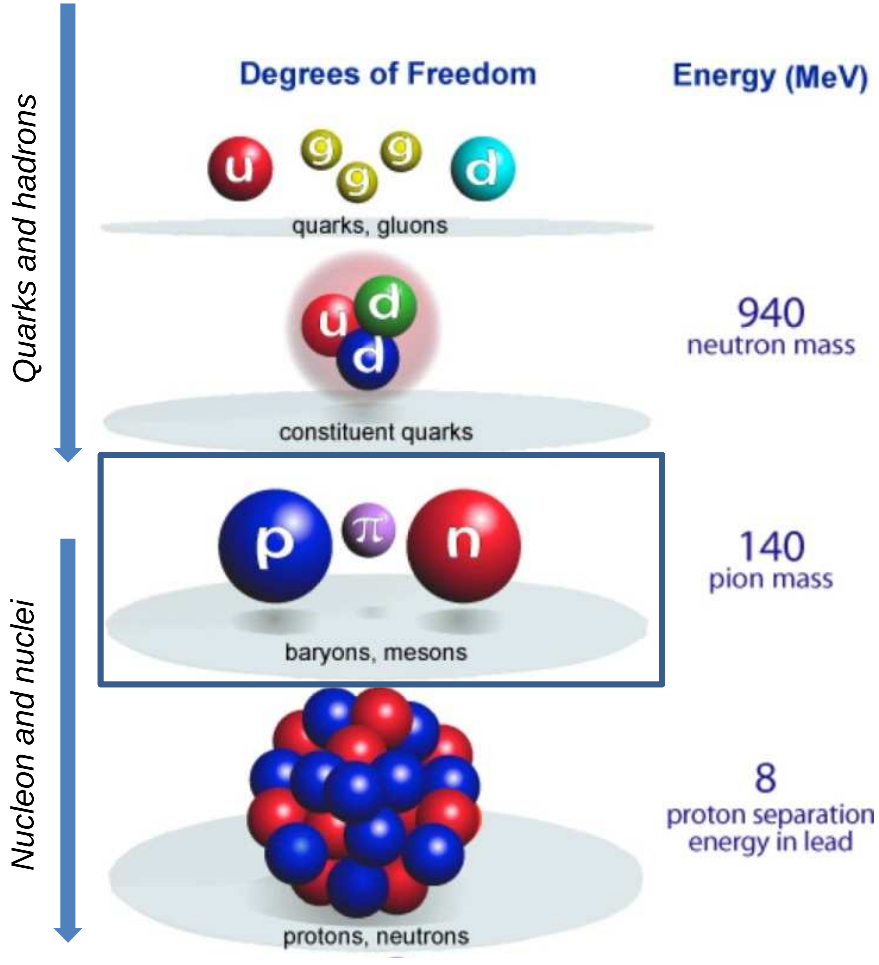
Introduction – Strong interaction in the nuclear medium: new trends

Denis Lacroix

GANIL-Caen

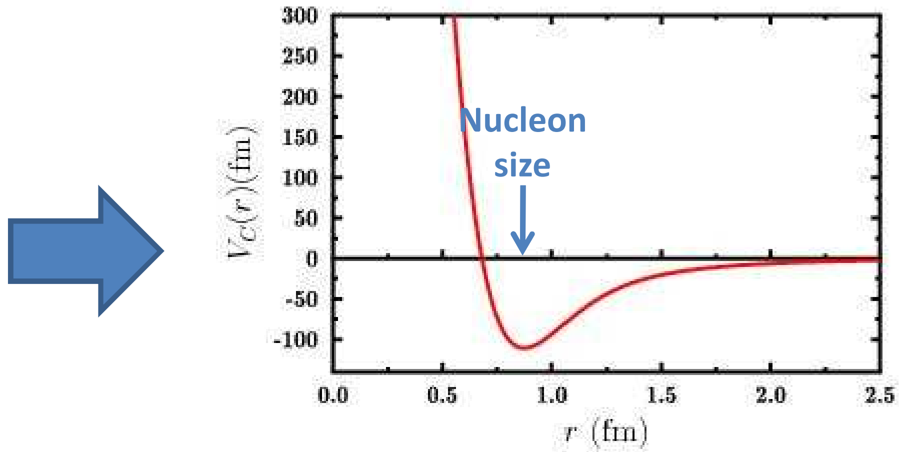
The NN interaction:

a crossroad between quark, mesons and nuclei



The high energy nuclear physicist viewpoint

- From QCD it is clear that NN int. is not a fundamental force
- Quarks and leptons are the elementary entities

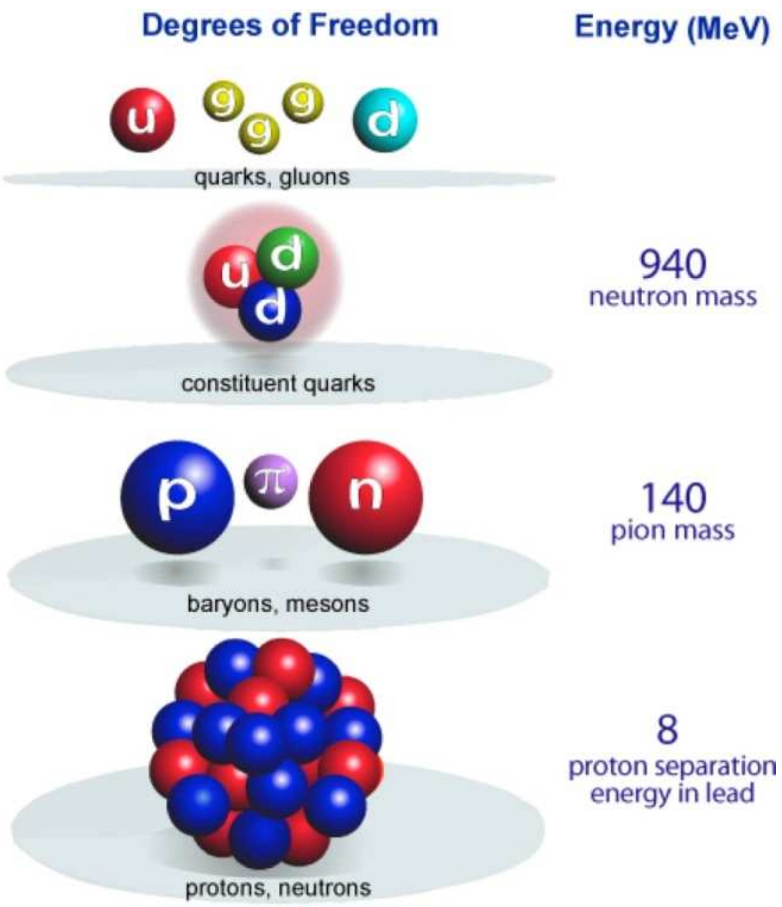


The low energy nuclear physicist viewpoint

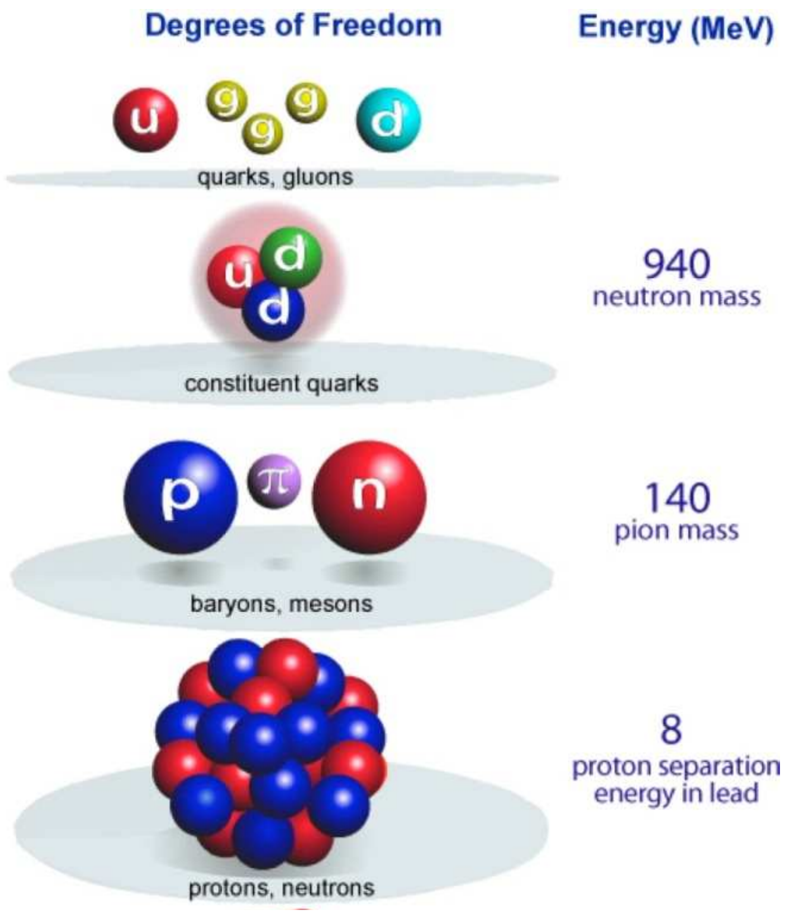
- NN-interaction is a fundamental force
- Nucleons are considered as Elementary (point-like) particles

A school on nuclear interaction: why and why now ?

Highlights on recent key issues



- **First Lattice QCD calc. of NN interaction**
- **NN int. from chiral pert. Theory and Effective Field Theory (EFT)**
- **New “soft” interaction (V_{lowk}…)**
- **Ab-initio calc. for light nuclei and hyperons**
- **3-body interaction**
- **Discussion on spin-orbit, tensor, pairing, 3-body…**
- **Standard Nuclear models (Energy Density Functional -Shell model) are being now revisited in a “bottom-up” philosophy**



I -conventional Nuclear Forces

- **quantum numbers**
- **phase shift analysis**
- **Adjusting semi-empirical forces**
- **Limitations and difficulties**

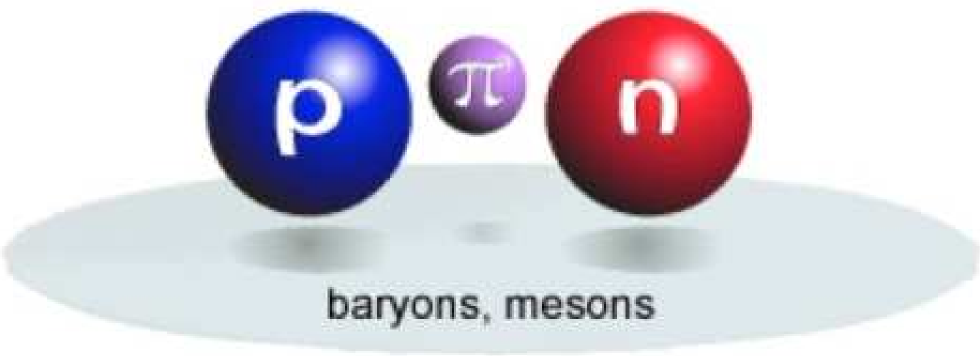
II-From quarks to nucleons and NN interaction.

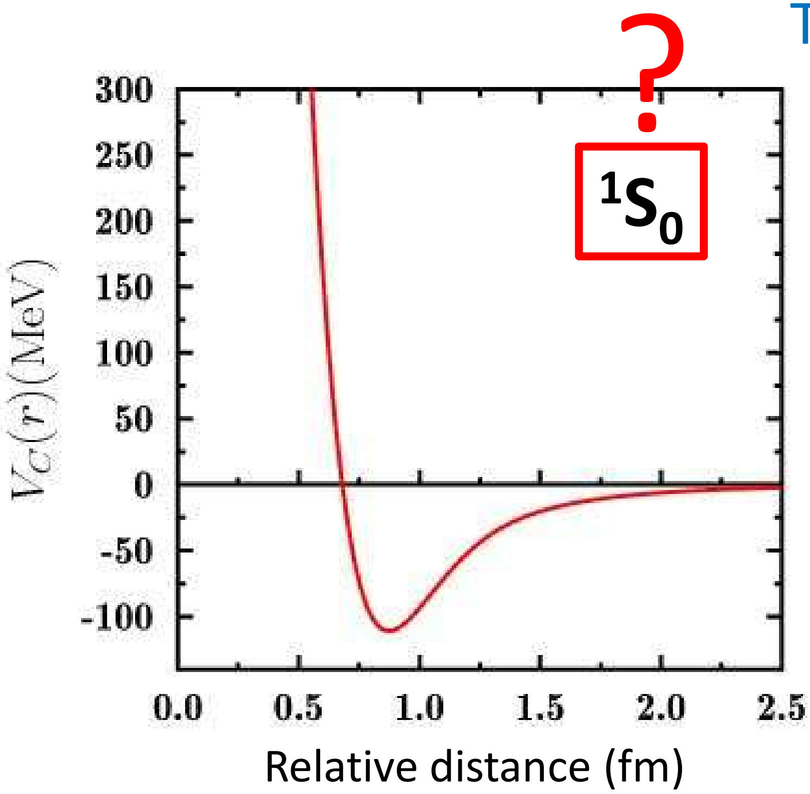
- **Lattice QCD**
- **Chiral pert Theory and Effective Field Theory**
- **Modern Forces**

III-From NN interaction to Nuclei,
Hypernuclei,
and Stars

- **New soft interaction**
- **Ab-initio theory and light nuclei**
- **Selected aspects of Shell Model and Energy Density Functional**

I-Conventional NN interaction





Two-body wave: $\Psi_{\rm NN} = \Psi(\mathbf{r}_1\sigma_1\tau_1;\mathbf{r}_2\sigma_2\tau_2)$

Quantum numbers: $L,\ S,\ T$ and $J = L + S$

Spin $\vert S\ M_S\rangle$		*Isospin* $\vert T\ T_z\rangle$		
$\vert 0\ 0\rangle$	$\vert\uparrow\downarrow\rangle - \vert\downarrow\uparrow\rangle$	$\vert 0\ 0\rangle$	$\vert{\rm np}\rangle - \vert{\rm pn}\rangle$	singlet
$\vert 1\ 1\rangle$	$\vert\uparrow\uparrow\rangle$	$\vert 1\ 1\rangle$	$\vert{\rm nn}\rangle$	triplet
$\vert 1\ 0\rangle$	$\vert\uparrow\downarrow\rangle + \vert\downarrow\uparrow\rangle$	$\vert 1\ 0\rangle$	$\vert{\rm np}\rangle + \vert{\rm pn}\rangle$	
$\vert 1\ -1\rangle$	$\vert\downarrow\downarrow\rangle$	$\vert 1\ -1\rangle$	$\vert{\rm pp}\rangle$	

