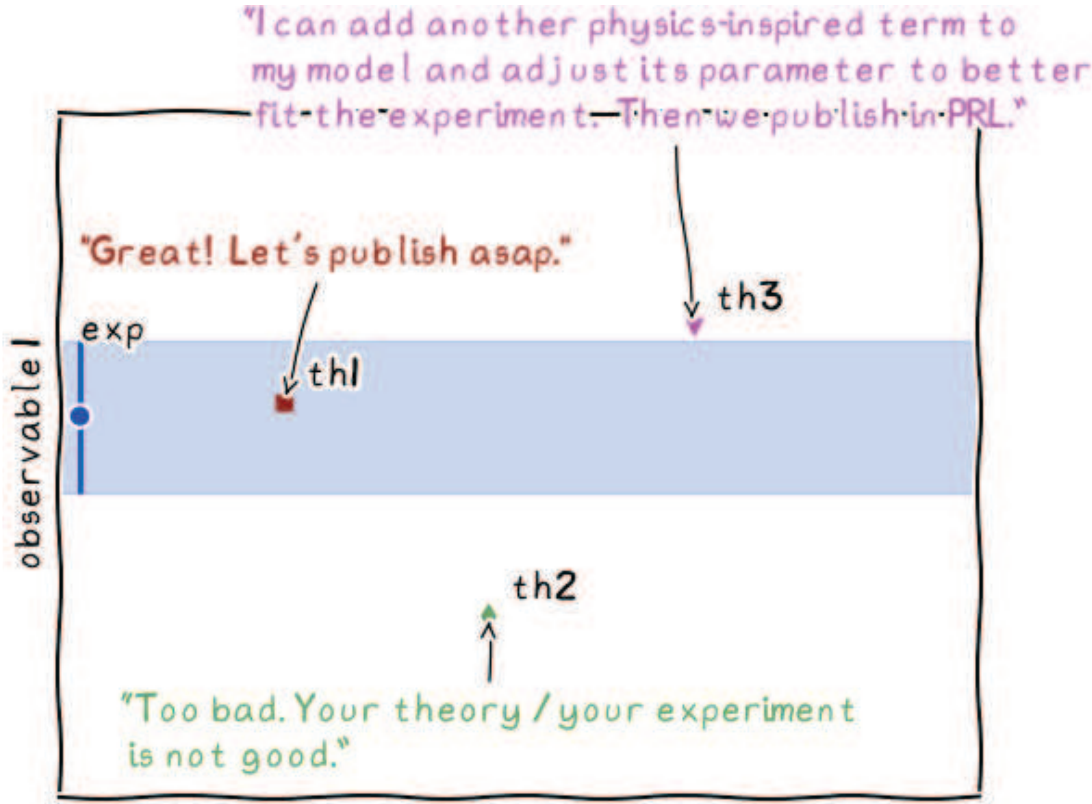
“Double-Blind” Theory Errors: Assess with pretense of no/very limited data.

