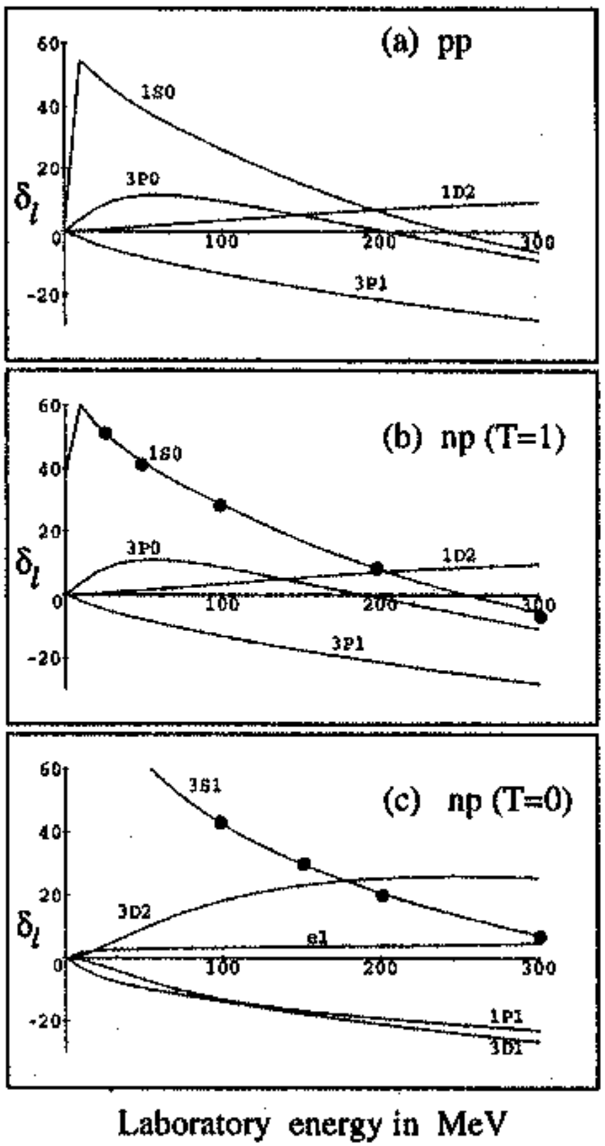
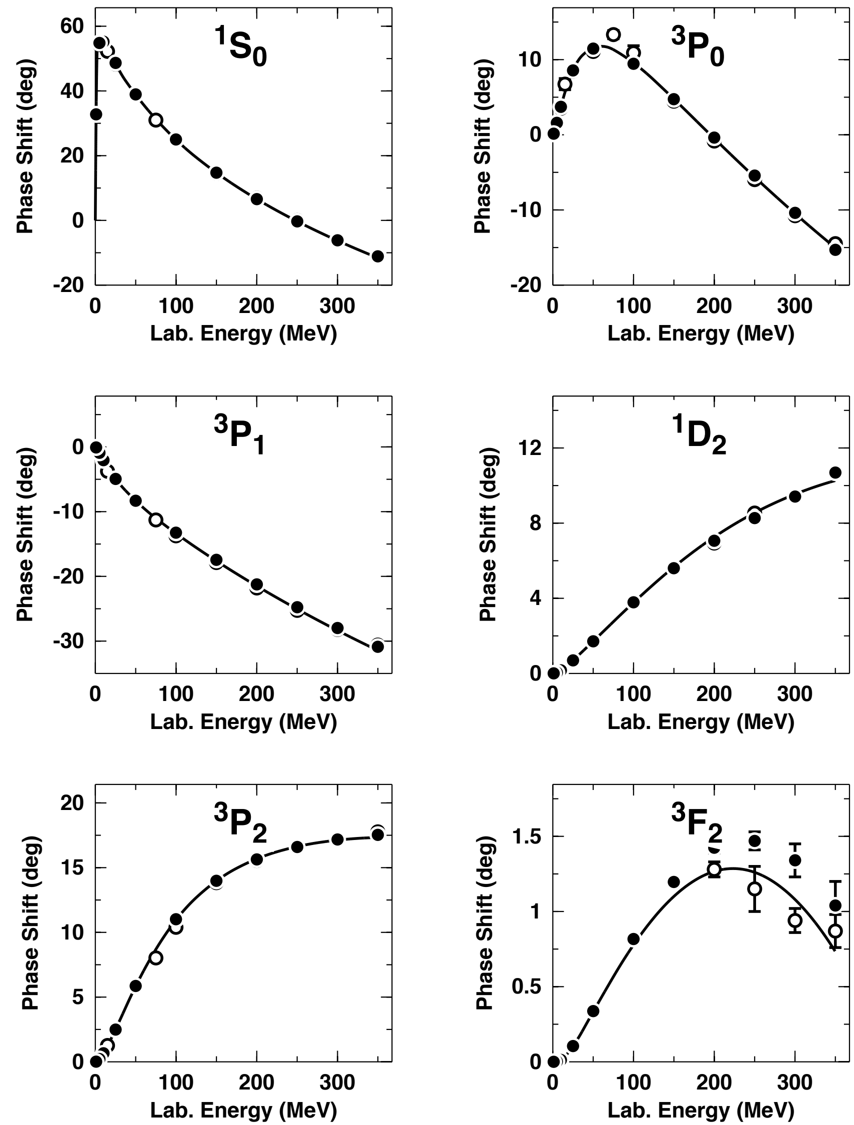
NN potentials from partial wave analysis