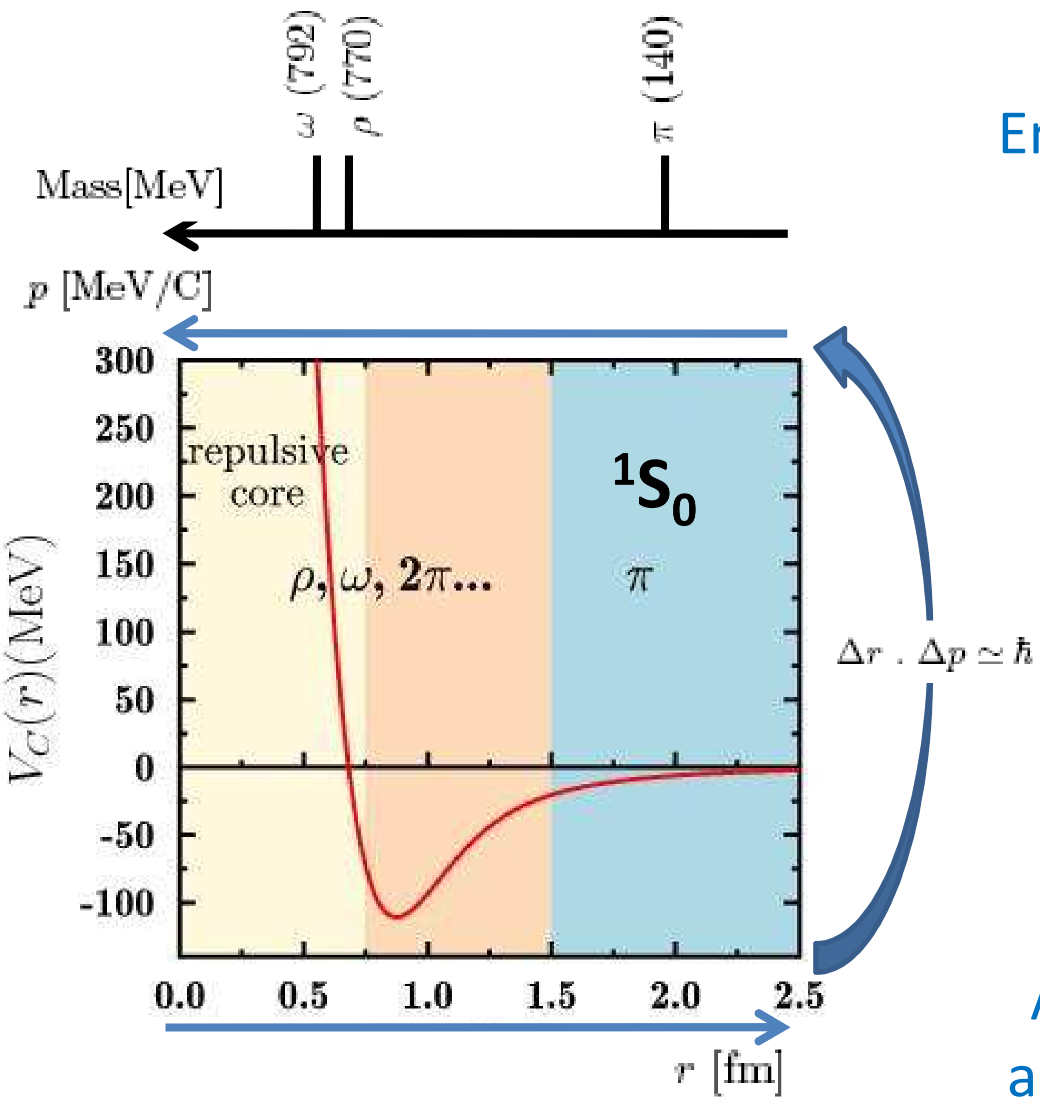
Channels: $^{2S+1}[L]_J$

$[L = 0, 1, 2, \cdots] =\ {\rm S},\ {\rm P},\ {\rm D}, \cdots$

S	T	n/p state	$J=0$	$J=1$	$J=2$
0	1	nn, pp, (np + pn)	$^1{\rm S}_0$		$^1{\rm D}_2$
1	0	(np − pn)		$^3{\rm S}_1, ^3{\rm D}_1$	
0	0	(np − pn)		$^1{\rm P}_1$	
1	1	nn, pp, (np + pn)	$^3{\rm P}_0$	$^3{\rm P}_1$	$^3{\rm P}_2, ^3{\rm F}_2$

Conventional NN interaction:

Semi-phenomenological parameterization



Energy scale and mesons:

$$V_{NN} = v_{NN}^{EM} + v_{NN}^{\pi} + v_{NN}^{Rep}$$

v_{NN}^{EM} : electro magnetic (Coulomb…)

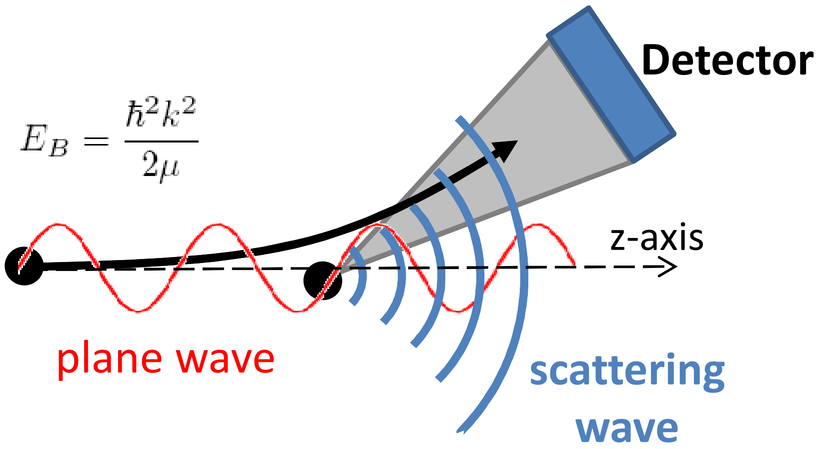
v_{NN}^{π} : long-range (one-pion exchange)

v_{NN}^{Rep} : short-range + medium range (phenomenological repulsive core)

Around 30 parameters to be adjusted on experimental data

Adjusting Conventional NN interaction:

Scattering theory: phase-shift…



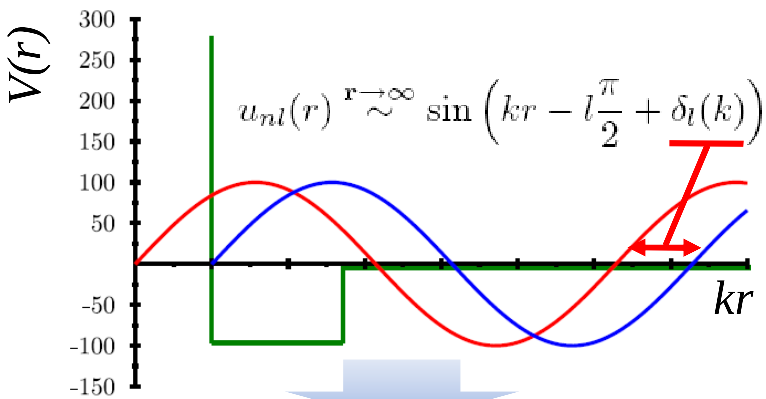
$$E_B = \frac{\hbar^2 k^2}{2\mu}$$

$$\Psi_{\rm scat}(\mathbf{r}) \overset{\mathbf{r}\to\infty}{\longrightarrow} e^{ikz} + f(\theta,\varphi)\frac{e^{ikr}}{r}$$

$$\sigma_k(\theta,\varphi) = |f(\theta,\varphi)|^2$$

Spherical symmetric potential:

$$\Psi_{\rm scat}(\mathbf{r}) = \sum_{nlm} c_{nlm}\frac{u_{nl}(r)}{r}Y_{lm}(\theta,\varphi)$$

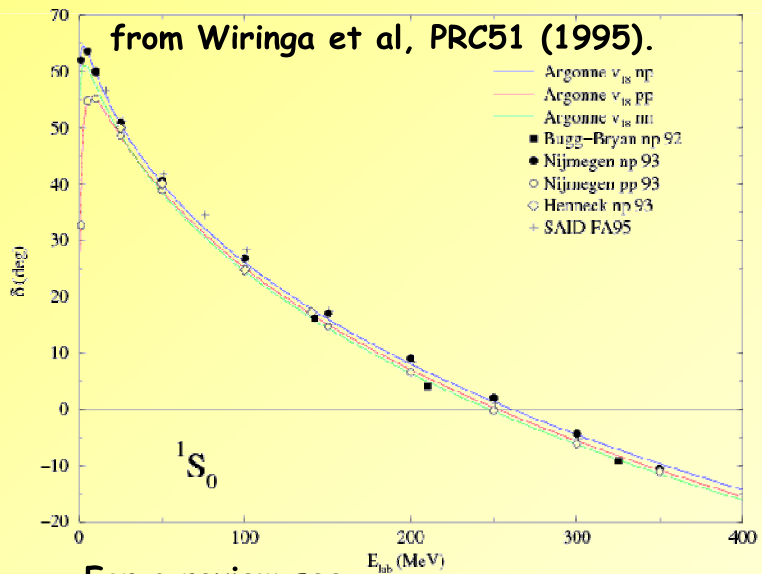


$$u_{nl}(r) \overset{\mathbf{r}\to\infty}{\sim} \sin\left(kr - l\frac{\pi}{2} + \delta_l(k)\right)$$

$$\sigma(k) = \frac{4\pi}{k^2}\sum_l (2l+1)\sin^2[\delta_l(k)]$$

Example (av18):

➡ **nn, pp, np data**

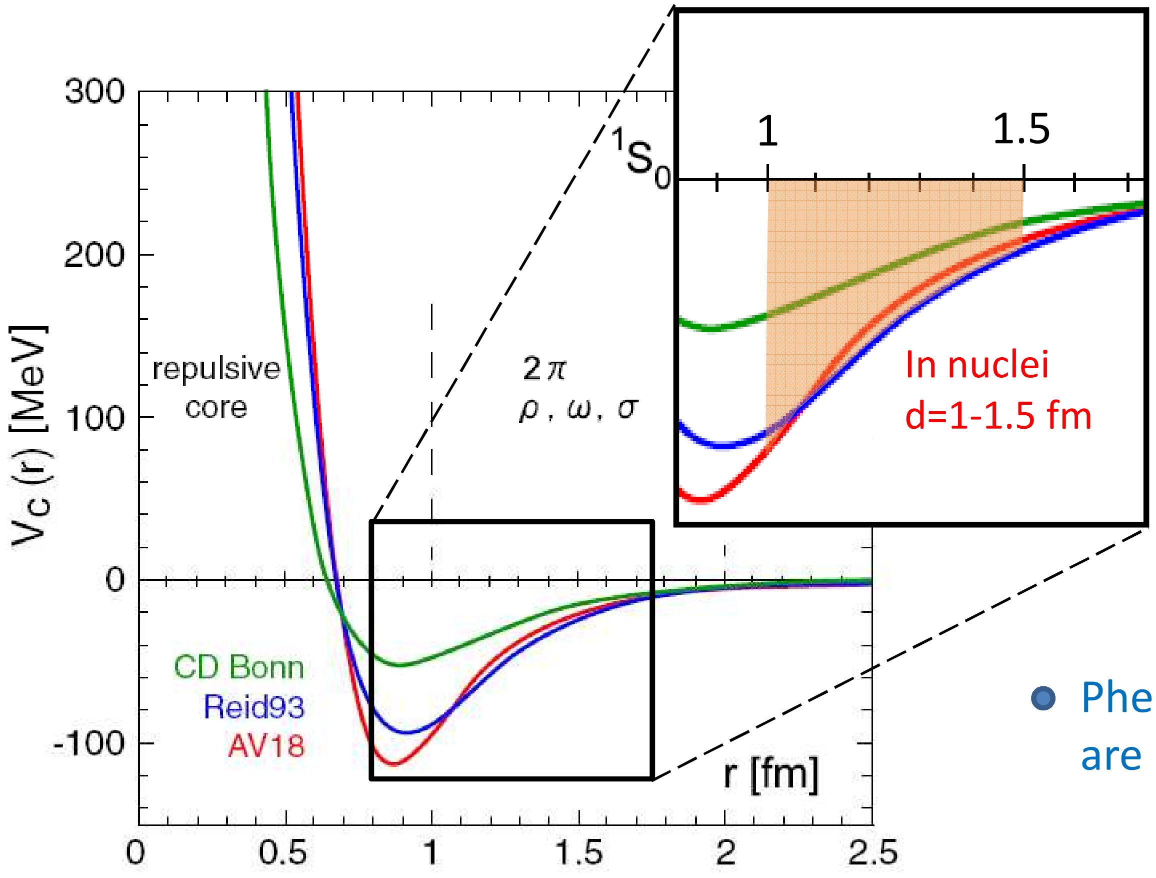


For a review see
Machleidt and Staus, J. Phys. G27 (2001)

- **Adjusted also on deuteron properties (B.E.)**

Drawbacks: non uniqueness

Adapted from Ishii, Aoki and Hatsuda, PRL 99 (2007)



- Phenomenological NN potentials are not unique
  (partially solved by V_{lowk})
- Difficult to improve systematically

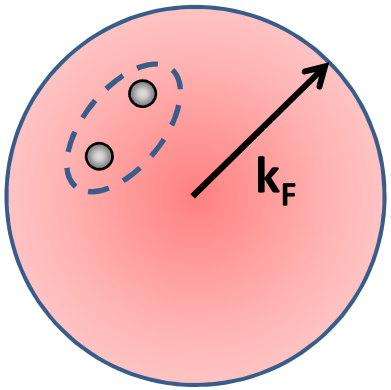
⇒ Need for a systematic constructive theory
(Effective Field Theory)

Conventional NN interaction:

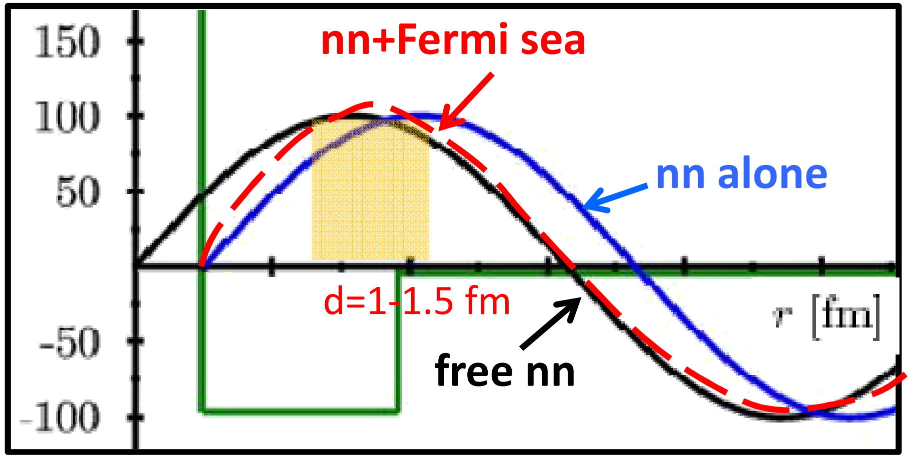
in-medium effects

What means in-medium effect ?

