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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1. The Goals of Modern Nuclear Physics
2. Chiral Effective Field Theory
3. Some Achievements and Targets
4. A Few Of The Issues I Need To Understand Better

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?

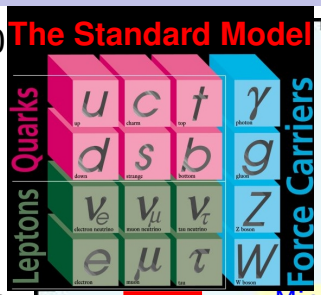
How to plan effective experiments & test theory?

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.

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

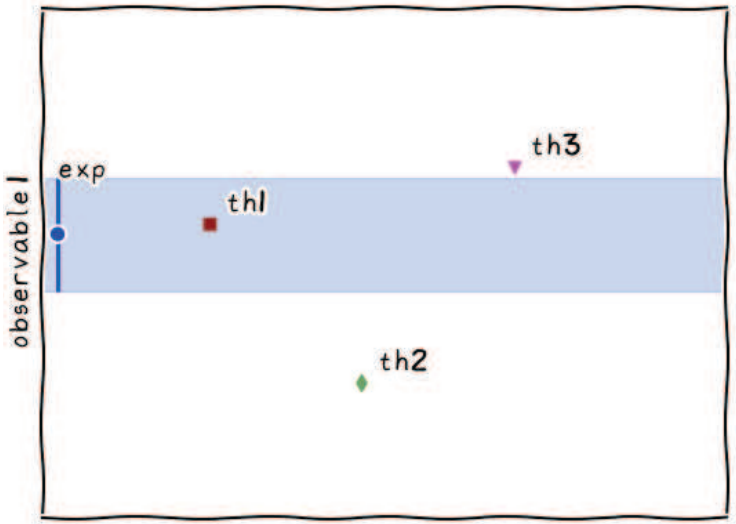
(a) Why Theory Error Bars Are Relevant

Ch. Forssén, idea: V. Nazarewicz

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.



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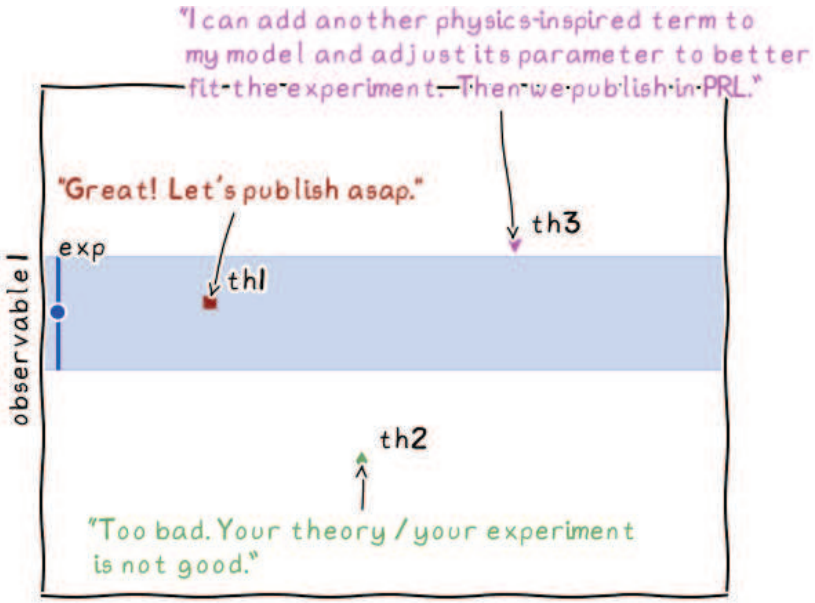

favourite theorist reaction until ca. 2020

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

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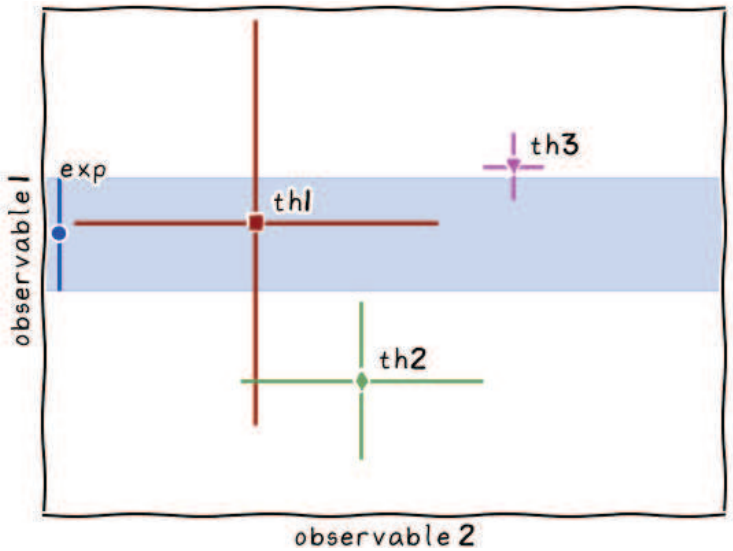

theories with uncertainties $\Longrightarrow$ falsifiable

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**

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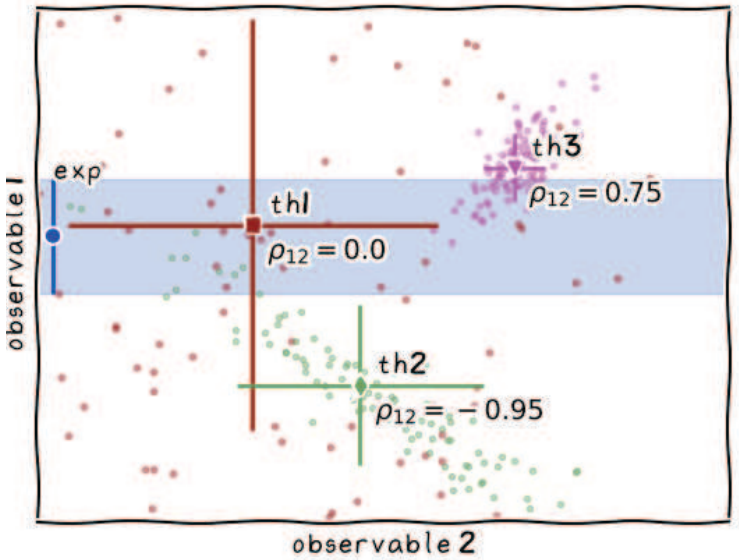

