NUCLEI IN THE STANDARD MODEL AND BEYOND

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"There are few problems in nuclear 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

Can we understand the emergence of nuclei within the Standard Model?

cf. Bjorken's talk

- nonperturbative physics in the simplest, nonrelativistic context

  nontrivial fixed point, limit cycle, …

- nuclear tests of physics beyond the Standard Model

  neutrinoless double-beta decay, nuclear electric dipole moments, …

Nuclear Effective Field Theory

implementation of the QFT paradigm in nuclear physics

solves the renormalization problems of the 50s

now the standard theory of nuclear physics

Outline

- Effective Field Theory
- Chiral EFT: Phenomenology, Fine-Tuning
- Pionless EFT: Unitarity, Lattice QCD
- Beyond the SM
- Conclusion

Standard Model:
not a fundamental theory but an effective field theory

successes of SM
Weinberg '67
...

gauge coupling unification, ...
Georgi, Quinn + Weinberg '76
...

} SM + higher-dimension ops

"Theorem"

Weinberg '79

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.

Euler + Heisenberg '36

...

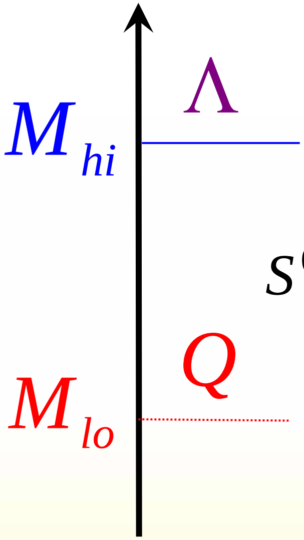
Weinberg '67 ... '79

Wilson, early 70s

...

EFT

momentum scales



arbitrary UV regulator

non-analytic functions, from loops

$$S^{(\bar{\nu})}(Q \sim M_{lo} \ll M_{hi}) - 1 \propto \sum_{\nu=0}^{\bar{\nu}} \left[\frac{Q}{M_{hi}}\right]^{\nu} F^{(\nu)}\left(\frac{Q}{M_{lo}}, \frac{Q}{\Lambda}; \gamma_i^{(\nu)}\left(\frac{\Lambda}{M_{lo}}, \frac{M_{lo}}{M_{hi}}\right)\right)$$

$$+\mathcal{O}\left(\frac{Q^{\bar{\nu}+1}}{M_{hi}^{\bar{\nu}+1}}, \frac{Q^{\bar{\nu}+1}}{M_{hi}^{\bar{\nu}}\Lambda}\right)$$

controlled

"low-energy constants" or "Wilson coefficients"

RG invariance

$$\frac{\Lambda}{S^{(\bar{\nu})}} \frac{\partial S^{(\bar{\nu})}}{\partial \Lambda} = \mathcal{O}\left(\frac{Q^{\bar{\nu}+1}}{M_{hi}^{\bar{\nu}}\Lambda}\right)$$

to minimize cutoff errors, $\Lambda \gtrsim M_{hi}$

for realistic error estimate, $\Lambda \in [M_{hi}, \infty)$

model independent

(OTHERWISE, SENSITIVE TO HIGH-MOM DETAILS)

QC(+E)D (-LITE)

$Q \ll M_{W,Z}$

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

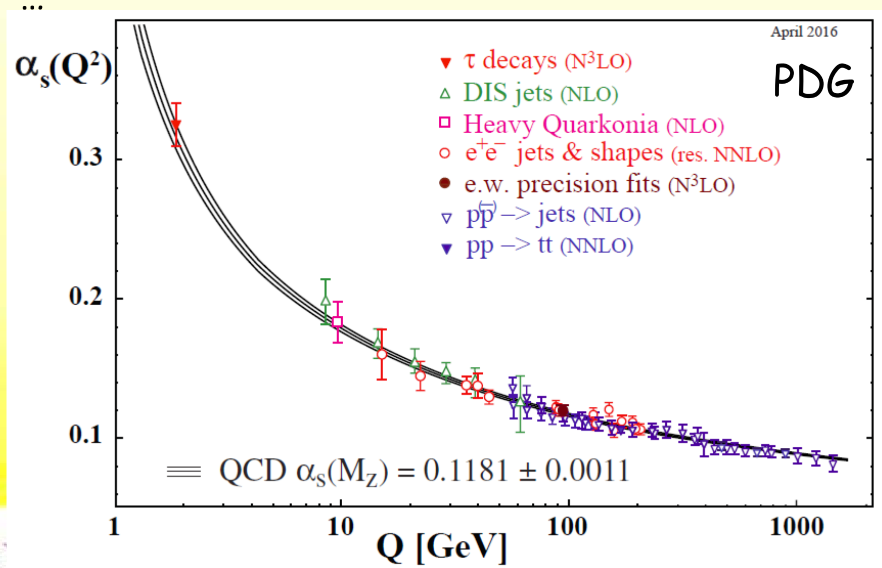
symmetries $\mathrm{SO}(3,1)$ global, $\mathrm{SU}(3)_c$ $(+\mathrm{U}(1)_{em})$ gauge

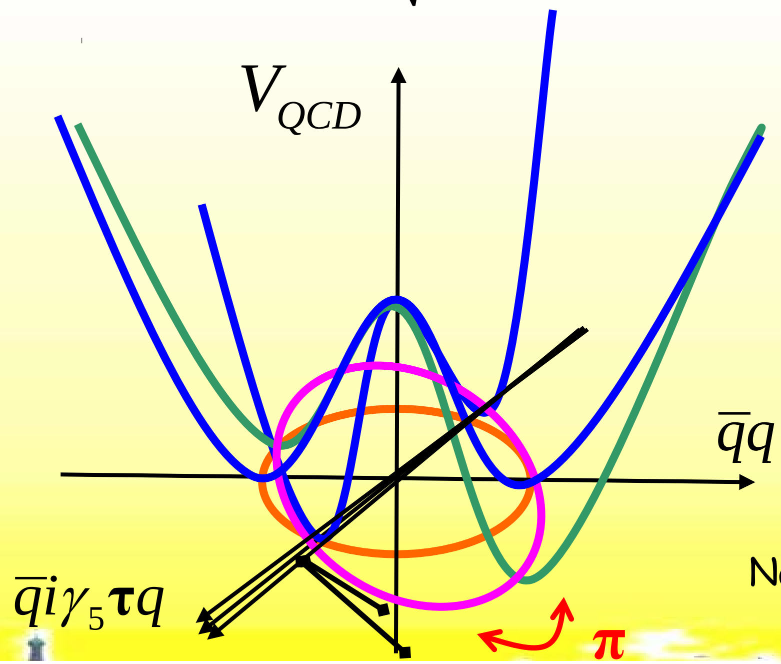
$$\mathcal{L}_{QCD} = \bar{q}\left(i\partial\!\!\!/ + g_s G\!\!\!/\right)q - \frac{1}{2}\mathrm{Tr}\,G^{\mu\nu}G_{\mu\nu} + \bar{m}\,\bar{q}\left(1-\varepsilon\tau_3\right)q + \ldots$$

Basic mass scales

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

Gross + Wilczek '73
Politzer '73
...