Example: two-nucleons in a Fermi see



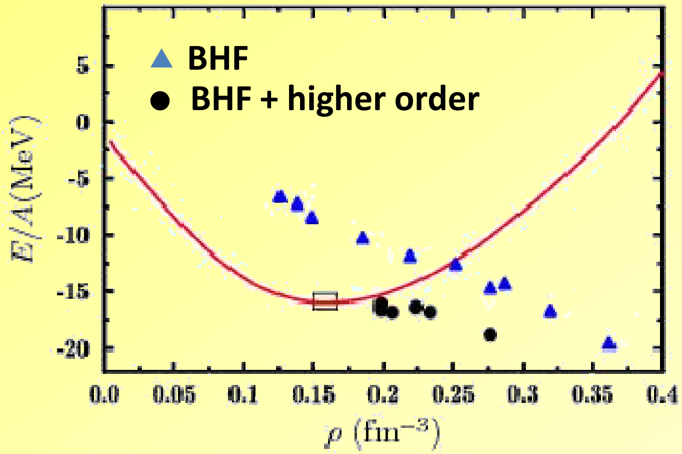
Gomes, Walecka and Weisskopf, Ann. Phys. (1958)



Stiff nn + Pauli ⇒

- In medium effects are large and crucial
- Leads to an independent particles + residual int. picture

J. Meyer, Ann. Phys. Fr (2001)



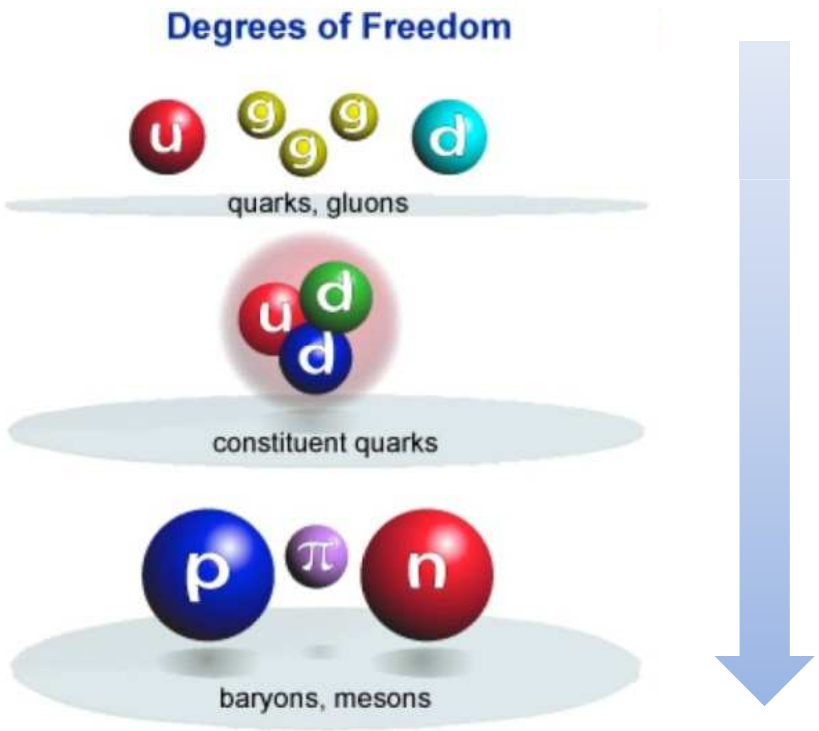
Formal theory of "dressed" interaction

$$G = V - V\frac{Q}{e}G = V - V\frac{Q}{e}V\frac{Q}{e}V + \dots$$

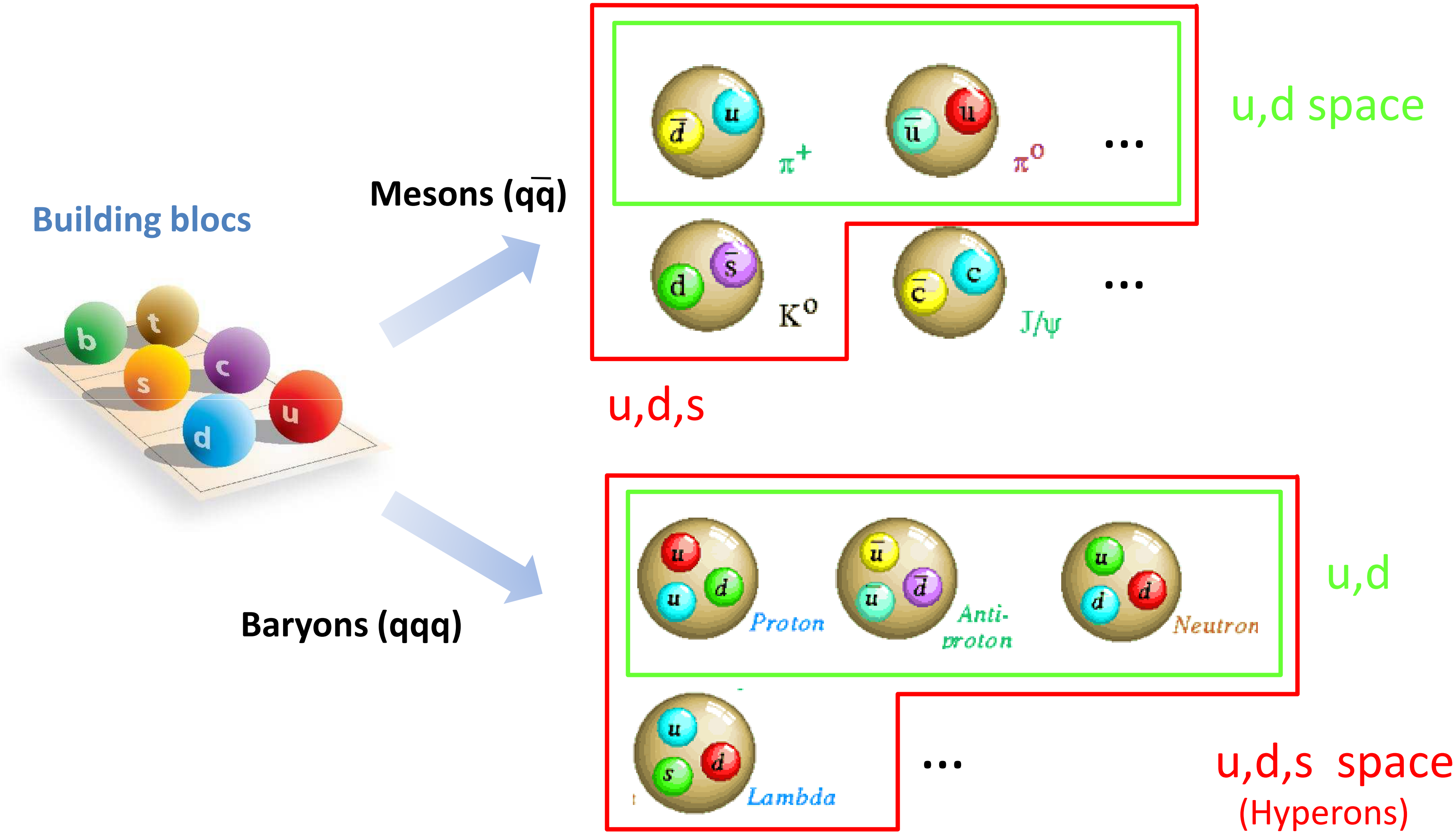
(Bethe-Goldstone Eq.)

- ☹ Difficult to work with conventional NN
- ☺ Has motivated Energy Density Func. (1972)
- ☺ Solved by V_{lowk} + 3-body

II-From quarks to nucleons and NN-interaction: New trends



Minimal reminder



In low energy nuclear physics we are mainly concerned with u,d,s space

(see lecture D. Watts)

First Lattice QCD application

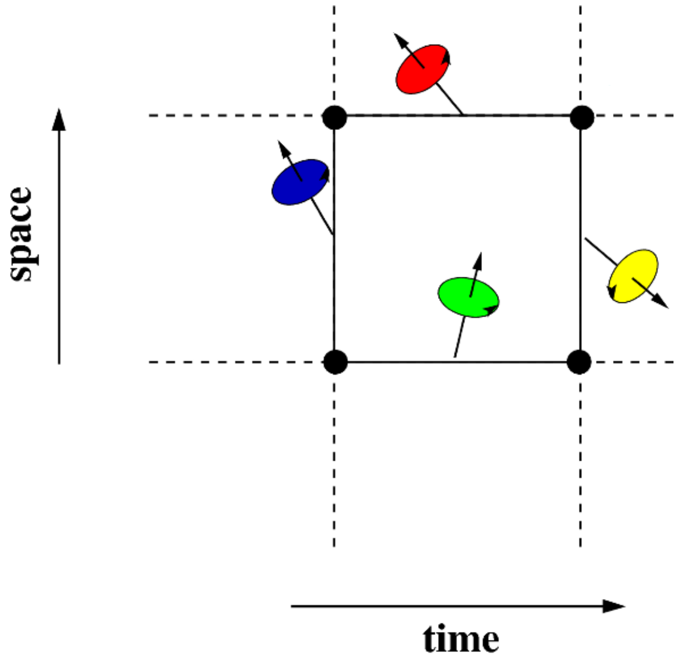
QCD Lagrangian discretized on a mesh

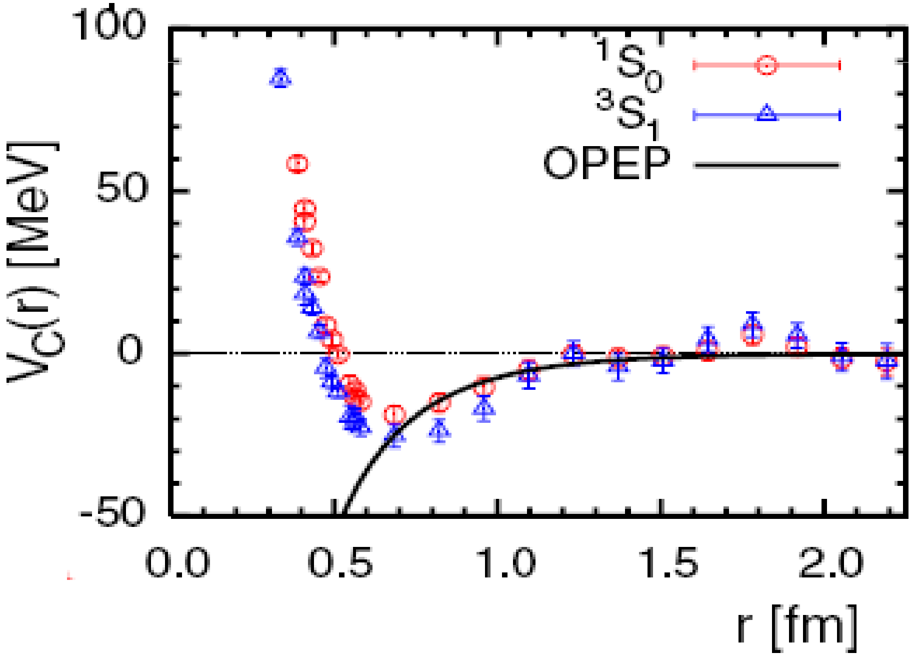
↓

Hadrons properties (NN-interaction)

$\mathcal{L}_{QCD}$

Free parameters: Quark masses



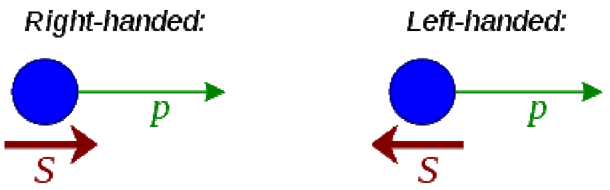


Ishii, Aoki and Hatsuda, PRL 99 (2007)

QCD Lagrangian

$$\mathcal{L}_{\rm QCD} = \mathcal{L}_{\rm QCD}^{\rm MassLess} - \bar{q}\mathcal{M}q$$

- $\mathcal{L}_{\rm QCD}^{\rm MassLess}$ → **Chiral symmetric**
- $\bar{q}\mathcal{M}q$ → **Explicitly breaks The chiral symmetry**



Quarks Masses

$$m_u \sim 2.4^{\pm 0.9}\,\mathrm{MeV}$$
$$m_d \sim 4.75^{\pm 1.25}\,\mathrm{MeV}$$
$$m_s \sim 100^{\pm 30}\,\mathrm{MeV}$$

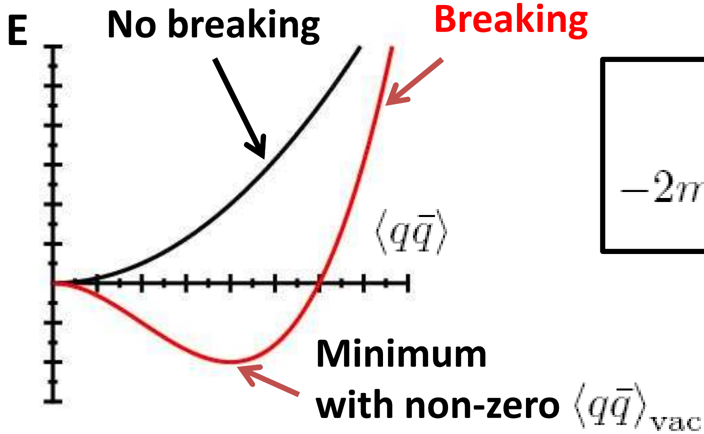
light quarks

GAP (1 GeV)

$$m_c \sim 1270^{+70}_{-110}\,\mathrm{MeV}$$
$$m_b \sim 4200^{+170}_{-70}\,\mathrm{MeV}$$
$$m_t \sim 171200^{\pm 2100}\,\mathrm{MeV}$$

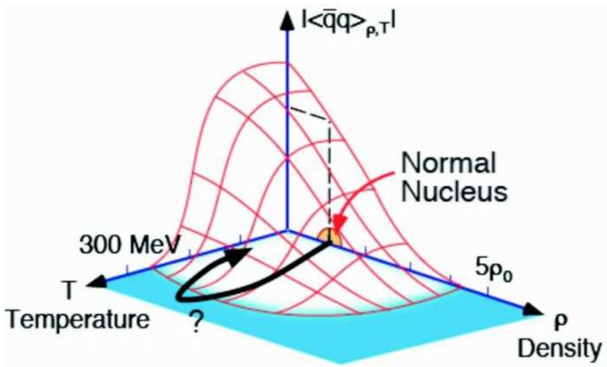
heavy quarks

Illustration of chiral symmetry Breaking consequences



Link with pion

$$-2m_q \langle q\bar{q}\rangle_{\rm vac} = m_\pi^2 f_\pi^2$$

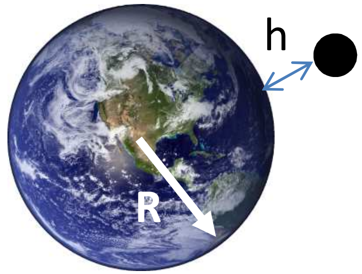


(see lecture C. Djalali)

➡ **treat the light quark masses perturbatively (chiral pert. theory) and use Effective Field Theory (EFT)**

What is EFT ?