(b) Why Theory Error Bars Are Relevant



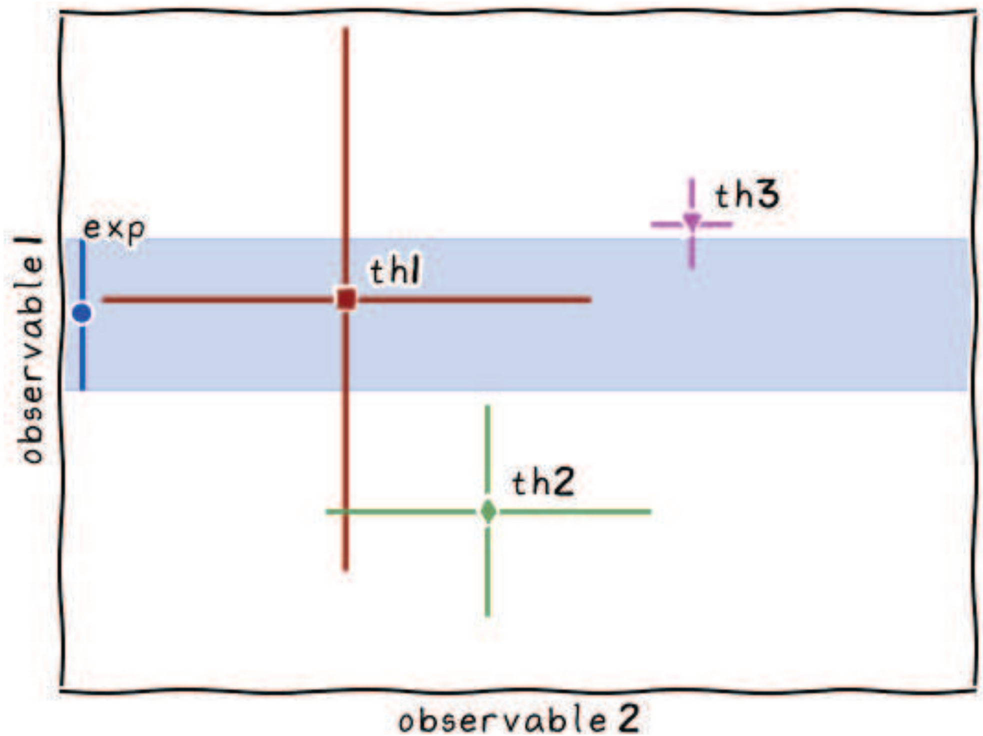
Ch. Forssén, idea: V. Nazarewicz

favourite theorist reaction until ca. 2020



(b) Why Theory Error Bars Are Relevant

theories with uncertainties $\Longrightarrow$ falsifiable

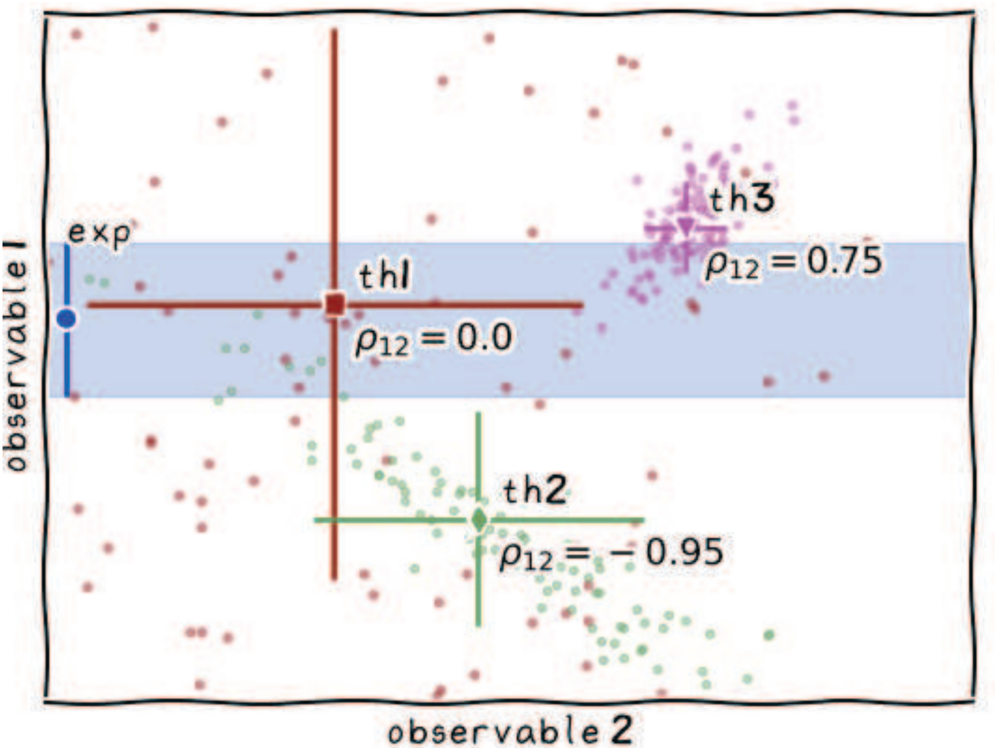


mindful of correlations:

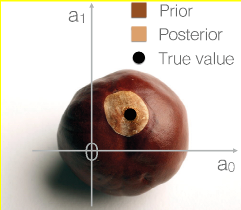
theory 1: low accuracy, imprecise

theory 2: mild tension with data of observable 1

theory 3: high-ish accuracy, strong tension with **theory 2**



(c) Extensive Use of Bayesian Statistics: Bayesian Uncertainty Quantification



BUQEYE Collaboration

No infinite sampling pool; data fixed; more data changes confidence.

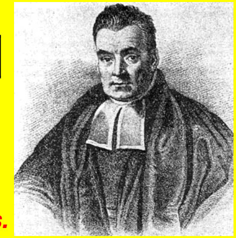
Call upon the Reverend Bayes for probabilistic interpretation!

e.g. **BUQEYE collaboration** **Furnstahl/Phillips/. . . 1506.01343+1511.01952+. . .**

New information increases level of confidence.

$\Longrightarrow$ **Smaller corrections, more reliable uncertainties.**

Clearly state your premises/assumptions – including *naturalness*.



- **Robust Estimate of Theory Truncation Errors & Correlations**: probability densities.
- **Experimental Design:** Which future data have likely biggest impact?
- **Model Mixing:** Extrapolate between theories at different scales.
- **Emulators:** Reduce CPU time by reduced-basis models, Eigenvalue Continuation,. . . trained on full results.

Annual ISNET workshops/conferences

ISNET Phys. G **42** no. 3 (2015)

J. Phys. G **46** no. 10 (2019)

Front. Phys. Res. Topics (2022)

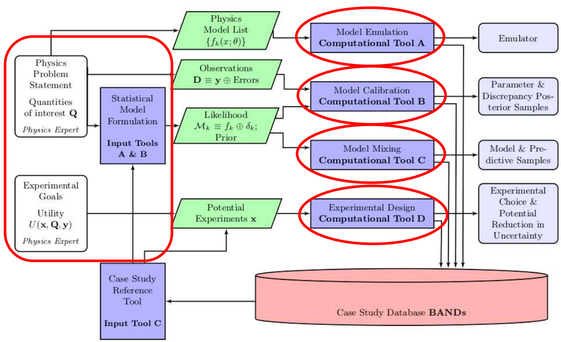
Open Source Software

Suites available

buqeye.github.io

bandframework.github.io

Goal: *Facilitate principled Uncertainty Quantification in Nuclear Physics*



Bayesian Analysis of Nuclear Dynamics

An NSF CSSI Framework
(5 years until 2026)
Look to https://bandframework.github.io/ for papers, talks, and software!
v0.3 released 10/23

No more excuses: Trust only theorists who show effort to estimate theory/truncation errors – or apologise when not.

Scientific Approach

As we know,
there are known knowns.
There are things we know we know.

We also know
there are known unknowns.

That is to say
we know there are some things
we do not know.

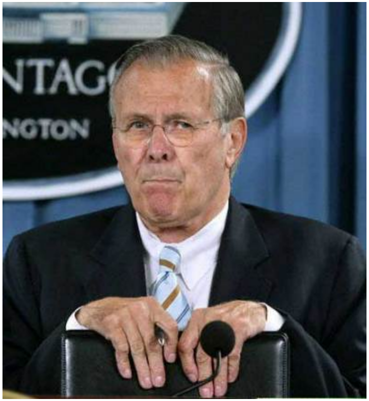
Scientific Approach

As we know,
there are known knowns.
There are things we know we know.

We also know
there are known unknowns.

That is to say
we know there are some things
we do not know.

But there are also unknown
unknowns,
the ones we don't know
we don't know.



Donald Rumsfeld, 12 Feb 2002

(a) Physical Models vs. Physical Theories

The Trouble With Nuclear Physics

In fact the trouble in the recent past has been a surfeit of different *models* [of the nucleus], each of them successful in explaining the behavior of nuclei *in some situations*, and each in *apparent contradiction with other successful models* or with our ideas about nuclear forces.

Rudolph E. Peierls: "The Atomic Nucleus", *Scientific American* **200 (1959)**, no. 1, p. 75; emphasis added

Model: Precise description tailored to one task (process/. . .). – *No "fail"* but "tuning".

Theory: Comprehensive, prescriptive, predictive, accurate, Explain-All-To-Some-Degree. – *Can fail.*

Totalitarian Principle/Swiss Basic Law/ Weinberg's "Folk Theorem": Throw In the Kitchen Sink

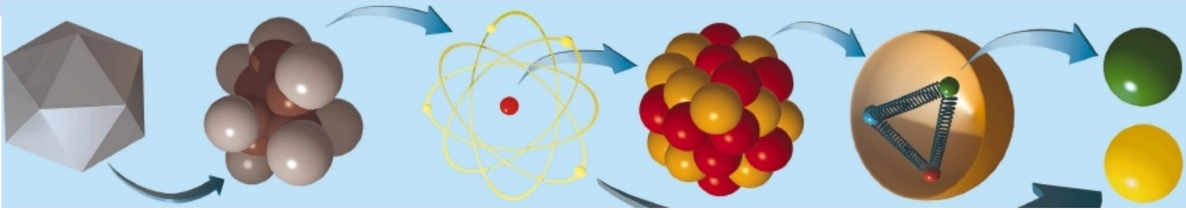
As long as you let it be the most general possible Lagrangian consistent with the symmetries of the theory, you're simply writing down the most general theory you could possibly write down.

