EFFECTIVE THEORIES
~~AND FUNDAMENTAL THEORIES~~

U. van Kolck

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Supported by CNRS and US DOE

Outline

- Case: Nuclear Forces
- Effective Field Theories
- Nuclear EFTs
- Summary

There are few problems in theoretical physics which have attracted more attention than that of trying to determine the fundamental interaction between two nucleons.
It is also true that scarcely ever has the world of physics owed so little to so many. (...)
It is hard to believe that many of the authors are talking about the same problem or, in fact, that they know what the problem is.

M. L. Goldberger
Midwestern Conference on Theoretical Physics, Purdue University, 1960

The Nuclear Force Problem: Is the Never-Ending Story Coming to an End?

R. Machleidt

Department of Physics, University of Idaho, Moscow, Idaho, U.S.A.

Table 1. Seven Decades of Struggle: The Theory of Nuclear Forces

1935	**Yukawa: Meson Theory**
1950's	*The "Pion Theories"* One-Pion Exchange: o.k. Multi-Pion Exchange: disaster
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1970's	Refine meson theory: Sophisticated 2π exchange models (Stony Brook, Paris, Bonn)
1980's	Nuclear physicists discover **QCD** Quark Cluster Models
1990's and beyond	Nuclear physicists discover **EFT** Weinberg, van Kolck **Back to Meson Theory!** *But, with Chiral Symmetry*

No renormalization-group invariance

split with particle physics

Life with models: refined description of two-body scattering; three-body forces?

Quantum Monte Carlo Calculations of Light Nuclei

$$v_{ij}^{\pi} + v_{ij}^{R} = \sum_{p=1,18} v_p(r_{ij}) O_{ij}^{p}$$

Steven C. Pieper and R. B. Wiringa
Physics Division, Argonne National Laboratory, Argonne, IL 60439;
email: spieper@anl.gov, wiringa@anl.gov

$$O_{ij}^{p=1,14} = [1, \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j, S_{ij}, \mathbf{L}\cdot\mathbf{S}, \mathbf{L}^2, \mathbf{L}^2(\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j), (\mathbf{L}\cdot\mathbf{S})^2] \otimes [1, \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j]$$

$$O_{ij}^{p=15,18} = [1, \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j, S_{ij}] \otimes T_{ij} \text{ , and } (\tau_{zi} + \tau_{zj})$$

from T.B. Clegg

Barker *et al.*, PRL **48** (1982) 918

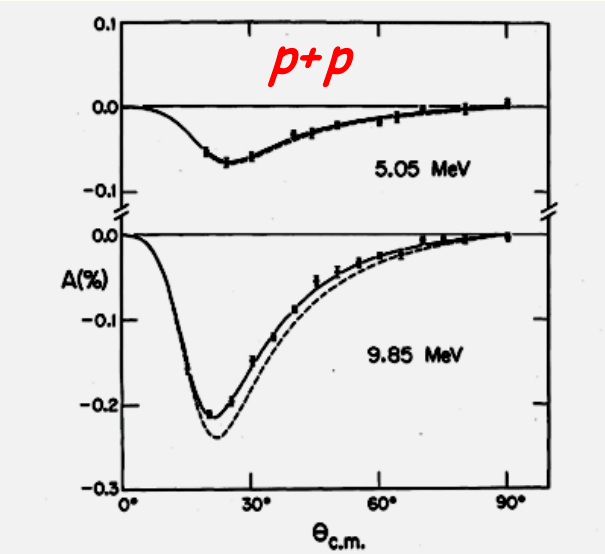
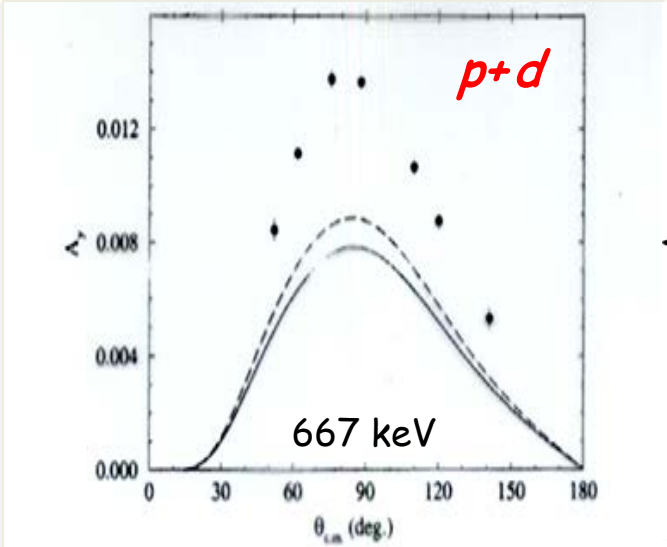


FIG. 2. Proton-proton analyzing power at 5.05 and 9.85 MeV plotted as a function of c.m. scattering angle. The solid curves through the data points are obtained from our phase-shift analyses. The dashed curves are the analyzing powers predicted from the Paris potential.

Brune *et al.*, PRC **63** (2001) 044013



Angular distribution for A_y for p-d scattering at $E_{c.m.}$ = 667 keV. The errors include the uncertainty in the beam polarization as well as statistical uncertainties. The solid and dashed curves are calculations with the AV18 and AV18+UR potentials, respectively.

Fisher *et al.*, PRC **74** (2006) 034001

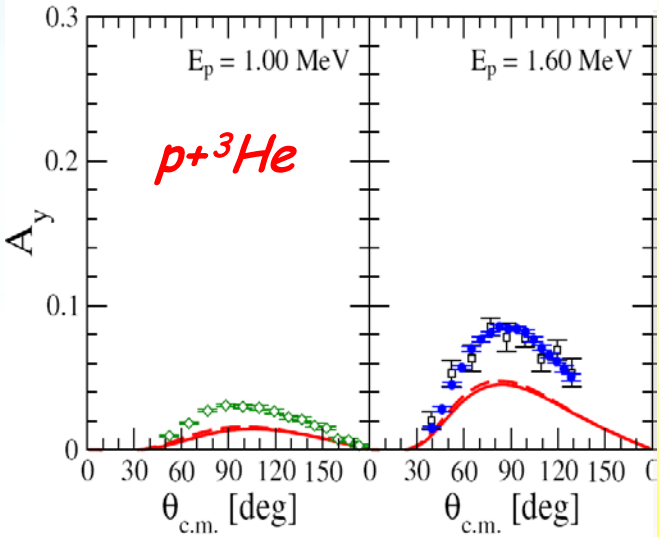
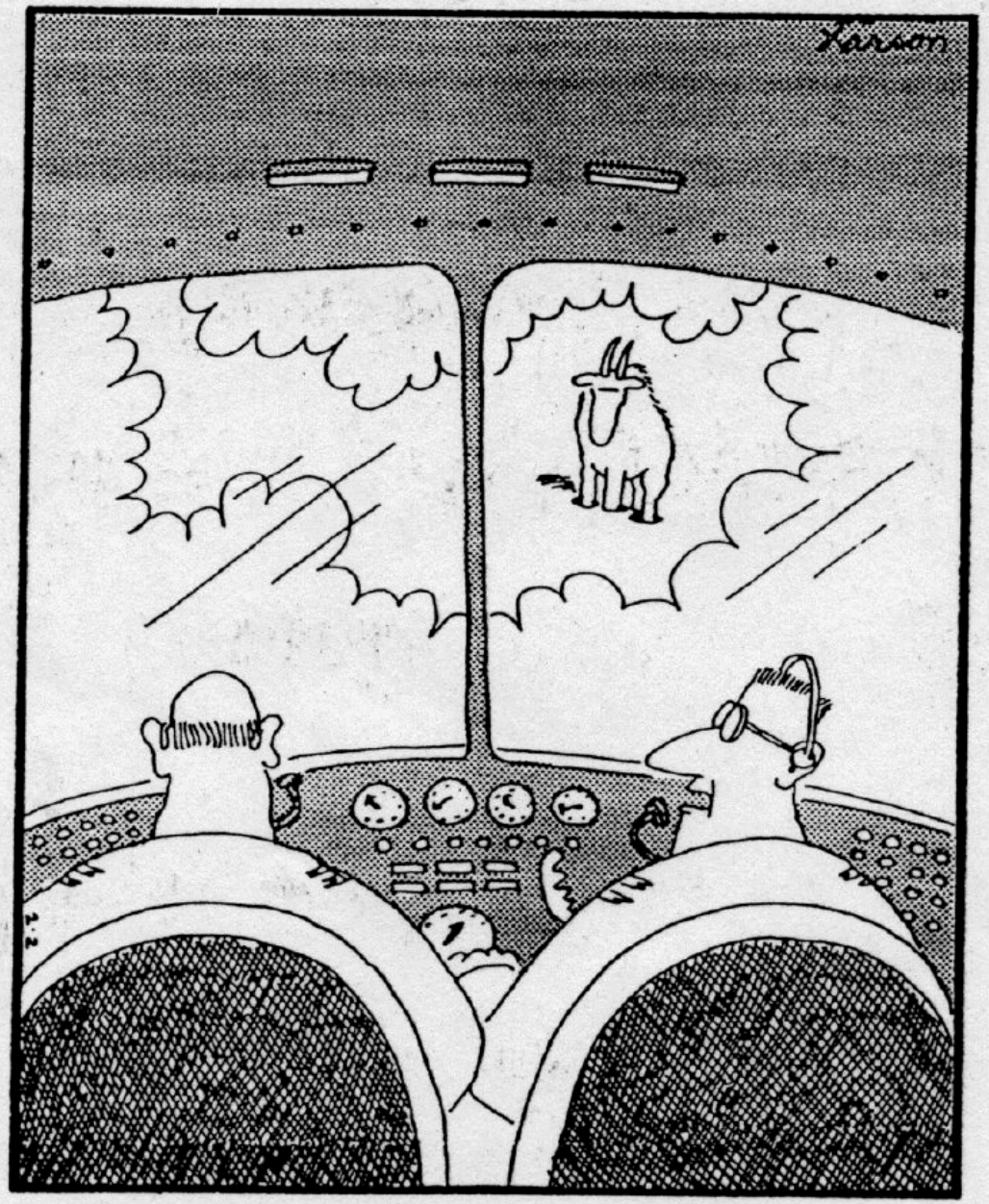