Gravitation **(Papenbrock -2008)**



$$h \ll R$$

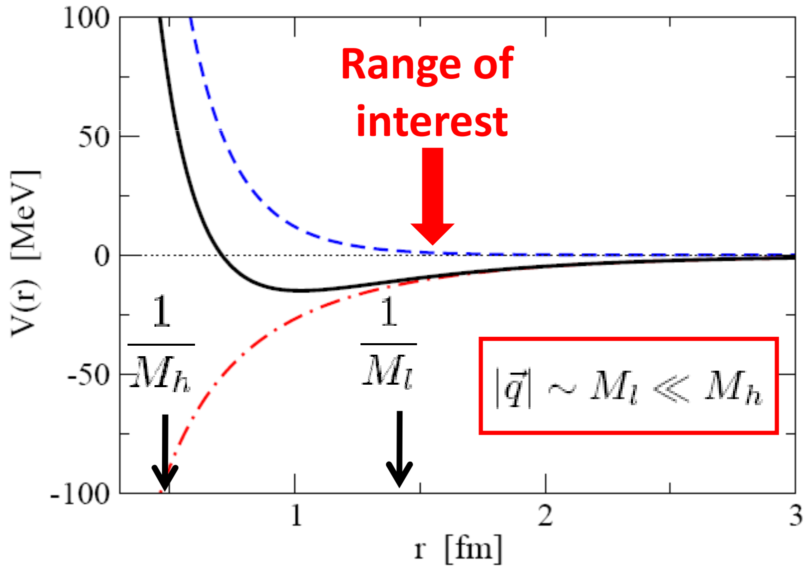
$$V(h) = -\frac{GMm}{R+h} = V(0) + \frac{GMm}{R}\left(\frac{h}{R}\right) + O\left(\frac{h^2}{R^2}\right)$$

Toy NN interaction **(Meissner-CISS08)**

$$V(\vec{r}) = \underbrace{\frac{\alpha_l}{4\pi r} e^{-M_l r}}_{\text{long-range}} + \underbrace{\frac{\alpha_h}{4\pi r} e^{-M_h r}}_{\text{short-range}}$$

$$V(\vec{q}) = \frac{\alpha_l}{\vec{q}^{\,2} + M_l^2} + \frac{\alpha_h}{\vec{q}^{\,2} + M_h^2}$$

$$V(\vec{q}) = V_{long}(\vec{q}) + V_{short}(0) - \frac{\alpha_h}{M_h^2}\left(\frac{\vec{q}}{M_h}\right)^2 + \cdots$$



Diverge at large ***q*** -Introduce a cutoff

$$\Lambda \sim M_h$$

$$V(\vec{q}) = V_{long}(\vec{q}) + \left[C_0 + C_2\left(\frac{\vec{q}}{\Lambda}\right)^2 + \cdots\right] f_\Lambda(\vec{q}^{\,2})$$

LO (C_0)

NLO ($C_0 + C_2(\vec{q}/\Lambda)^2$) **…**

Modern theory of Nuclear Forces

Chiral Lagrangian and Effective Field Theory

$|\vec{q}| \sim M_\pi \simeq 140$ MeV

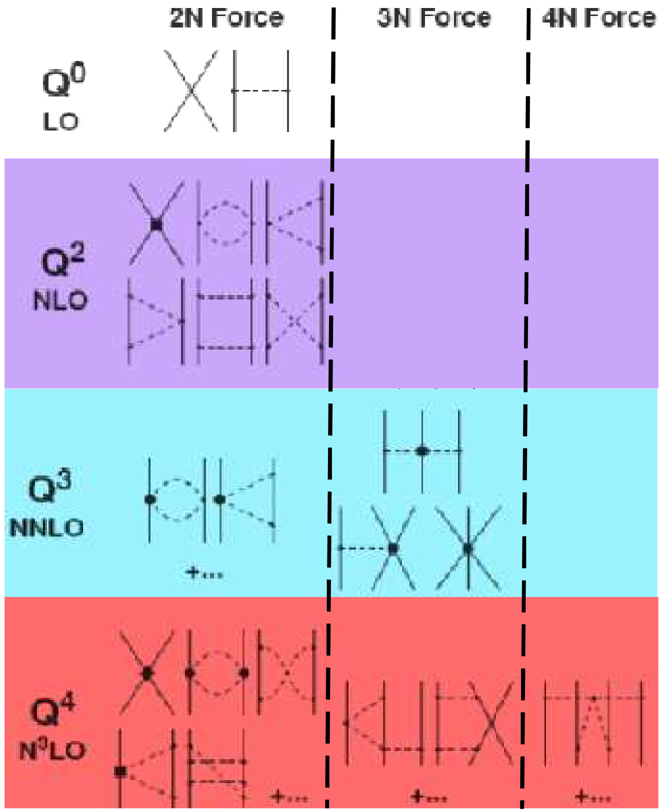
$\Lambda_{QCD} \simeq 1$ GeV

➡ **develop in** $\left(\frac{\vec{q}}{\Lambda}\right)$

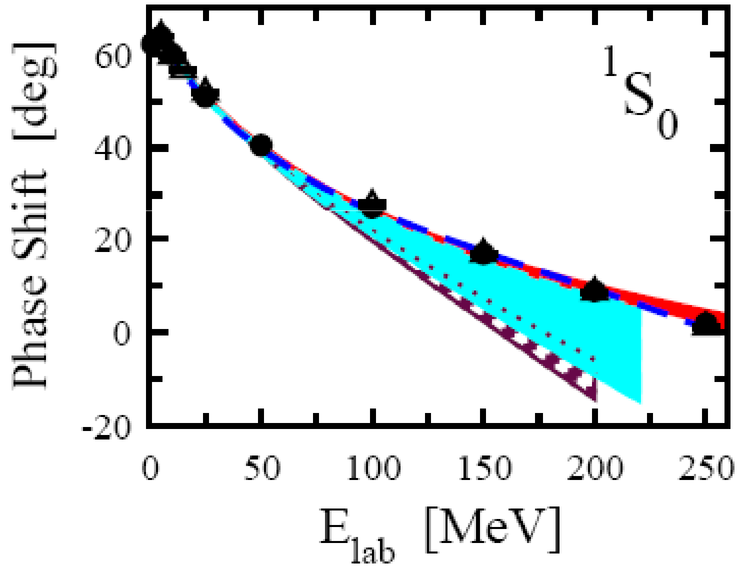
Starting point : Chiral Lagrangian

$$\mathcal{L}_{QCD} \longrightarrow \mathcal{L}_{EFT} = \mathcal{L}_{\pi\pi} + \mathcal{L}_{\pi N} + \mathcal{L}_{NN} + \cdots$$

Feynman diagrams



Epelbaum et al, arXiv:0811.1338



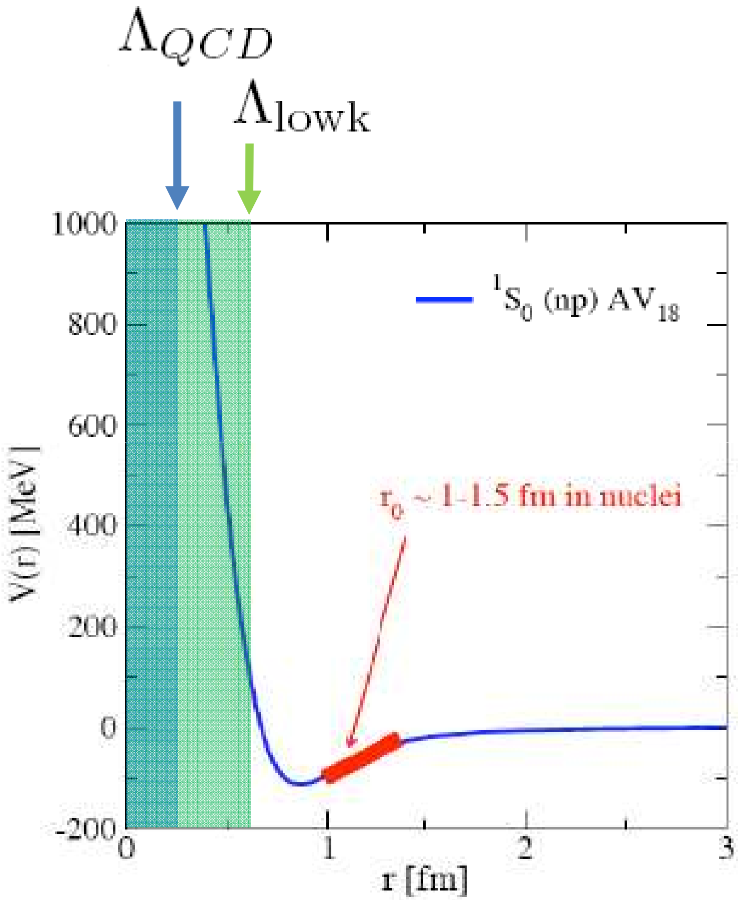
- **Direct link to QCD (chiral)**
- **Systematic Constructive method**
- **Consistent NN, 3N, 4N …**

(see lecture E. Epelbaum)

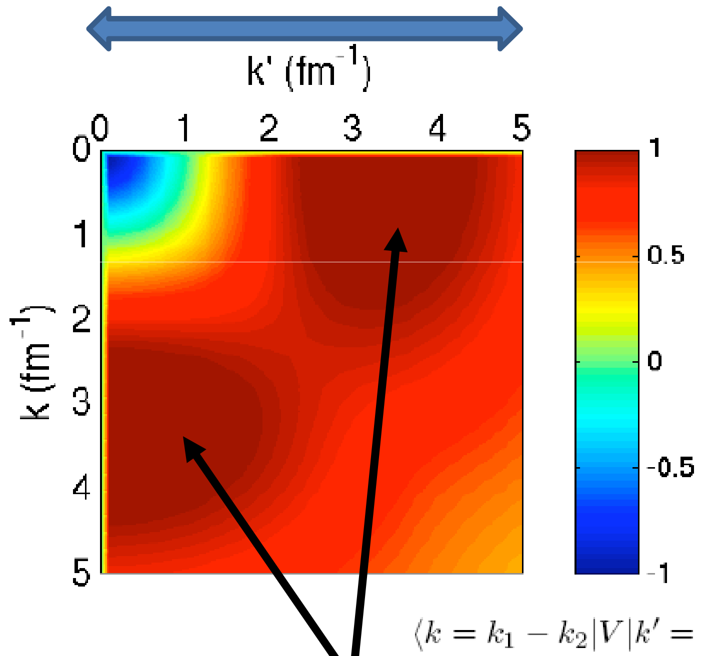
Modern theory of Nuclear Forces

Soft interaction

- ~~Systematic Improvement~~
- **Hard to work with bare NN interaction (Hard core)**



Potential suited to understand physics of high and low energy nuclear physics



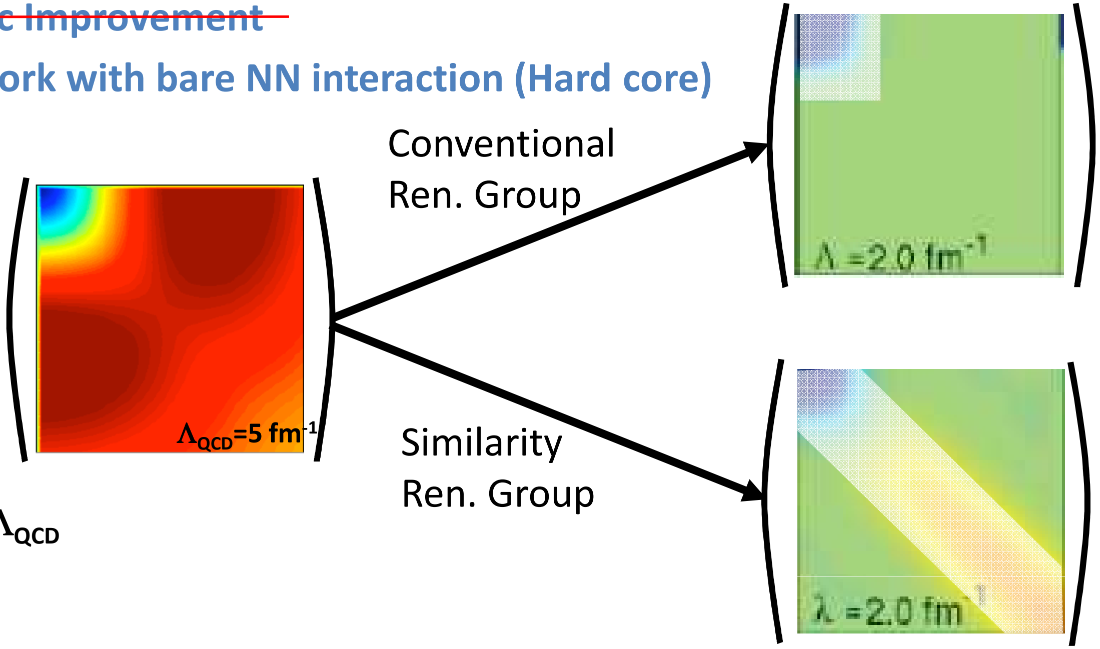
Difficult high momentum component

(adapted from Bogner -Trento2009)

Modern theory of Nuclear Forces

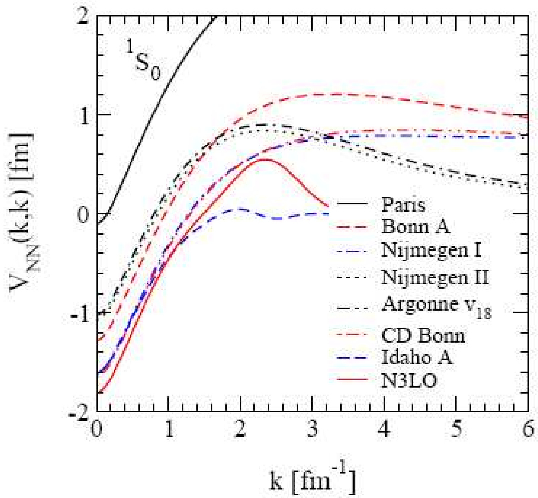
Soft interaction

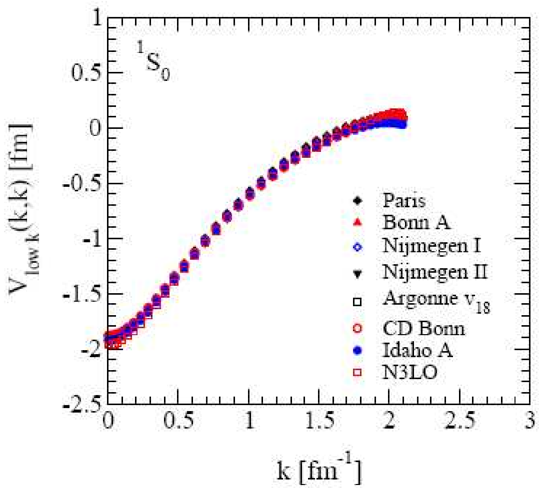
- ~~Systematic Improvement~~
- Hard to work with bare NN interaction (Hard core)