Original: Weinberg: Physica 96A (1979) 327 – here 1997 version

"EFT = Symmetries + Parametrisation of Ignorance"?? WHAT CAN POSSIBLY GO WRONG???

(b) Way Out: $\Delta x\,\Delta p \gtrsim \hbar$, or What You See Is What You Get

Weinberg: "folk lore theorem"



To probes with wavelength λ, object of size R appears

point-like for $\lambda \gg R$, blurry for $\lambda \gtrsim R$, composed for $\lambda \lesssim R$.

- **Example Radiation Multipoles**: $P_{El} \xrightarrow{\lambda \gg R} \sum_{\text{ang. mom. } l} a_l \left(\frac{\text{size } R}{\text{wavelength } \lambda} \right)^{2l}$ e.g. atoms: $\frac{R \sim 1\text{Å}}{\lambda \sim 5000\text{Å}}$.

Converges if **Separation of Scales** $Q = \frac{\text{target size } R}{\text{resolution } \lambda} < 1$ **&** a_l **of natural size** $\Longrightarrow$ **error-estimate, space for improvement**

EFT Tenet: **Short-distance physics does not have to be right for a good calculation, because a low-energy process cannot probe details of the high-energy structure.**

$\Longrightarrow$ ***Effective Field Theories***

Identify those degrees of freedom and symmetries which are *appropriate* to resolve the *relevant* Physics at the scale of interest.

Systematic approximation of real world with **estimate of theoretical uncertainties.**

(c) The Low-Energy Method: Chiral Effective Field Theory

$\mathcal{L}_{\text{QCD}} = \bar{q}[i\partial\!\!\!/ + gA\!\!\!/ - m_q]q - \frac{1}{2}\text{tr}[F^{\mu\nu}F_{\mu\nu}]$ has *few* parameters: $\alpha_S + 6$ masses.

Degrees of freedom $\pi, N, \Delta(1232)$ + all interactions allowed by symmetries: Chiral SSB, gauge, iso-spin,. . .

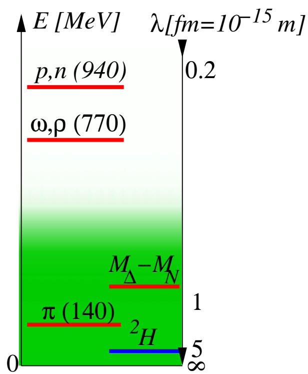
$\Longrightarrow$ **Chiral Effective Field Theory χEFT $\equiv$ low-energy QCD**

$$\mathcal{L}_{\chi\text{EFT}} = (D_\mu \pi^a)(D^\mu \pi^a) - m_\pi^2\, \pi^a \pi^a + \dots + N^\dagger[\text{i}\, D_0 + \frac{\vec{D}^2}{2M} + \frac{g_A}{2f_\pi}\, \vec{\sigma}\cdot\vec{D}\pi + \dots]N + C_0\left(N^\dagger N\right)^2 + \dots$$

Controlled approximation $\Longrightarrow$ *Model-independent, error-estimate*.

Expand in $\frac{\omega}{\Lambda_\chi}$ and $\delta = \frac{M_\Delta - M_N}{\Lambda_\chi} \approx \sqrt{\frac{m_\pi}{\Lambda_\chi}} \approx 0.4 \ll 1$ (numerical fact)

Pascalutsa/Phillips 2002



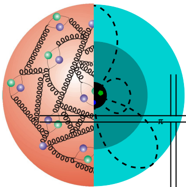
(d) Few-Nucleon Interactions in χEFT

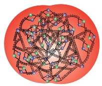
Weinberg, Ordóñez/Ray/van Kolck, Friar/Coon, Kaiser/Brockmann/Weise, Epelbaum/Glöckle/Meißner, Entem/Machleidt, Kaiser, Higa/Robilotta, Epelbaum, . . .

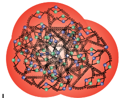
$\frac{\text{typ. momentum}}{\text{breakdown scale}} \ll 1$

Long-Range: correct symmetries and IR degrees of freedom: **Chiral Dynamics**

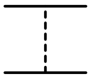
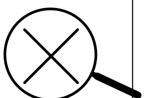
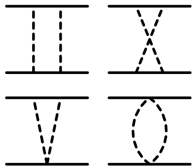
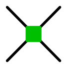
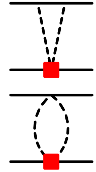
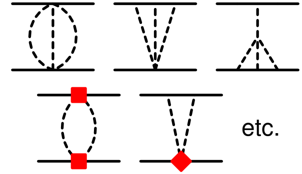
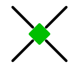
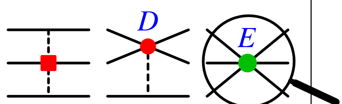
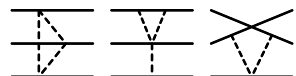
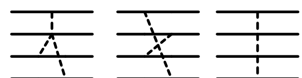
Short-Range: symmetries constrain contact-ints to simplify UV: **Minimal parameter-set**







Hierarchy: 2NI-effects $\gg$ 3NI-effects $\gg$ 4NI-effects

	LO	NLO	N^{2}LO	N^{3}LO
$2N$ ints	  2 parameter	  $\propto p^2$ $+7$ parameter	 — $+0$ parameter	 etc.  $\propto p^4$ $+15 = 24$ param.
$\frac{\chi^2}{\text{d.o.f}}$ in np		36.2	10.1	1.10 (AV 18: 1.04, 40 param.)
$3N$ ints	—	—	 2 parameter	 etc. parameter-free, in progress
$4N$ ints	—	—	—	 etc. parameter-free

(e) What Can Possibly Go Wrong??

Check assumptions:

– $p_{\text{typ.}} \nearrow \bar{\Lambda}_{\text{EFT}} \implies Q \not\ll 1$?

