

The nuclear interaction: Post-modern developments

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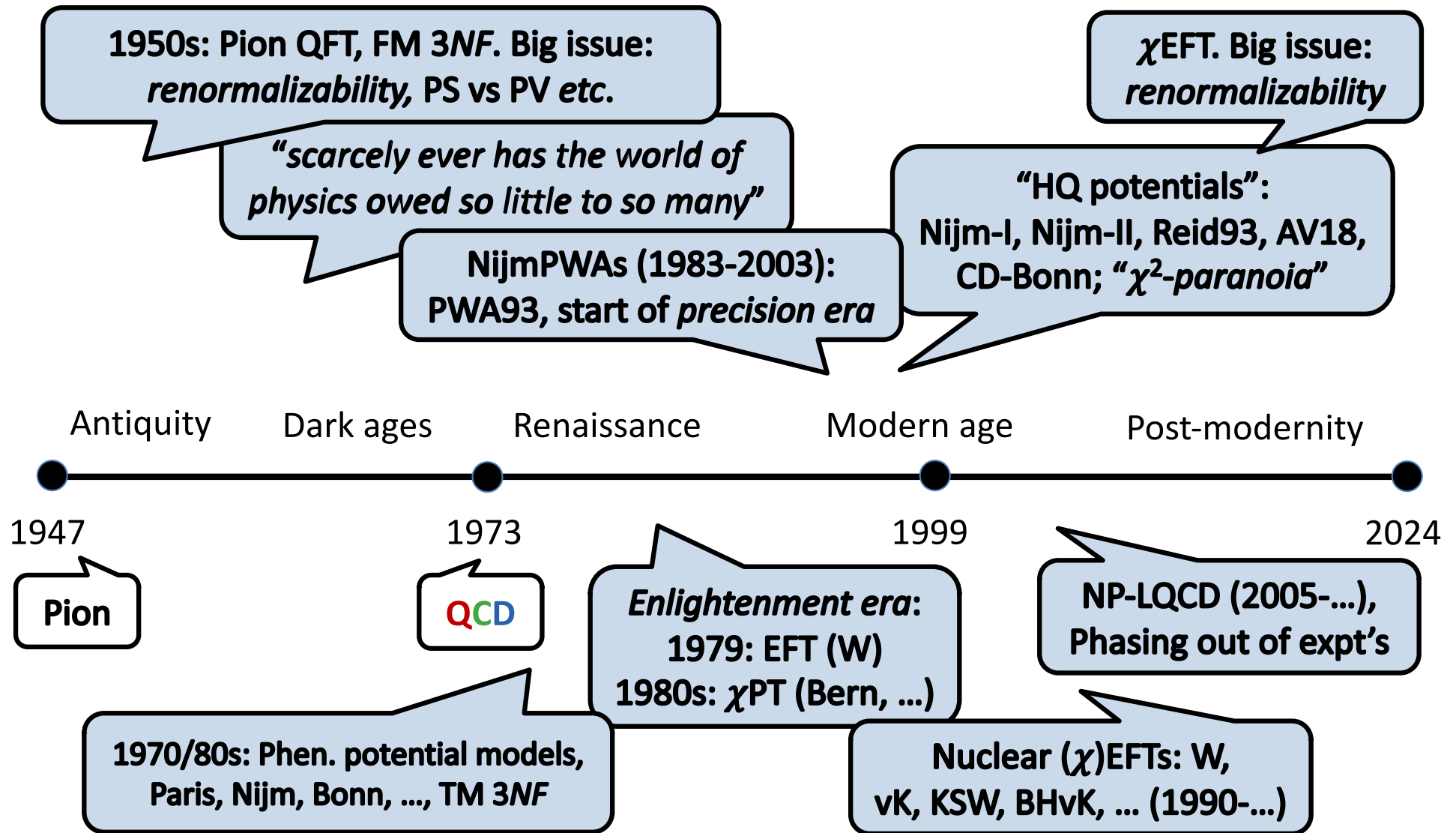


Opinions are my own

The EFT wars (1998-2005)

- ECT*, Trento, 1999: *“Nuclear forces: Modern developments”*
- INT, Seattle, 2001: *“Theories of nuclear forces and few-nucleon systems”*
- INT, Seattle, 2003: *“Theories of nuclear forces and nuclear systems”* (program), with 1-week workshop *“Two- and three-nucleon forces”*
- ECT*, Trento, 2005: *“Nuclear forces and QCD: Never the twain shall meet?”*
- ...
- ✓ Hammer, König, van Kolck, RMP 2020:
 - *“EFTs have, in fact, revolutionized nuclear physics”*
- ✓ Time to take stock!