Phen. Potential at a given scale Λ_{QCD}

Example : V_{lowk}





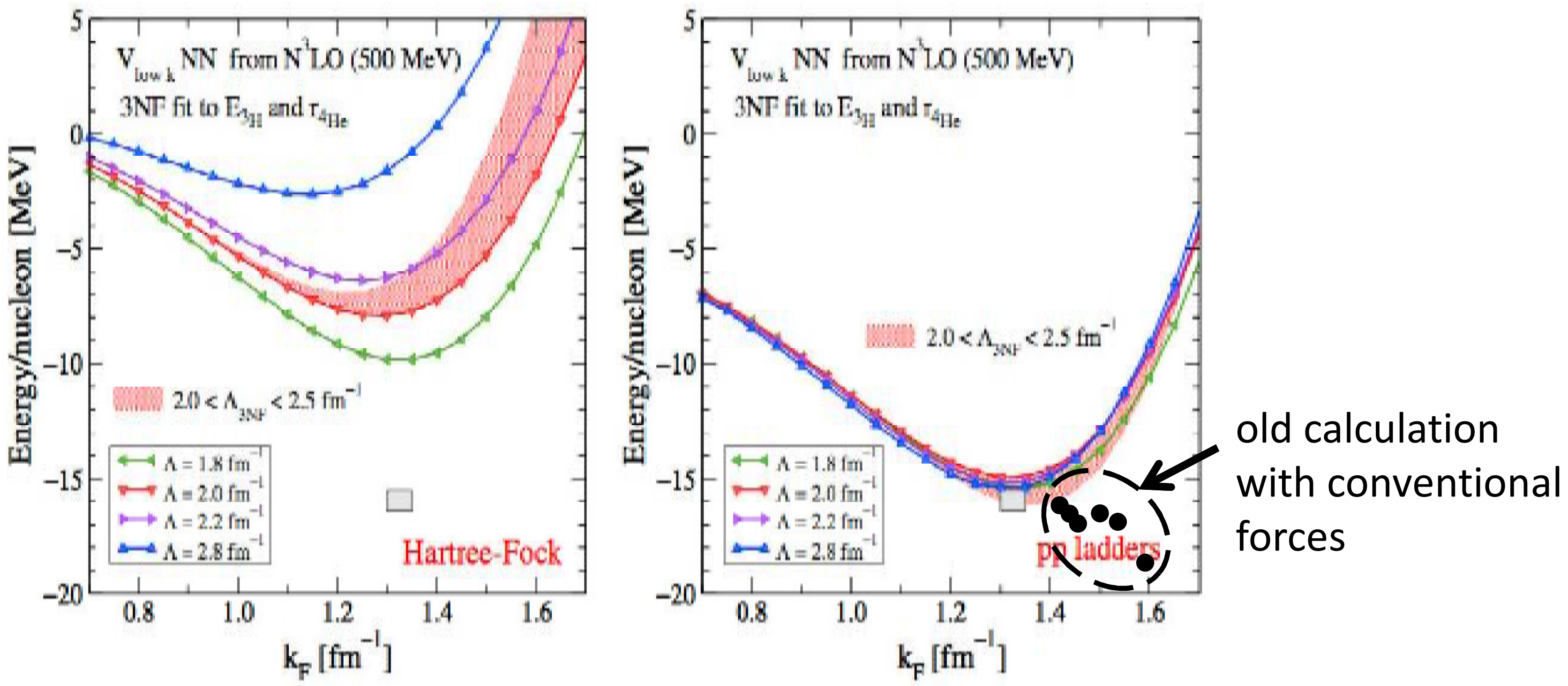
Bogner et al, Phys. Rep. (2005)

- **Soft interaction are adjusted to not change low energy properties**
- **All interaction leads to Same soft int.** 🙂
- **Easier to work with soft int.** 🙂
- **Renormalization generates 3-body, 4-body…**

(adapted from Bogner -Trento2009)

Nuclear matter properties

Bogner, Schwenk, Furnstahl, Nogga, NPA 763 (2005) .

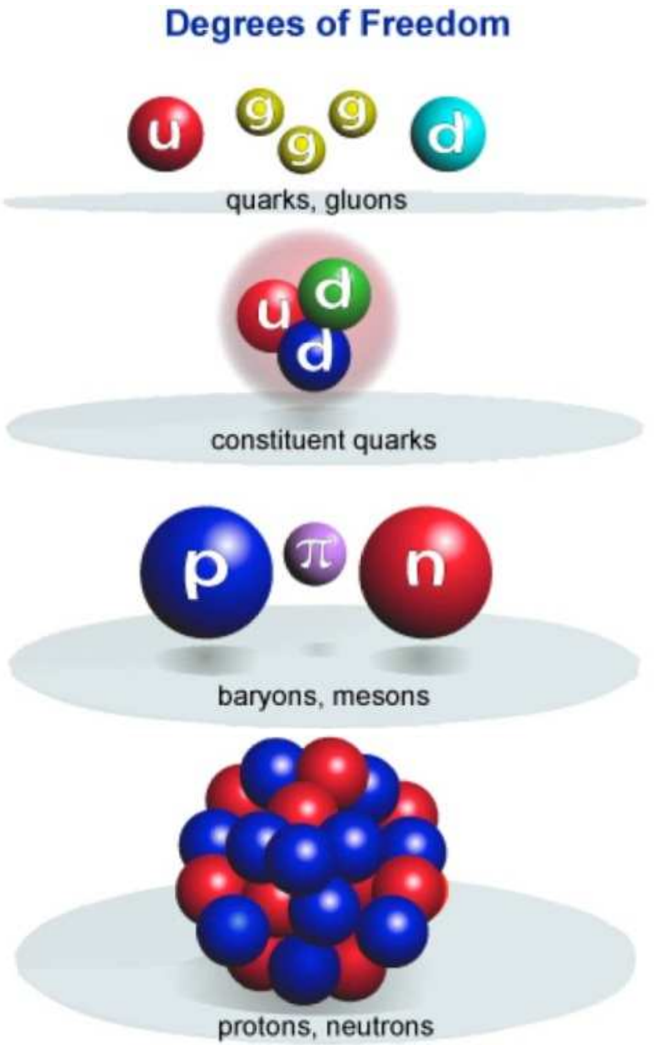


➡ **Already at the Hartree-Fock level saturation is obtained.**

➡ **Perturbative does now converge**

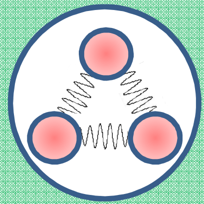
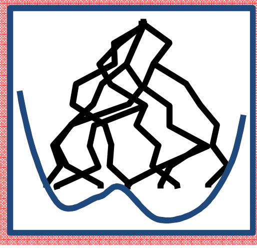
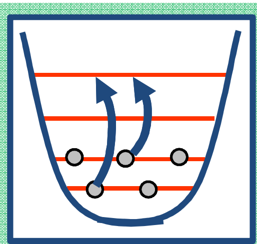
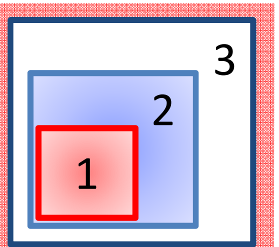
➡ **Note that three-body is essential.**

III - From NN-interaction to nuclei, hypernuclei



Ab-initio calculations of nuclei

A non-exhaustive guiding tour

Name	Short description	Variational	Scale as	Up to
Few-body (Faddeev…)	$H\Psi = E\Psi$ 	Yes	M^A	A = 2-4
Green-Function Monte-Carlo (GFMC)	$\Psi(\tau) = e^{-(H-E_0)\tau}\Psi_T, = [e^{-(H-E_0)\Delta\tau}]^n\Psi_T$ + auxiliary field 	Yes	$\frac{M!}{(M-A)!A!}$	A <12
No-core Shell Model	$H\Psi = E\Psi$ 	Yes	4^A	A <16
Coupled-Cluster (CC)	$\lvert\Psi\rangle = e^S\lvert\Psi_0\rangle$ $S = S_1 + S_2 + \cdots$ 	No	$(M-A)^4 A^2$	A <100 Only doubly-magic for now

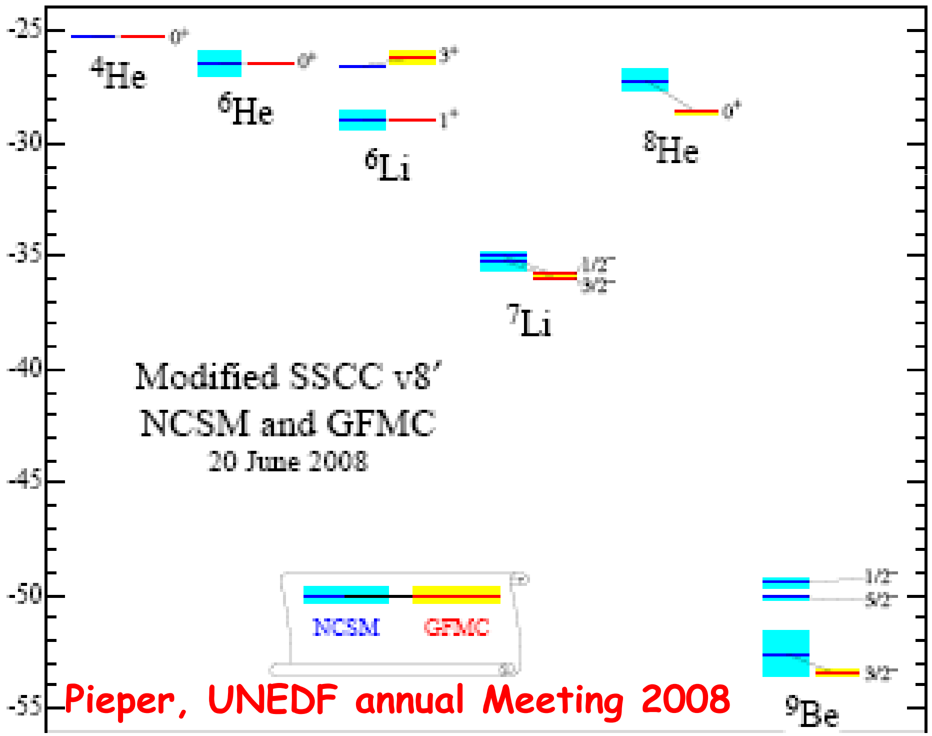
M : configuration space size

Benchmark (A = 4)

Kamada et al, PRC64 (2001)

	Faddeev	GFMC	NCSM
E (MeV) A=4	-25.94 (5)	-25.93 (2)	-25.8 (20)

Benchmark (A > 4)

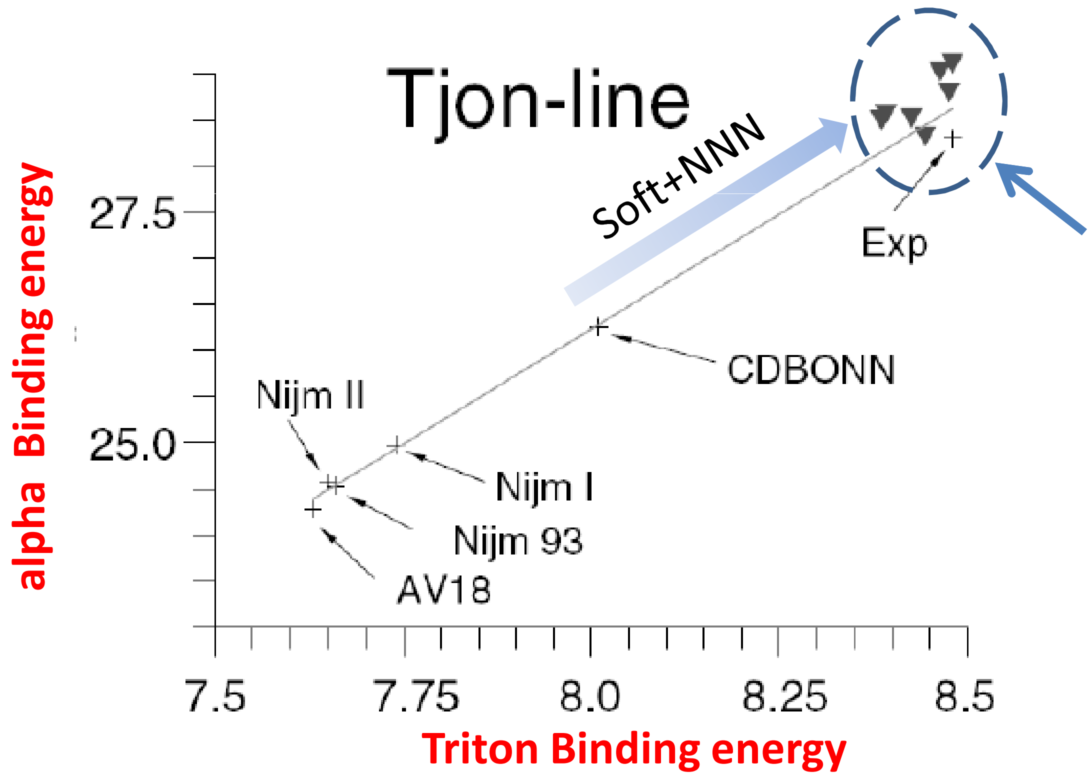


GFMC: Pieper et al, PRC (2004).
NCSM: Navratil et al, arXiv:0904.0463

Powerfulness :Light nuclei and three body force

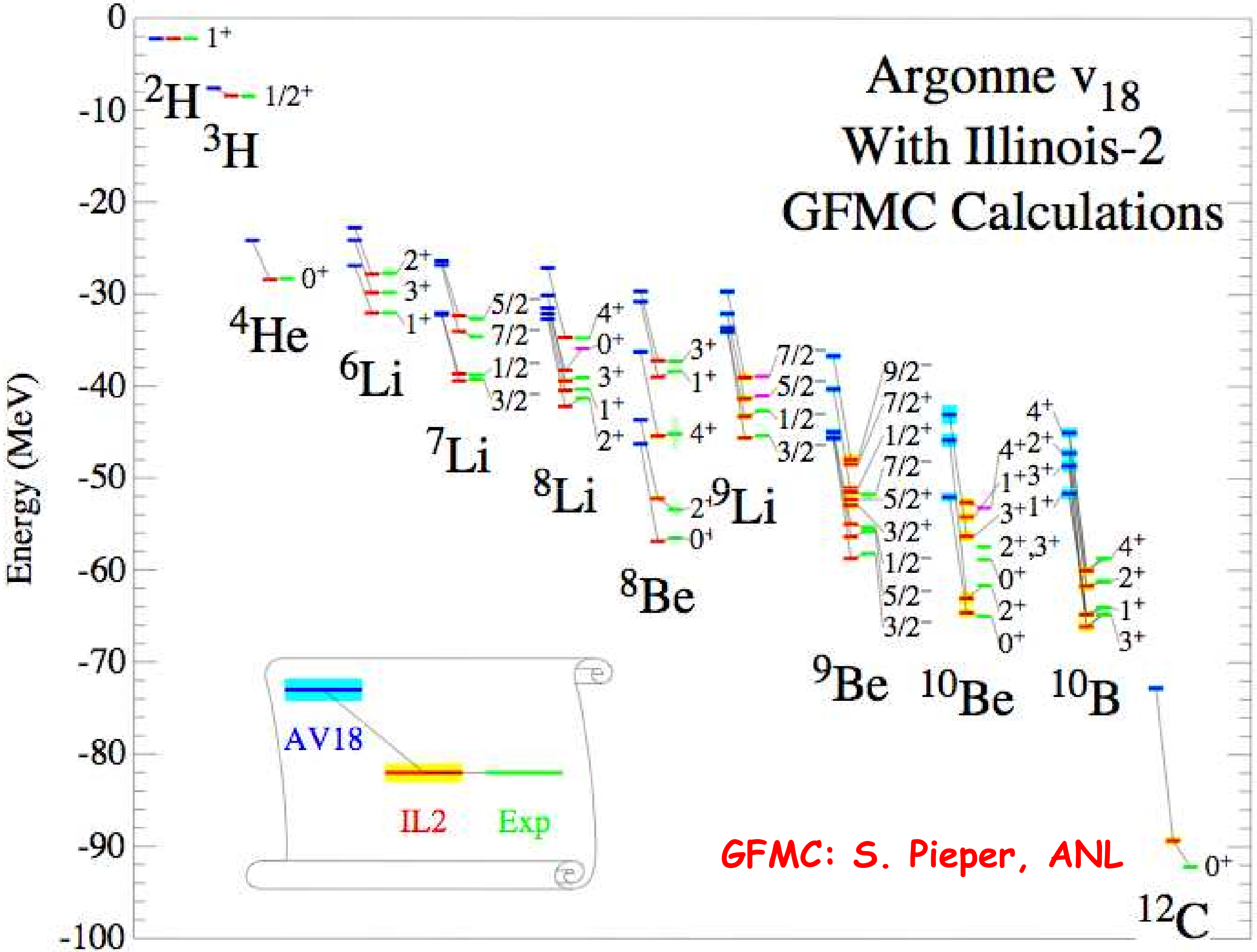
Why we need a three-body force ?