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(a) Physical Models vs. Physical Theories

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

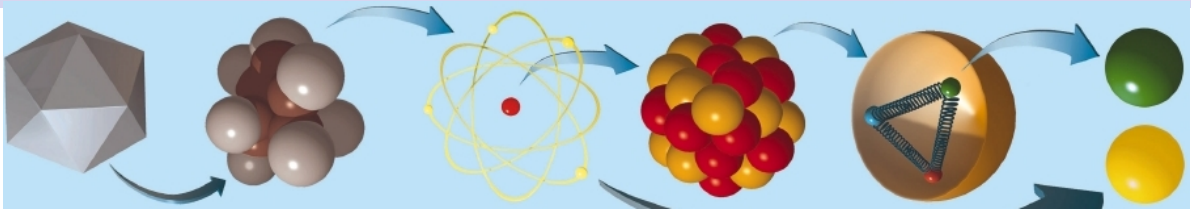


As long as you let it be the most general possible Lagrangian consistent with the symmetries of the theory, you're simply writing down the most general theory you could possibly write down.

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

(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**: $P_{El} \overset{\lambda \gg R}{\longrightarrow} \sum_{\text{ang. mom. } l} a_l \left(\frac{\text{size } R}{\text{wavelength } \lambda} \right)^{2l}$ 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

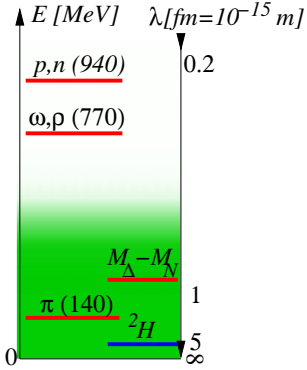
$\mathcal{L}_{\rm QCD} = \bar{q}[i\partial\!\!\!/ + gA\!\!\!/ - m_q]q - \frac{1}{2}\mathrm{tr}[F^{\mu\nu}F_{\mu\nu}]$ has *few* parameters: $\alpha_S + 6$ masses.

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**

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

Controlled expansion in $\delta = \dfrac{M_\Delta - M_N}{\Lambda_\chi} \approx \sqrt{\dfrac{m_\pi}{\Lambda_\chi}} \approx 0.4 \ll 1$ (numerical fact) Pascalutsa/Phillips 2002 $\Longrightarrow$ **Model-independent, uncertainty estimate.**



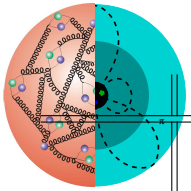
(d) Few-Nucleon Interactions in χEFT

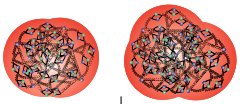
Weinberg, Ordóñez/Ray/van Kolck, Friar/Coon, Kaiser/Brockmann/Weise, Epelbaum/Glöckle/Meißner, Entem/Machleidt, Kaiser, Higa/Robilotta, Epelbaum, ...

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

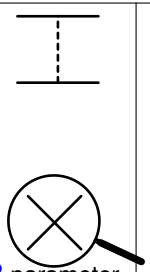
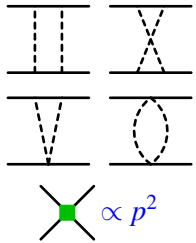
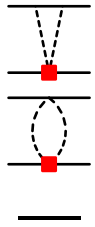
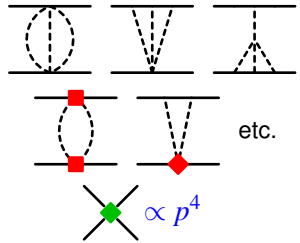
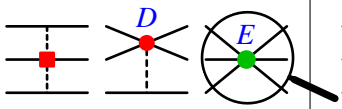
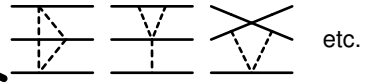
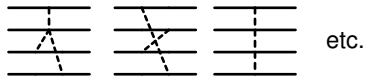
Long-Range: correct symmetries and IR degrees of freedom: **Chiral Dynamics**

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) Even Weinberg Can Be Wrong

Beane/...2002, Nogga/Timmermans/van Kolck 2005, Birse 2005-07;
NLO: Song/Lazauskas/van Kolck [1612.09090]

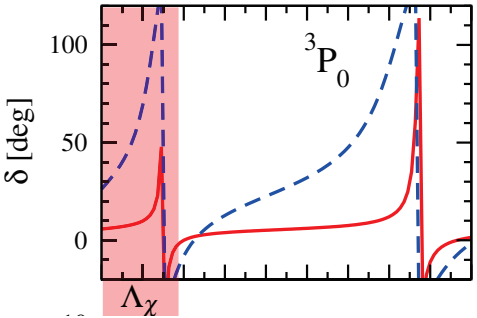
Consistency check **of Weinberg's proposal: Observables cut-off dependent at LO?**
Need 4 ***new*****, momentum-dependent LECs for low attractive triplets:** $^3P_{0,2}$, $^3D_{2,3}$.

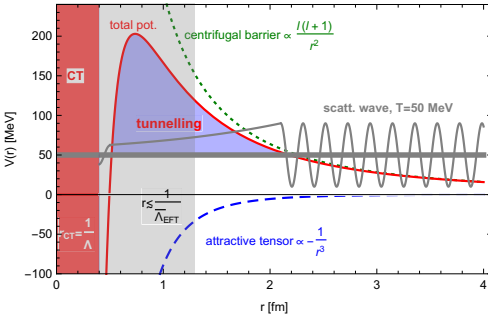
Low attractive P/D-wave triplets: Weinberg predicts zero LECs at LO (momentum-independence).

phase-shift $\delta(\text{cut-off } \Lambda)$:

$E_{\text{lab}} = 10$ MeV
50 MeV
100 MeV
190 MeV

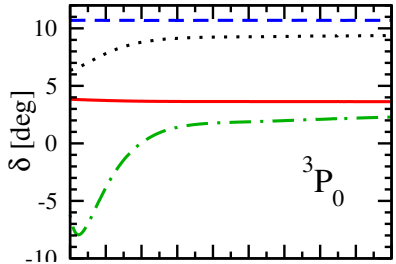
$$V(r) \propto -\frac{\#}{r^3} + \frac{l(l+1)}{r^2}$$





Without CT cutoff-dependent even for $\Lambda \approx \overline{\Lambda}_\chi$. $\Longrightarrow$ **Short-distance missing.** $\Longrightarrow$ ***Not renormalised.***

Λ-Dependence With Counter Term



(f) NN χEFT Power Counting Comparison

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

order	**Weinberg** (Pragm. Prop.) PL**B251** (1990) 288 etc.	**Long/Yang** PR**C86**(2012) 024001 etc.
Q^{-1}	LO of $^1S_0$, $^3S_1$, OPE	plus $^3P_{0,2}$
$Q^{-\frac{1}{2}}$	none	none
Q^0	none	NLO of $^1S_0$
$Q^{\frac{1}{2}}$	none	none
Q^1	LO of $^3SD_1$, $^1P_1$, $^3P_{0,1,2}$; NLO of $^1S_0$, $^3S_1$	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
# at Q^0	$+0$	$+1$
# at Q^1	$+7$	$+8$
total at Q^1	9	13

With same χ^2/d.o.f., the *self-consistent* proposal with least parameters *wins*: minimum information bias.

(g) EFT and Information Theory: Lossless Compression vs. Data Reproduction

Information-Theory Aspect of the EFT Promise:

Encode information about unresolved short-range

at given resolution and *at given order*

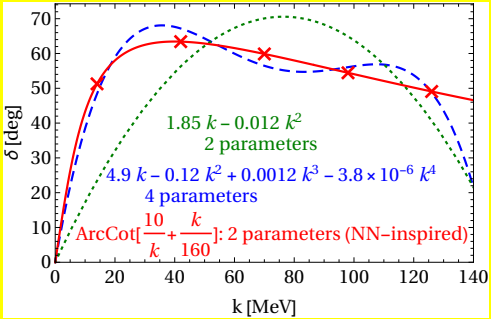
into smallest number of independent CTs:

minimal set of parameters for *lossless compression*:

$\Longrightarrow$ **Falsifiability; robust predictions to uncover**

new Physics, Alternative Worlds, hidden symmetries

(unitarity, large-N_c Schindler/Springer 2018-,. . .).



(h) EFT = Symmetries + Parametrise Ignorance: What Can Possibly Go Wrong??

Expand observables as $\mathcal{O} = c_0 + c_1 Q^1 + c_2 Q^2 + \ldots$

with $Q = \dfrac{\text{typ. momentum } p_{\text{typ.}}}{\text{breakdown scale } \bar{\Lambda}_{\text{EFT}}} < 1.$

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

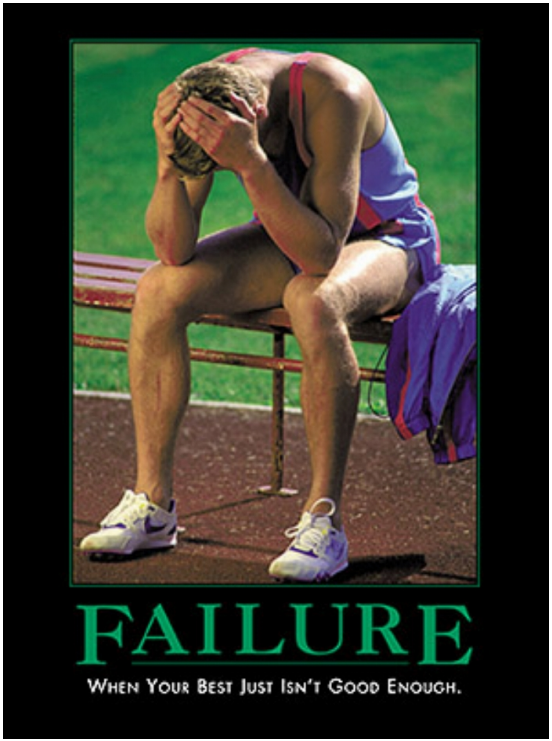
Check the *Quantitatively Predicted* Convergence Pattern:

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

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

– Order by order smaller corrections.

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

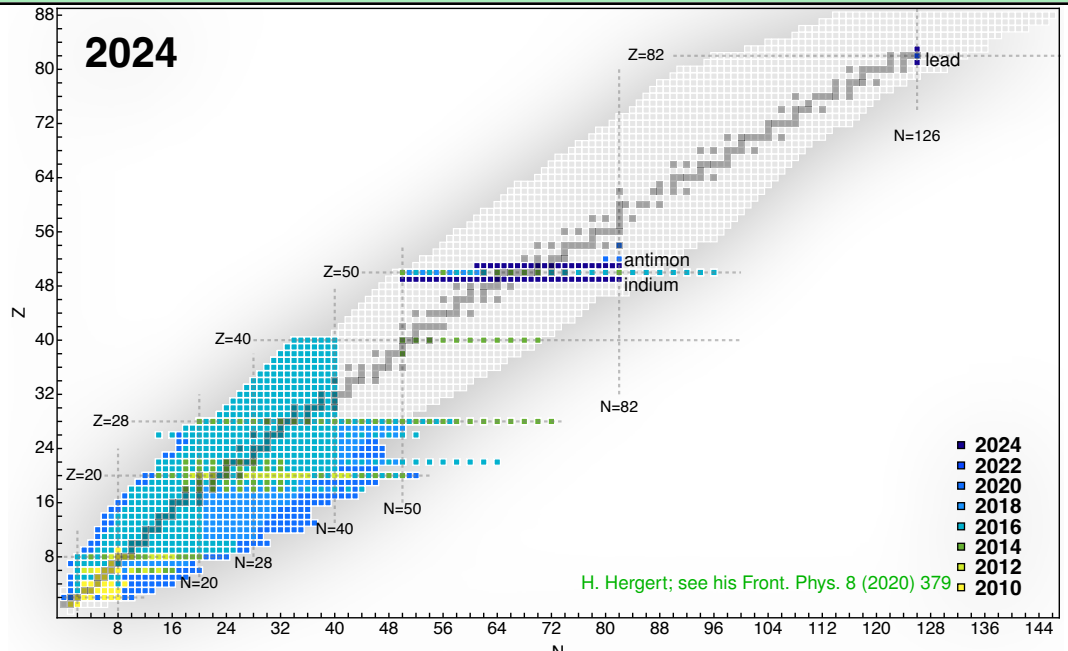


Falsifiability: Convergence to Nature tests assumptions. – *After* theoretical uncertainties determined.