"EFTs carry seed of own destruction." D. R. Phillips

– No separation/jungle of scales? e.g. N^* at $2\ \text{GeV}$

– Wrong constituents/degrees of freedom?

new d.o.f. e.g. QED at $100\ \text{GeV}$ without W, Z

phase transition changes d.o.f. $N, \pi \to$ quarks, gluons

– Nature *refuses* to have assumed symmetry?

e.g. impose Parity in weak interactions

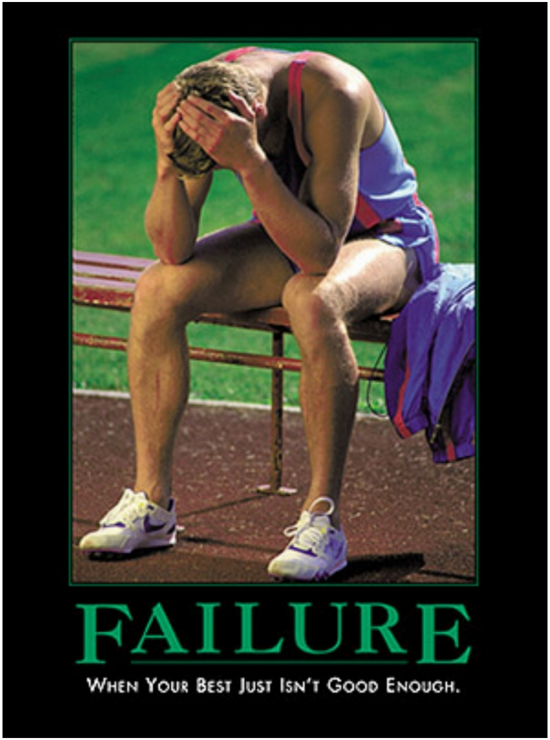
Check the *Quantitatively Predicted* Convergence Pattern:

– Convergence? ***Coefficients of Natural Size?***

$\implies$ Bayesian Statistics predicts 1σ "error-bars". $\to$ later

– Order by order smaller corrections.

– Order by order less cut-off/RScheme dependence.



Falsifiability: Convergence to Nature tests assumptions. – *After* theoretical uncertainties determined.

The Three Big Lies of Nuclear Theory

Nuclear Power is Safe.

They have Weapons of Mass Destruction.

The Three Big Lies of Nuclear Theory

Nuclear Power is Safe.

They have Weapons of Mass Destruction.

My Power-Counting is Systematic.

(g) NN χEFT Power Counting Comparison

prepared for Orsay Workshop by Grießhammer 7.3.2013
based on and approved by the authors in private communications

Derived with explicit & implicit assumptions; contentious issue.
Proposed order Q^n at which counter-term enters *differs*. $\Longrightarrow$ Predict *different* accuracy, # of parameters.

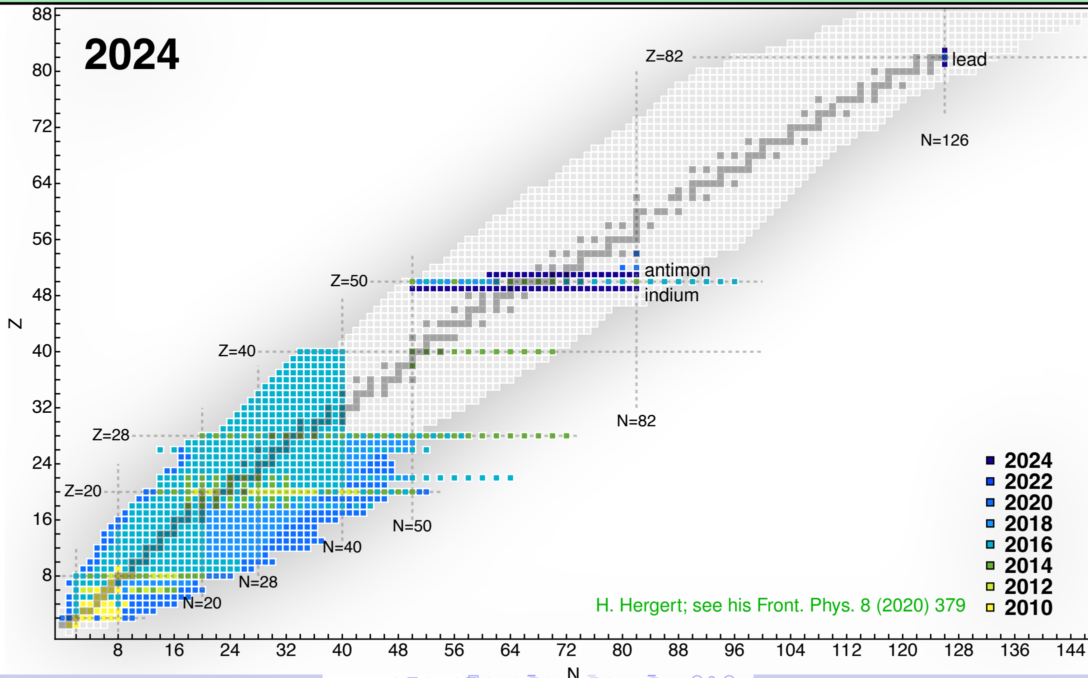
order	**Weinberg** (modified) PLB**251** (1990) 288 etc.	**Birse** PRC**74** (2006) 014003 etc.	**Pavon Valderrama et al.** PRC**74** (2006) 054001 etc.	**Long/Yang** PRC**86**(2012) 024001 etc.
Q^{-1}	LO of $^1S_0$, $^3S_1$, OPE	plus $^3D_1$, $^3SD_1$	plus $^3P_{0,2}$, $^3D_2$	plus $^3P_{0,2}$
$Q^{-\frac{1}{2}}$	none	LO of $^3P_{0,1,2}$, $^3PF_2$, $^3F_2$, $^3D_2$	LO of $^3SD_1$, $^3D_1$, $^3PF_2$, $^3F_2$	none
Q^0	none	NLO of $^1S_0$		
$Q^{\frac{1}{2}}$	none	NLO of $^3S_1$, $^3D_1$, $^3SD_1$	none	none
Q^1	LO of $^3SD_1$, $^1P_1$, $^3P_{0,1,2}$; NLO of $^1S_0$, $^3S_1$	none	none	LO of $^3SD_1$, $^1P_1$, $^3P_1$, $^3PF_2$; NLO of $^3S_1$, $^3P_0$, $^3P_2$; N^{2}LO of $^1S_0$
# at Q^{-1}	2	4	5	4
# at Q^0	$+0$	$+7$	$+5$	$+1$
# at Q^1	$+7$	$+3$	$+0$	$+8$
total at Q^1	9	14	10	13

Note: "LO of $^1S_0$, $^3S_1$, OPE" spans all columns at Q^{-1}; "NLO of $^1S_0$" spans the Birse, Pavon Valderrama et al. and Long/Yang columns at Q^0.

With same χ^2/d.o.f., the *self-consistent* proposal with least parameters *wins*: minimum information bias.
Still, use it pragmatically to develop numerics & first glimpses at final theory – with caveat on systematics!