Those who don't know history...



The clash of 1999

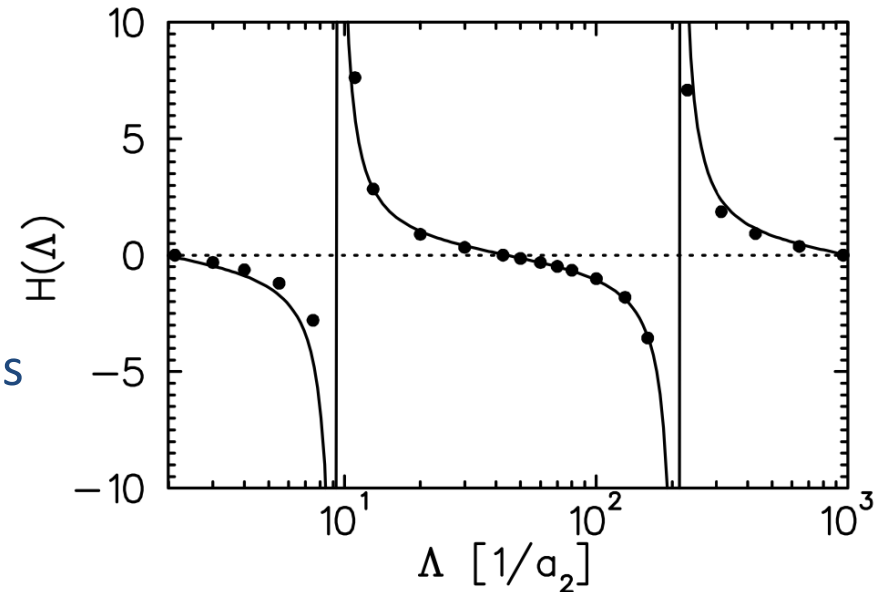
✓ *Casus belli* :

- “Phenomenology” vs EFT



Model and definition dependence

- Off-shell NN versus $3N$ in triton
- Need? for precision
 - Use of “HQ” NN potential models
- Need? for “full relativity”
- ...



✓ BHvK 1998/00: 3-body system with short-range interactions

- 3BF required at LO for renormalization
- Discovery of the limit cycle of RG flow
 - “*Is this math or physics?*”
 - “*This is just Russian zero-range theory*”




- ✓ *“Within 1-2 years we will all be using χ PT-designed products (3rd-generation forces, “standard” 3NF)”*
- ✓ *“EFT is like Antarctica, cold and barren, freeze out everything!”*

The evolutionary landscape in 1999



The Standard
of Nuclear Physics

blah

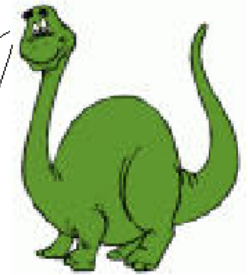


The true landscape

what does the
cockroach see?



what does the
dinosaur see?



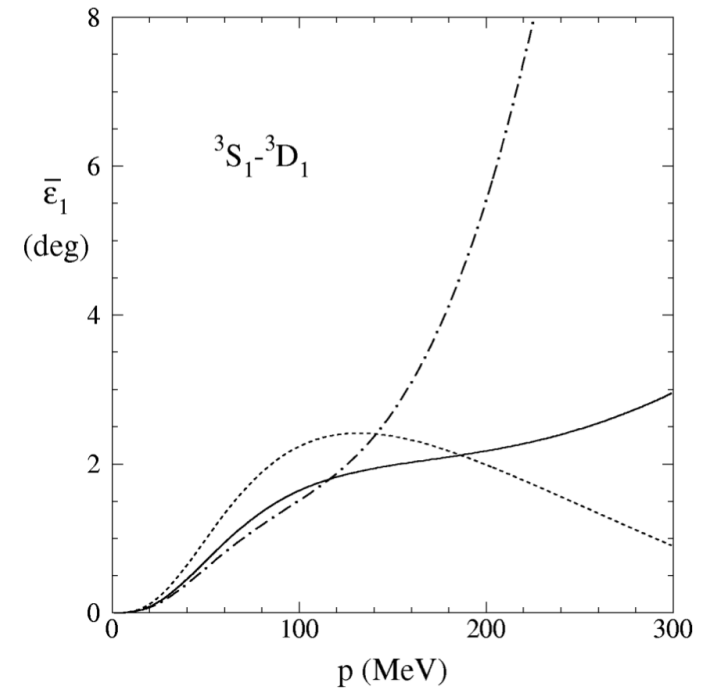
- “Cockroaches can’t do much, but they *feel good* about it, because it is connected to QCD (well, sort of...)”
- Dinosaurs can do a lot, but they should *feel bad* about it, because there is only a tenuous connection to QCD”
 - Tom Cohen
- ✓ However, “*One does not applaud the tenor for clearing his throat*”
 - Isabelle de Merteuil