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

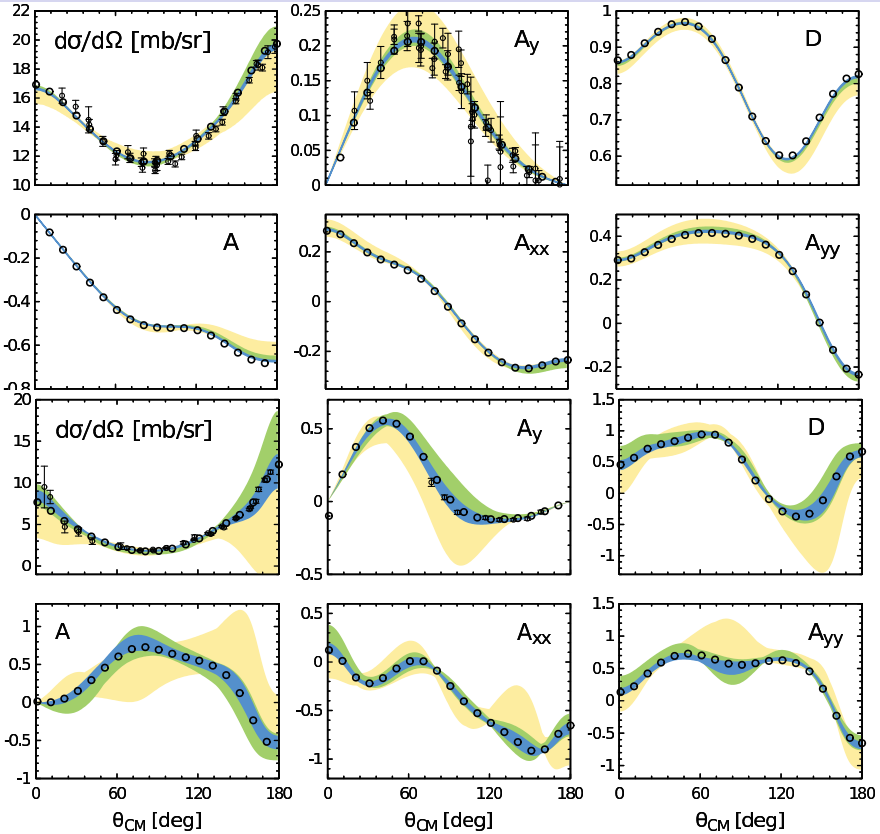
***Ab Initio*: method to reliably extrapolate, in a controlled and systematic way, to regions outside the ones used for inferring the model parameters. [...] a systematically improvable approach for quantitatively describing nuclei using the finest resolution scale possible while maximizing its predictive capabilities.**

Ekström/Forssén/Hagen/Jansen/Jiang/Papenbrock Front. Phys. 11 (2023) 1129094 [2212.11064]