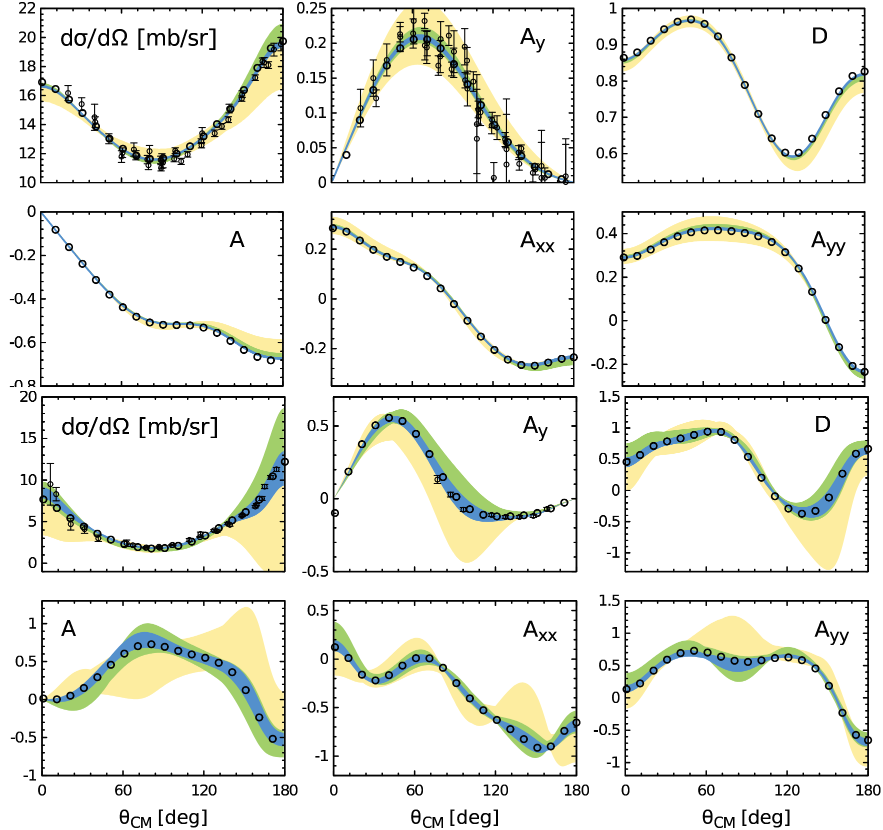
(a) The Nuclear Chart In the *Ab-Initio* High-Accuracy Era

ab initio: method to reliably extrapolate, in a controlled and systematic way, to regions outside the ones used for inferring the model parameters. [. . .] a systematically improvable approach for quantitatively describing nuclei using the finest resolution scale possible while maximizing its predictive capabilities. Ekström/. . . : Front. Phys. 11 (2023) 1129094



(b) np Scattering Observables at $E_{\rm cm} = 50$ & 200 MeV

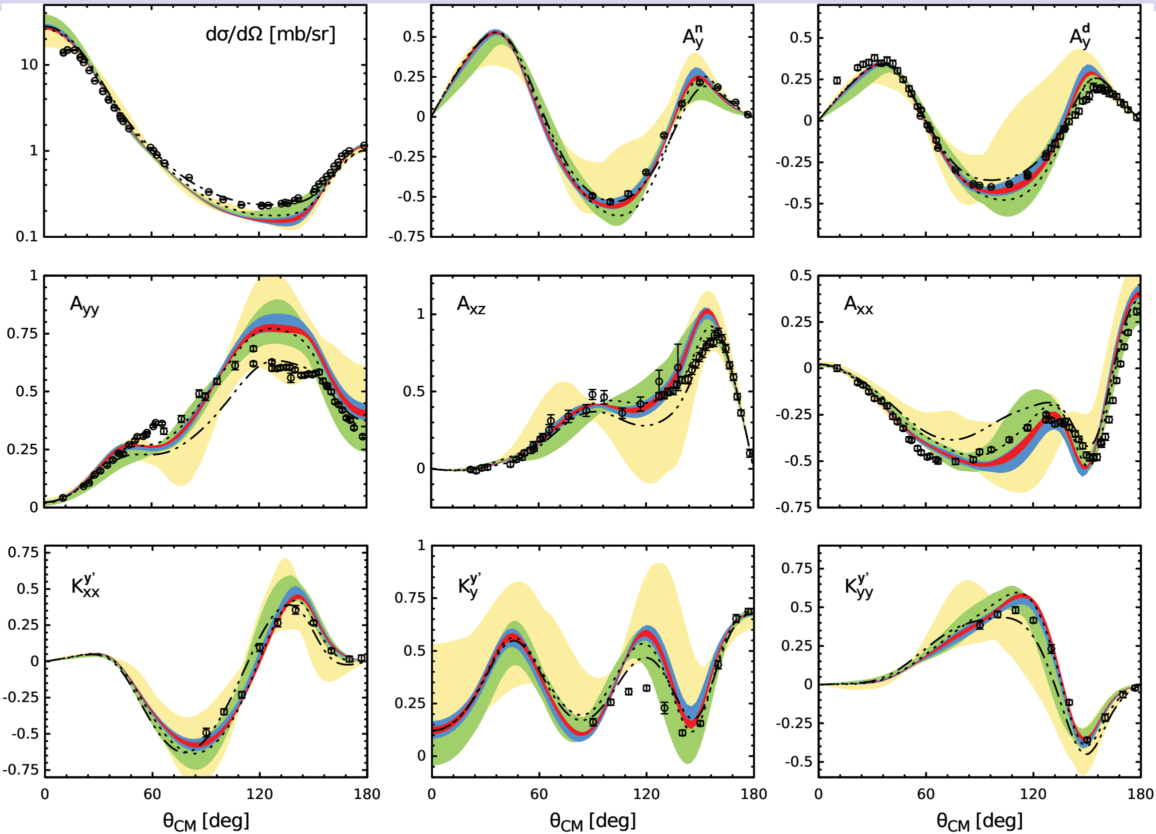
Epelbaum/. . . 1412.0142



Bands estimate theory uncertainties by higher-order effects: LO → NLO → N^{2}LO —- N^{5}LO now also available.