χ EFT: no rose garden?

- ✓ Plan A: χ EFT
 - KSW, 1996/8; K, 2020: “perturbative pions”
 - “This is just effective-range expansion”
 - CH, 1998/9; FMS, 2000: “PC not effective”



- ✓ → Plan B: “pionful” EFT → “pionless” EFT
- ✓ “It won’t work, not enough separation of scales”



- ✓ *Noblesse oblige*: An EFT should deliver
 - Controlled expansions with systematic error estimates
 - Consistent with the symmetries & scales of **QCD** → power counting
 - Renormalizable = “cutoff independence” of observables
 - Requires a sufficient # counterterms at each order



Pionless (nucleons-only, contact, ...) EFT

✓ “Sir, [pionless EFT] is like a dog’s walking on his hind legs. It is not done well; but you are surprised to find it done at all.”

– Samuel Johnson

✓ “It won’t work for nuclear matter, not even for ${}^4\text{He}$ ”

✓ PHM 2004/5: 4-body system with short-range interactions

– No 4BF required at LO for renormalization!

– Explanation of “Tjon line”: $B({}^3\text{H})$ vs $B({}^4\text{He})$

✓ A post-modern success story!

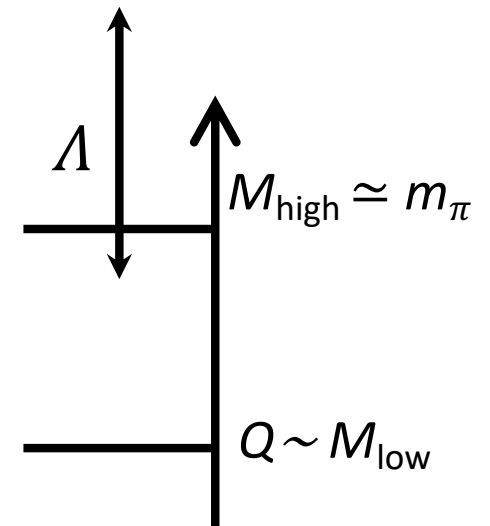
– Universality of QM few-body system, “Efimov physics”