Paris potential



CD-Bonn potential

Scattering length and effective range

At very low energies, the ℓ=0 total cross section remains finite for NN scattering

$$\lim_{E\to 0} \sigma = 4\pi a^2$$

S-wave scattering length

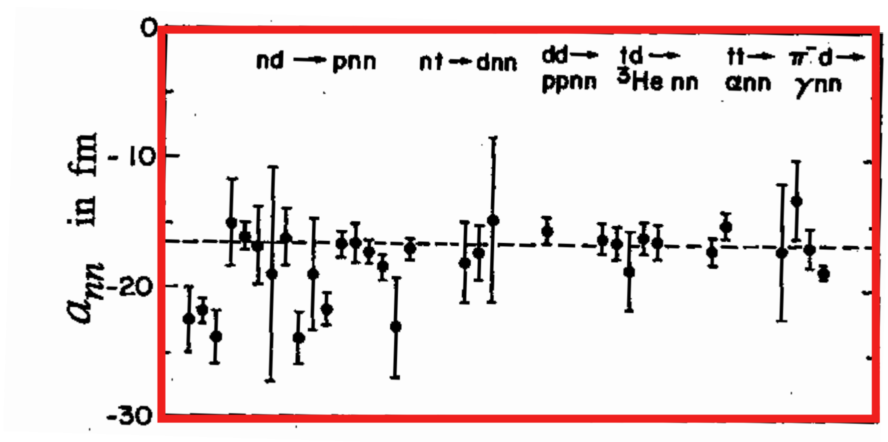
$$a = \lim_{k\to 0} \Re\left\{-\frac{1}{k} e^{i\delta_0} \sin\delta_0\right\}$$