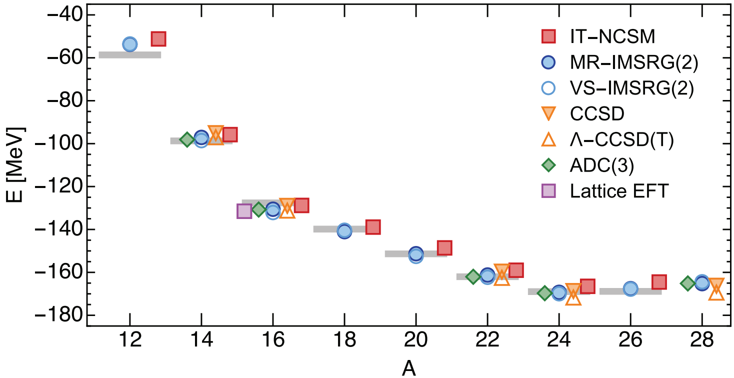
(c) 3N: Polarised Deuteron-Proton Scattering

Epelbaum/... [arXiv:1802.08584]



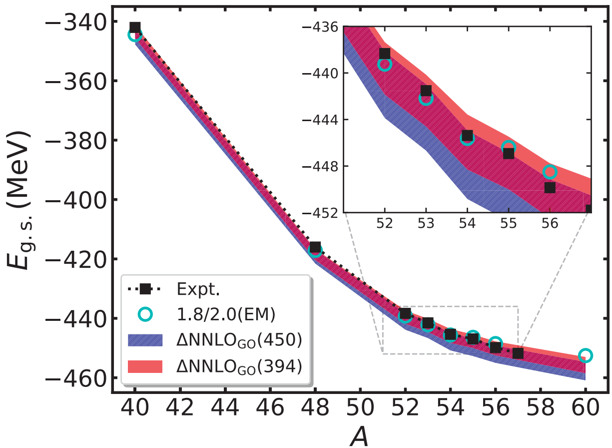
Bands estimate theory uncertainties by higher-order effects: LO → NLO → N^2LO → N^3LO

(d) Isotopic Medium Mass Chains with *Ab-Initio* Methods



Oxygen chain

Hergert: Front. Phys. 8 (2022) 379

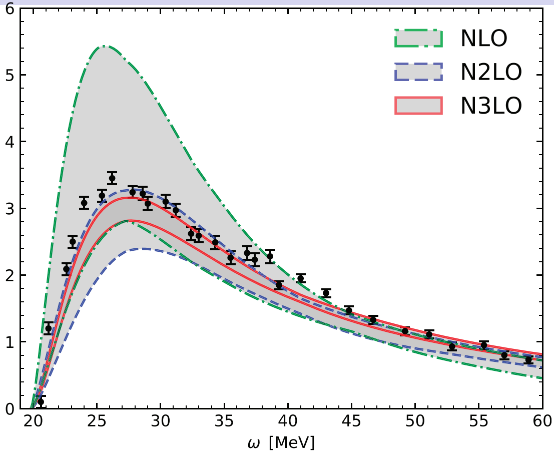


Calcium chain

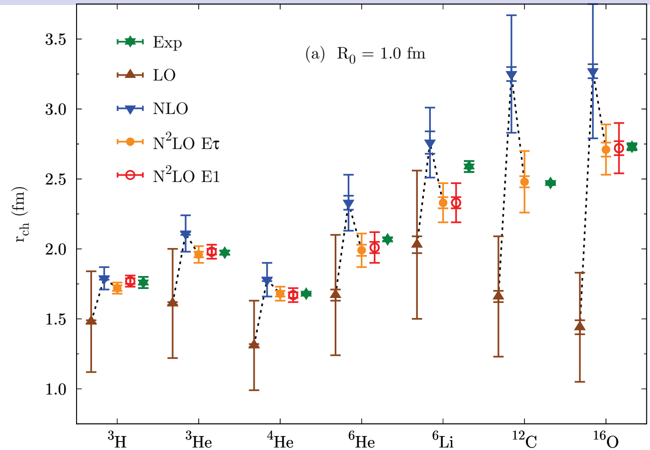
Forssén et al. 2006.16774

Theory methods agree: numerics (largely) under control.

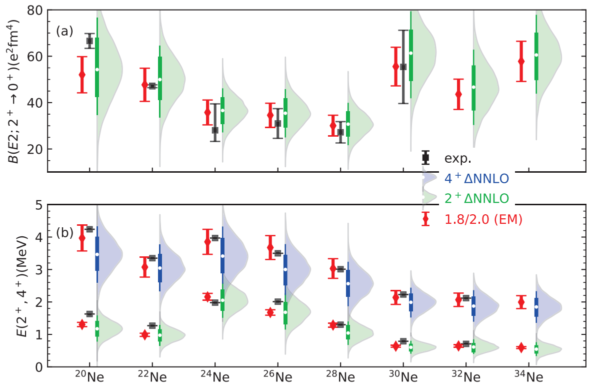
(e) Electromagnetic Properties of Light Nuclei: Theory Errors Shrink with Order



^{4}He photodissociation Bacca/...



charge radii Lonardoni/... PRC 97 (2021) 044318



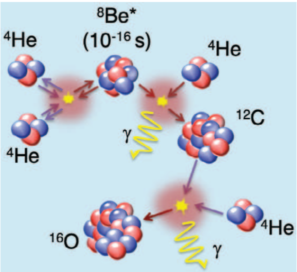
Ne isotopic chain:

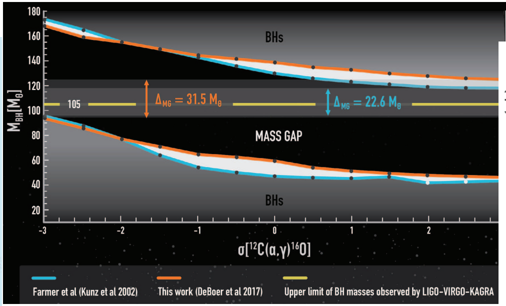
$E2(2^+ \to 0^+)$ transition strength

energies of 2^+ & 4^+

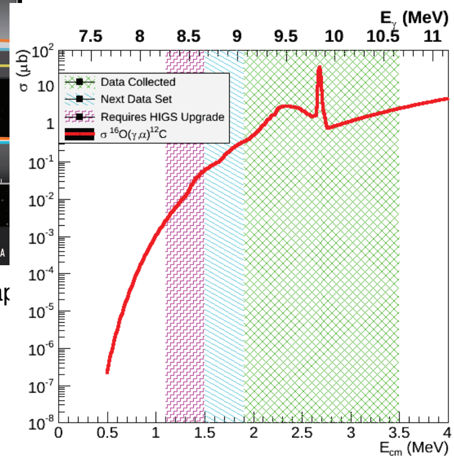
Sun/...2404.00058

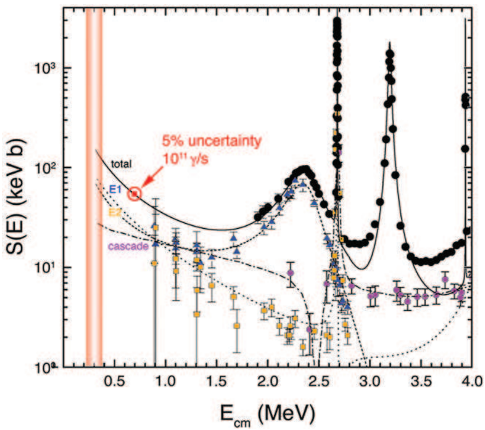
(f) ^{16}O Formation in the Solar CNO Cycle (Teller's "sett atmosphere on fire")