FIG. 5. (Color online) Measured p-^{3}He proton analyzing power A_y (solid circles) at five different energies are compared with the data of Ref. [10] (open squares), Ref. [22] (open diamonds), and Ref. [67] (open circles). Curves show the results of theoretical calculations for the AV18 (dashed lines) and AV18/UIX (solid lines) potential models.



"Say . . . What's a mountain goat doing way up here in a cloud bank?"

77

Time for a paradigm change, perhaps?

The Nuclear Force Problem: Is the Never-Ending Story Coming to an End?

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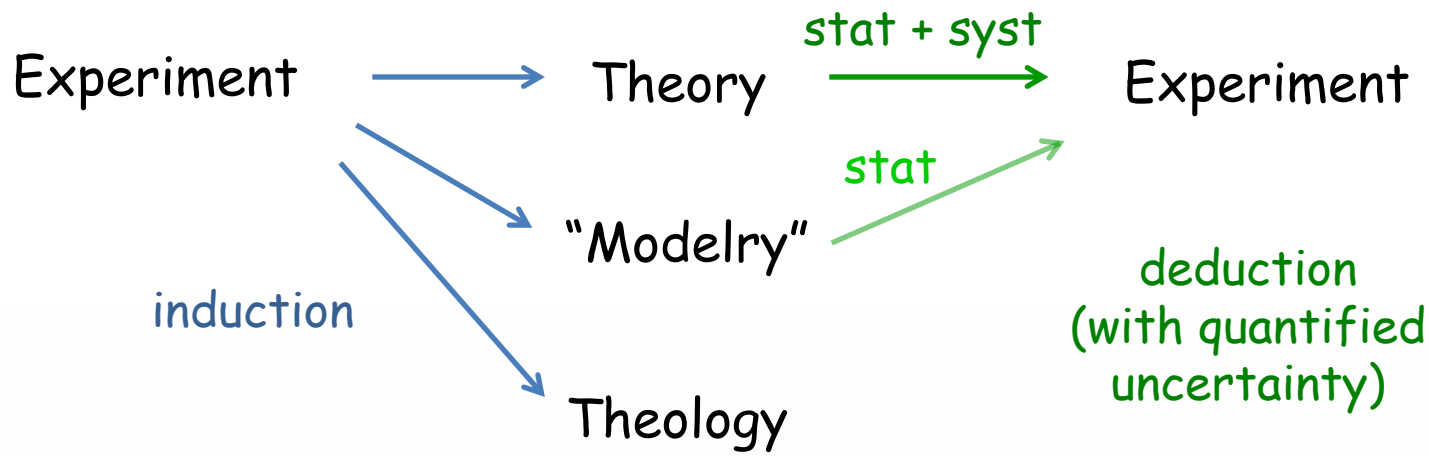
TERMINOLOGY



Post-quantum mechanics
("realistic"?) attitude:
only observable quantities
(S-matrix elements) matter

Here

$$\hbar = 1, c = 1$$

$$[m] = [E] = [\vec{p}]$$

$$= [\vec{x}]^{-1} = [t]^{-1}$$

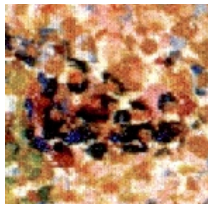
experiments only probe finite momenta Q

i.e. only distances $\Delta r \gtrsim 1/Q$

EFFECTIVE (FIELD) THEORIES ©

Ingredients

- Relevant degrees of freedom



Ingredients

- Relevant degrees of freedom

  choose the coordinates that fit the problem

- All possible interactions

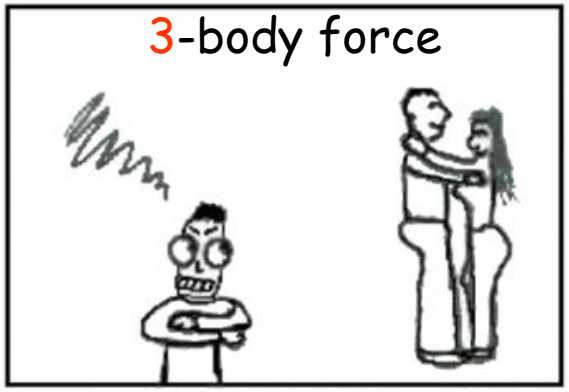
Example: Earth-moon-satellite system

$R_m \simeq 1.7$ Mm $\qquad d \simeq 384$ Mm $\qquad R_E \simeq 6.4$ Mm

2-body forces → 2+3-body forces

change in resolution

"renormalization group"



Wikipedia

Ingredients

- Relevant degrees of freedom

choose the coordinates that fit the problem

- All possible interactions

what is not forbidden is compulsory

- Symmetries

A farmer is having trouble with a cow whose milk has gone sour. He asks three scientists—a biologist, a chemist, and a physicist—to help him. The biologist figures the cow must be sick or have some kind of infection, but none of the antibiotics he gives the cow work. Then, the chemist supposes that there must be a chemical imbalance affecting the production of milk, but none of the solutions he proposes do any good either. Finally, the physicist comes in and says, "First, we assume a spherical cow…"

$$\sum_{ij} \alpha_{ij} u_i v_j \rightarrow \vec{u} \cdot \vec{v} \quad + \sum_{ij} \delta\alpha_{ij} u_i v_j$$

no, say, $u_1 v_2$

$$\left|\delta\alpha_{ij}\right| \ll 1$$

amenable to perturbation theory

Ingredients

- Relevant degrees of freedom

  choose the coordinates that fit the problem

- All possible interactions

  what is not forbidden is compulsory

- Symmetries

  not everything is allowed

- Naturalness

't Hooft '79

After scales have been identified,
the remaining, dimensionless parameters are

$$\mathcal{O}(1)$$

unless suppressed by a symmetry

cow
non-sphericity
...

Occam's razor:

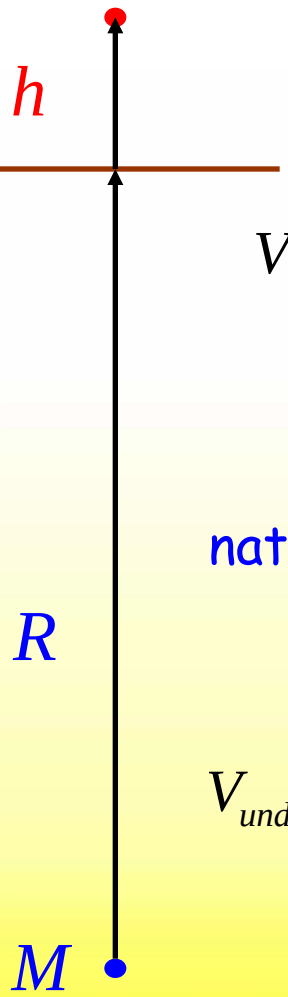
simplest assumption, to be revised if necessary

fine-tuning!