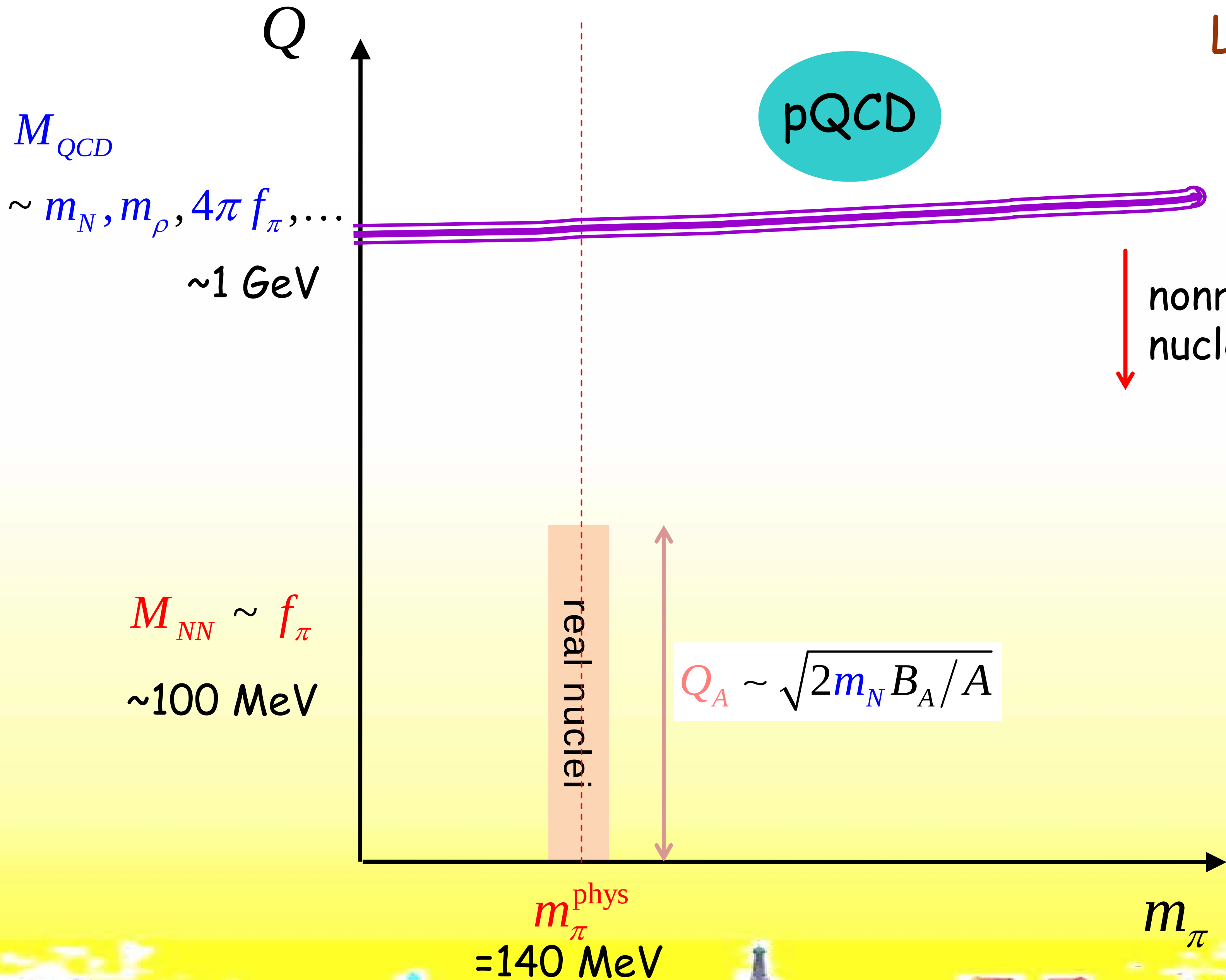




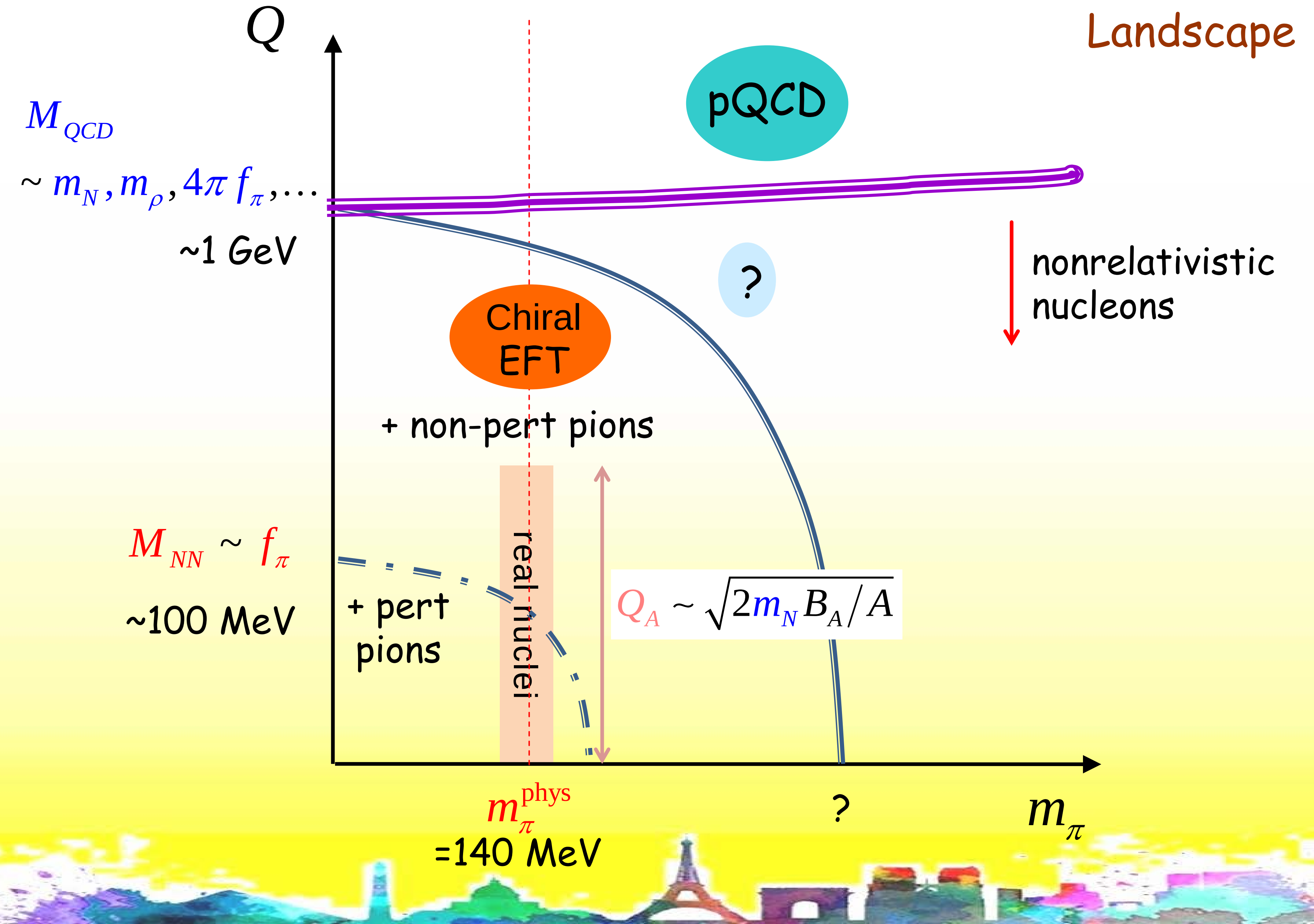
Nambu '64
...

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

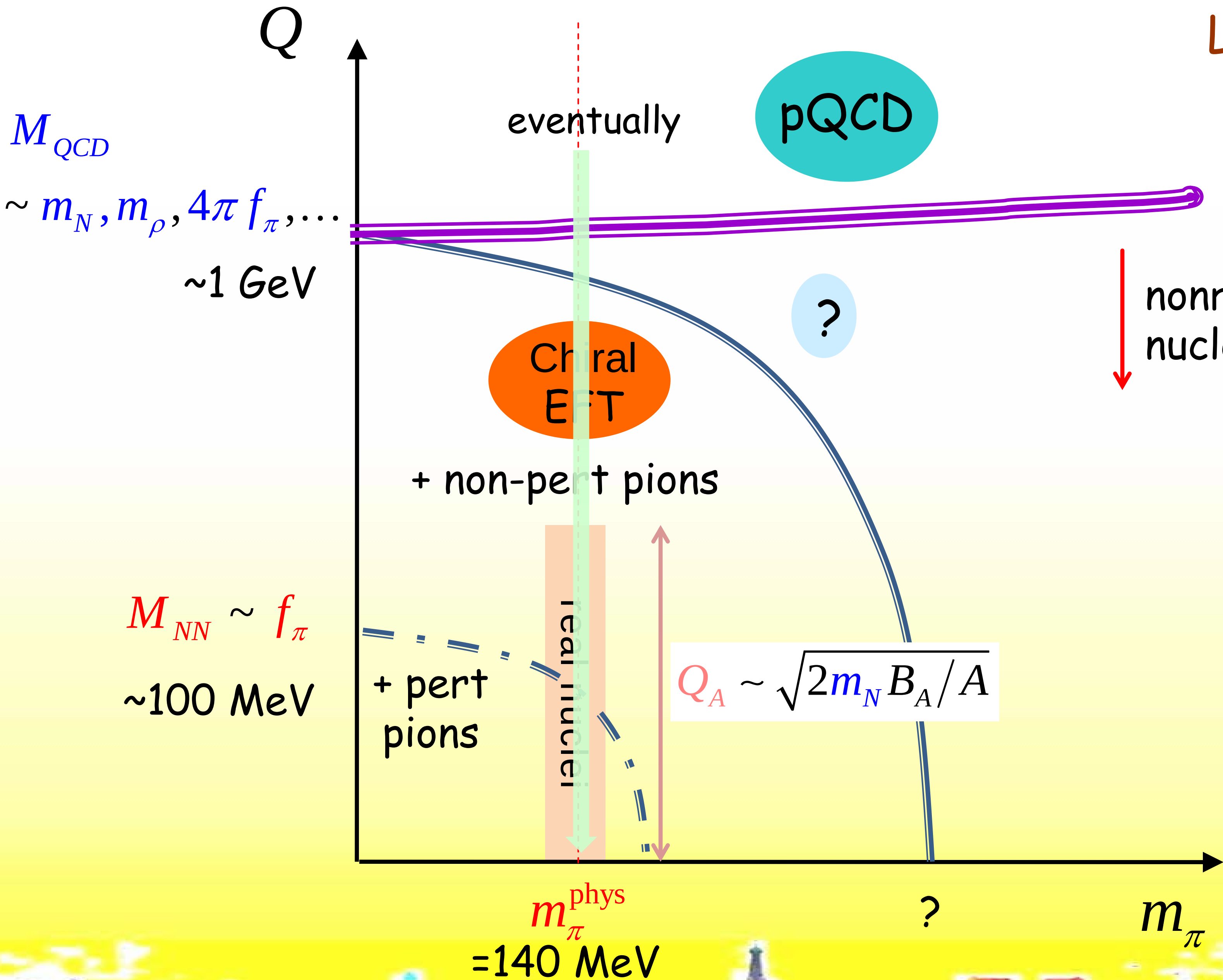
The Nuclear EFT Landscape



The Nuclear EFT Landscape



The Nuclear EFT Landscape



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

Chiral EFT

d.o.f.s

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

+ Deltas + Roper + …?

symmetries

SO(3,1) global, $SU(3)_c$ (+$U(1)_{em}$) gauge, ~~SU(2)×SU(2) global~~

(trivial)