– Working nuclear EFT for $Q \ll m_\pi$

– Consensus on power counting

– 3BF at LO, N²LO; 4BF at NLO

– KGHvK, 2017: Expansion around the unitary limit



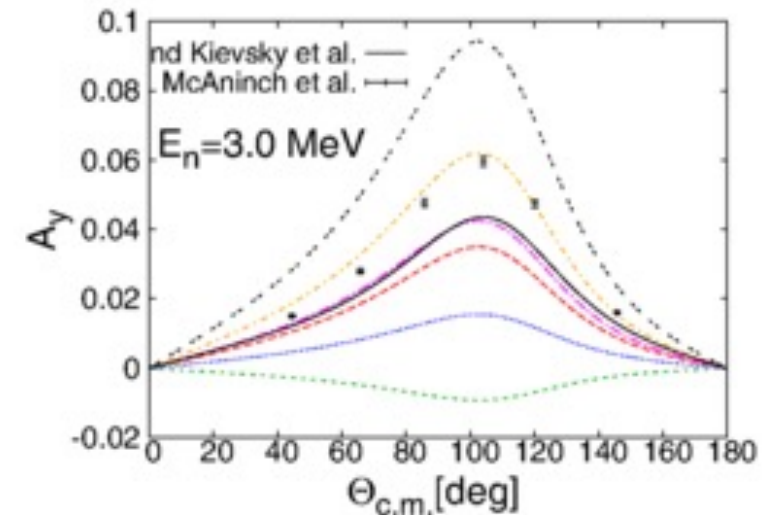
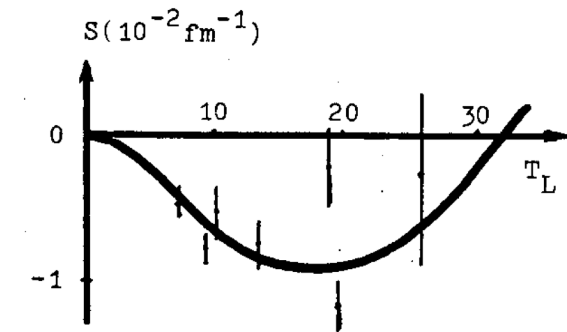
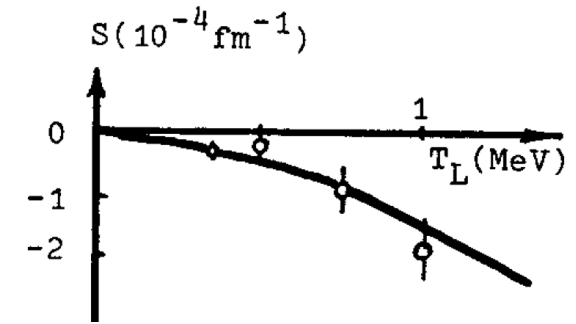
The shape of things to come

- ✓ How far can this be pushed?
 - How many nucleons? $\geq {}^{16}\text{O}, {}^{40}\text{Ca} \leftrightarrow 4\alpha$
 - Expected accuracy?

- ✓ For NN , EFT \equiv ERE, breaks down for $T_L \simeq 10$ MeV
 - ER parameters are highly correlated
 - Curved “shape” for $T_L < 10$ MeV due to OPE
 - pp PWA 0-30 MeV: OPE + 10 parameters
 - 1S_0 (3), 3P_0 (2), 3P_1 (2), 3P_2 (2), 1D_2 (1)

- ✓ A_y puzzle in n - d scattering at 3 MeV
 - MSV, 2016: N³LO, vary ${}^3P_{0,1,2}$ LECs by 15%

- ✓ Not very effective at higher orders? 🤔



Chiral (pionful) EFT

- ✓ Weinberg proposal (1990/2):
 - IR-enhancement in reducible diagrams, requires resummation
 - Truncate potential, solve QM scatt. eq. → “nonperturbative pions”
 - Power counting: χ PT for long range, NDA for short range
 - Pioneered by ORvK, 1992/6

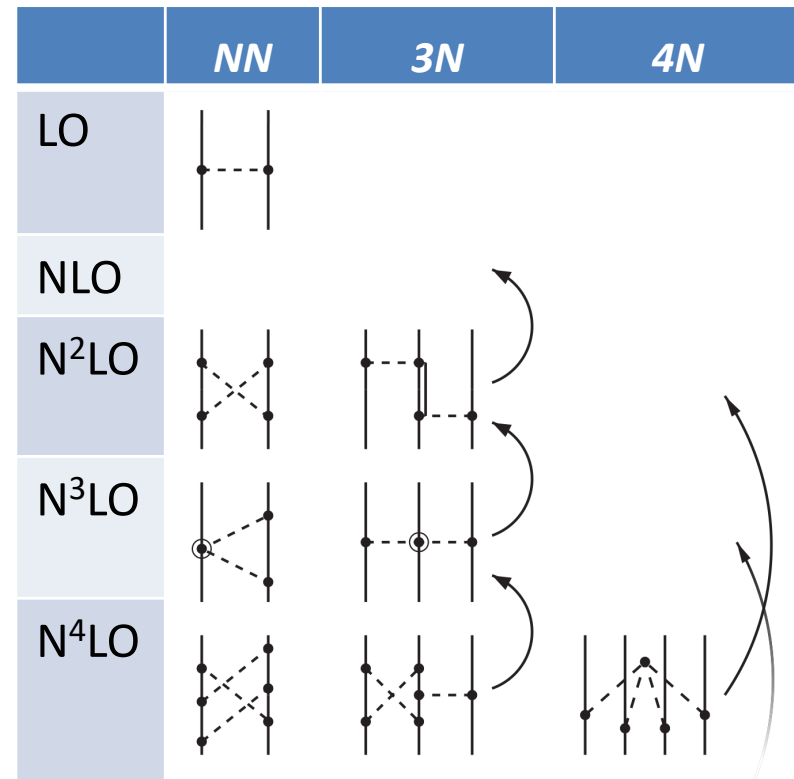
- ✓ Quantitative “ χ EFT-inspired potentials”