- **For saturation of nuclear matter**
- **For B. E. of nuclei**
- **Spin-orbit splitting**



With V_{lowk} And three-body force

Nogga et al, PRL 85 (2000).



The complete Bottom-up approach

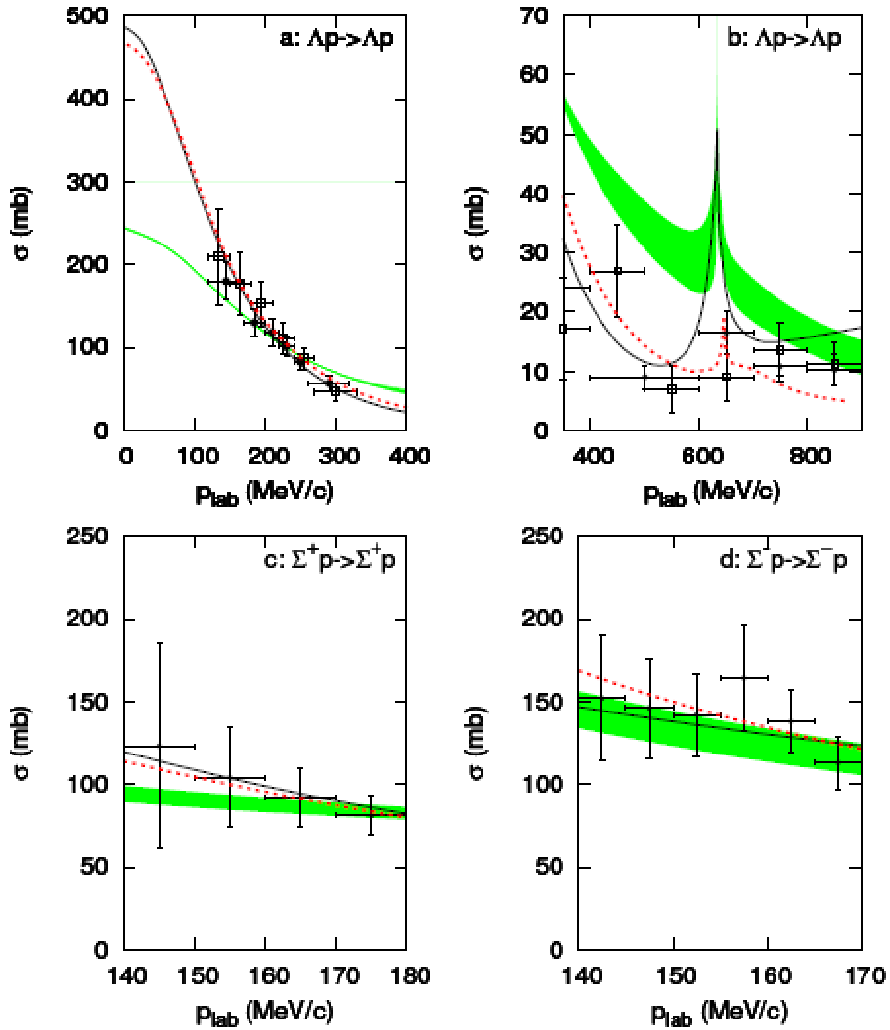
QCD (chiral)

NN+NNN (EFT)

nuclei

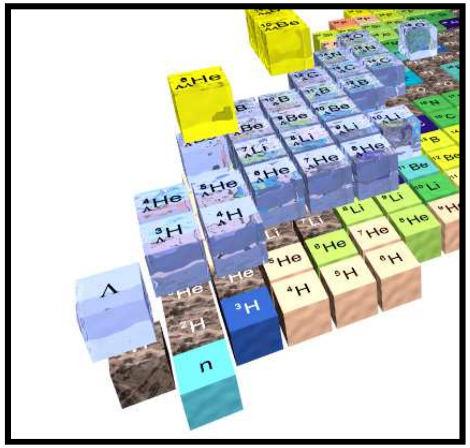
(see lecture W. Catford)

YN Interaction

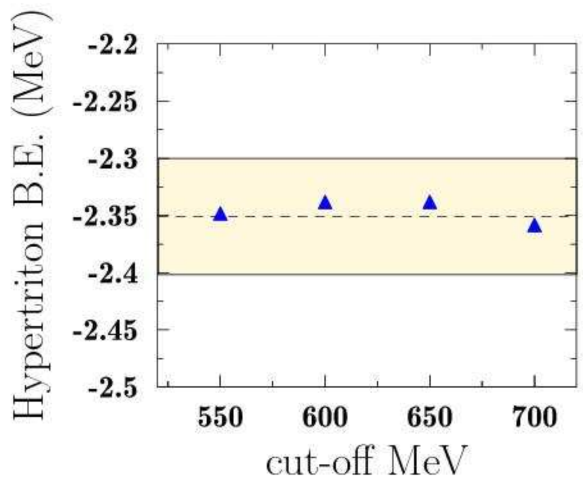


Polinder et al, NPA (2006)

■ LO EFT
— Jülich 04
— Nijm 97f



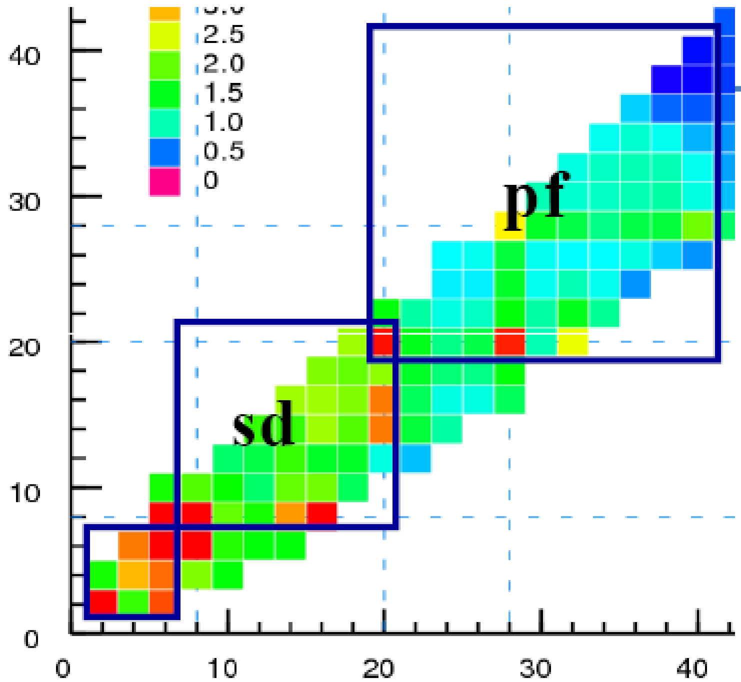
35 data only
(for comparison
nn, np… between 2000/3000 data)



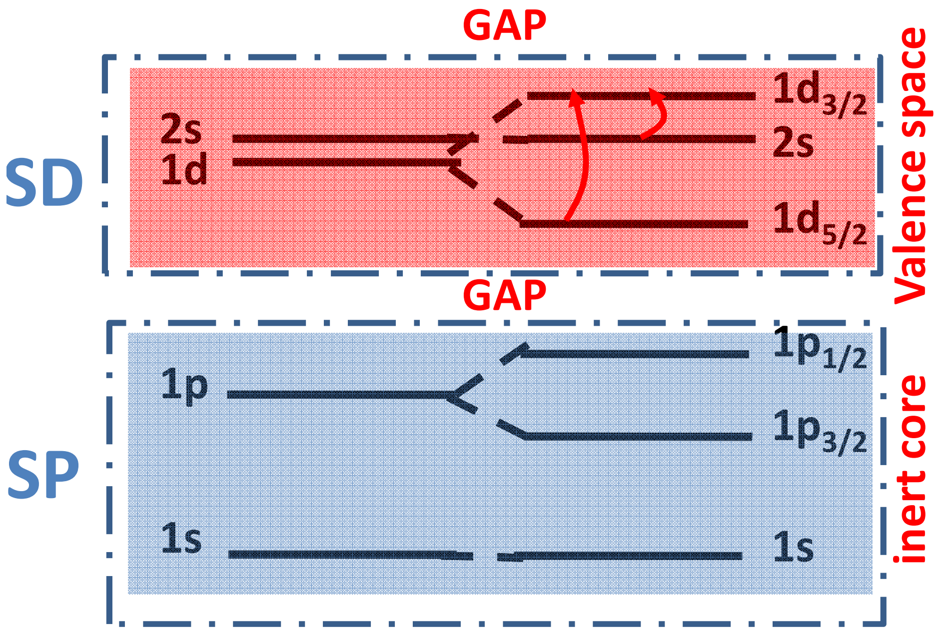
(see lecture I. Vidana)

Nuclear structure for heavier nuclei

Conventional Shell model



FP



(see lecture N. Smirnova)

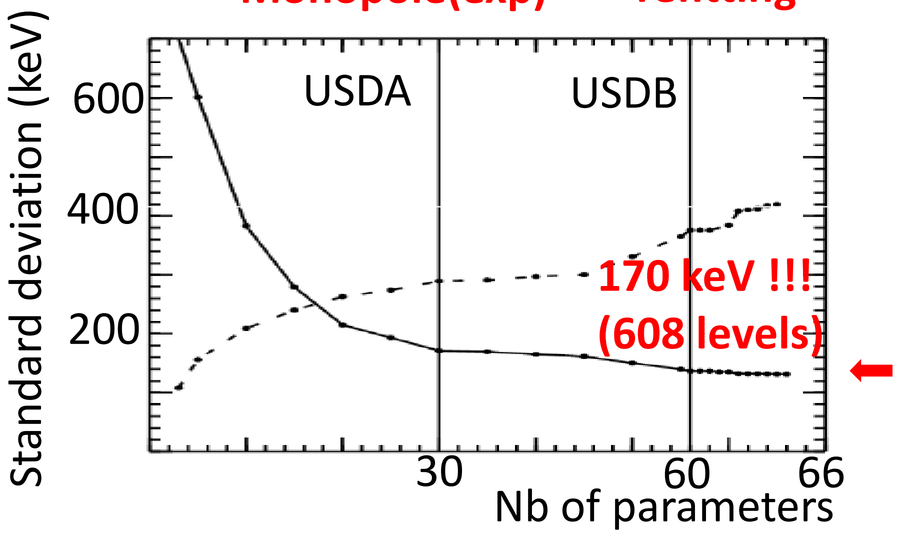
Highlights on "standard" shell-model

$$\Psi = \Phi_{[0p0h]} + \Phi_{[1p1h]} + \Phi_{[2p2h]} + \cdots$$

Configuration interaction

H = SPME (Exp) + TBME (G)

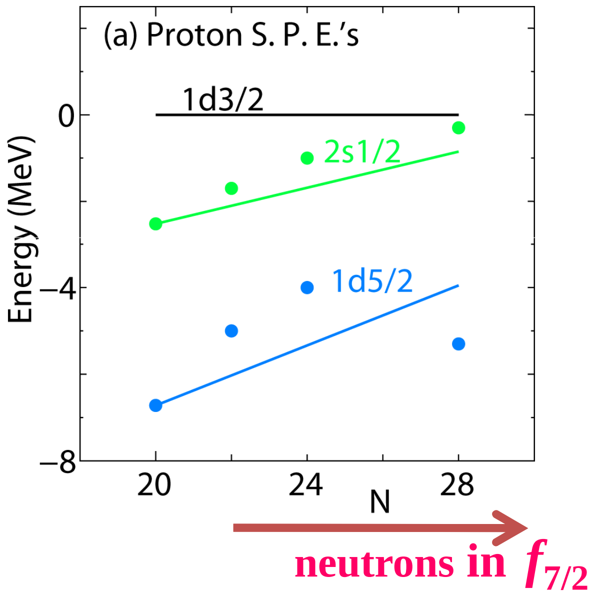
ex : sp shell	ε_i	G_{ijkl}
number	**3**	**63**
	Monopole(exp)	**refitting**



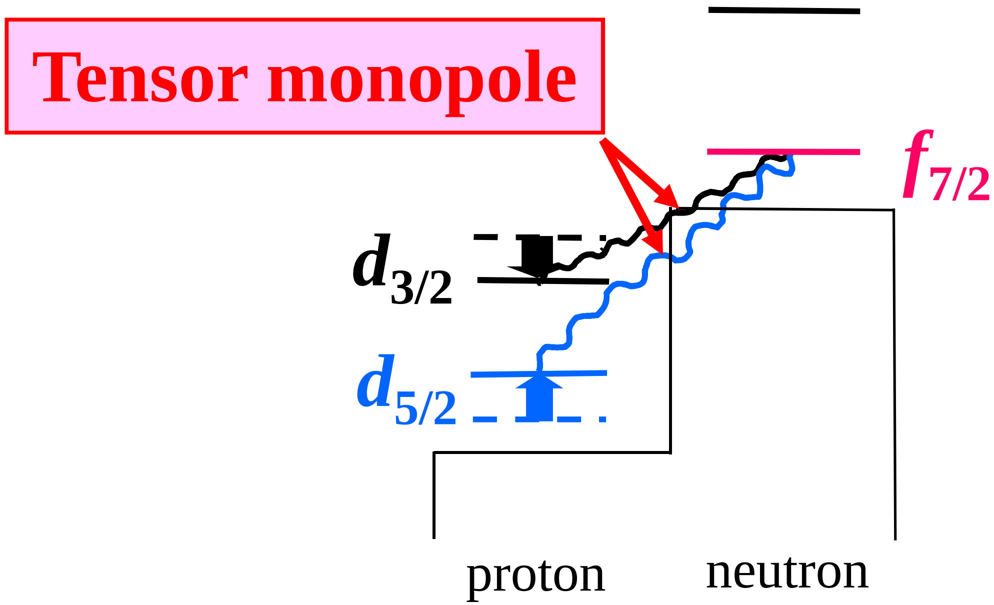
A. Brown ECT* (2007).