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

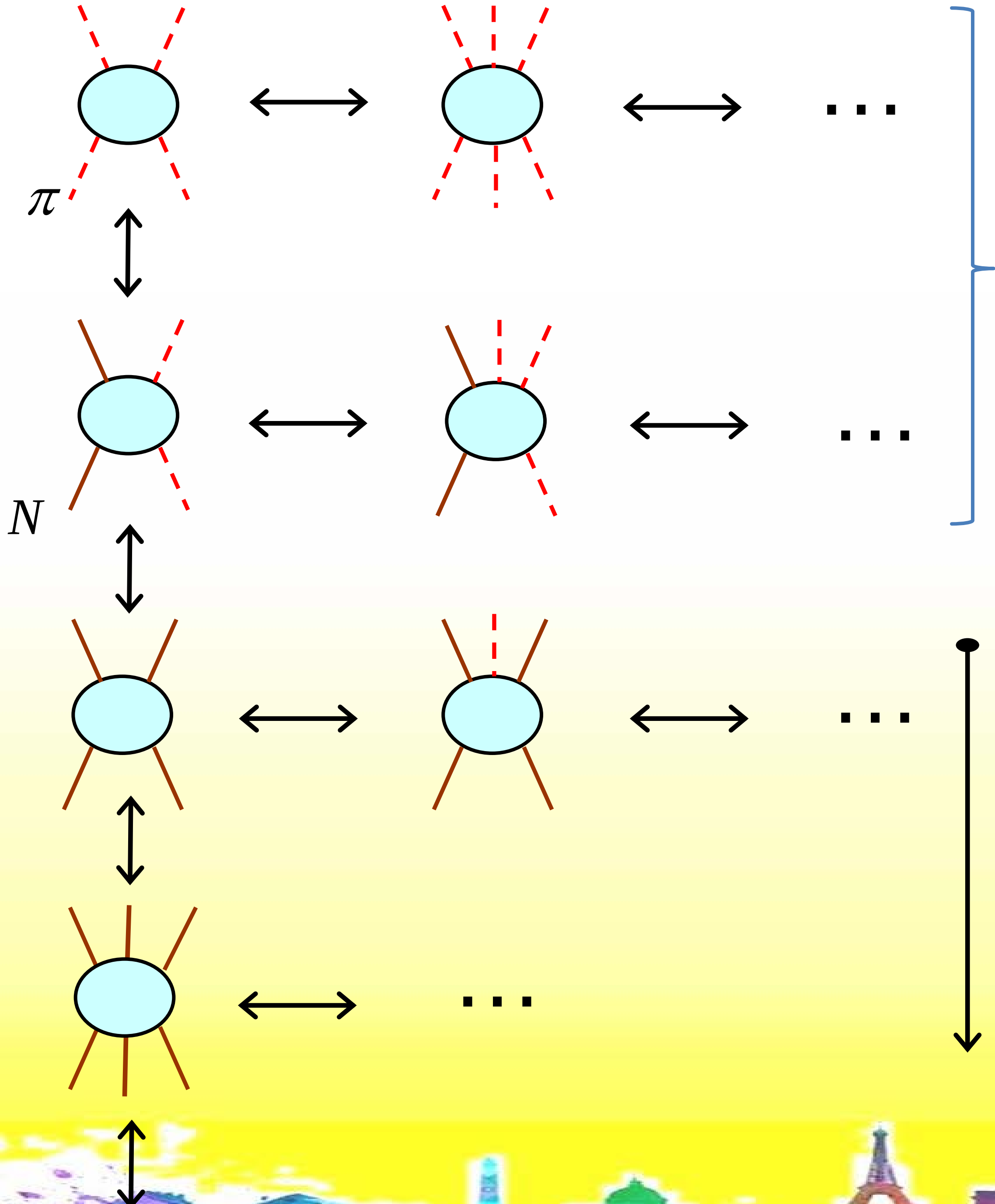
$$+ C_0\, N^+ N\, N^+ N + \ldots$$

cf. Adler's talk

other spin/isospin,
chiral partners,
more derivatives and fields,
powers of pion mass

expansion in:

$$\frac{Q}{M_{QCD}} \sim \begin{cases} Q/m_N & \text{non-relativistic} \\ Q/m_\rho, \ldots & \text{multipole} \\ Q/4\pi f_\pi & \text{pion loop} \end{cases}$$



Weinberg '79
Gasser + Leutwyler '84
...

Chiral Perturbation Theory

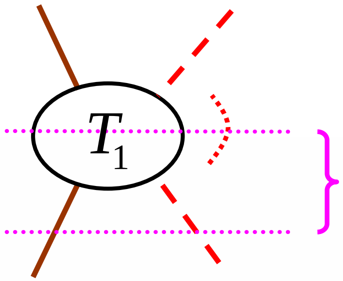
Gasser, Sainio + Švarc '87
Bernard, Kaiser + Meißner '90
Jenkins + Manohar '91
...

Non-perturbative!

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

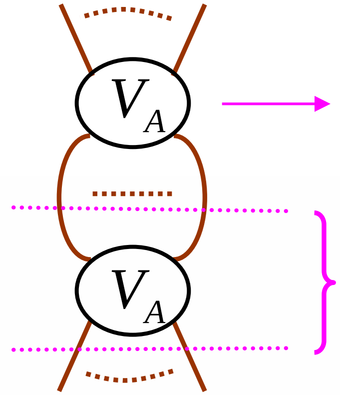
Weinberg '90'91'92
Rho '91
Ordóñez + v.K. '92
...

chiral perturbation theory



$$\frac{1}{\Delta E} \sim \frac{1}{Q}$$

vs.

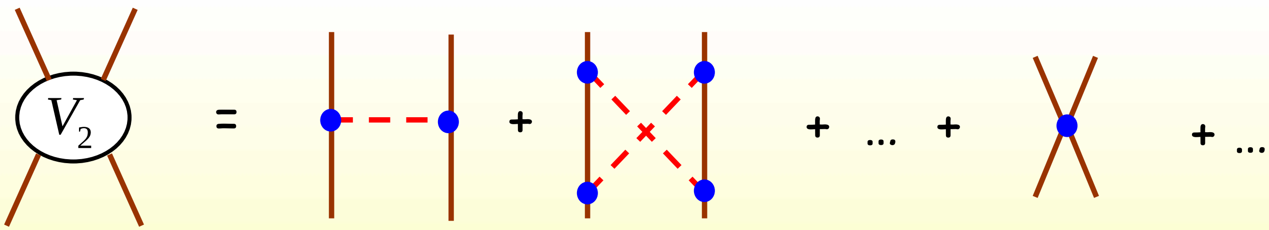


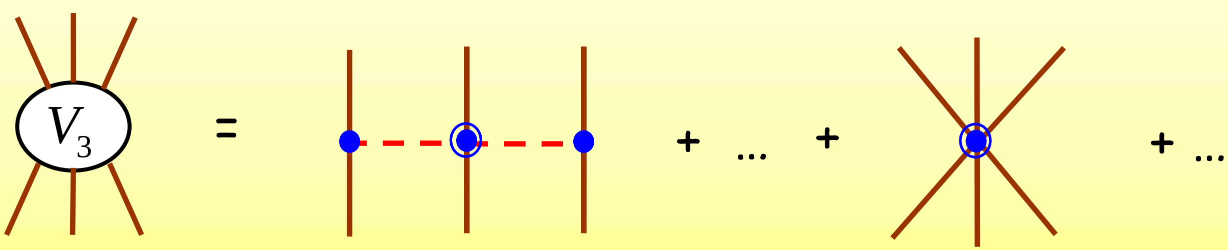
A-nucleon irreducible

A-nucleon reducible:

$$\frac{1}{\Delta E} \sim \frac{m_N}{Q^2}$$

infrared enhancement



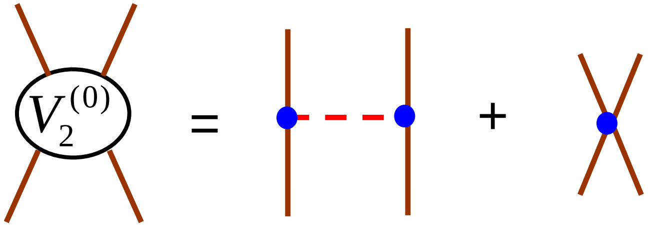


etc.

more nucleons

higher powers of Q

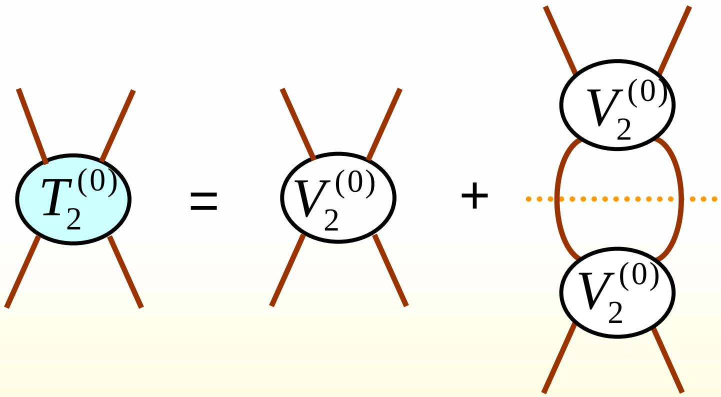
From naïve dimensional analysis (Georgi + Manohar '84)



$$\sim \frac{4\pi}{m_N M_{NN}}$$

$$M_{NN} \equiv \frac{1}{g_A^2}\frac{4\pi f_\pi}{m_N} f_\pi \sim f_\pi$$

Kaplan, Savage + Wise '98



$$\sim \frac{4\pi}{m_N M_{NN}}\left[1+\frac{m_N Q}{4\pi}\frac{4\pi}{m_N M_{NN}}+\ldots\right]$$

loop

$$\sim \frac{4\pi}{m_N M_{NN}}\frac{1}{1-\dfrac{Q}{M_{NN}}}$$

$$M_{lo} = M_{NN} \sim f_\pi \ll M_{QCD}$$

bound state

$$Q \sim M_{NN} \sim 100 \text{ MeV}$$

$$-E \sim \frac{M_{NN}^2}{M_{QCD}} \sim 10 \text{ MeV}$$

Nuclear scale arises naturally in QCD due to spontaneous chiral symmetry breaking

cf. Friar, Madland + Lynn '96

...