is positive if there is a bound state

$$k \cot\delta_0 = -\frac{1}{a} + \frac{1}{2} r_e k^2$$

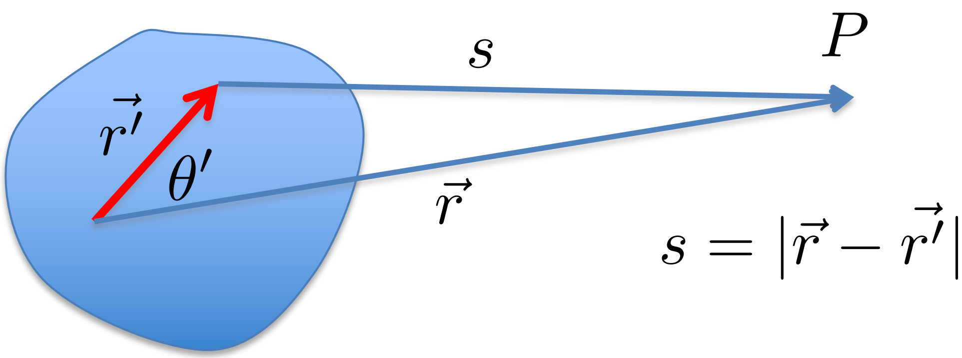
effective range

		$S=0,\ T=1$ (fm)	$S=1,\ T=0$ (fm)
pp	a	-17.1 ± 0.2	—
	r_e	2.794 ± 0.015	—
nn	a	-16.6 ± 0.6	—
	r_e	2.84 ± 0.03	—
np	a	-23.715 ± 0.015	5.423 ± 0.005
	r_e	2.73 ± 0.03	1.73 ± 0.02



Resolution and Effective Field Theory

multipole expansion
of electrostatic potential



$$V(\vec{r}) = \frac{1}{4\pi\varepsilon_0} \sum_{n=0}^{\infty} \frac{1}{r^{n+1}} \int (r')^n P_n(\cos\theta') \rho(\vec{r'}) d^3 r'$$

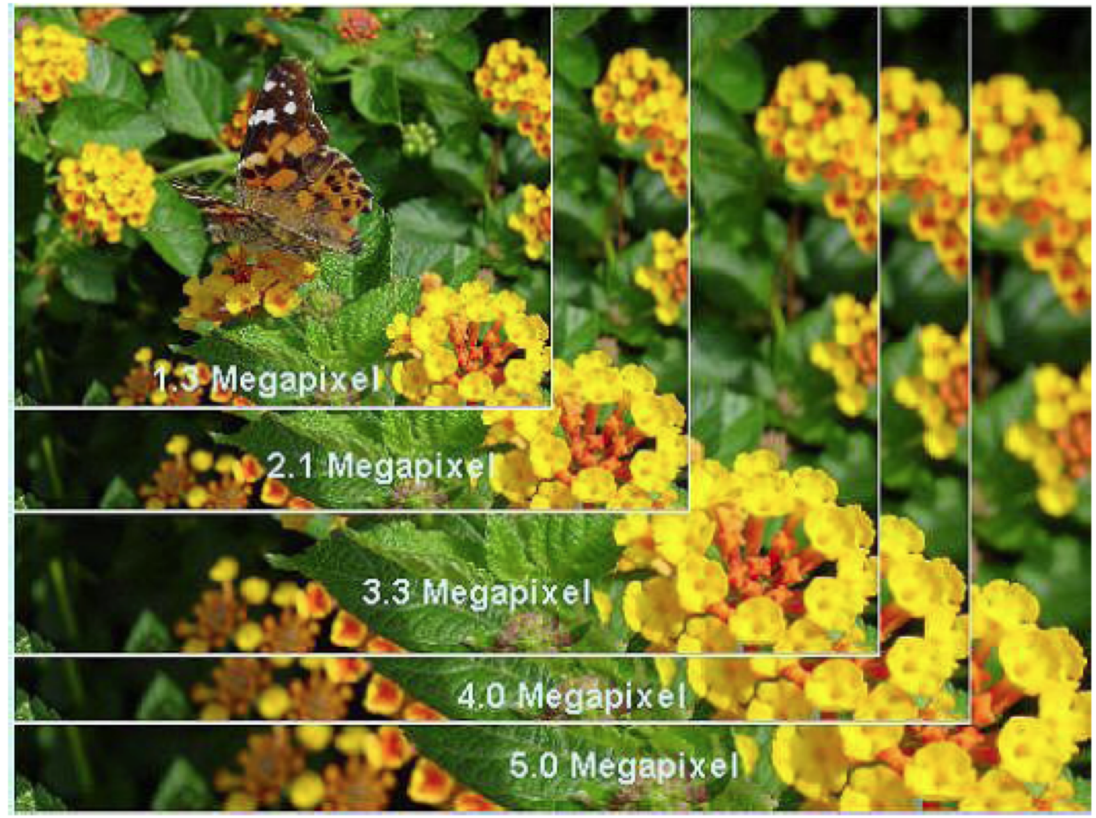
$$V(\vec{r}) = \frac{1}{4\pi\varepsilon_0} \left(\frac{Q}{r} + \frac{\vec{p}\cdot\vec{r}}{r^3} + \frac{1}{2} \sum_{i,j} Q_{ij} \frac{x_i x_j}{r^5} \cdots \right)$$

$$\vec{p} = \int \vec{r'} \rho(\vec{r'}) d^3 r' = \sum_{k=1}^{N} q_k \vec{r'_k}$$