➡ Expansion in powers of $\frac{Q}{M}$

mass scale of
underlying theory

A classical example: the flat Earth
light object near surface of a large body



$$E \sim mgh \ll E_{und} \equiv mgR$$

d.o.f.: mass m

sym: $V_{eff}(h,x,y) = V_{eff}(h)$

$$V_{eff}(h) = m\sum_{i=0}^{\infty} g_i h^i = \text{const} + mg\left\{h + \eta h^2 + \ldots\right\}$$

parameters

(neglecting quantum corrections…)

naturalness: $$\frac{m g_{i+1} h^{i+1}}{m g_i h^i} = \frac{E}{E_{und}} \times \mathcal{O}(1) = \frac{h}{R} \times \mathcal{O}(1) \Longleftrightarrow g_{i+1} = \mathcal{O}\left(\frac{g}{R^i}\right)$$

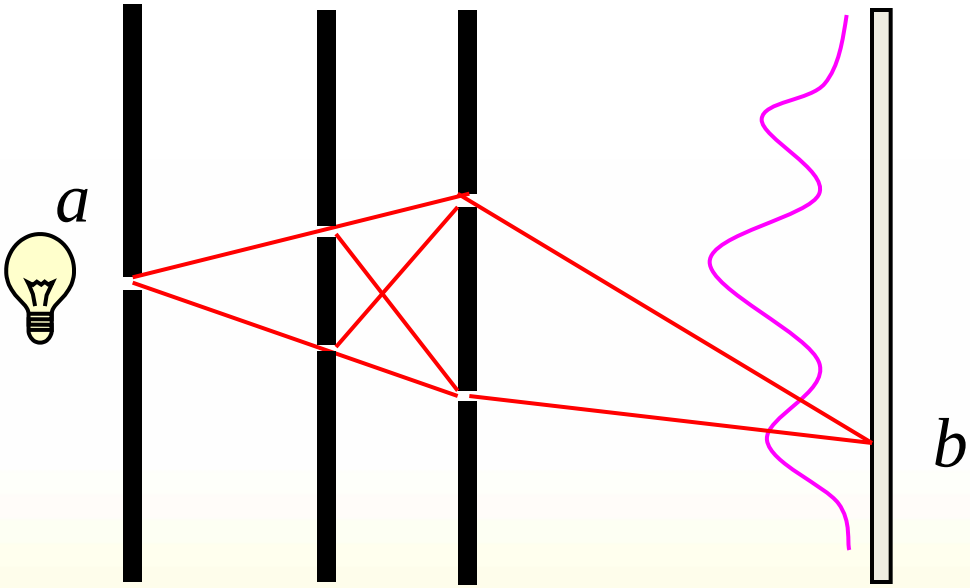
$$V_{und}(h) = -GMm\frac{1}{R+h} = m\underbrace{\left(\frac{GM}{R^2}\right)}_{\equiv g}\sum_{i=0}^{\infty}\left(\frac{-1}{R}\right)^{i-1} h^i \Rightarrow g_{i+1} = (-1)^i \frac{g}{R^i}$$

$h \ll R$

itself the first term in a low-energy EFT of general relativity…

Going a bit deeper…

A short path to quantum mechanics



$$P = |A_1 + A_2 + A_3 + A_4|^2$$

sum over
all paths

RULE

$$A_i \propto \exp\left(i \int_a^b dt\, L(q(t)) \right)$$

each path contributes a phase
given by the classical action

Path Integral

Feynman '48

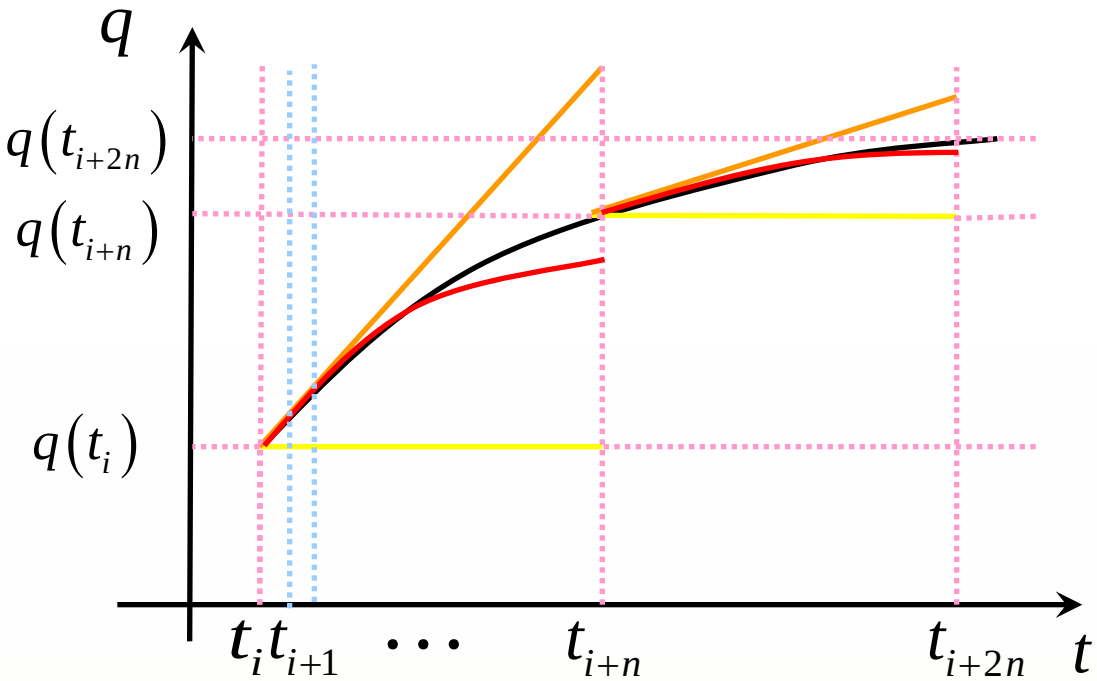
$$A = \int Dq \exp\left(i \int dt\, L(q(t)) \right)$$

$$\prod_i \int dq(t_i)$$

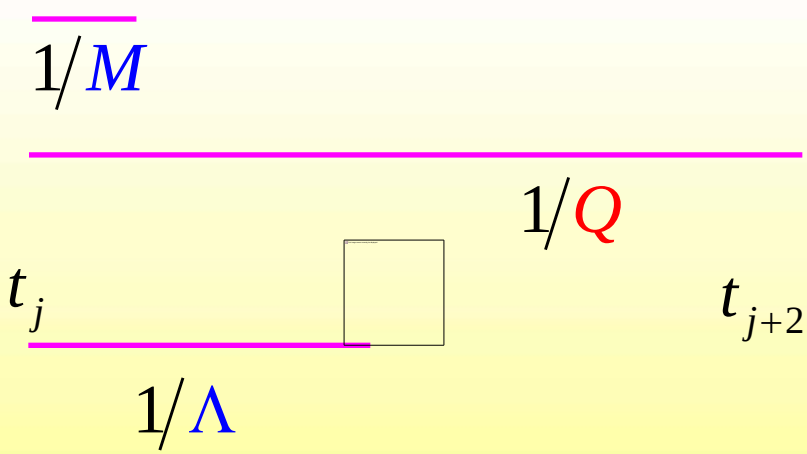
"regularization"

classical path

$$\delta\left(\int dt\, L(q(t)) \right) = 0$$



EFFECTIVE THEORY



scale of fine-structure of dynamics

scale of variation of long-range dynamics

coarse-graining scale (cutoff)

$$L(q(t_i)) \to L\left(q(t_i) + \left.\frac{dq}{dt}\right|_{t_i}(t-t_i) + \frac{1}{2}\left.\frac{d^2q}{dt^2}\right|_{t_i}(t-t_i)^2 + \ldots\right)$$

More generally,

$$A = \int Dq \, \exp\left(i \int dt \, L_{und}(q)\right) \times \int D\tilde{q} \, \delta\left(\tilde{q} - f_{\Lambda}(q)\right)$$

$$= \int D\tilde{q} \, \exp\left(i \int dt \, L_{EFT}(\tilde{q})\right) \qquad \Uparrow \qquad \prod_i \int d\tilde{q}(t_i) \, \delta\left(\tilde{q}(t_i) - f\left(q(t_i)\right)\right)$$

$$L_{EFT}(\tilde{q}) = \sum_{d,n=0}^{\infty} c_{d,n}(M, \Lambda) \, O_{d,n}\left(\tilde{q}, \left(\frac{d^d \tilde{q}}{dt^d}\right)^n\right)$$

Wilson or low-energy coefficients (LECs)

operators or interactions

$c_{d,n} \sim c_{0,0} / M^{dn}$ natural

local $\begin{cases} q: \ \Delta t < 1/M \\ \tilde{q}: \ \Delta t \sim 1/E > 1/M \end{cases}$

e.g. $$L_{EFT}(\tilde{q}) = \frac{m}{2}\left(\frac{d\tilde{q}}{dt}\right)^2 + \frac{m\omega^2}{2}\tilde{q}^2 + c_{0,0}\tilde{q}^4 + c_{1,2}\tilde{q}^2\left(\frac{d\tilde{q}}{dt}\right)^2 + \ldots$$

"second quantization" + Lorentz invariance

$$q(t) \to \psi(\vec{r},t), \psi^*(\vec{r},t) \qquad \to \psi(x), \psi^*(x)$$ representation of $SO(3,1)$

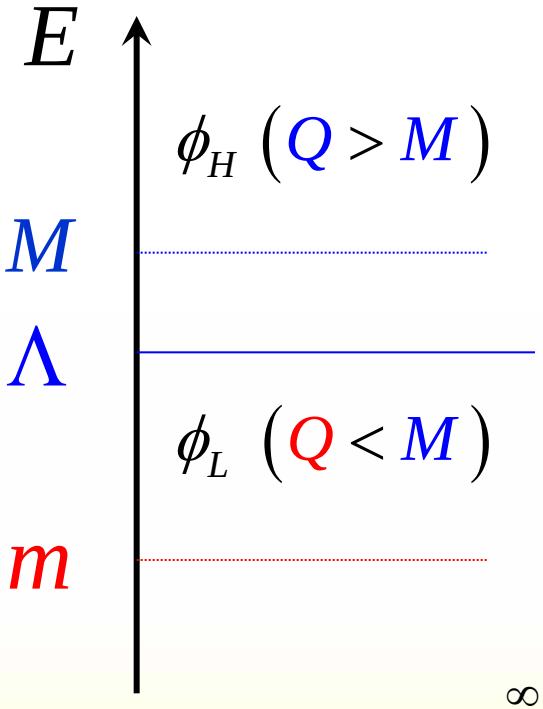
$$dt \to dt\, d^3r \qquad \equiv d^4x$$ scalar

$$\frac{d}{dt} \to \frac{\partial}{\partial t}, \frac{\partial}{\partial \vec{r}} \qquad \to \frac{\partial}{\partial x^\mu}$$ vector

$$\int dt\, L\big(q(t)\big) \to \int dt \int d^3r\, \mathcal{L}\big(\psi(\vec{r},t)\big) = \int d^4x\, \mathcal{L}\big(\psi(x)\big)$$ scalar