- Epelbaum *et al.*, 1998-...;
- Entem & Machleidt, 2003-...;
- Piarulli *et al.*, 2015-...; ...
- Totally awesome!

- ✓ Early questions:

- Friar “amendment” to PC (1997)
- PC more effective with Δ -isobar?



The demise of Weinberg PC

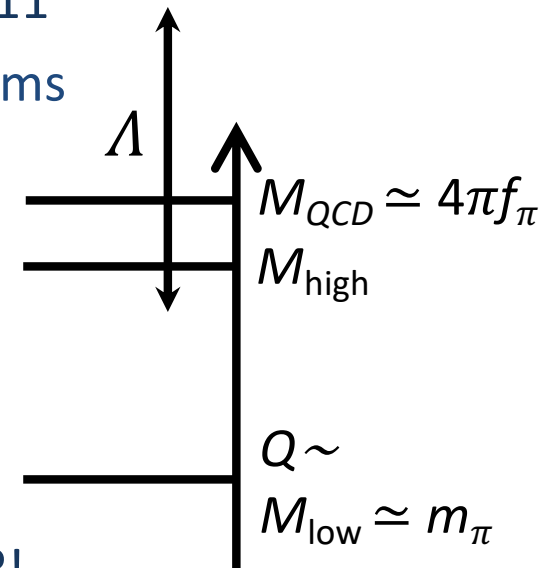
- ✓ Weinberg PC inconsistent (\rightarrow cutoff dependence):
 - KSW 1996: $C_0 \rightarrow C_0 + m_\pi^2 D_2$ in 1S_0
 - NTVK, 2005: $\sim -1/r^3$ tensor force \rightarrow promote counterterms ($\# = \infty$)
 - P-VR-A, 2006, ...: ditto for higher-order potentials (TPE) $\sim -1/r^{3-6}$
 - P-VP, 2015; external currents
 - ...

#=29	Long range	1S_0	3S_1	ε_1	1P_1	3P_0	3P_1	3P_2	ε_2	1D_2	3D_1	3D_2	3D_3
LO	OPE	✓	✓			✓		✓				✓	✓
NLO		✓											
N ² LO	LO TPE	✓	✓	✓	✓	✓	✓	✓				✓	✓
N ³ LO	NLO TPE	✓											
N ⁴ LO	N ² LO TPE, LO ThPE	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Partly perturbative pions

- ✓ Diagnosis: Nonperturbative renormalization of singular potentials
 - Dangerous (*wrong*) to iterate subleading singular potentials
 - Risk to include only a subset of higher-order counterterms needed
 - Too strong cutoff dependence too far below M_{high}
 - Cf. potential models regulated with short-range “form factors”

- ✓ Post-modern proposal: NTvK, 2005; LY, 2011/12; P-V, 2011
 - LO = nonperturbative, include promoted counterterms
 - OPE perturbative for high L , say $L > L_{\text{critical}} = 2, 3$
 - NTvK, 2005; B, 2006
 - Subleading potentials in DW perturbation



- ✓ Is a perturbative approach practical for the community?!

χ -symmetry vs χ^2 -paranoia vs χ^2 -by-eye

- ✓ Reign of Terror: Big colorful error bands to pretend that the EFT works
- ✓ Cool EFT-adapted tools:
 - “Lepage plots” (1997)
 - G 2016: Residual cutoff dependence of EFT results
 - SP, 2009; FKPW, 2015-; ...: Bayesian inference
- ✓ For serious tests of EFT, need *quantitative work, with errors*
 - Extract parameters, LECs *etc.*, in an *unbiased* way
 - Also requires *consensus on the database*
 - Test predicted EFT hierarchy of NN , $3N$, $4N$, ... forces \rightarrow small effects
 - RTFdS, 1999: OPE and TPE (N^3 LO) in pp χ PWA
 - Nothing remotely similar to this exists for $3N$, $4N$ scattering
- ✓ What actually *are* the “accuracy requirements of the nuclear community”?