- **Shell Model is the tool of choice to understand level scheme**
- **Physics of *Shell evolution, magicity, pairing, deformation, spin-orbit, tensor, …***

(see lecture O. Sorlin)



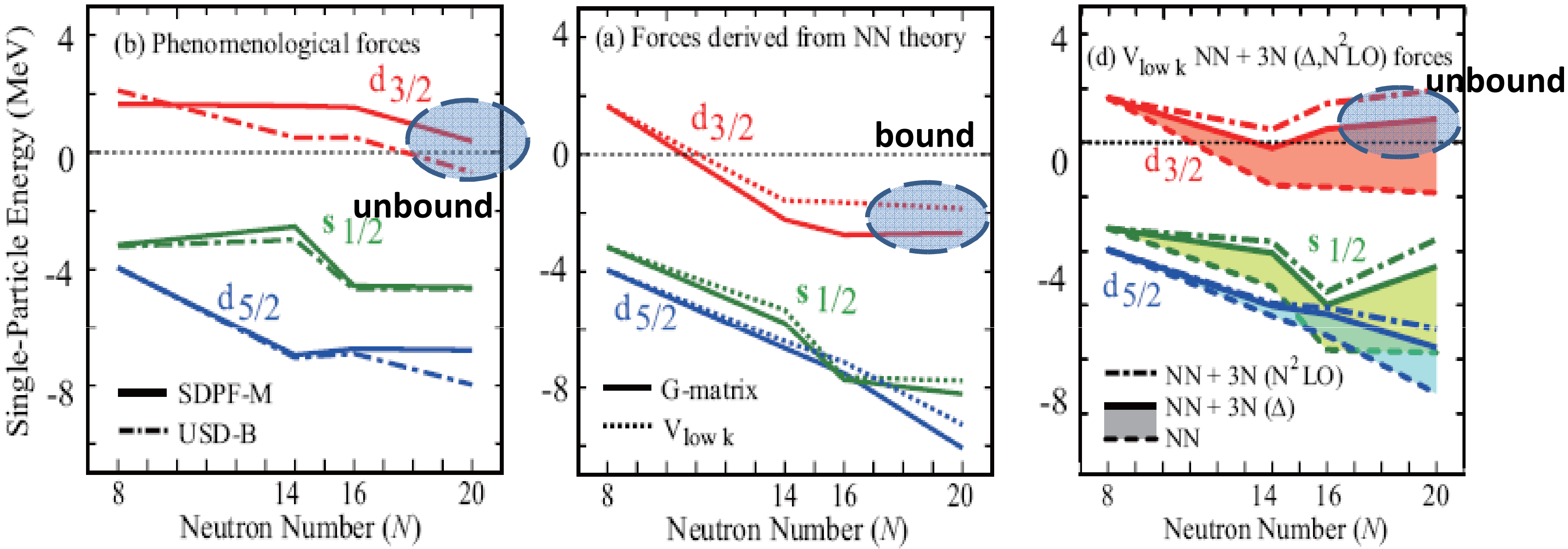
Otsuka *et al.*, PRL 95 (2005)



- **Still very phenomenological (empirical monopoles, refitting procedure)**

Towards the next generation of Shell Model

NN forces From EFT → G-matrix → Shell-Model

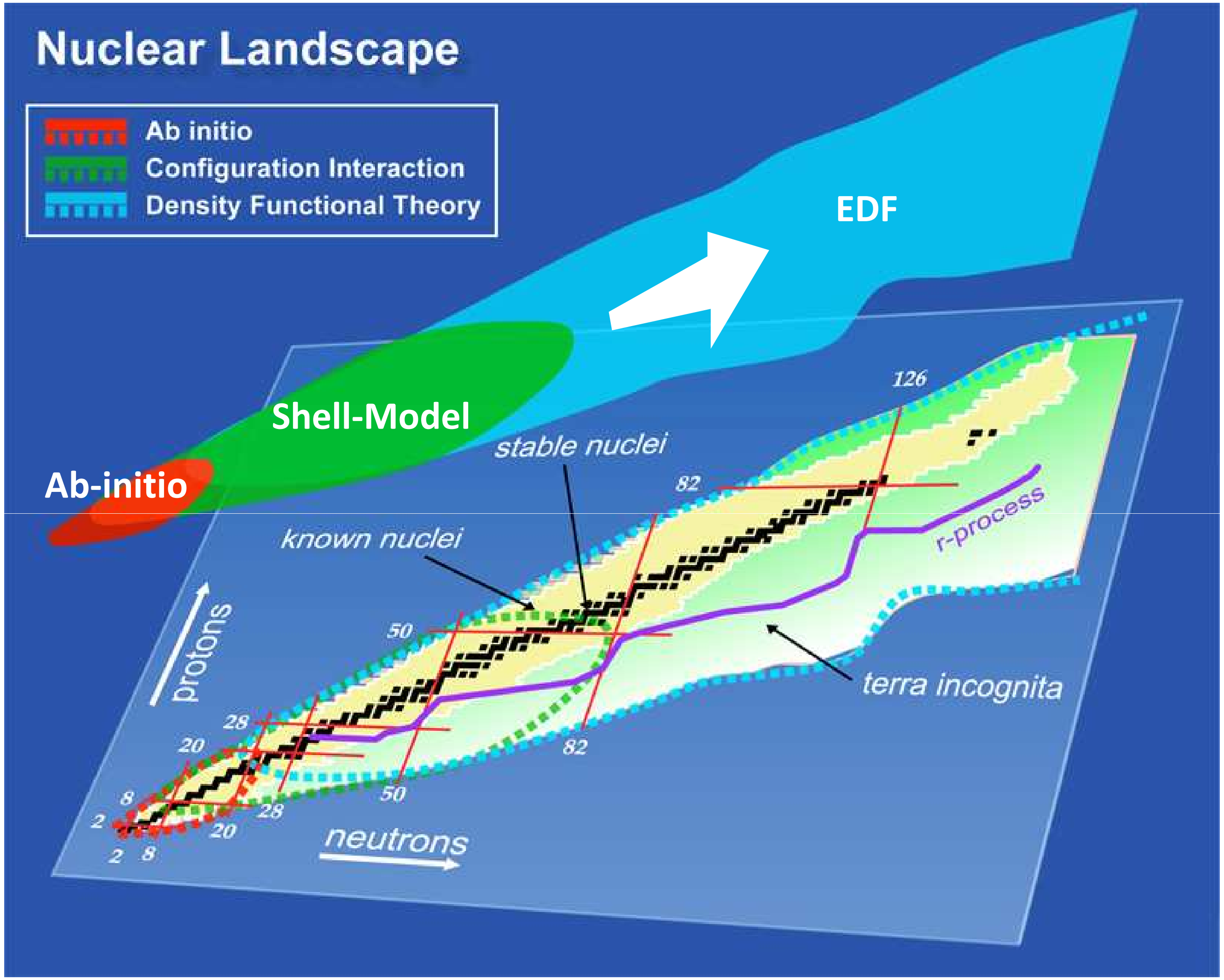


Otsuka et al, arXiv:0908.2607

- **Conventional interaction contain much more than dressed "two-body"**
- **Predicting power and interpretation ?**
- **Shell model : restricted to -nuclear structure**
  -low energy excitation
  -A<130 (now fp shell)

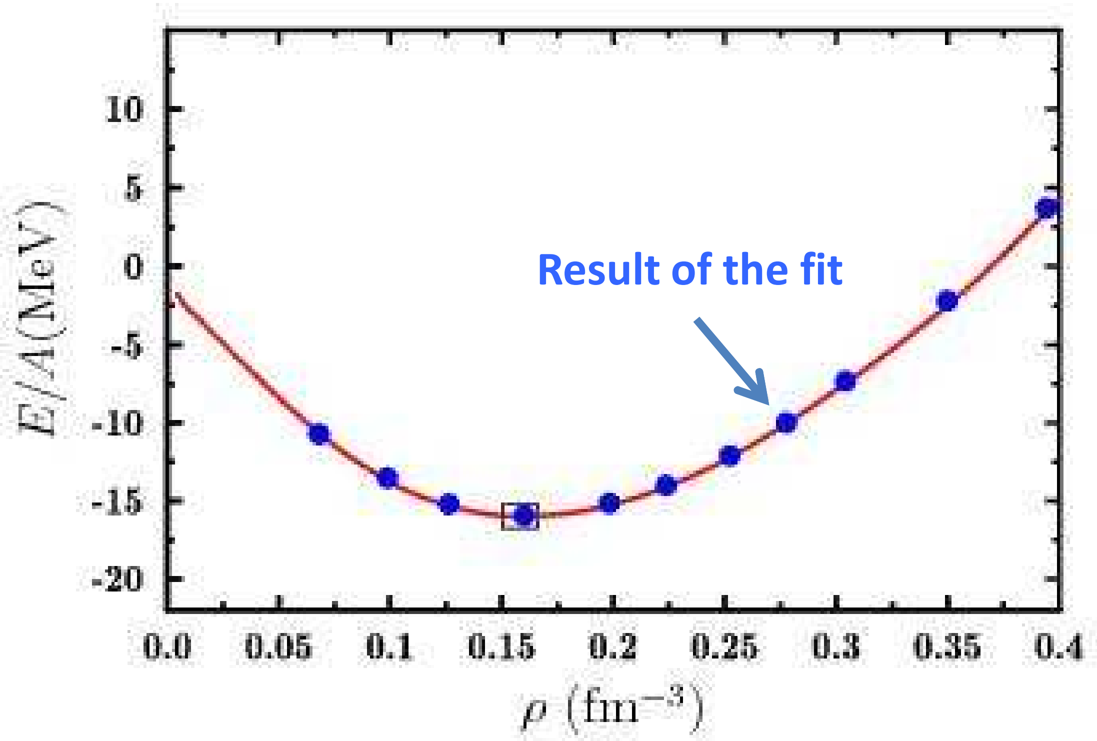
A unified theory for nuclear structure, reactions and stars

The Energy Density Functional (EDF) Concept



http://unedf.org/

EDF from a simple perspective



Exercise : fit the curve with

$$E = \left\langle \frac{p^2}{2m} \right\rangle + U[\rho]$$

In nuclear matter:

$$\left\langle \frac{p^2}{2m} \right\rangle = \frac{3}{5} \left(\frac{3\pi^2}{2} \right)^{2/3} \rho^{5/3}$$

Fit with

$$U[\rho] = \sum_n c_n \rho^n$$

An excellent fit is obtained

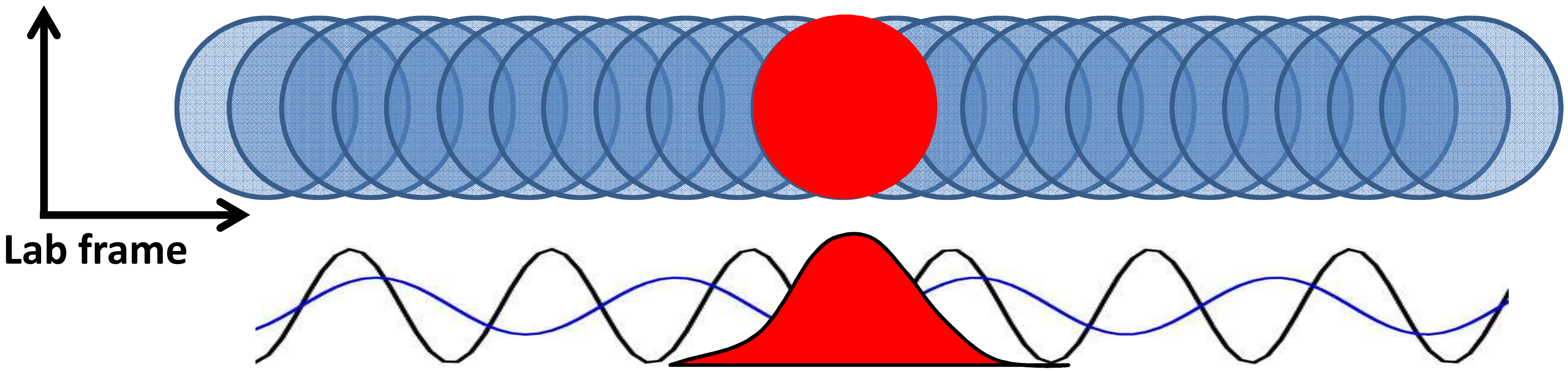
Example of functional

- **Skyrme –Vautherin and Brink, PRC (1972)**
- **Gogny –Dechargé and Gogny, Phys. Rev. C (1980) .**

EDF:

- Pre-suppose the existence of a universal functional of the density matrix (looks like Density Functional Theory)
- Use and abuse of Broken symmetries (should be restored)

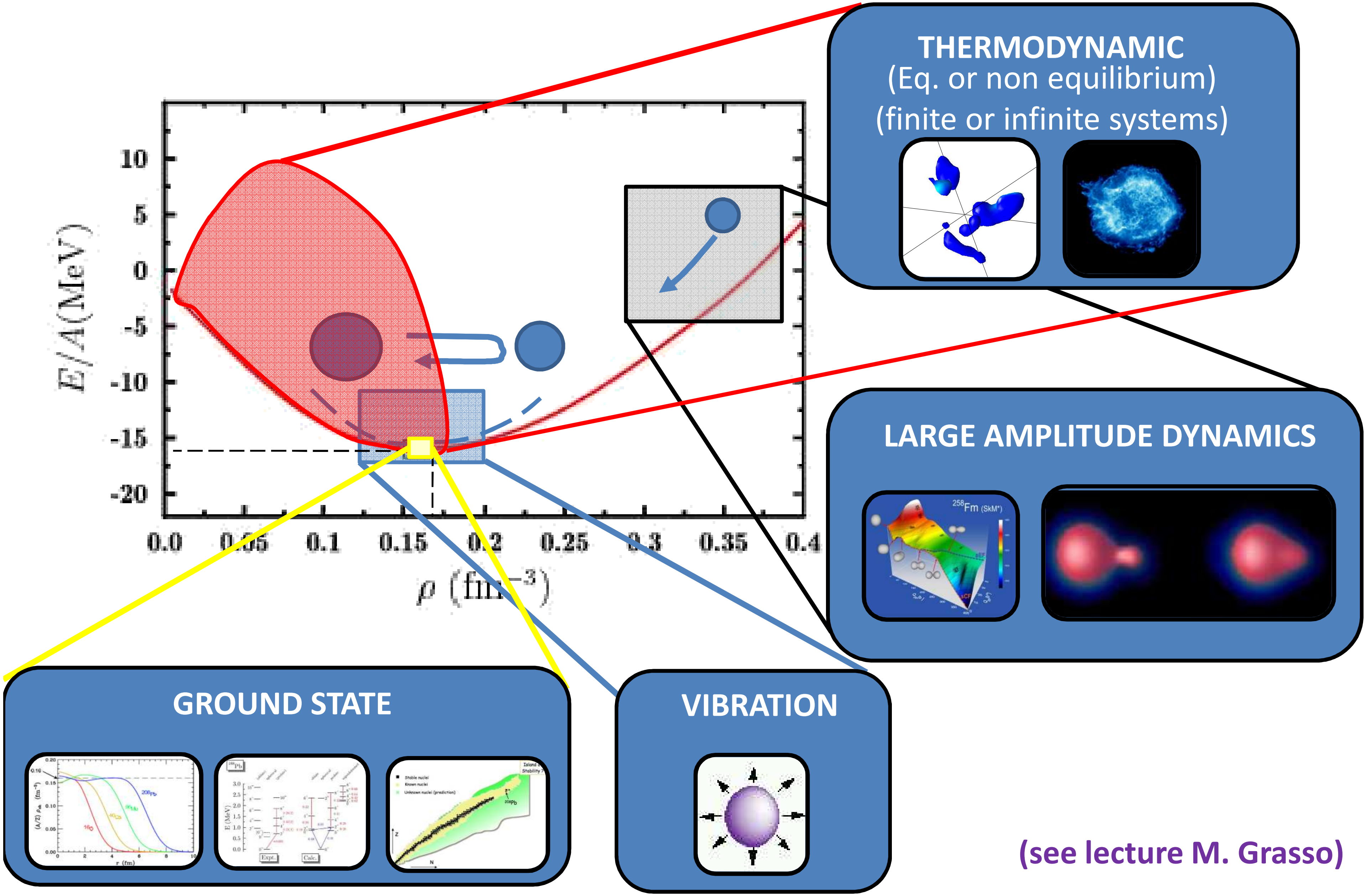
  Translation, Rotation, Particle number.