EFFECTIVE FIELD THEORIES

Euler + Heisenberg '36
Weinberg '67 … '79
Wilson, early 70s
…



$$Z = \int D\phi_H \int D\phi_L \exp\left(i\int d^4x\, \mathcal{L}_{und}(\phi_H, \phi_L)\right)$$
$$\times \int D\varphi\, \delta\left(\varphi - f_\Lambda(\phi_L)\right)$$
$$= \int D\varphi \exp\left(i\int d^4x\, \mathcal{L}_{EFT}(\varphi)\right)$$

$$\mathcal{L}_{EFT} = \sum_{d=0}^{\infty} \sum_{i(d,n)} c_i(M,\Lambda)\, O_i\left((\partial, m)^d \varphi^n\right)$$

renormalization-group invariance

$$\frac{\partial Z}{\partial \Lambda} = 0$$

details of the underlying dynamics

local

$$\phi_H : \Delta x \sim \frac{1}{Q} < \frac{1}{M}$$

$$\phi_L : \Delta x \sim \frac{1}{Q} > \frac{1}{M}$$

underlying symmetries

characteristic external momentum

$$\begin{cases} T = T^{(\infty)}(Q) \sim \underbrace{N(M)}_{\text{normalization}} \sum_{\nu=\nu_{\min}}^{\infty} \sum_{i} \underbrace{\tilde{c}_{\nu,i}(\Lambda)}_{\text{combinations of LECs}} \left[\frac{Q}{M}\right]^{\nu} \underbrace{F_{\nu,i}\left(\frac{Q}{m};\frac{Q}{\Lambda}\right)}_{\text{"non-analytic", from the solution of a dynamical equation (e.g. Schrödinger eq.)}} \\ \frac{\partial T}{\partial \Lambda} = 0 \end{cases}$$

"power counting" $\nu = \nu(d, n, \ldots)$

e.g. # loops in a Feynman diagram

For $Q \ll M$, truncate consistently with RG invariance so as to allow systematic improvement (perturbation theory):

$$T = T^{(\bar{\nu})}\left[1 + \mathcal{O}\left(\frac{Q}{M}, \frac{Q}{\Lambda}\right)\right] \qquad \frac{\Lambda}{T^{(\bar{\nu})}} \frac{\partial T^{(\bar{\nu})}}{\partial \Lambda} = \mathcal{O}\left(\frac{Q}{\Lambda}\right)$$

N.B. Want large "model space" to reduce cutoff errors $\Lambda \gtrsim M$
but no need for (possibly ill-defined) $\Lambda \to \infty$

Two possibilities:

- know <u>and</u> can solve underlying theory --

  get c_i 's in terms of parameters in $\mathcal{L}_{und}$ by matching

- know <u>but</u> cannot solve, or do <u>not</u> know, underlying theory --

  invoke Weinberg's "folk theorem":

The quantum field theory generated by the most general Lagrangian with some assumed symmetries will produce the most general S matrix incorporating quantum mechanics, Lorentz invariance, unitarity, cluster decomposition and those symmetries, with no further physical content.

S. Weinberg '79

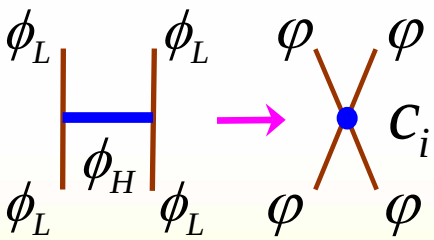
Why is this useful?

Because in general the appropriate degrees of freedom below M are not the same as above

φ

$\phi = (\phi_H, \phi_L)$

Examples:



- M is mass of physical particle -- virtual exchange in coefficients c_i (Appelquist-Carazzone decoupling theorem)
- M is scale associated with breaking of continuous symmetry -- appearance of massless Goldstone bosons or gauge-boson mass (Goldstone's theorem, Higgs mechanism)
- M is scale of confinement -- rearrangement of whole spectrum
- M is radius of Fermi surface -- BCS behavior

Bira's Recipe for an EFT

1. identify degrees of freedom and symmetries
2. construct most general Lagrangian
3. assume certain scales, do power counting
4. calculate observables in successive orders with all momenta $Q < \Lambda$
5. relate $c_i(\Lambda), \Lambda$ to observables and check they are independent of Λ
6. check convergence:

   not a model form factor

   if good, declare victory

   if not, repeat from 3; if problem remains, repeat from 1

"Modern S-matrix theory" - S. Weinberg

- ✓ No dependence on specific fields
- ✓ Quantum field theory a tool to generate most general S matrix

"New conceptualization" of renormalization

- ✓ Reg + renorm is the process of connecting Lag to observables
- ✓ No infinities, nothing under the rug
- ✓ Choice of reg is psychology, RG invariance is physics
- ✓ Importance of lowest-dimension operators explained

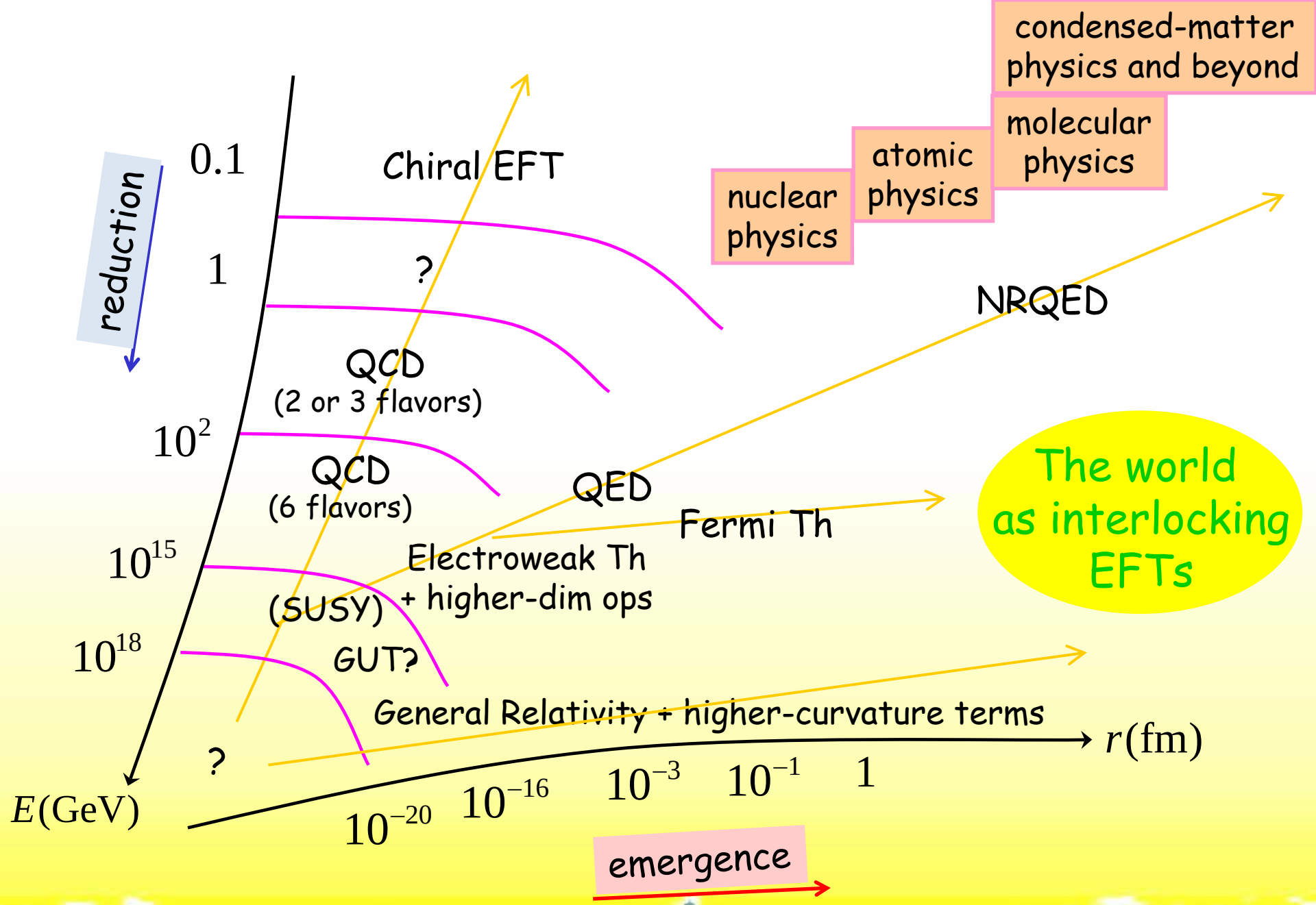
The mother of all models

- o models have fewer, but *ad hoc,* interactions and do not necessarily match the underlying theory
- o models with the correct symmetry pattern can be reproduced by EFT with an infinite number of constraints in the LECs
- o models useful in the identification of relevant degrees of freedom and symmetries, but plagued with uncontrolled errors

A significant change in physicists' attitude towards what should be taken as a guiding principle in theory construction is taking place in recent years in the context of the development of EFT. For many years (...) renormalizability has been taken as a necessary requirement. Now, considering the fact that experiments can probe only a limited range of energies, it seems natural to take EFT as a general framework for analyzing experimental results.