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

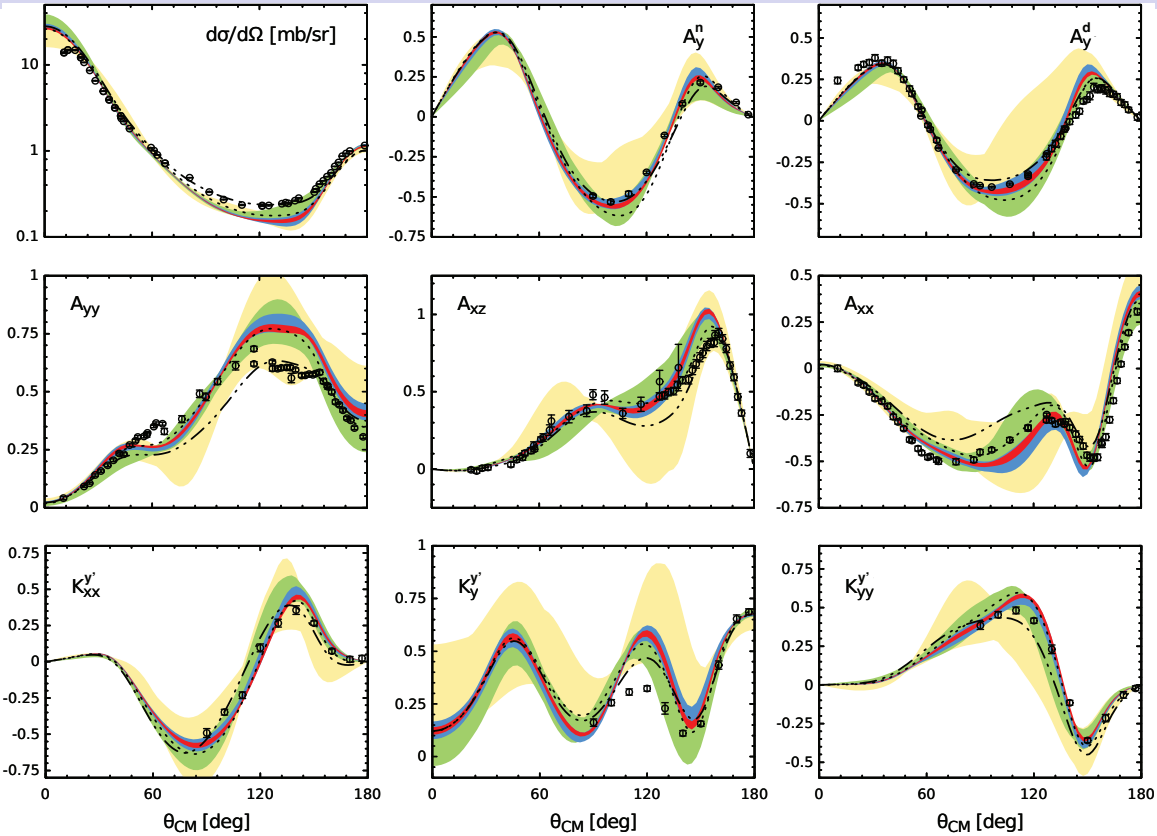
Epelbaum/...1412.0142



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

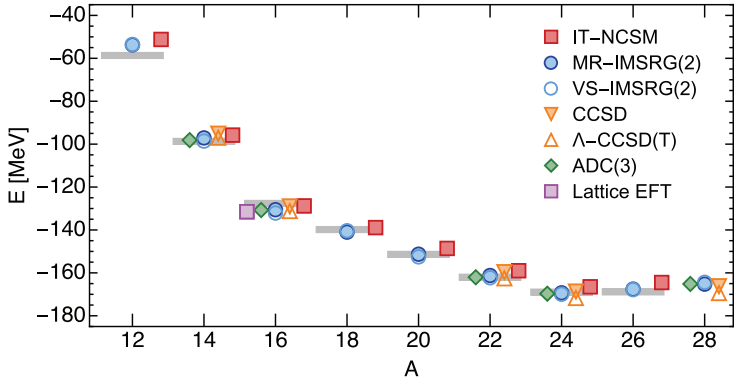
(c) 3N: Polarised Deuteron-Proton Scattering

Epelbaum/... [arXiv:1802.08584]



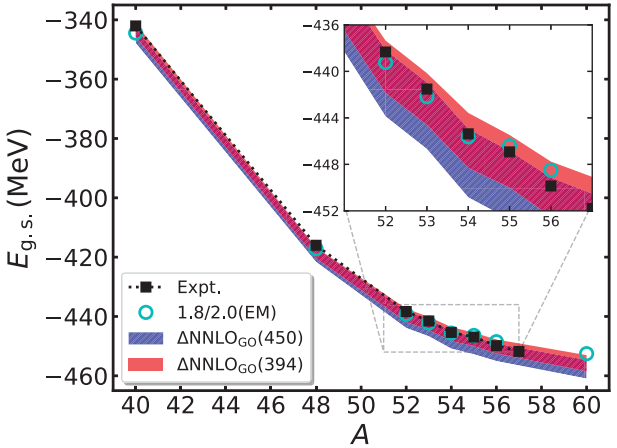
Bands estimate theory uncertainties by higher-order effects: LO → NLO → N^2LO → N^3LO

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



Oxygen chain

Hergert: Front. Phys. 8 (2022) 379

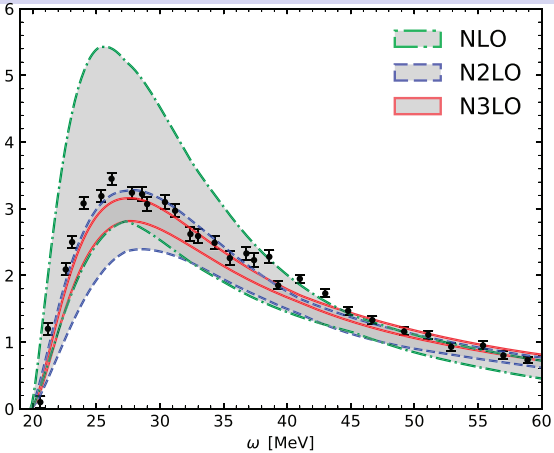


Calcium chain

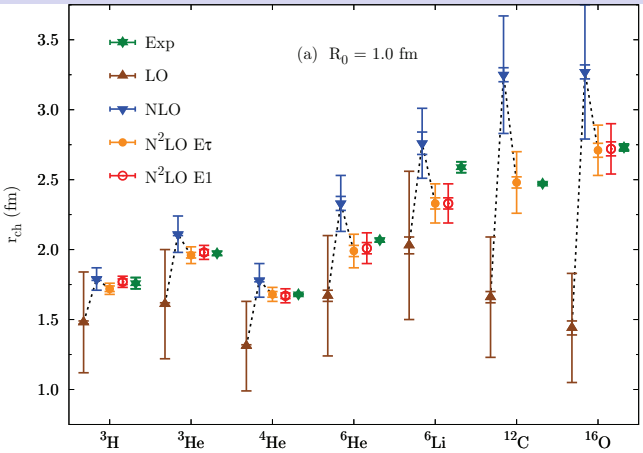
Forssén et al. 2006.16774

Theory methods agree: numerics (largely) under control.

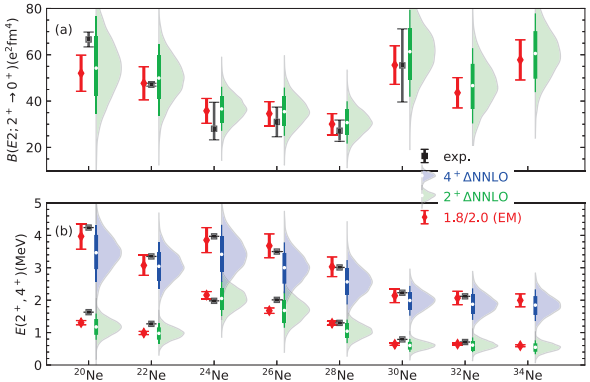
(e) Electromagnetic Properties of Light Nuclei: Uncertainties Shrink with Order



^{4}He photodissociation Bacca/...