- Goes much beyond the Hartree-Fock theory
- Should a priori be considered and named “Ab-initio” theory” (not yet)
- Around 10-20 parameters-Deviation of 500 keV for ground state energy

A unified theory for nuclear structure, reactions and stars

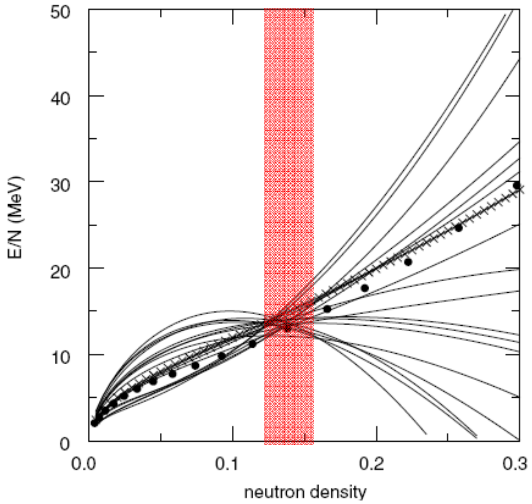
Range of application



A unified theory for nuclear structure, reactions and stars

Uncertainties and Predicting power in conventional EDF

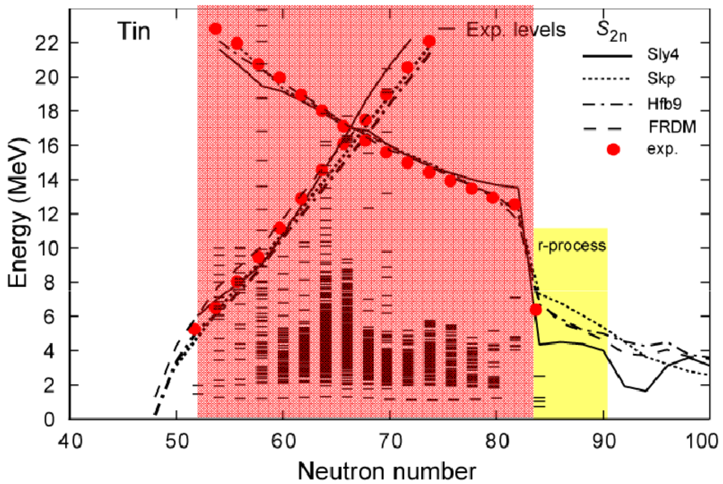
EOS of pure neutron matter



Brown, PRL85 (2000).

Conventional EDF are adjusted on a selected set of experimental data in finite and infinite systems

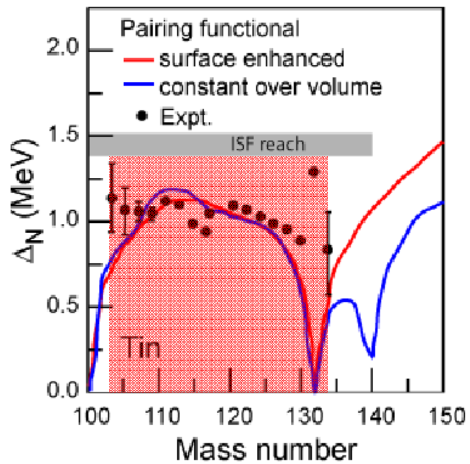
S_{2n} and S_{2p} in Tin isotopic chain



http://www.nscl.msu.edu/future/isf

Experimentally known

Pairing gap



Large uncertainty in unknown region

Strategy

Exp./Th. → **Add more data (RIB, reactions, stars)**

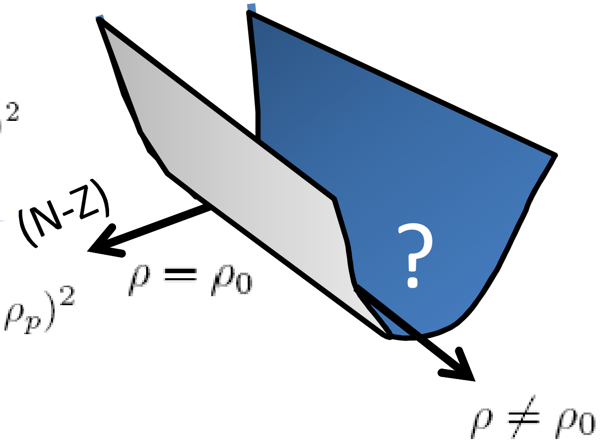
Th./Exp. → **Use the "bottom-up" approach**

Strategy 1: exploring unknown region

Illustration with the Symmetry energy

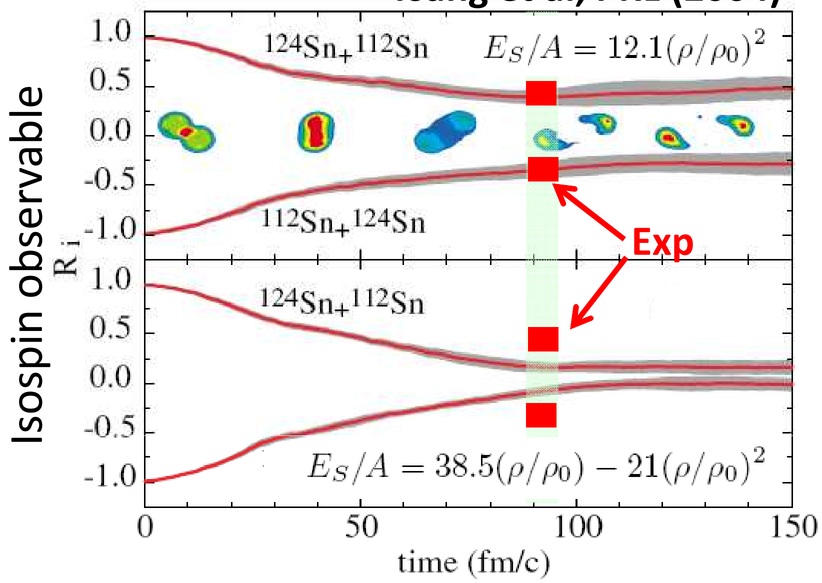
$E_{LD} \propto a_S (N-Z)^2$

$E_{EDF} \propto a_S[\rho](\rho_n - \rho_p)^2$



Constraint from Heavy-Ion reactions

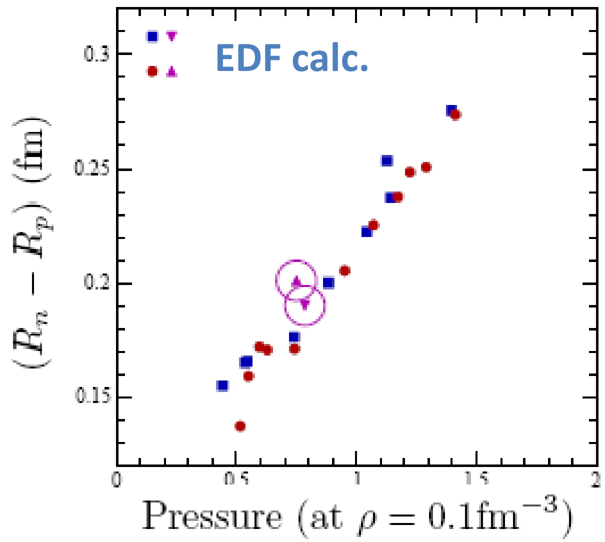
Tsang et al, PRL (2004)



(see lecture M.F. Rivet)

Constraint from Astrophysics

Steiner et al, Phys. Rep. (2005)



$$\text{Radius} \times \text{Pressure}^{-1/4} \simeq \text{cte}$$

Lattimer et al, Phys. Rep. (2000)

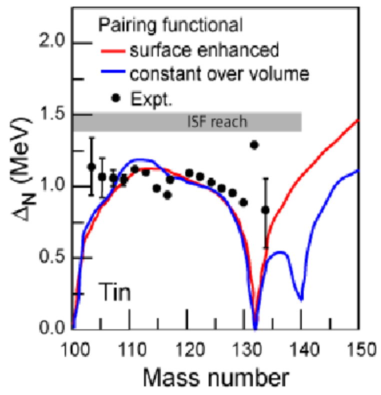
- **Measurement of neutron star radii constraint the asymmetry energy**
- **Cooling of proto-neutron star**
- **Exotic phases** **(see lecture P. Pizzochero)**

Strategy 2: From QCD to EDF

The long term plan

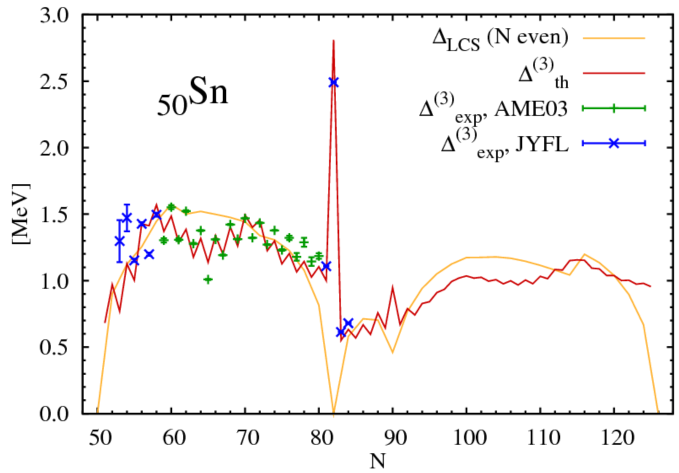
QCD
↓
EFT
↓
Interaction
↓
Ab-initio EDF

Illustration with the pairing gap



NSCL white paper

V_{lowk} + Coulomb



Duguet and Lesinski, arXiv:0907.1043

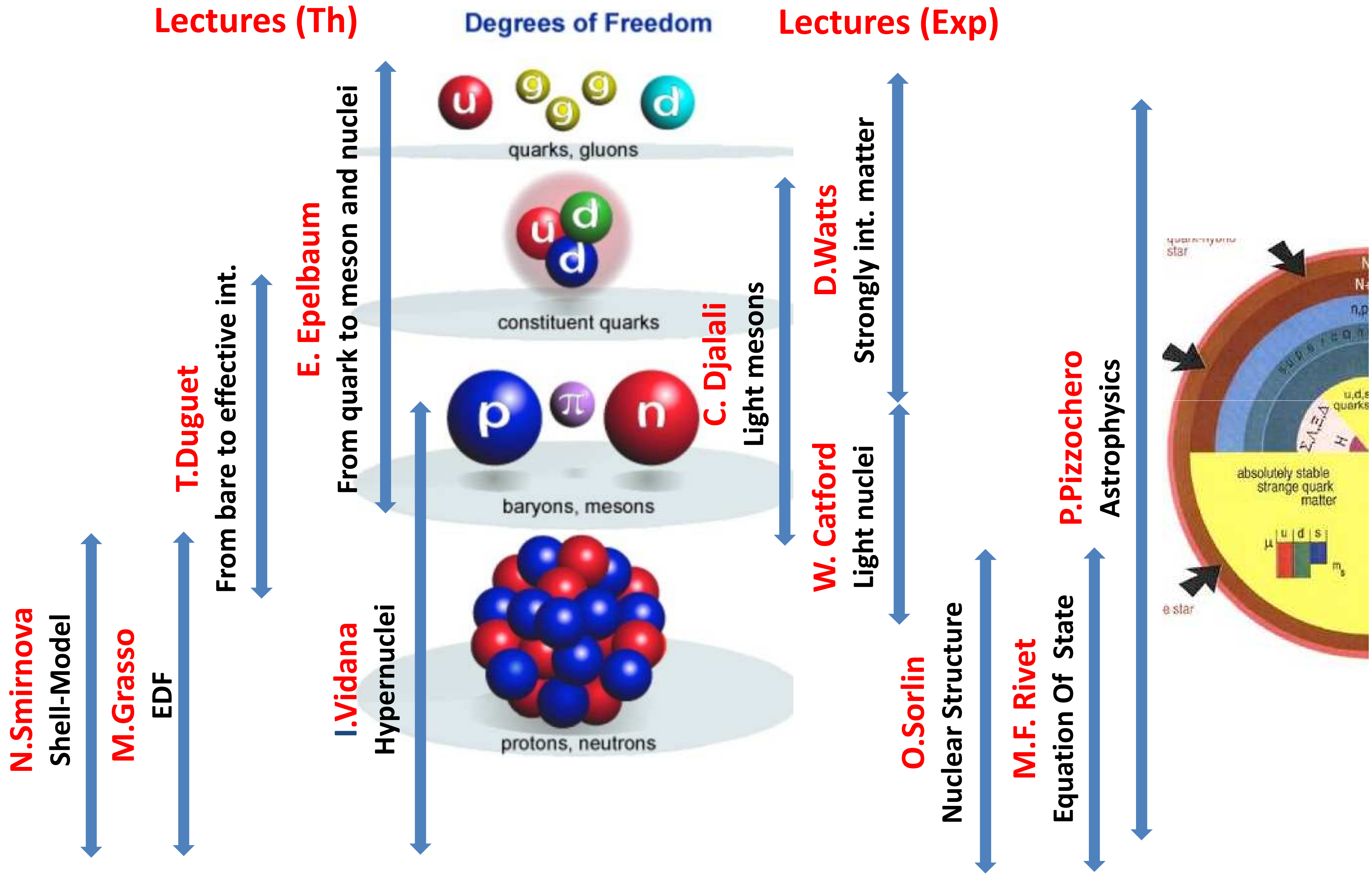
Different strategies

- **Direct use of new NN interaction In specific channels**
- **Compute exactly well identified limits and use them in the EDF adjustment**
- **Combine Many-body Theory with EDF concept**

(see lecture T. Duguet)

Summary

EJC2009 Lectures



Many thanks to the lecturers and organizing committee!