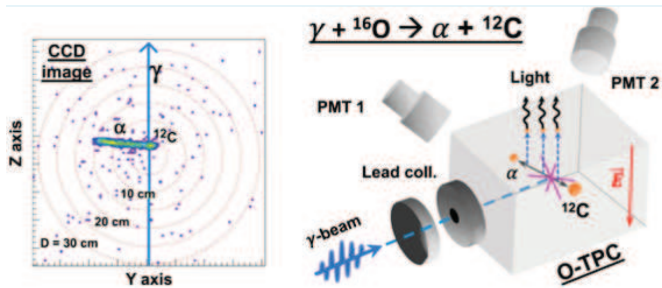


Also critical fofr size of Black Hole mass gap

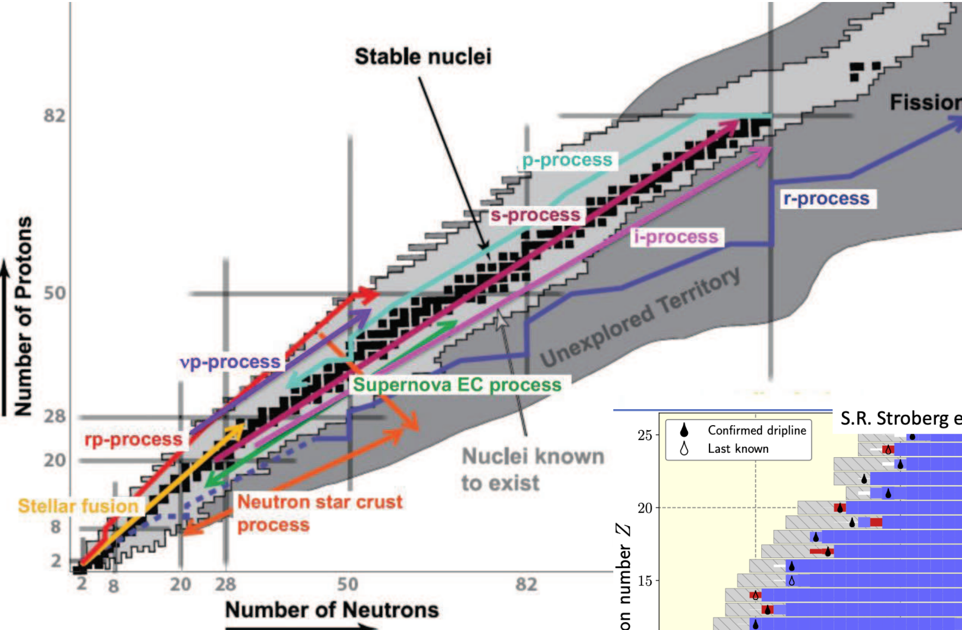


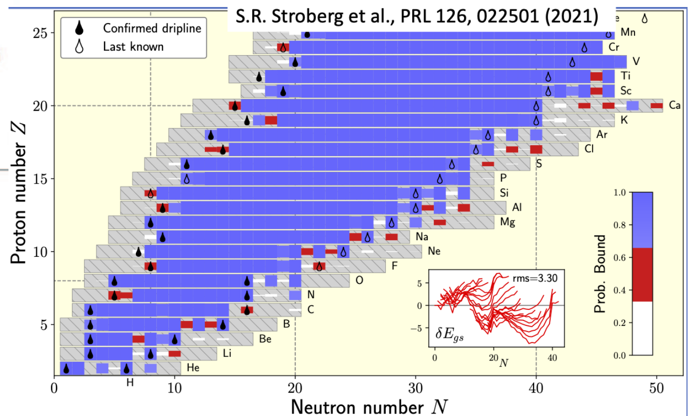


$^{12}C(\alpha,\gamma)^{16}O$ needed to $\lesssim 10\%$ at $\lesssim 400$ keV



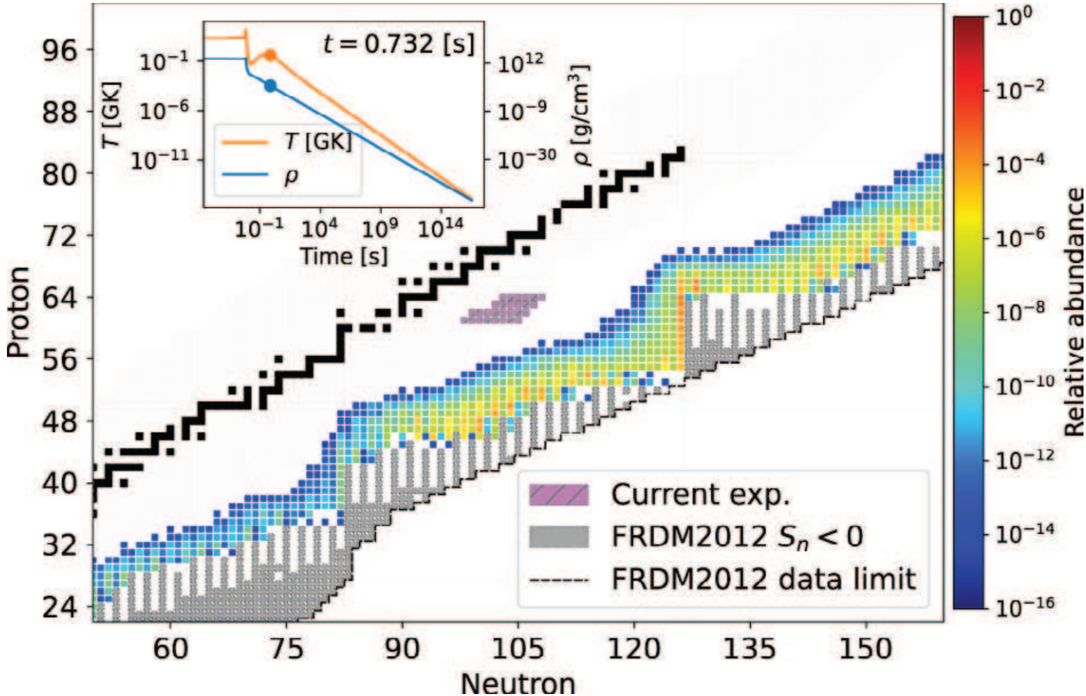
Measure $^{16}O(\gamma,\alpha)^{12}C$ at $\omega \lesssim 8$ MeV, detailed balance.