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



Ne isotopic chain:

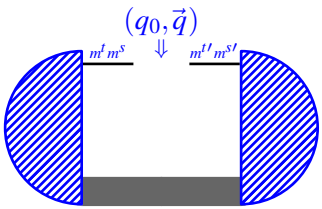
$E2(2^+ \to 0^+)$ transition strength

energies of 2^+ & 4^+

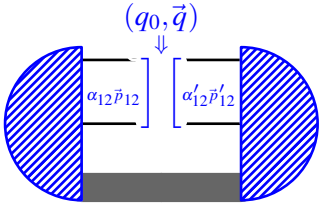
Sun/...2404.00058

(f) Threshold π^0 Photo/Electro-Production With TDAs

Alex Long: PhD 2026 [2606.23331]
with code suite at zenodo.18893804
publications in preparation



1 **Active Nucleon: one-body density**

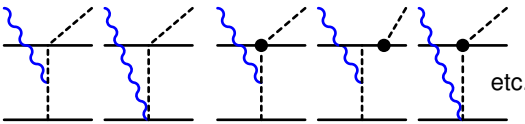


2 **Active Nucleons: two-body density**

onebody NLO ($\mathcal{O}(Q^4)$) BKM 1994-6



twobody NLO ($\mathcal{O}(Q^4)$, recoil≈ 0) Beane/...1997 Krebs/...2004



$2i[E_{0+}(\vec{\epsilon}_T \cdot \vec{J}_A) + L_{0+}(\vec{\epsilon}_L \cdot \vec{J}_A)]$		E_{0+}^{1N}	E_{0+}^{2N}	$E_{0+}[10^{-3} m_\pi^{-1}]$	L_{0+}^{1N}	L_{0+}^{2N}	$L_{0+}[10^{-3} m_\pi^{-1}]$	$a_0\,(\gamma\pi^0)$
^{3}H	**TDA**	-0.99	-4.03	$-5.03(14)$	-1.04	-3.27	$-4.31(12)$	25.25(143)
	Lenkewitz/...2013	-0.93	-4.03	$-4.96(7)$	-0.99	-3.20	$-4.19(7)$	24.60(67)
	Braun/...(LO) 2019	-0.94	-3.55	$-4.49(44)$	–	–	–	20.16(391)
^{3}He	**TDA**	1.74	-4.01	$-2.26(17)$	-1.92	-3.24	$-5.16(15)$	5.12(74)
	Lenkewitz/...2013	1.71	-3.97	$-2.26(10)$	-1.89	-3.16	$-5.05(10)$	5.11(47)
	Braun/...(LO) 2019	1.77	-3.53	$-1.76(44)$	–	–	–	3.10(154)
^{6}Li	**TDA**	0.25	-2.26	$\mathbf{-2.00(8)}$	-0.99	-1.79	$-2.77(8)$	10.69(89)
	Braun/...(LO) 2019$\times\sqrt{2}$	0.26	-2.15	$-1.89(25)$	–	–	–	9.52(260)
	SAL Bergström/...1999			$\mathbf{-1.63(12)}$				

NLO small, twobody large. Error: theory dominates, numerics tiny. Precursors: Lenkewitz: AV18+UIX, no full error analysis. Braun: Idaho, LO, $\sqrt{2}$ in ^{6}Li, numerics dominant.

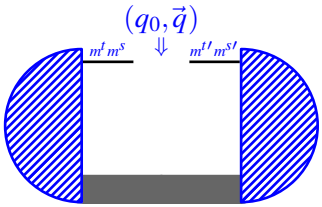
^{6}**Li Data SAL Bergström/...1999** within 2σ, $\frac{\text{theory}}{\text{data}} \approx 1.23(10)$ like in χEFT prediction $d(\gamma,\pi^0)d$ Beane/...1997 SAL 1998

$\Longrightarrow$ "πEC Structure" OK? Discrepancy dominated by 1N amplitude + boost?

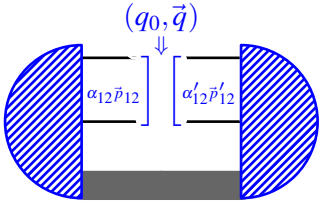
^{3}He$(\gamma,\pi^0)^3$He very sensitive to $E_{0+}^{\pi^0 n}$ $\Longrightarrow$ measure at MAMI?!!

(g) Threshold Elastic π Scattering With TDAs

Alex Long: PhD 2026 [2606.23331]
with code suite at zenodo.18893804
publications in preparation



1 **Active Nucleon: one-body density**

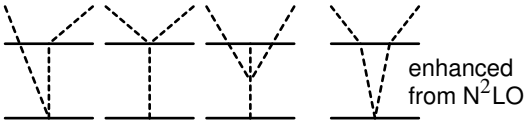


2 **Active Nucleons: two-body density**

onebody: scatt. lengths analysis Hoferichter/...2009

$a^+ = -2.35(104)$, $a^- = 87.89(179)$ $[10^{-3} m_\pi^{-1}]$

twobody NLO+ ($\mathcal{O}(Q^{4+})$) Weinberg 1992, Beane/...1998-2003, S. Liebig/...2011



$a_{\pi A}$ $[10^{-3} m_\pi^{-1}]$		a^{1N} (wf norm)	a^{2N}	a^{3N}	a^{4N}	$a^{tot}_{\pi A}$
^{3}He	π^+ **TDA**	$-103.9(54)$	$-23.57(75)$	–	–	$-127.5(55)$
	π^- **TDA**	$88.5(54)$		–	–	$64.9(55)$
	π^- Liebig/...		$-21.26(2)$	$-4.77(8)$	–	$62.5(54)$
	π^- atom 1977					$56(6)$
	π^- atom 1980					$43(5)$
	π^- atom 1984					$41(4)$
	π^0 **TDA**	$-7.7(34)$	$-21.60(71)$	–	–	$-29.3(35)$
^{3}H	π^+ **TDA**	$88.5(54)$	$-23.51(76)$	–	–	$65.0(55)$
	π^- **TDA**	$-103.9(54)$		–	–	$-127.4(55)$
	π^0 **TDA**	$-7.7(34)$	$-21.78(71)$	–	–	$-29.5(35)$
^{4}He	$\pi^\pm$ **TDA**	$-10.4(46)$	$-49.2(16)$	–	–	$-59.6(49)$
	$\pi^\pm$ Liebig/...		$-45.8(6)$	–	$2.31(31)$	$-53.9(47)$
	π^0 **TDA**		$-45.9(15)$	–	–	$-56.3(49)$
^{6}Li	$\pi^\pm$ **TDA**	$-15.8(70)$	$-86.7(27)$	–	–	$-102.5(75)$
	π^0 **TDA**		$-80.6(25)$	–	–	$-96.3(74)$

NLO small (≈N^{2}LO).

Twobody large, grows with A.

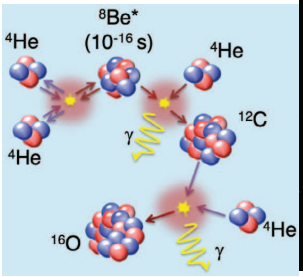
2N charge/isospin-breaking by m_π, $B(A)$ is tiny.