T.Y. Cao

Renormalization, From Lorentz to Landau (and Beyond), L.M. Brown (ed), 1993


condensed-matter physics and beyond
molecular physics
atomic physics
nuclear physics
reduction
0.1
1
10^2
10^{15}
10^{18}
Chiral EFT
?
QCD
(2 or 3 flavors)
QCD
(6 flavors)
(SUSY)
GUT?
?
NRQED
QED
Fermi Th
Electroweak Th
+ higher-dim ops
General Relativity + higher-curvature terms
The world as interlocking EFTs
E(GeV)
r(fm)
10^{-20}
10^{-16}
10^{-3}
10^{-1}
1
emergence

$$\left(\text{fundamental} - \text{effective}\right)\text{theory} \approx \text{theology}$$

but back to nuclear forces:

QCD

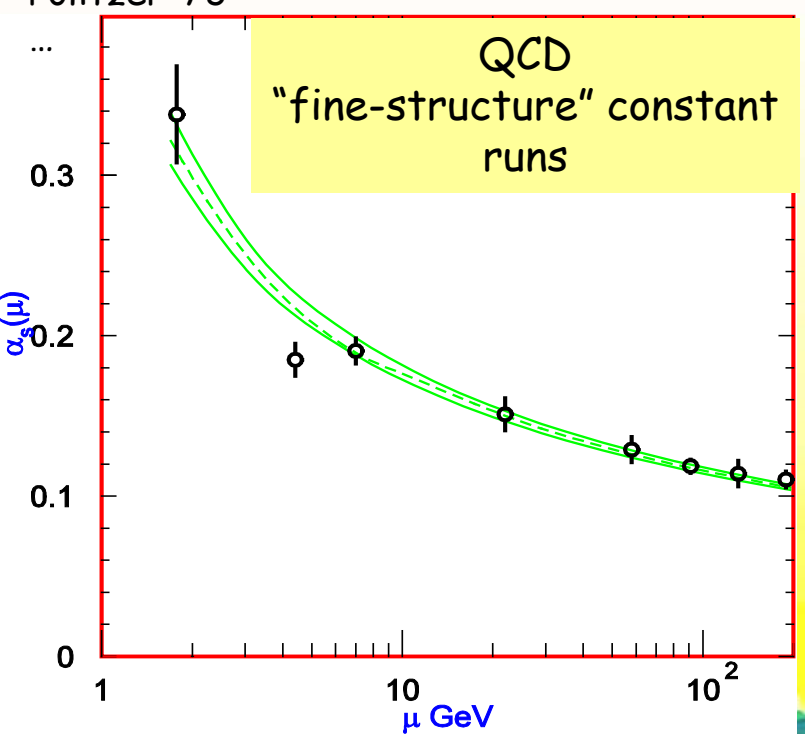
d.o.f.s quarks: $q = \begin{pmatrix} u \\ d \end{pmatrix}$ gluons: G^a_μ (photon: A_μ)

$Q \lesssim M_{EW}$ symmetries $SO(3,1)$ global, $SU_c(3)$ gauge ($+U_{em}(1)$ gauge)

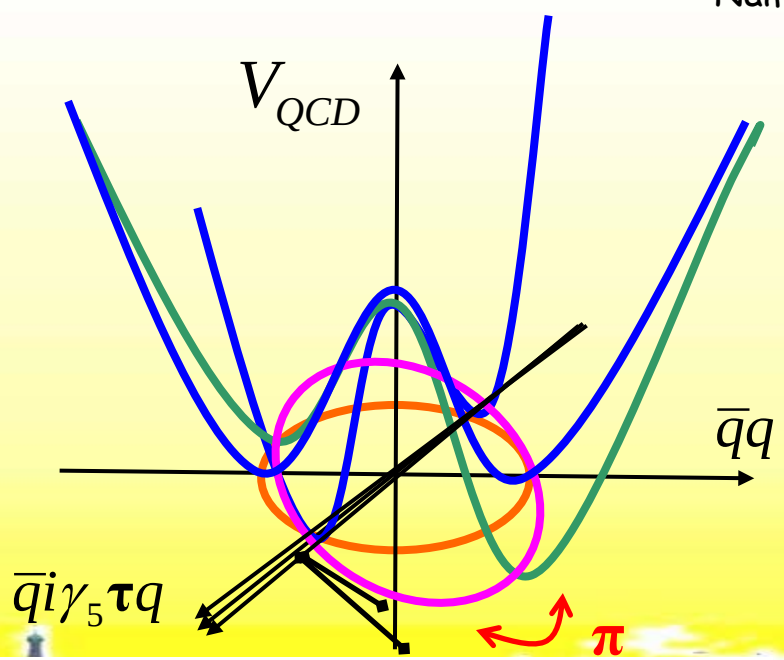
$$\mathcal{L}_{QCD} = \underbrace{\bar{q}\left(i\partial\!\!\!/ + g_s G\!\!\!/\right)q - \frac{1}{2}\mathrm{Tr}\, G^{\mu\nu}G_{\mu\nu}}_{} + \underbrace{\bar{m}\,\bar{q}\left(1-\varepsilon\tau_3\right)q}_{} + \ldots$$

Basic mass scales $M_{QCD} \sim m_N, m_\rho, 4\pi f_\pi, \ldots \sim 1\ \mathrm{GeV}$ $m_\pi \sim \sqrt{\bar{m}M_{QCD}} \simeq 140\ \mathrm{MeV}$

Gross + Wilczek '73
Politzer '73
...

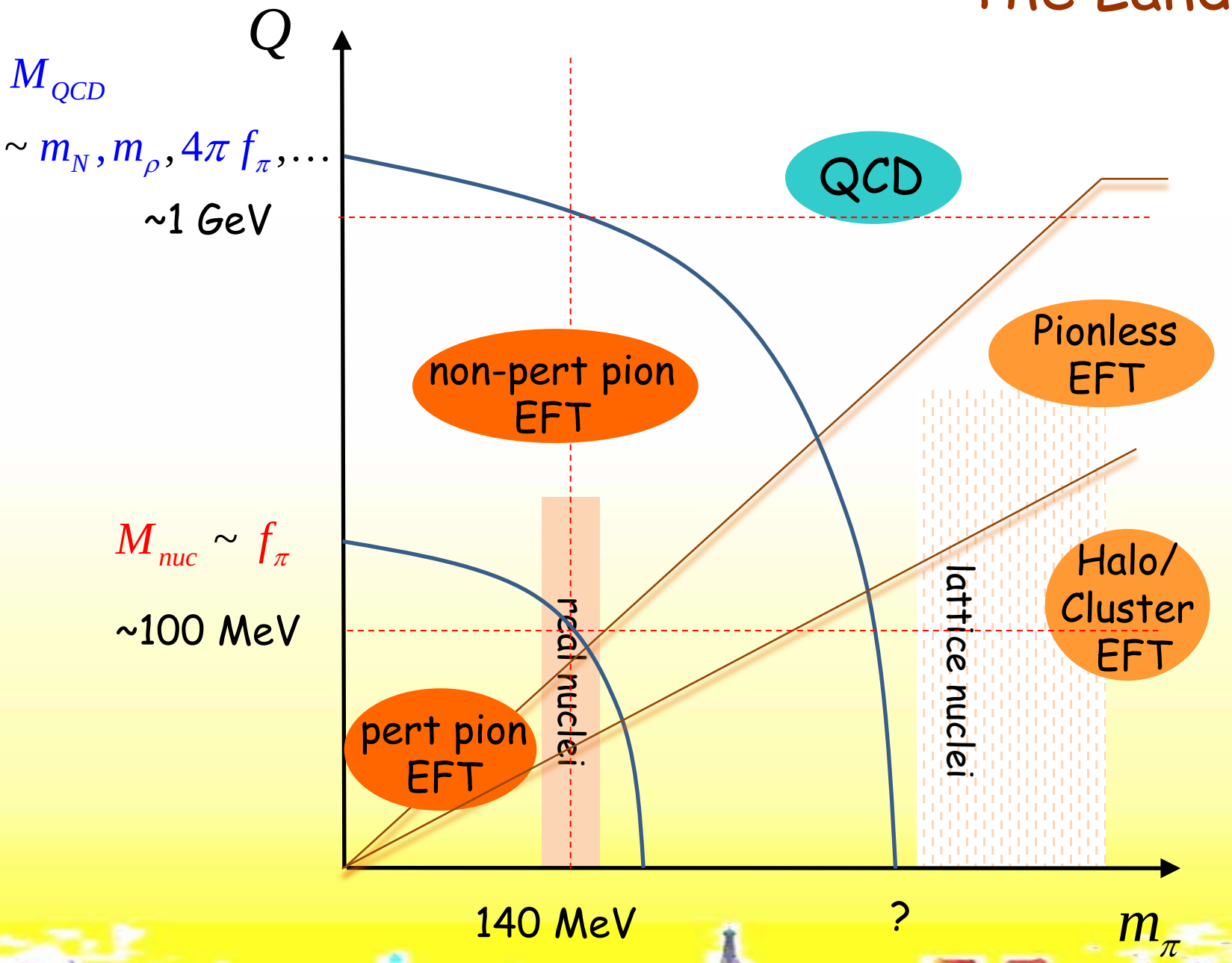


Nambu '60
...