add more derivatives, many-nucleon interactions

$$M_{QCD}^{-1}\vec{\nabla} \qquad \left(f_{\pi}^{-2}M_{QCD}\right)^{-1}N^{\dagger}N$$

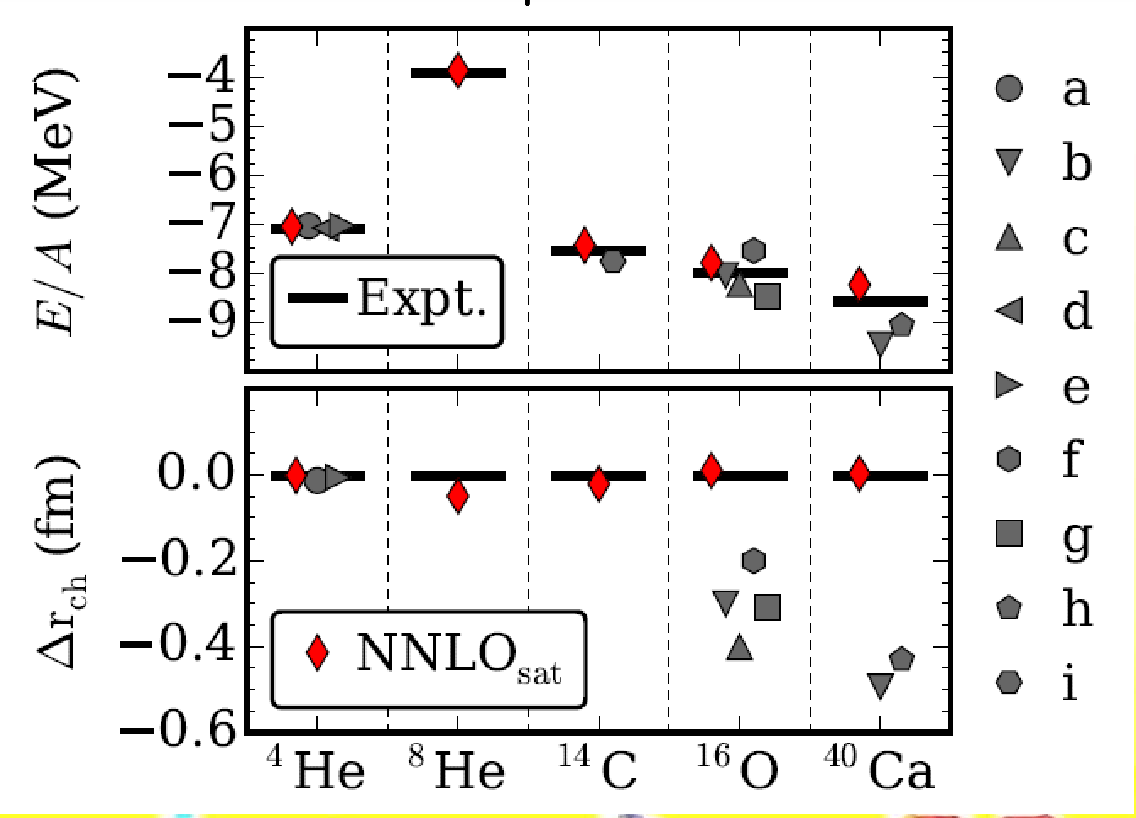
Ordóñez, Ray
+ v.K. '94'96
Epelbaum Glöckle
+ Meißner '98
...
Entem + Machleidt
'03
...

Current standard in nuclear physics:
solve the many-body Schrödinger equation numerically
with a truncated "chiral potential"

One of countless examples: Ekström *et al.* '15

binding energy
per nucleon

expt - th
charge radius
difference



various
chiral
potentials

Problem

Kaplan, Savage + Wise '96
Nogga, Timmermans + v.K. '05
Pavón Valderrama + Ruiz Arriola '06
Birse '06
...

no RG invariance
-- existing results for fixed regulator

Partial solution

Kaplan, Savage + Wise '98
...
Fleming, Mehen + Stewart '00

- Pions in perturbation theory
  -- only works for $Q \lesssim M_{NN}$
- Subleading potentials in perturbation theory

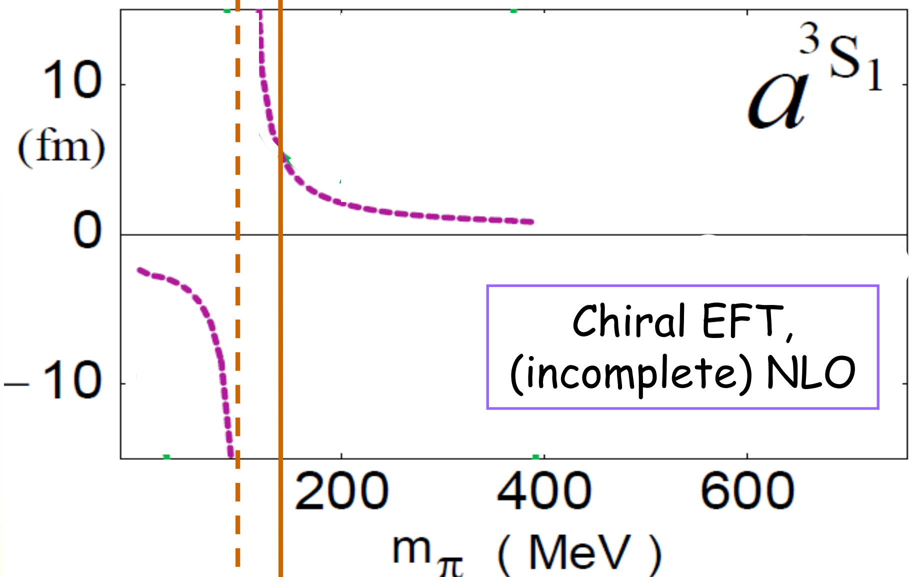
Solution

Nogga, Timmermans + v.K. '05
Birse '06
Long + v.K. '08
Pavón Valderrama '11'12
Long + Yang '12'13
...

- Correct NDA
  -- running of some LECs: $M_{QCD}^{-1} \to f_{\pi}^{-1}$
- Subleading potentials in perturbation theory

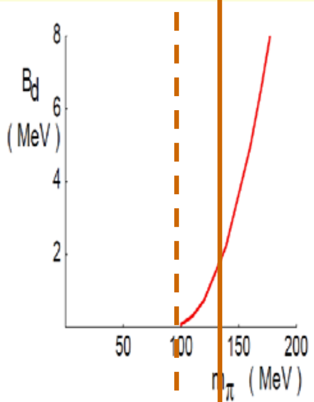
Fine-Tuning

unitarity limit



m_π (MeV)

$m_\pi^*(M_{QCD})$ $\quad m_\pi \simeq 140$ MeV



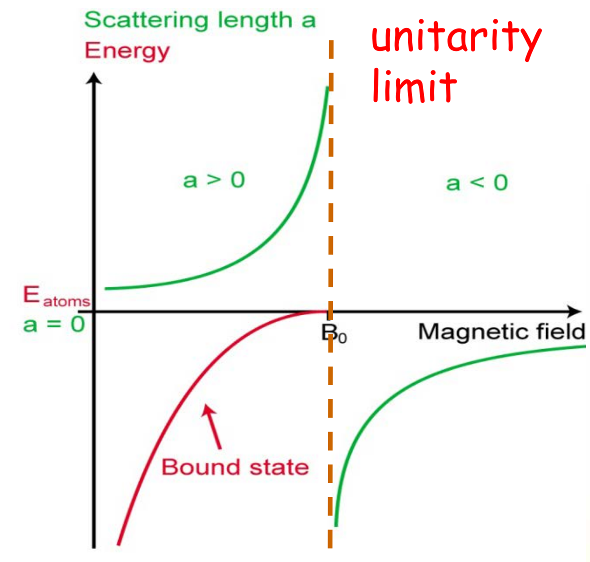
m_π (MeV)

Beane, Bedaque, Savage + v.K. '02
Braaten + Hammer '03
...