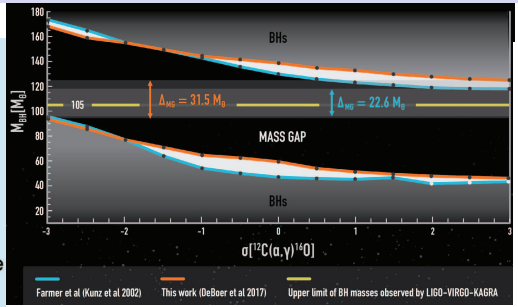
Error: numerics tiny, order-by-order & Λ dominate.

Consistent with Liebig/...2011: χEKM potential, significant numerics error. 3N, 4N within uncertainties.

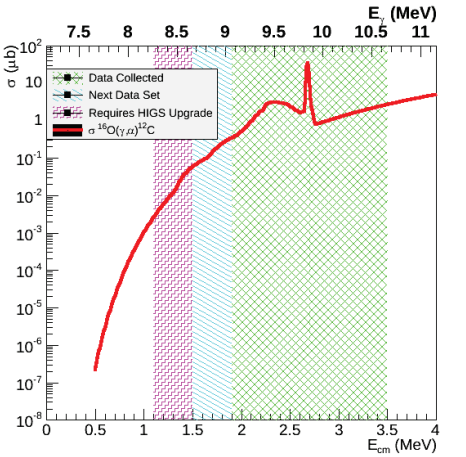
2-3σ tension with extractions from $\pi^-{}^3$He atom persists.

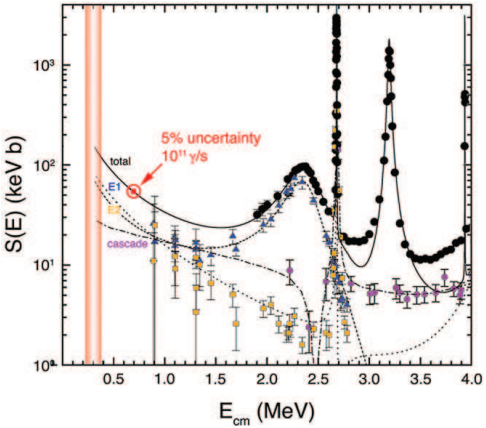
(h) ^{16}O Formation in the Solar CNO Cycle (Teller's "set atmosphere on fire")



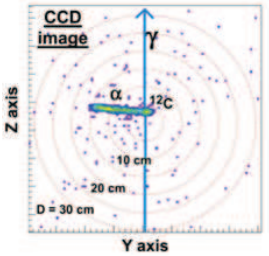


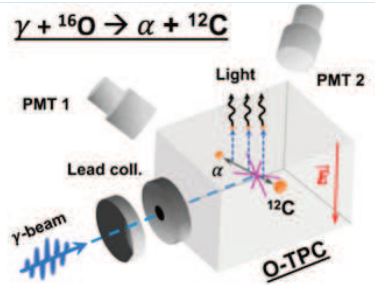
Critical for Black Hole mass gap: $\nexists$ in grav. wave





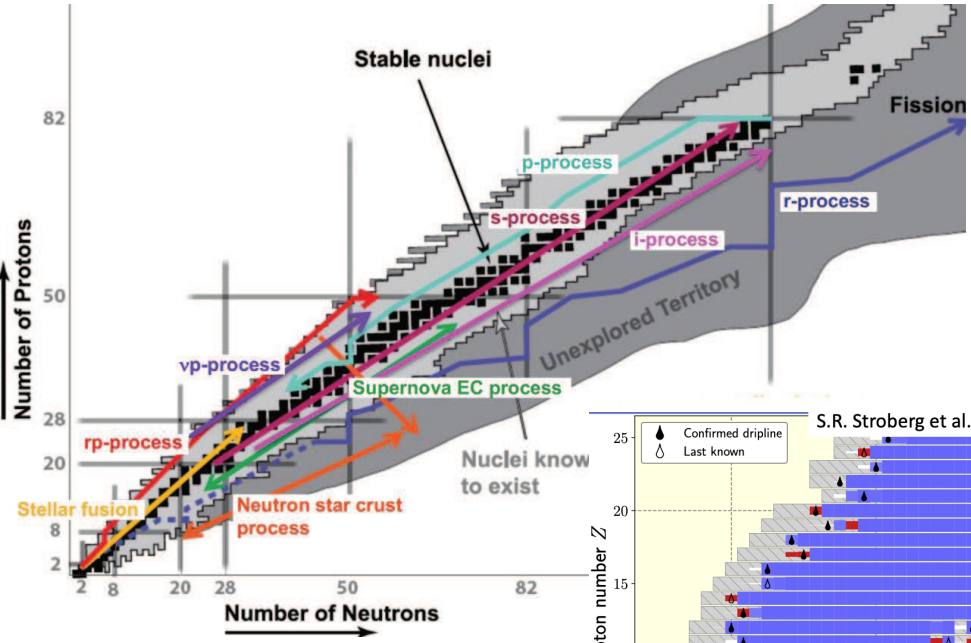
$^{12}C(\alpha,\gamma)^{16}O$ needed to $\lesssim 10\%$ at $\lesssim 400$ keV

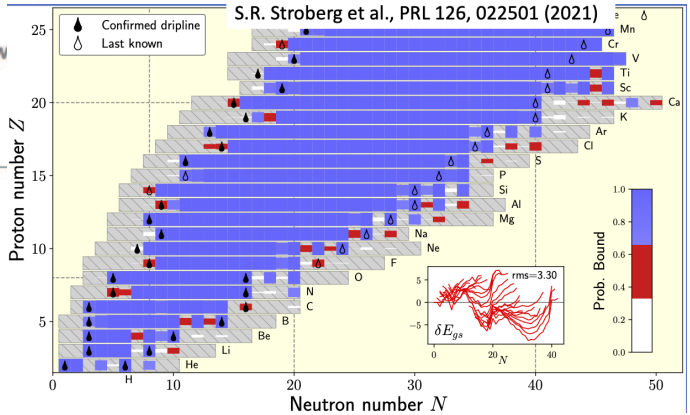




Measure $^{16}O(\gamma,\alpha)^{12}C$ at $\omega \lesssim 8$ MeV, detailed balance.