$f_\pi \sim M_{QCD}/4\pi + \mathcal{O}(\bar{m}) \simeq 100\ \mathrm{MeV}$

The Landscape



Chiral EFT

$Q \sim m_\pi \ll M_{QCD}$

d.o.f.s

nucleons: $N = \begin{pmatrix} p \\ n \end{pmatrix}$ (+ Delta isobar, Roper)

pions: $\boldsymbol{\pi} = \begin{pmatrix} (\pi^+ + \pi^-)/\sqrt{2} \\ -i(\pi^+ - \pi^-)/\sqrt{2} \\ \pi^0 \end{pmatrix}$ (photon: A_μ)

symmetries

$SO(3,1)$ global, $\cancel{SU(2)_L \times SU(2)_R}$ global ($+U_{em}(1)$ gauge)

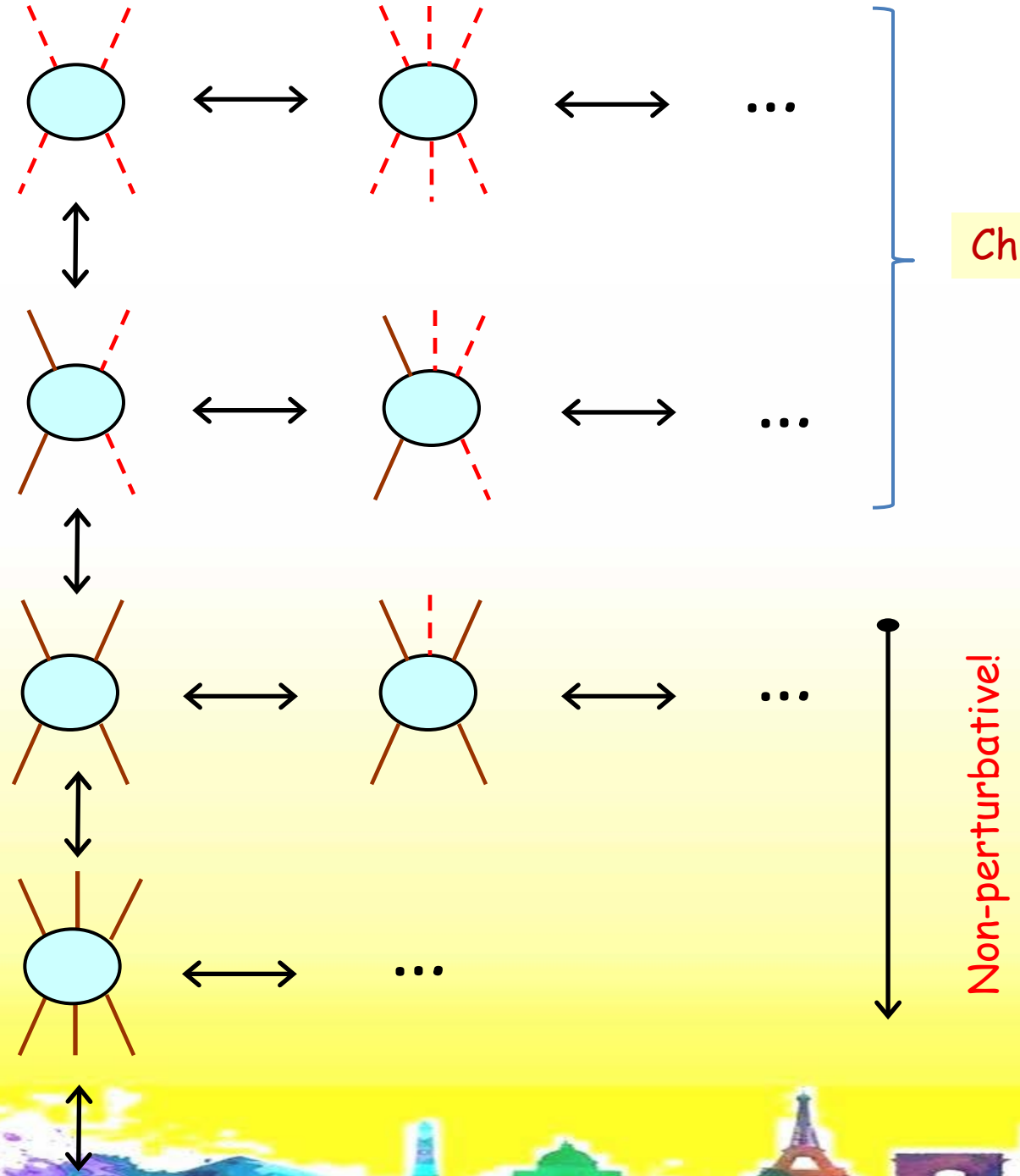
$$\mathcal{L}_{\chi EFT} = \frac{1}{2} D_\mu \boldsymbol{\pi} \cdot D^\mu \boldsymbol{\pi} - \frac{m_\pi^2}{2} \frac{\boldsymbol{\pi}^2}{1 + \boldsymbol{\pi}^2/4 f_\pi^2} + N^+ \left(i\mathcal{D}_0 + \frac{\vec{\mathcal{D}}^2}{2m_N} \right) N + \frac{g_A}{2 f_\pi} N^+ \vec{S} \boldsymbol{\tau} N \cdot\cdot \vec{D} \boldsymbol{\pi}$$

$$+ C_0 N^+ N N^+ N + C_2' N^+ N \left(\vec{\mathcal{D}} N^+ \right) \cdot \vec{\mathcal{D}} N + \ldots$$

other spin/isospin ,
more derivatives,
powers of pion mass,
Deltas and Ropers,
few-body forces,
etc.

$$D_\mu = \left(1 + \boldsymbol{\pi}^2/4 f_\pi^2\right)^{-1} \partial_\mu \qquad \mathcal{D}_\mu = \partial_\mu + \frac{i}{2 f_\pi^2} \left(\boldsymbol{\pi} \times D_\mu \boldsymbol{\pi} \right) \cdot \mathbf{t}^{(I)}$$

chiral covariant derivatives



Weinberg '79
Gasser + Leutwyler '84
...

Chiral Perturbation Theory

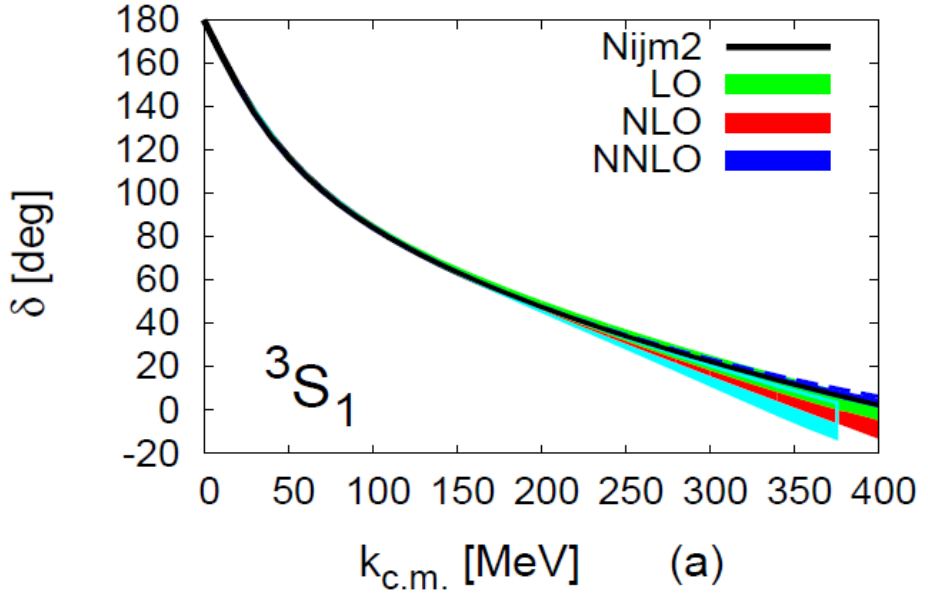
Gasser, Sainio + Svarc '87
Bernard, Kaiser + Meissner '90
Jenkins + Manohar '91
...

Non-perturbative!

Weinberg '90'91
Ordóñez + v.K. '92
Weinberg '92
v.K. '94
...