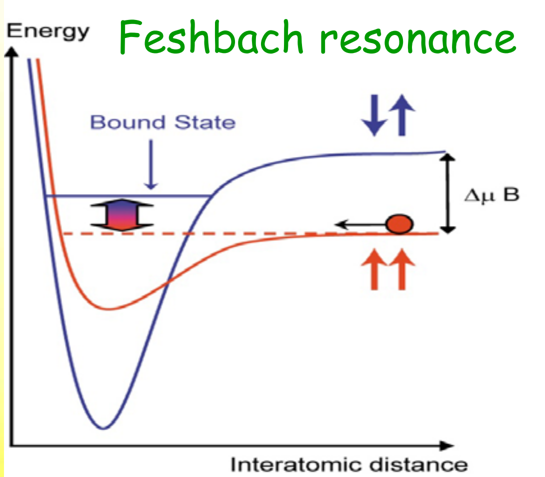
New scale emerges

$$\aleph \sim \frac{m_\pi - m_\pi^*}{m_\pi^*} M_{NN}$$

cf.



unitarity limit

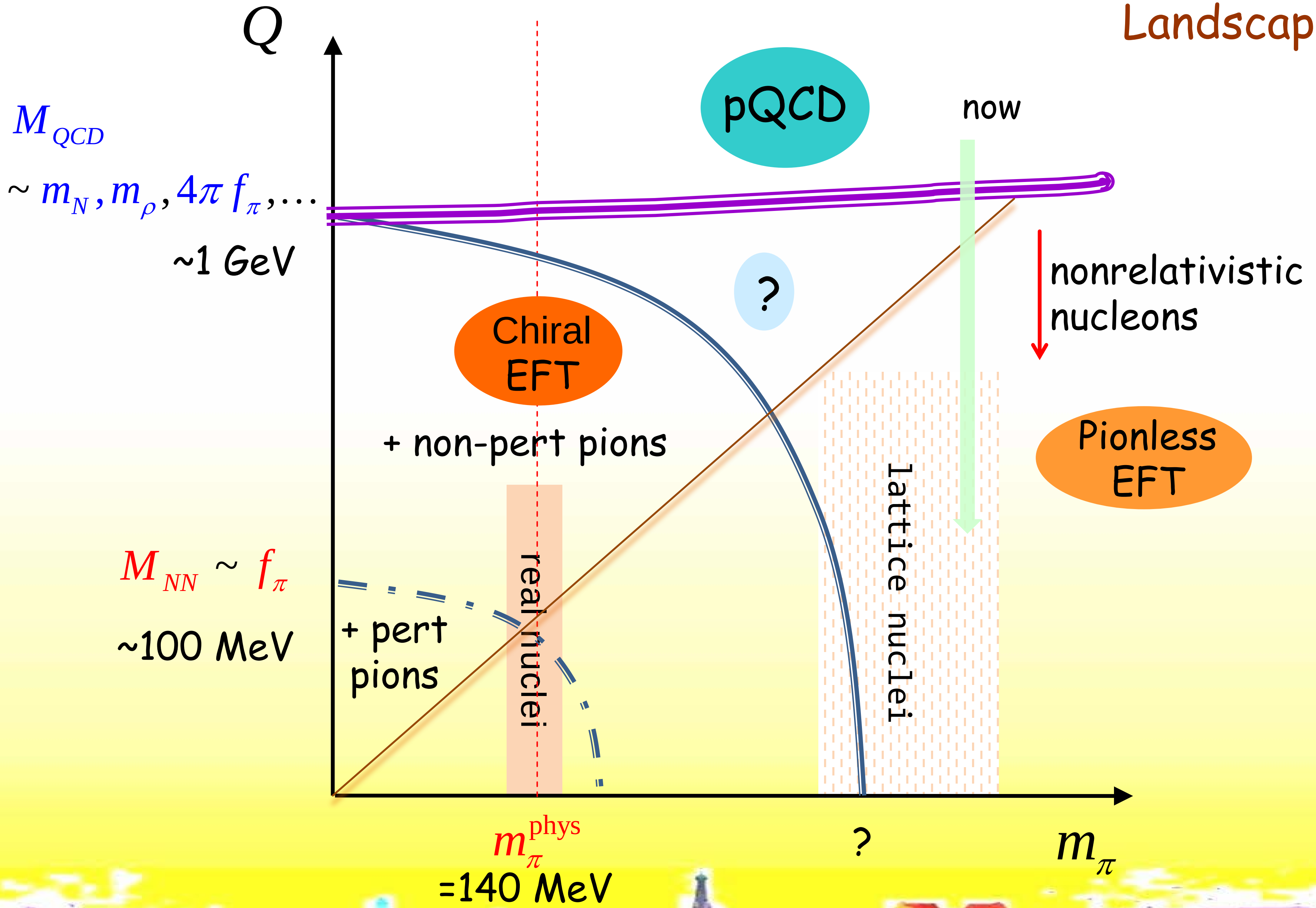


Feshbach resonance

MIT webpage

or "accidentally", *e.g.* ^{4}He atoms

The Nuclear EFT Landscape



$Q \ll m_\pi$

Pionless EFT

d.o.f.s nucleons: $N = \begin{pmatrix} p \\ n \end{pmatrix}$ (+ photon: A_μ)

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

(trivial)

$$\mathcal{L}_{\not{\pi} EFT} = N^+\left(i\partial_0 + \frac{\vec{\nabla}^2}{2m_N}\right)N + C_0\, N^+N\, N^+N + D_0\, N^+N\, N^+N\, N^+N + \ldots$$

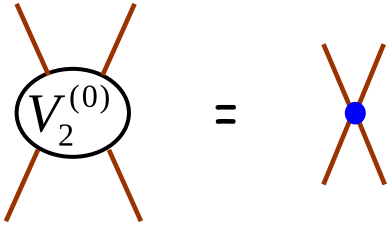
more derivatives
and fields,
isospin violation

Universality:
first orders
apply also to
neutral atoms

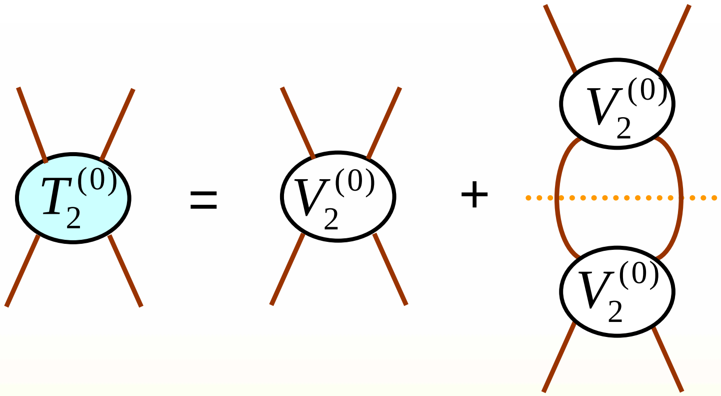
$$m_\pi \to 1/l_{\text{vdW}} \quad \textit{where} \quad V(r) = -\frac{l_{\text{vdW}}^4}{2mr^6} + \ldots$$

Bedaque, Hammer
+ v.K. '99'00
Bedaque, Braaten
+ Hammer '01
...

Bedaque + vK '97
vK '97
Kaplan, Savage + Wise '98
...



$$\sim \frac{4\pi}{m_N \aleph} \qquad \aleph \sim \frac{m_\pi - m_\pi^*}{m_\pi^*} M_{NN}$$



$$\sim \frac{4\pi}{m_N \aleph} \frac{1}{1 - \frac{Q}{\aleph}}$$

bound state

$$Q \sim \aleph \sim 30 \text{ MeV}$$

$$-E \sim \frac{\aleph^2}{M_{QCD}} \sim 1 \text{ MeV}$$

$$\gamma_0 \equiv \frac{m_N \Lambda}{4\pi} C_0 \qquad \Lambda \frac{d\gamma_0}{d\Lambda} = \gamma_0 \left(1 + \gamma_0\right)$$

Mehen, Stewart + Wise '99

fixed points: $\gamma_0 = \begin{cases} 0 & \text{trivial (perturbative)} \\ -1 & \text{nontrivial: unitarity} \end{cases}$

Weinberg '91

$$\aleph = 0$$

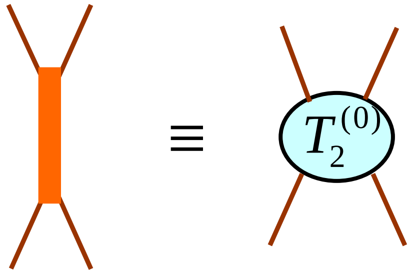
no physical scale:
scale invariance

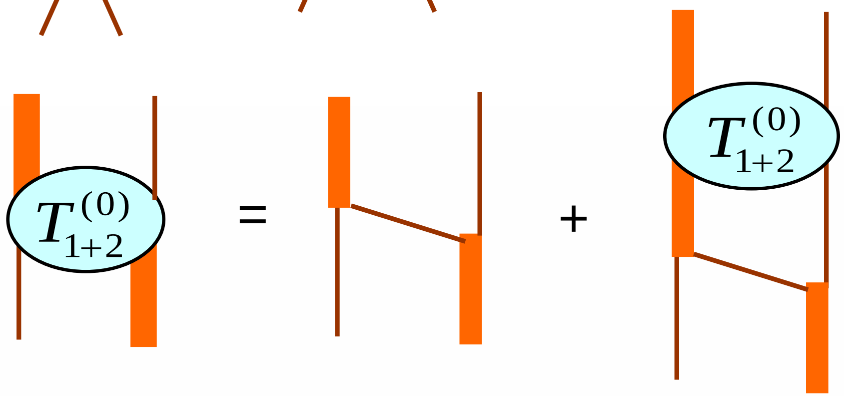
Bedaque, Hammer + v.K. '99 '00

Hammer + Mehen '01

Bedaque *et al.* '03

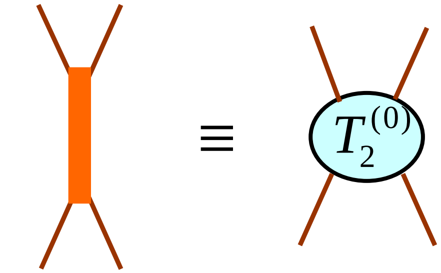
...