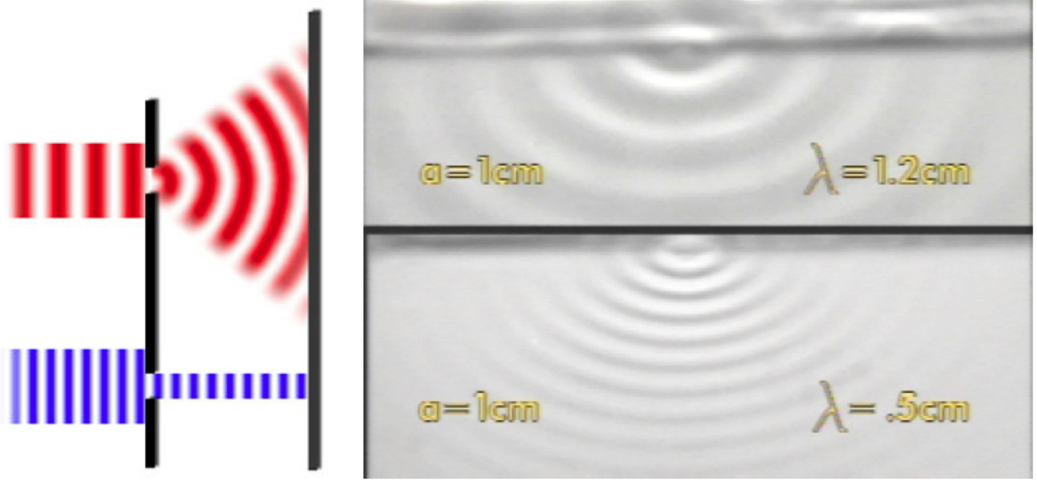
$$Q_{ij} = \int (3x'_i x'_j - r'^2 \delta_{ij}) \rho(\vec{r'}) d^3 r'$$

Digital Resolution: Higher Resolution is Better (?)

- Computer screens, printers, digital cameras, TV's . . .
- Higher resolution $\Longrightarrow$ more pixels
- Pixel size $\ll$ characteristic scale $\Longrightarrow$ greater detail
- Greater resolution $\Longrightarrow$ more $$$