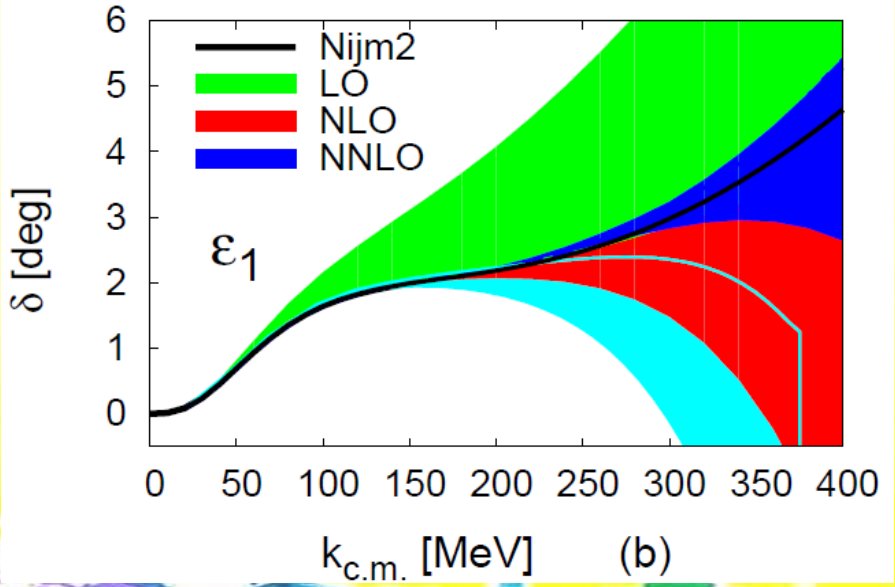
Example: *NN* scatterng

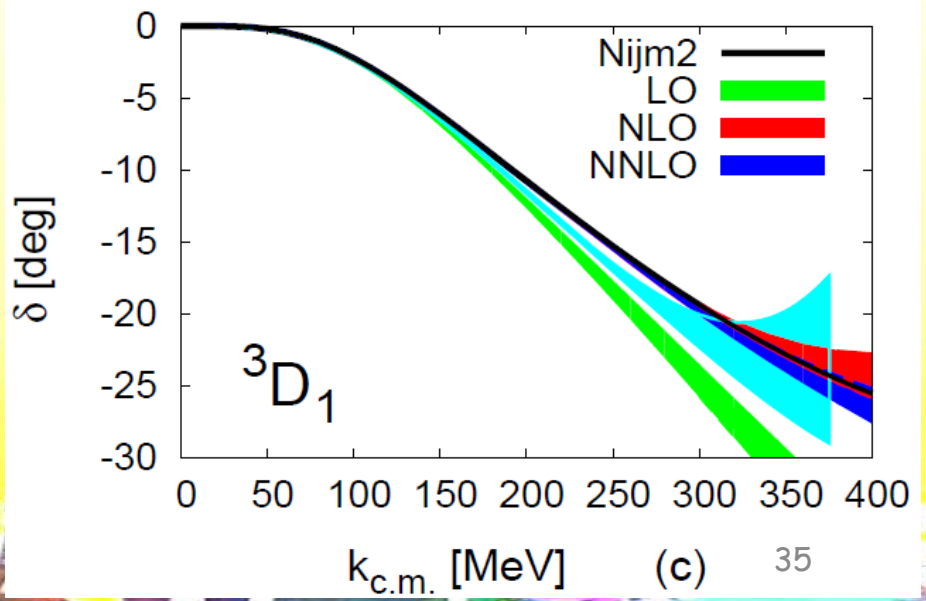
Pavón Valderrama '10



bands:
coordinate-space cutoff variation 0.6 – 0.9 fm

cyan:
NNLO in Weinberg's scheme





Re-inserted nuclear physics
in the context of particle physics

Took about 10 years
to be accepted by nuclear community

… and then only for the wrong reasons:
results comparable to those of
phenomenological potentials
when treated as
a phenomenological potential

Example: ground energies of many nuclei

***Ab Initio* Path to Heavy Nuclei**

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(Dated: December 20, 2013)

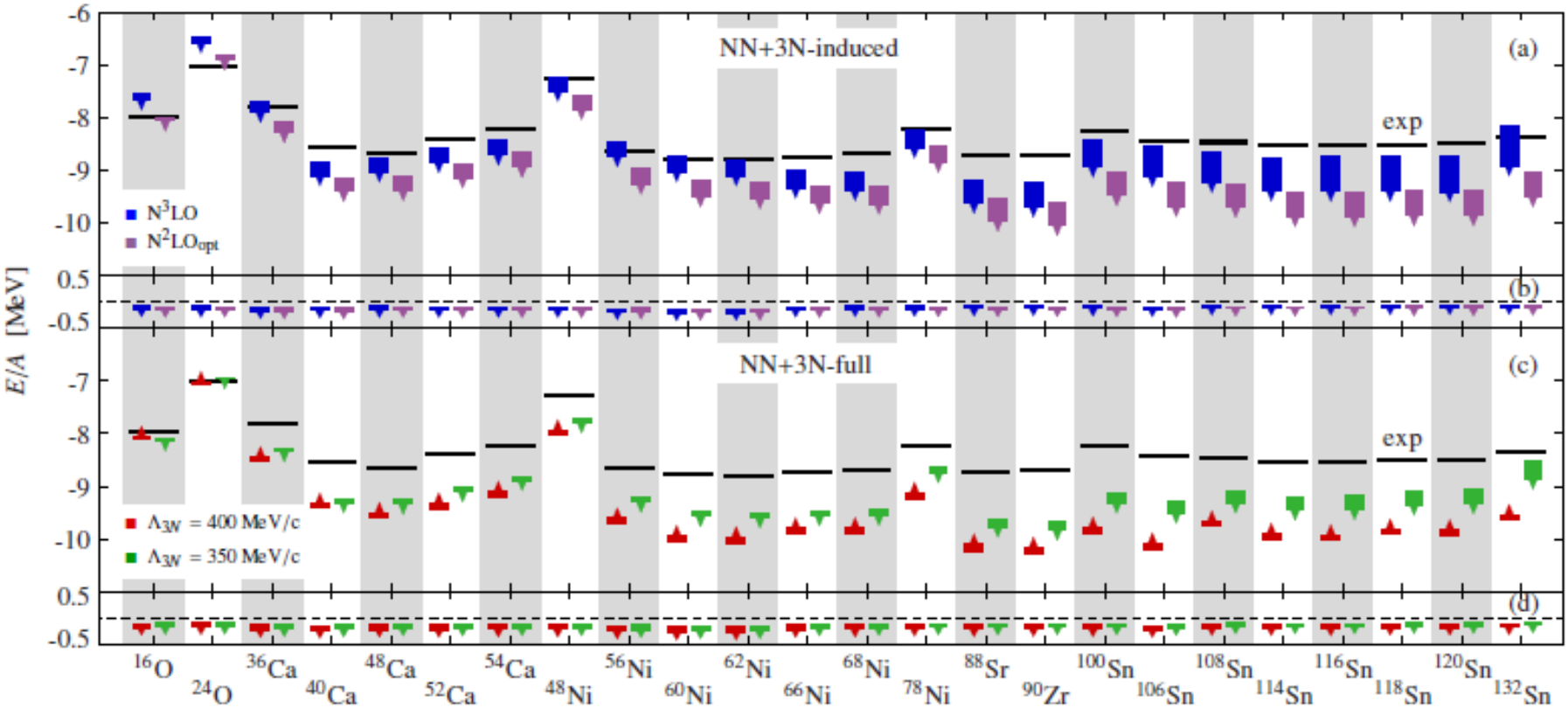

FIG. 5: (Color online) Ground-state energies from CR-CC(2,3) for (a) the NN+3N-induced Hamiltonian starting from the N^{3}LO and N^{2}LO-optimized NN interaction and (c) the NN+3N-full Hamiltonian with Λ_{3N} = 400 MeV/c and Λ_{3N} = 350 MeV/c. The boxes represent the spread of the results from α = 0.04 fm^4 to α = 0.08 fm^4, and the tip points into the direction of smaller values of α. Also shown are the contributions of the CR-CC(2,3) triples correction to the (b) NN+3N-induced and (d) NN+3N-full results. All results employ $\hbar\Omega$ = 24 MeV and 3N interactions with $E_{3\max}$ = 18 in NO2B approximation and full inclusion of the 3N interaction in CCSD up to $E_{3\max}$ = 12. Experimental binding energies [32] are shown as black bars.