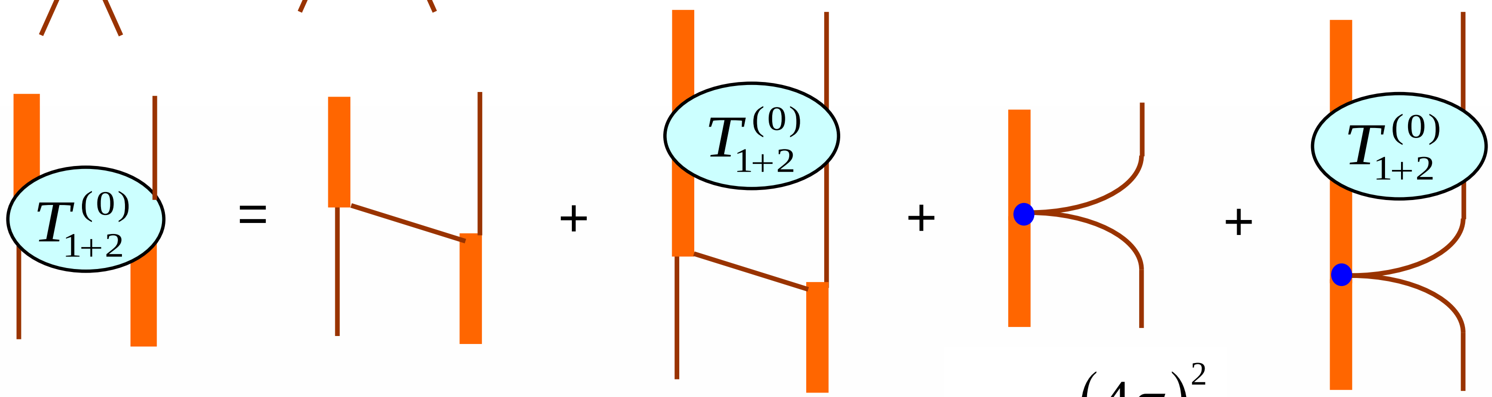




$$\Rightarrow \; T_{1+2} \xrightarrow{p \gg \aleph} A \cos\left(s_0 \ln \frac{p}{\Lambda} + \delta \right)$$

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





$$\Rightarrow \quad T_{1+2} \xrightarrow{p \gg \aleph} A \cos\left(s_0 \ln \frac{p}{\Lambda_*} + \tilde{\delta} \right)$$

$$D_0 \sim \frac{(4\pi)^2}{m_N \aleph^4}$$

cf. Wilson '71

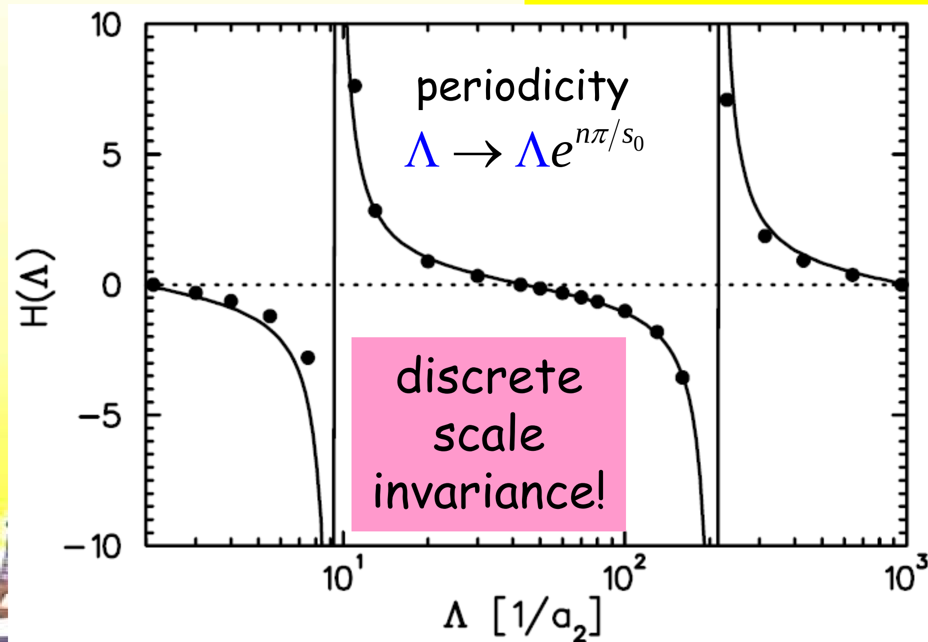
RG limit cycle!

dimensionful parameter
(dimensional transmutation)

$$H(\Lambda) \equiv \frac{\Lambda^2 D_0(\Lambda)}{m_N C_0^2(\Lambda)}$$

$$\simeq \frac{\sin\left(\ln(\Lambda/\Lambda_*) + \arctan(1/s_0)\right)}{\sin\left(\ln(\Lambda/\Lambda_*) - \arctan(1/s_0)\right)}$$

$$s_0 = 1.00624...$$



Physical quark masses:

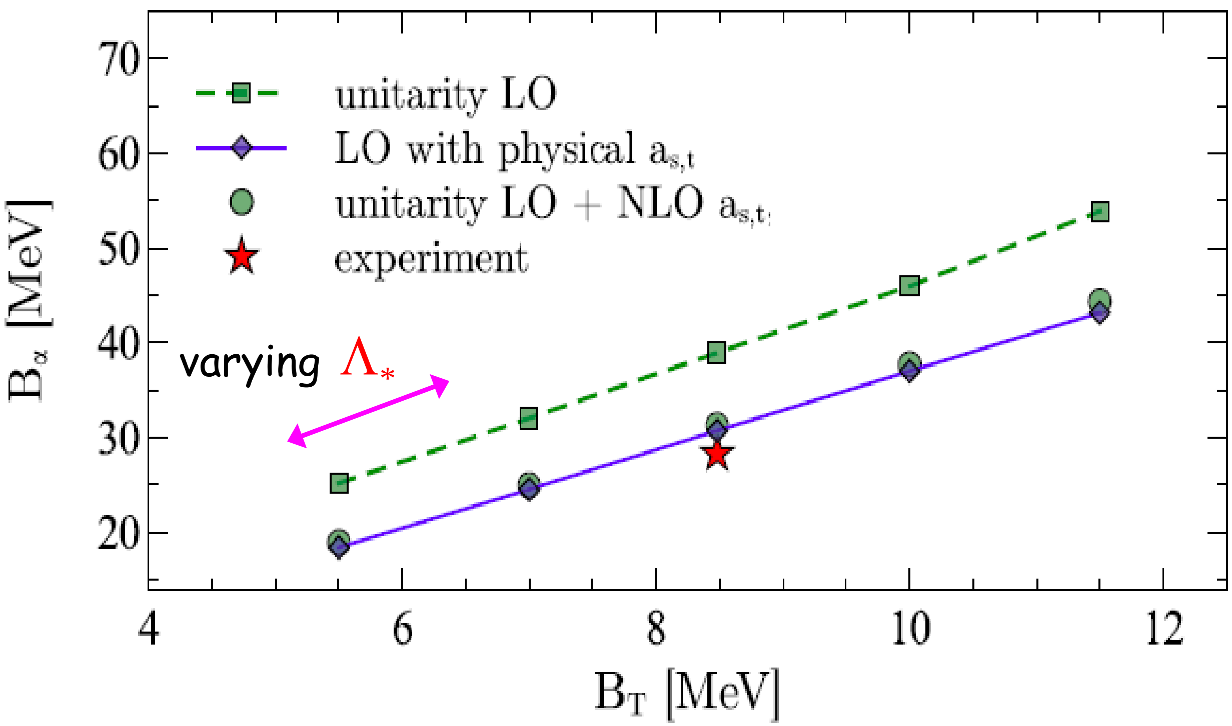
König, Grießhammer, Hammer + v.K. '17

expansion around two-body unitarity limit in $\aleph/\Lambda_*$ ➡ **ONE** parameter at LO Λ_*

- geometric towers of states (Efimov '71)
- ground states: $\frac{B_A^{(0)}(\Lambda_*)}{A} = \kappa_A \frac{B_3(\Lambda_*)}{3}$

universal numbers

$A = 4$



Tjon line

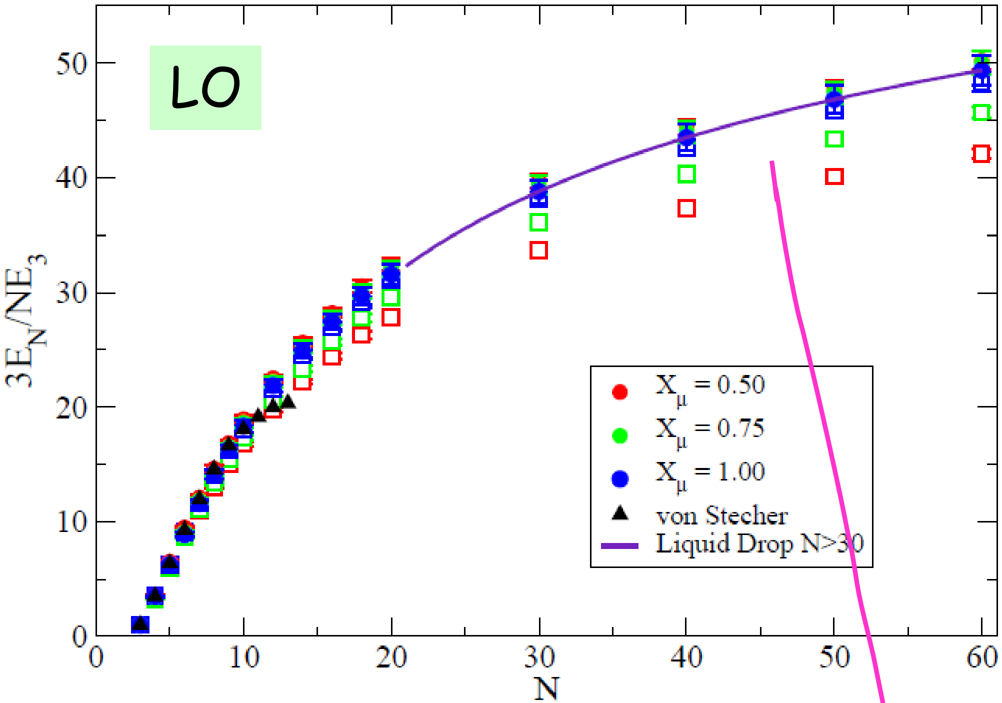
LO $\kappa_4 \simeq 3.5$

incomplete NLO

(Faddeev-Yakubovski equations)