(i) Nuclear Chart for Nuclear Astrophysics





Dripline position not known.

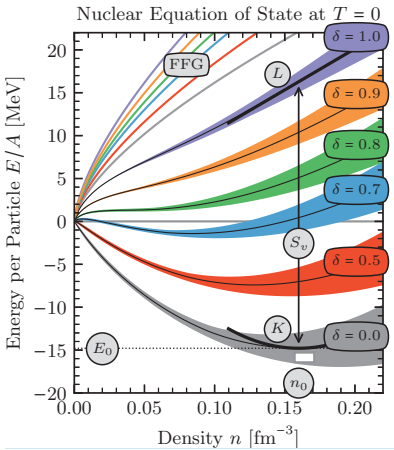
Cannot measure all nuclei & excitations.

$\Longrightarrow$ Train theory on judiciously chosen "doable but relevant" data.

dripline position from Model Mixing

(j) A Goal: Nuclear Equations of State & Neutron Stars

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



Remain Elusive:

– Order-by-order convergence;
usually not strict pert.

– Saturation point.

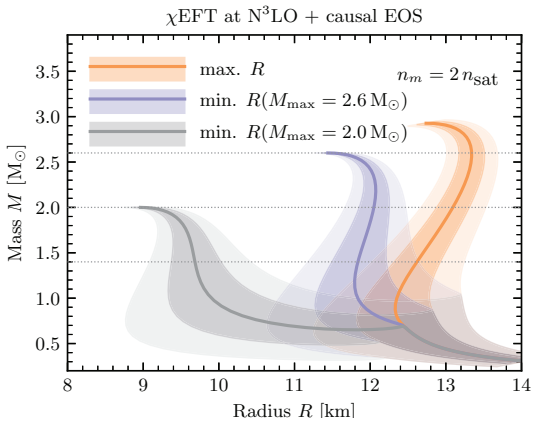
$\Longrightarrow$ Fine tuning??

Only indirect data,

disputed info from

n skin thickness.

$\Longrightarrow$ n matter (even dilute)?!



4. A Few Of The Issues I Need To Understand Better

nucl-phys is mature field. $\Longrightarrow$ Accuracy over discovery. $\Longrightarrow$ Need well-characterised environments.

- Need well-characterised energy spectrum, particle contents, intensity/time/spatial/... profile: $\pm$%-level error!

$\Longrightarrow$ Scale back on "frontier" ambitions, invest in reproducible/well-characterised shots?

- **Average-Shot Analysis:** Hinges on repeat rate: "Many" shots to hopefully average out for well-characterised *mean* energy spectrum, particle contents, intensity/time/spatial/... profiles on $\pm$%-level error.
- **Event-By-Event Analysis:** Characterise each event well! Large fluctuations offer chance for rare events?
- What is information$\pm$error content of single shot?
- 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-characterised beam profiles?

  Optimisation problem: Which "experimentally doable" combination most sensitive?
- Secondary neutron or pion beams: pion scattering, neutron properties/r-process, magnetar Physics?

$$\text{n flux} \gtrsim 10^{8}\frac{1}{\mathrm{cm^2\,ps}} \approx 10^{20}\frac{1}{\mathrm{cm^2\,s}},\ \rho \approx 10^{11}\frac{1}{\mathrm{cm^3}} \Longleftrightarrow \text{supernova: } 10^{28}\frac{1}{\mathrm{cm^2\,s}}$$

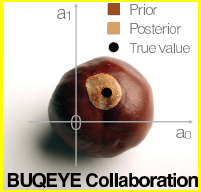
$\Longrightarrow$ Still may allow for Rare-Event detection?!

- Direct measurement of neutron-neutron, nucleus-pion,... scattering lengths?

  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 & Pion matter explorations? – $\mathrm{nnn} \to \mathrm{nnn}$ – Three-Nucleon Interactions $\to$ Jerry Yang's talk

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

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



Finite sampling pool; data fixed; more data changes confidence.

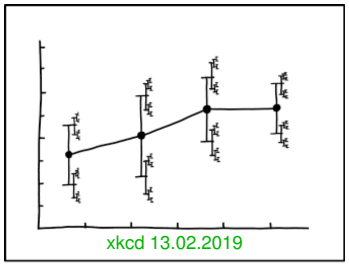
$\Longrightarrow$ **Bayesian Statistics: New information increases level of confidence.**

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

Reasonable people can reasonably disagree about reasonable assumptions, but no reasonable discussion without disclosing them.



Trust only theorists who show effort to estimate theory/truncation errors – or apologise when not.



- **Robust Estimates of Theory Truncation Errors & Correlations**
- **Quantitative Checks of Convergence Pattern, δ, $\overline{\Lambda}_{\text{EFT}}$, Naturalness**
- **Experimental Design:** Which future data have likely biggest impact?
- **Model Mixing:** Extrapolate theories valid for different scales & environments.
- **Emulators:** Reduced basis reduces CPU time, Eigenvalue Continuation,...

Annual ISNET workshops/conferences

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

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

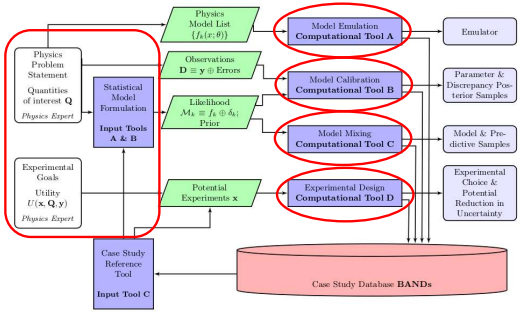
Front. Phys. Res. Topics (2022)

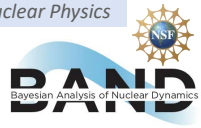
Open Source Software Suites:

buqeye.github.io

bandframework.github.io

Goal: *Facilitate principled Uncertainty Quantification in Nuclear Physics*





An NSF CSSI Framework (5 years until 2026)

Look to https://bandframework.github.io/ for papers, talks, and software!

v0.3 released 10/23