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But that's another talk…

Here only two points:

- connection with underlying theory
- interplay with experimental data

Pionless EFT

$Q \ll m_{\pi\pi} \lesssim M_{QCD}$

d.o.f.s

nucleons: $N = \begin{pmatrix} p \\ n \end{pmatrix}$ (+ Delta isobar, Roper)

pions: $\boldsymbol{\pi} = \begin{pmatrix} (\pi^+ + \pi^-)/\sqrt{2} \\ -i(\pi^+ - \pi^-)/\sqrt{2} \\ \pi^0 \end{pmatrix}$ (photon: A_μ)

symmetries

$SO(3,1)$ global ($+U_{em}(1)$ gauge)

$$\mathcal{L}_{\chi EFT} = \frac{1}{2} D_\mu \boldsymbol{\pi} \cdot D^\mu \boldsymbol{\pi} - \frac{m_\pi^2}{2} \frac{\boldsymbol{\pi}^2}{1+\boldsymbol{\pi}^2/4f_\pi^2} + N^+ \left(i\partial_0 + \frac{\nabla^2}{2m_N} \right) N + C_0 N^+ N N^+ N + \frac{g_A}{2f_\pi} N^+ \vec{S}\boldsymbol{\tau} N \cdot \vec{D}\boldsymbol{\pi}$$

$$+ C_0 N^+ N N^+ N + C_2' N^+ N \left(N^+ \vec{D}^2 N - \vec{D}^2 N^+ N \right) + \ldots$$

other spin/isospin,
more derivatives,
powers of pion mass,
more-body forces,
etc.

$$D_\mu = \left(1 + \boldsymbol{\pi}^2/4f_\pi^2\right)^{-1} \partial_\mu$$

$$\mathcal{D}_\mu = \partial_\mu - \frac{i}{2f_\pi^2} \left(\boldsymbol{\pi} \times D_\mu \boldsymbol{\pi} \right)^{(1)}$$

(but different LECs)

chiral covariant derivatives

Barnea, Contessi, Gazit, Pederiva + v.K. '13

m_π	140	510	805	805
Nucleus	[Nature]	[5]	[6]	[This work]
n	939.6	1320.0	1634.0	1634.0 *
p	938.3	1320.0	1634.0	1634.0
nn	-	7.4 ± 1.4	15.9 ± 3.8	15.9 ± 3.8 *
D	2.224	11.5 ± 1.3	19.5 ± 4.8	19.5 ± 4.8 *
^{3}n	-			-
^{3}H	8.482	20.3 ± 4.5	53.9 ± 10.7	53.9 ± 10.7 *
^{3}He	7.718	20.3 ± 4.5	53.9 ± 10.7	53.9 ± 10.7
^{4}He	28.30	43.0 ± 14.4	107.0 ± 24.2	89 ± 36
^{5}He	27.50			98 ± 39
^{5}Li	26.61			98 ± 39
^{6}Li	32.00			122 ± 50

[5] Yamazaki *et al.* '12
[6] Beane *et al.* '12
[This work] Barnea *et al.* '13

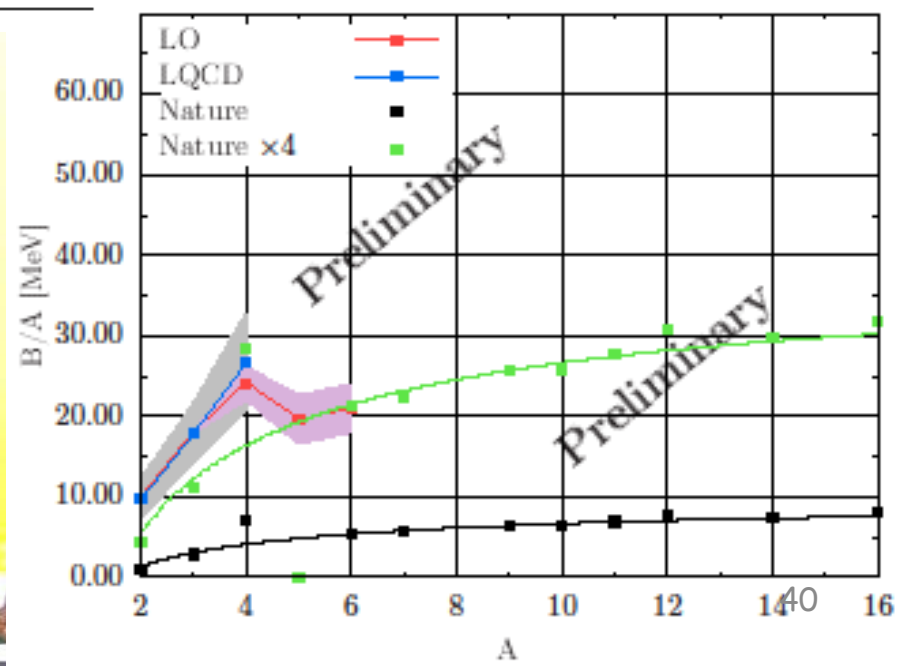
input

check

predictions

Lattice QCD

Pionless EFT at LO

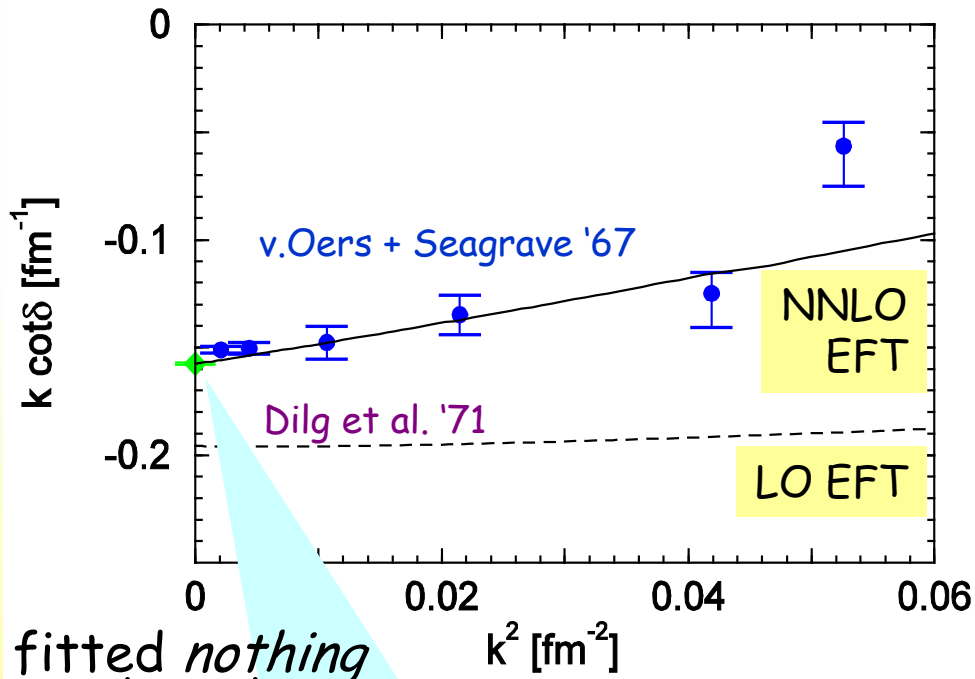


nd scattering with *NN* input

$S_{3/2}$

Bedaque + v.K. '97
Bedaque, Hammer + v.K. '98
...

no 3-body force up to NNNNLO



fitted *nothing*
predicted

$$a_{3/2} = 6.33 \pm 0.10 \text{ fm (NNLO)}$$
$$a_{3/2} = 6.35 \pm 0.02 \text{ fm (exp)}$$

QED-like precision!

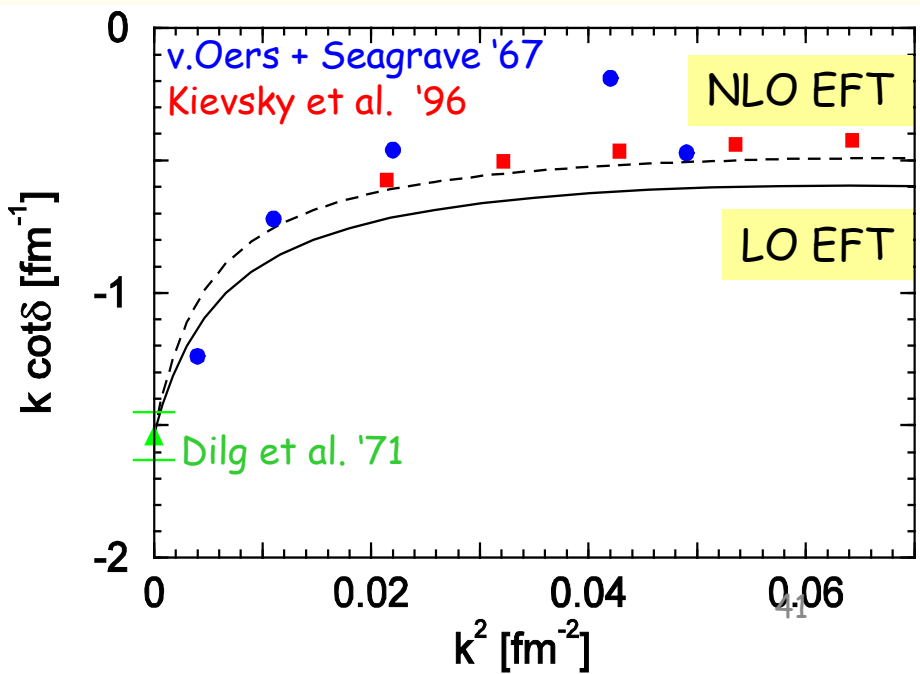
$S_{1/2}$

Bedaque, Hammer + v.K. '99 '00
Hammer + Mehen '01
Bedaque *et al.* '03
...

3-body force already at LO

fitted D_0 ➡ $a_{1/2} = 0.65 \text{ fm (exp)}$
predicted

$$B_t = 8.3 \text{ MeV (NLO)}$$
$$B_t = 8.48 \text{ MeV (exp)}$$



Many other successes,
but still ignored
by nuclear community
(perhaps because it cannot be treated as
a phenomenological potential)

Summary

EFT is a general framework for theory construction

- ✓ same method across scales
- ✓ model independent
- ✓ controlled expansion

EFT is (very slowly) becoming the paradigm in nuclear physics

- ✓ encodes QCD (and, more generally, B/SM)
- ✓ incorporates hadronic physics
- ✓ generates nuclear structure