“You’re entering a world of pain”...



- ✓ KVGG, 2017: Promote 3NF to LO?
 - NTVK, 2005; SLvK, 2017; YEFH, 2021: Not required for cutoff independence
- ✓ Promote two-pion exchange to LO?!

Two-pion exchange as a leading-order contribution in chiral effective field theory

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A comparison of two possible nuclear effective field theory expansions around the one- and two-pion exchange potentials

 (Received 1 December 2021; revised

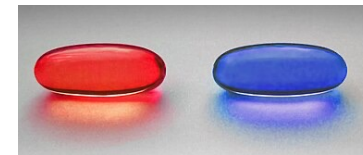
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(Dated: December 6, 2021)

arXiv:2112.02076v1 [nucl-th] 3 Dec 2021

- ✓ But what about QCD...?
 - Departures from NDA: Fine-tunings in QCD?
 - Pious hope: $M_{\text{high}} \simeq M_{\text{QCD}}$, but maybe “not enough scale separation”?!



The evolutionary landscape in 2024

How one of the world's most successful indoor pests took over the planet

By Amanda Schupak, CNN

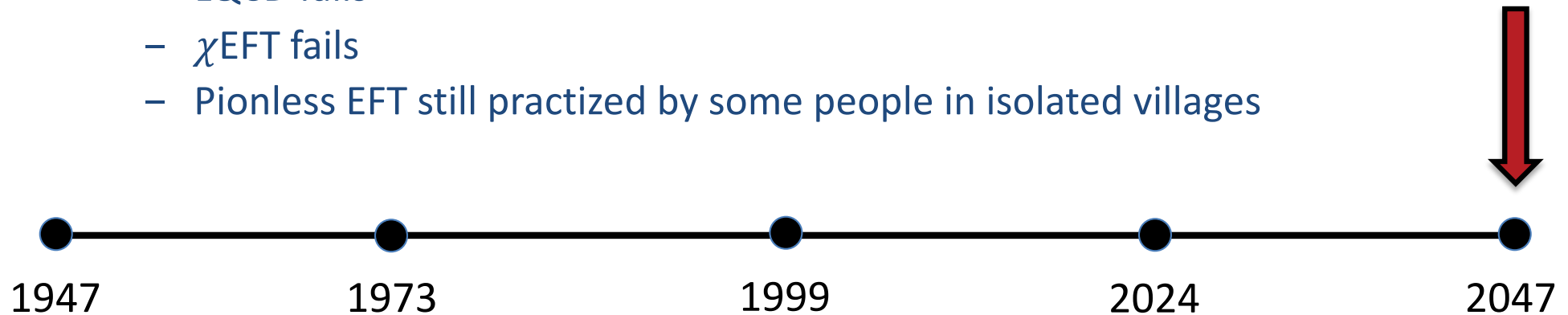
3 minute read · Updated 12:15 PM EDT, Tue May 28, 2024



Quo vadis, EFT?

✓ Dystopia:

- No more experiments
- LQCD fails
- χ EFT fails
- Pionless EFT still practiced by some people in isolated villages



✓ Utopia: Consensus on renormalizable χ EFT that

- Works for few-nucleon systems & light nuclei
- Works for nuclear matter
- Is understood within (L)QCD
- Dedicated EFTs for specific aspects of nuclear structure

I ♥
PIONS

✓ Realpolitik: LQCD takes the place of experiment, no “nuclear theory” needed

Workshop questions

1. Have chiral-EFT-inspired potentials fully replaced phenomenological approaches?
2. What are the limitations of these potentials, and how can they be improved?
3. Are chiral potentials converging appropriately, and is leading-order physics adequately captured?
4. What is the role and scope of power counting?
5. How significant is relativity in these models?
6. Do we fully understand the dynamical implications of QCD?
7. What are the prospects of EFTs (pionless, halo/cluster, chiral) for light & heavier nuclei?
8. How have simpler EFTs, such as pionless and halo/cluster EFTs, influenced chiral EFT?
9. How do EFTs help us to quantify uncertainties?