dripline position from Model Mixing

(g) Nuclear Chart for Nuclear Astrophysics

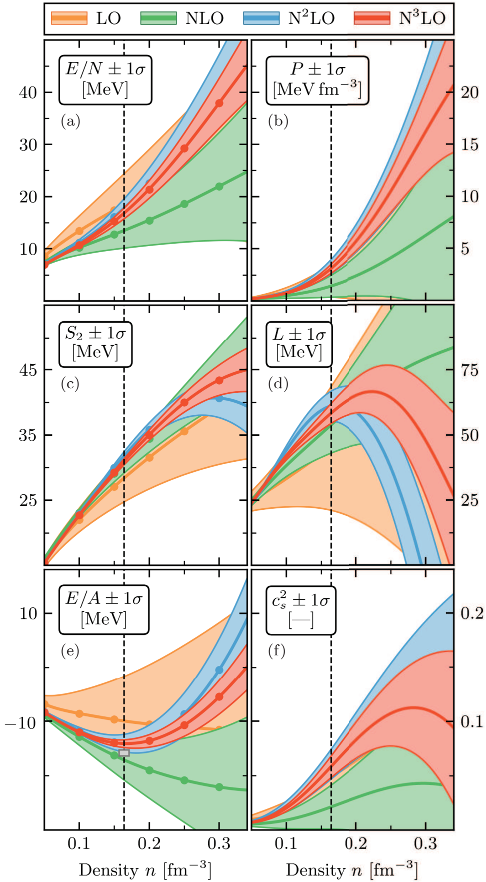


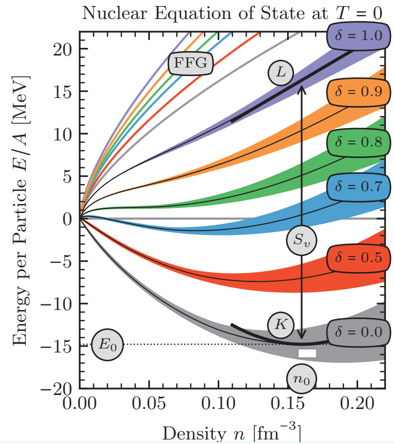
r-process paths in neutron star mergers – gray: unbound nuclei

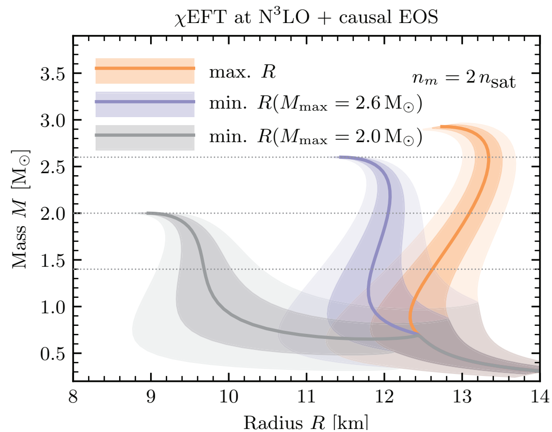
Cannot measure all nuclei & excitations. $\Longrightarrow$ **Train theory on judiciously chosen “doable but relevant” data.**

(h) Nuclear Equations of State and Neutron Stars

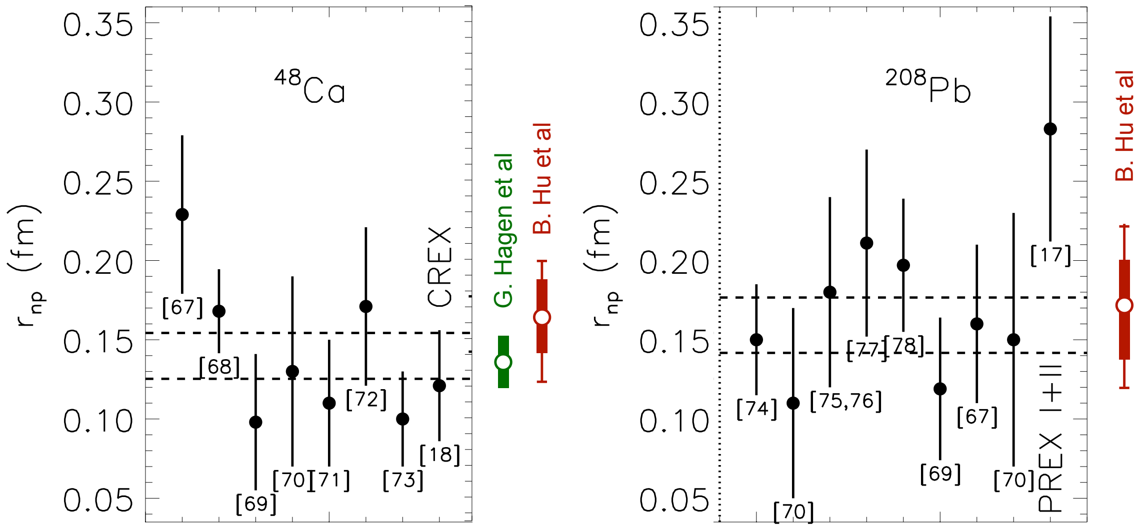
Drischler et al PRL 125 (2024) 202702
Ann Rev Nucl Part Phys 71 (2021) 40







(i) Constraining Neutron Equation of State by Neutron Skin Thickness Lattimer 2023



B. Hu et al (Nature Phys. 2022)

Observable	median	68% CR	90% CR
$R_{\text{skin}}(^{48}\text{Ca})$	0.164	[0.141, 0.187]	[0.123, 0.199]
$R_{\text{skin}}(^{208}\text{Pb})$	0.171	[0.139, 0.200]	[0.120, 0.221]

Only indirect information on neutron matter & nuclear symmetry energy parameters.

Disputes whether data actually sensitive to neutron skin parameters.

4. A Few Issues I Need To Understand Better for Lasers: $\omega \lesssim 100\ \mathrm{MeV}$

- Energy resolution; event-by-event fluctuations of beam intensity, energy profile,. . .
- High-accuracy ($\lesssim 3\%$) monitoring of beam intensity, energy spectrum, beam focussing, particle content?
- Pile-Up? Event rate in "one shot"? Used to 1 every $1000\ \mathrm{s}$, but now heavily pulsed beam. . .
- How well can one separate signal (e.g. neutrons) from background (e.g. photons)?
- Convolute theory with several well-defined beam profiles?

  Optimisation problem: Which "experimentally doable" combination most sensitive?
- Secondary neutron or pion beams: pion scattering, neutron properties/r-process?
- Direct measurement of neutron-neutron scattering length?

  So far best is indirectly from $d(n,pn)n$, but tensions: $a_{\mathrm{nn}} = \begin{cases} [-16.3 \pm 0.4]\ \mathrm{fm} & \text{Bonn 2000/2001} \\ [-18.7 \pm 0.7]\ \mathrm{fm} & \text{TUNL 1999/2006} \end{cases}$
- Neutron matter explorations?
- $\mathrm{nnn} \to \mathrm{nnn}$?

The efficient person gets the job done right. The effective person gets the right job done.