Gandolfi, Carlson, Vitiello + vK '17

Bosons at unitarity



increasing Λ

(Variational and Diffusion Monte Carlo)

saturation!

$$\kappa_N = \kappa_\infty \left[1 + \eta N^{-1/3} + \mathcal{O}\left(N^{-2/3}\right) \right]$$

$$\kappa_\infty = 90 \pm 10 \qquad \eta = -1.7 \pm 0.3$$

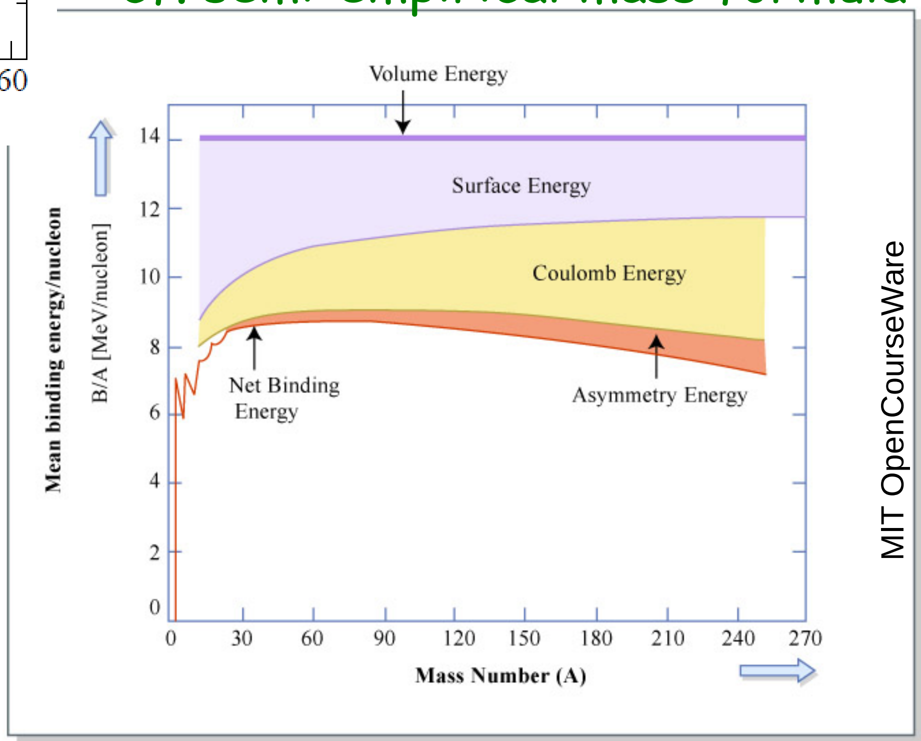
volume surface

awaiting atomic experiments...

Von Weizsäcker '35

...

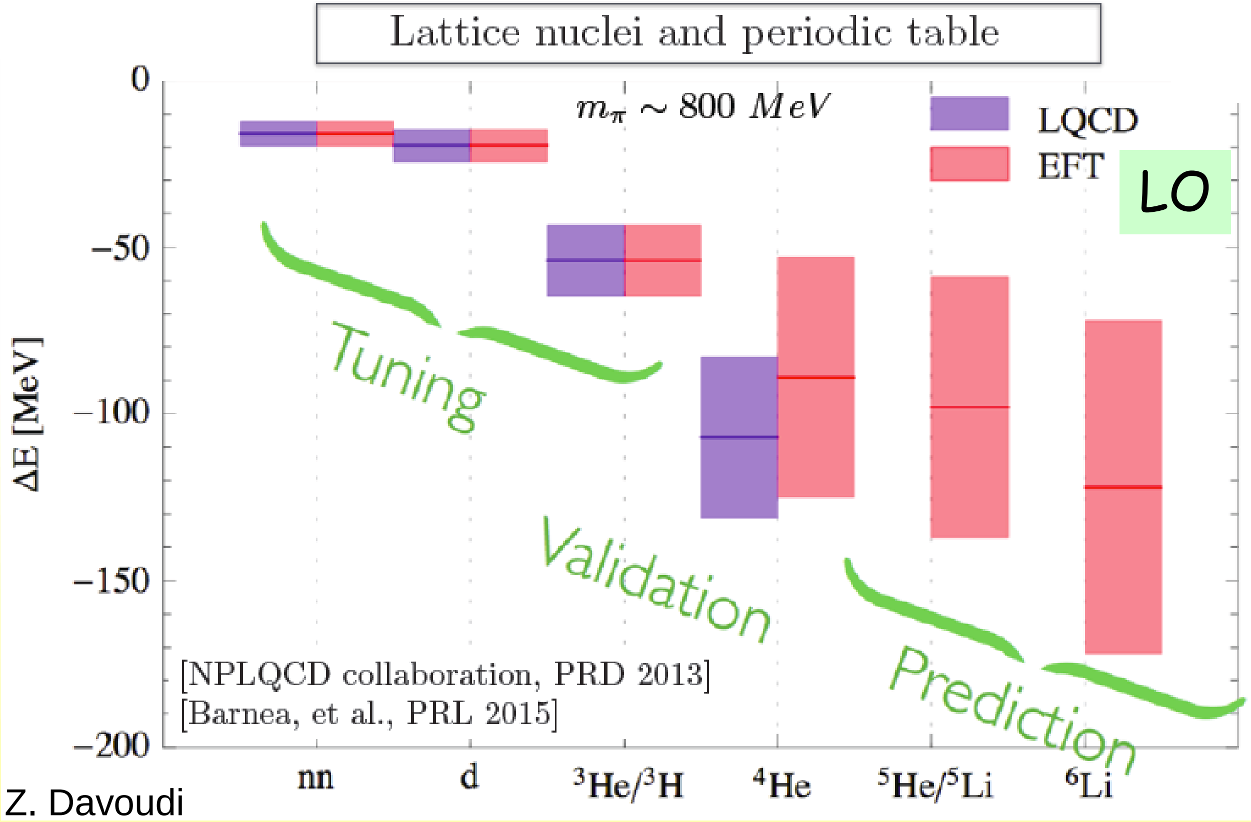
cf. semi-empirical mass formula



Unphysical quark masses: three parameters at LO

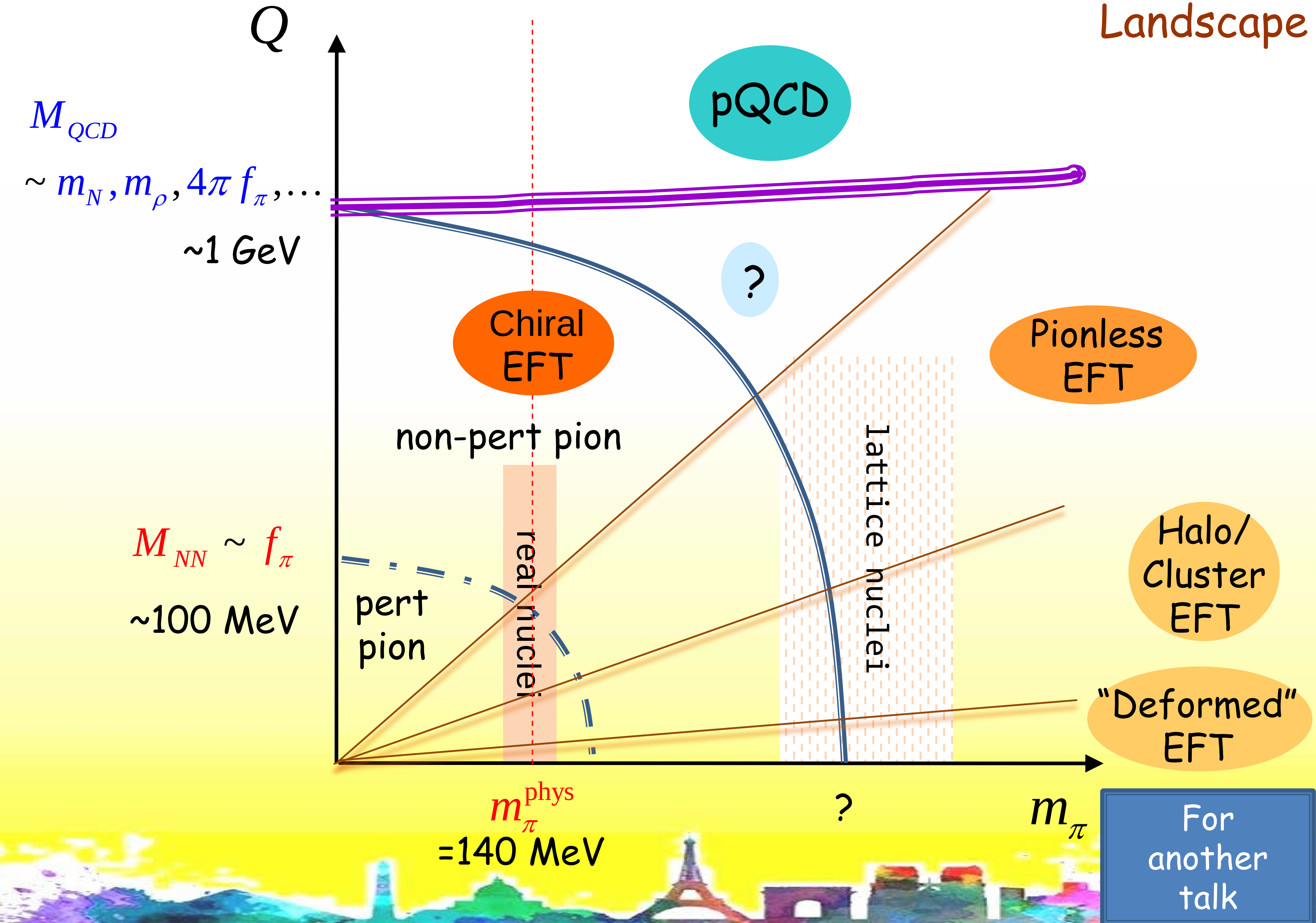
$\Lambda_*, \aleph_{^3S_1}, \aleph_{^1S_0}$

Barnea, Contessi,
Gazit, Pederiva
+ v.K. '15



Qualitatively similar to physical pion mass,
just more bound by a factor ~5

The Nuclear EFT Landscape



Beyond the SM

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_{\mathrm{dim}=5} + \mathcal{L}_{\mathrm{dim}=6} + \ldots$$

Weinberg '79

Buchmüller + Wyler '86
Weinberg '89
de Rújula *et al.* '91
...
Ng + Tulin '11

$\Delta L = 2$ → neutrinoless double-beta decay

T violation → nuclear electric dipole moments

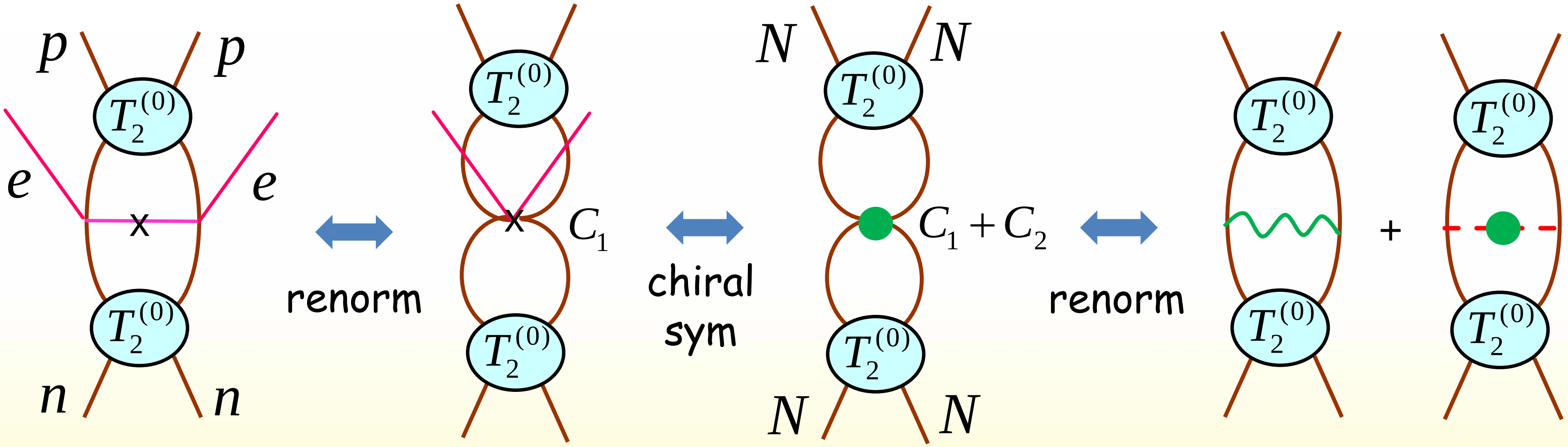
Two examples

$Q \ll M_{W,Z}$

Neutrinoless double-beta decay

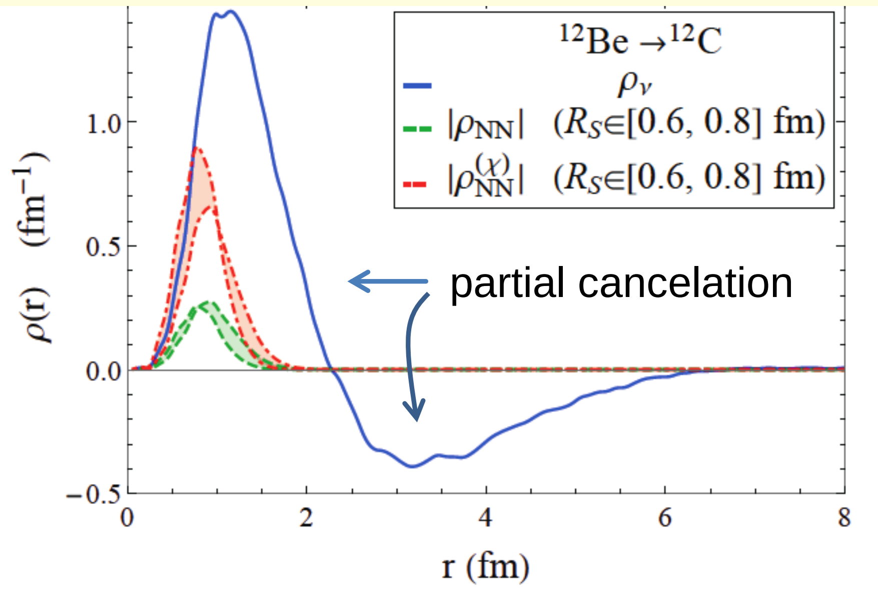
Cirigliano *et al.* '18

$$\mathcal{L}_{\text{dim}=5} = -\frac{m_{\beta\beta}}{2} \nu_{eL}^T C \nu_{eL} + \ldots \qquad m_{\beta\beta} \equiv \sum_{i=1}^{3} U_{ei}^2 m_{\nu i}$$



lattice QCD needed to disentangle C_1 and C_2

determining $C_1 + C_2$ from NN data and assuming $C_1 \sim C_2$



$$A_{0\nu 2\beta} = \int dr\, \rho(r)$$

$$\frac{A_{NN}}{A_\nu} \simeq 0.3 - 0.6$$

$Q \ll M_{W,Z}$

Nuclear electric dipole moments

De Vries *et al.* '10'11'13
Bsaisou *et al.* '12'13'15
Dekens *et al.* '14

$$\mathcal{L}_{\dim=4,6} = \ldots + \frac{\bar{m}}{2}\left(1-\varepsilon^2\right)\bar{\theta}\;\bar{q}i\gamma_5 q - \frac{1}{2}\bar{q}\left(c_q^{(0)} + c_q^{(1)}\tau_3\right)\sigma_{\mu\nu}\tilde{G}^{\mu\nu}q - \frac{1}{2}\bar{q}\left(d_q^{(0)} + d_q^{(1)}\tau_3\right)\sigma_{\mu\nu}q\,\tilde{F}^{\mu\nu}$$
$$+\frac{c_G}{6} f^{abc} G^a_{\mu\nu}\tilde{G}^{b\nu\rho}G^{c\mu}_{\rho} + \frac{C_1}{4}\left(\bar{q}q\;\bar{q}i\gamma_5 q - \bar{q}\boldsymbol{\tau}q\cdot\bar{q}i\gamma_5\boldsymbol{\tau}q\right) + \frac{C_8}{4}\left(\bar{q}\lambda^a q\;\bar{q}i\gamma_5\lambda^a q - \bar{q}\boldsymbol{\tau}\lambda^a q\cdot\bar{q}i\gamma_5\boldsymbol{\tau}\lambda^a q\right)$$
$$+\frac{D_1}{4}\varepsilon_{3ij}\;\bar{q}\tau_i\gamma^\mu q\;\bar{q}\tau_j\gamma_\mu\gamma_5 q + \frac{D_8}{4}\varepsilon_{3ij}\;\bar{q}\tau_i\gamma^\mu\lambda^a q\;\bar{q}\tau_j\gamma_\mu\gamma_5\lambda^a q + \ldots$$

Neutron EDM d_n can be produced by any source, but
different chiral properties of sources → different magnitudes for nuclear EDMs

		θ term	qCEDM	qEDM	gCEDM, PS4QO	LR4QO
^{1}H	d_p/d_n	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
^{2}H	d_d/d_n	$\mathcal{O}(1)$	$\mathcal{O}\left(M_{QCD}^2/m_\pi^2\right)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}\left(M_{QCD}^2/m_\pi^2\right)$
^{3}He	d_h/d_n	$\mathcal{O}\left(M_{QCD}^2/m_\pi^2\right)$	$\mathcal{O}\left(M_{QCD}^2/m_\pi^2\right)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}\left(M_{QCD}^2/m_\pi^2\right)$
^{3}H	d_t/d_h	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$

+ specific relations

Farley *et al.* '04
…

storage-ring measurements (CERN?) could teach us about sources!

Conclusion

- Effective field theory allows us to connect the Standard Model and nuclear physics in a controlled and systematic way

- We are in position to use nuclei as a laboratory to test physics beyond the SM