Consequences

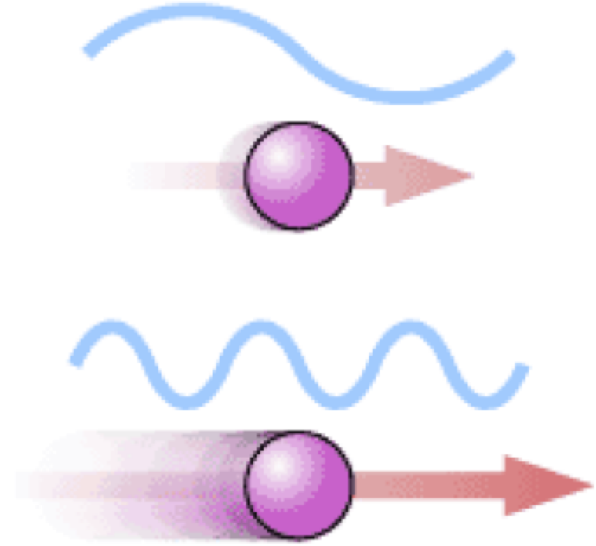


For a slit of width a,

$$\theta_{\min} = \sin^{-1}(\lambda/a)$$

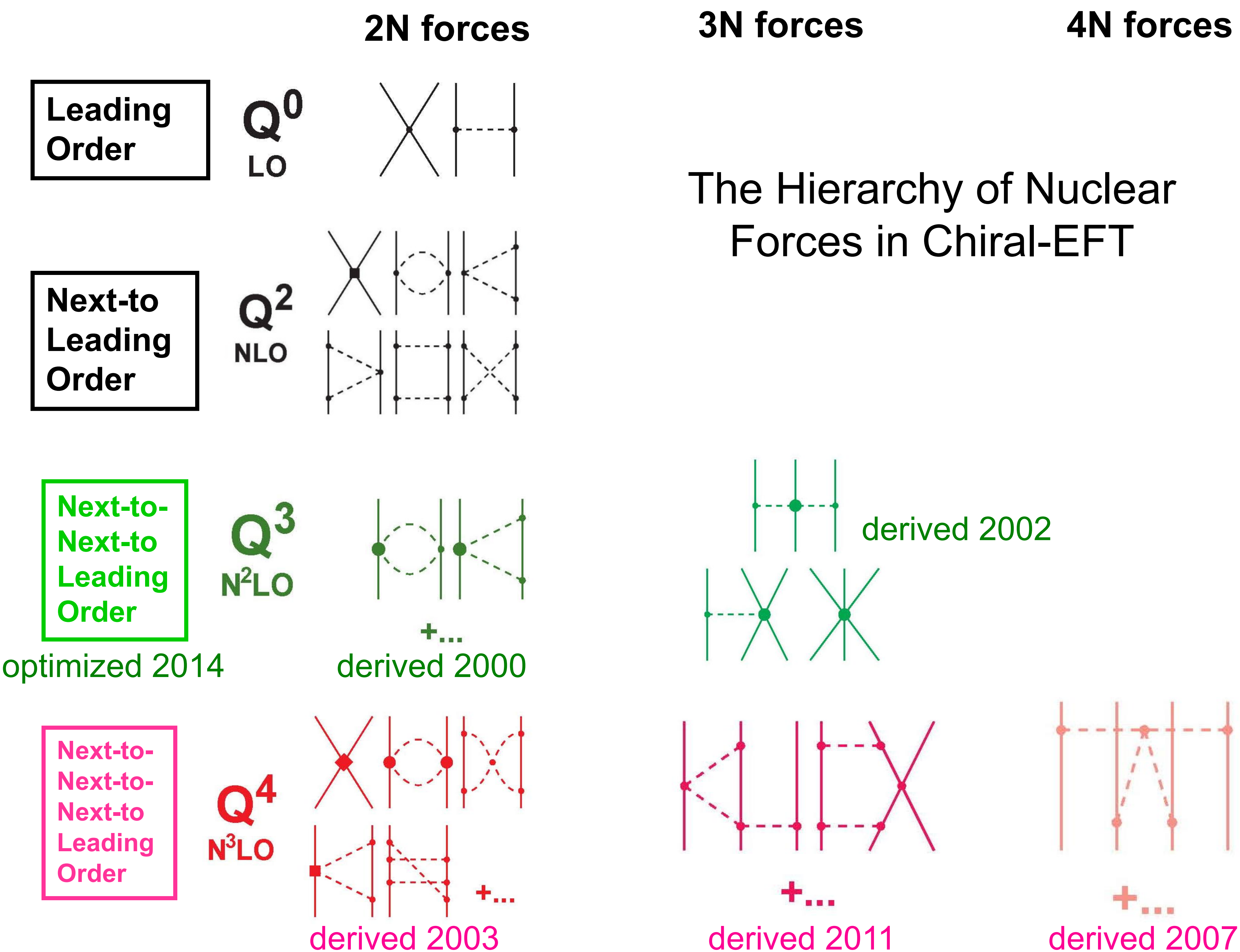
so if $\lambda \geq a$, you don't learn anything about the details of the slit

- de Broglie relation: $\lambda = h/p$



- $\lambda \approx 10^{-10}$ m $\Longrightarrow$ probe atoms
- $\lambda \approx 10^{-14}$ m $\Longrightarrow$ probe nucleus
- $\lambda \approx 10^{-18}$ m $\Longrightarrow$ probe quarks

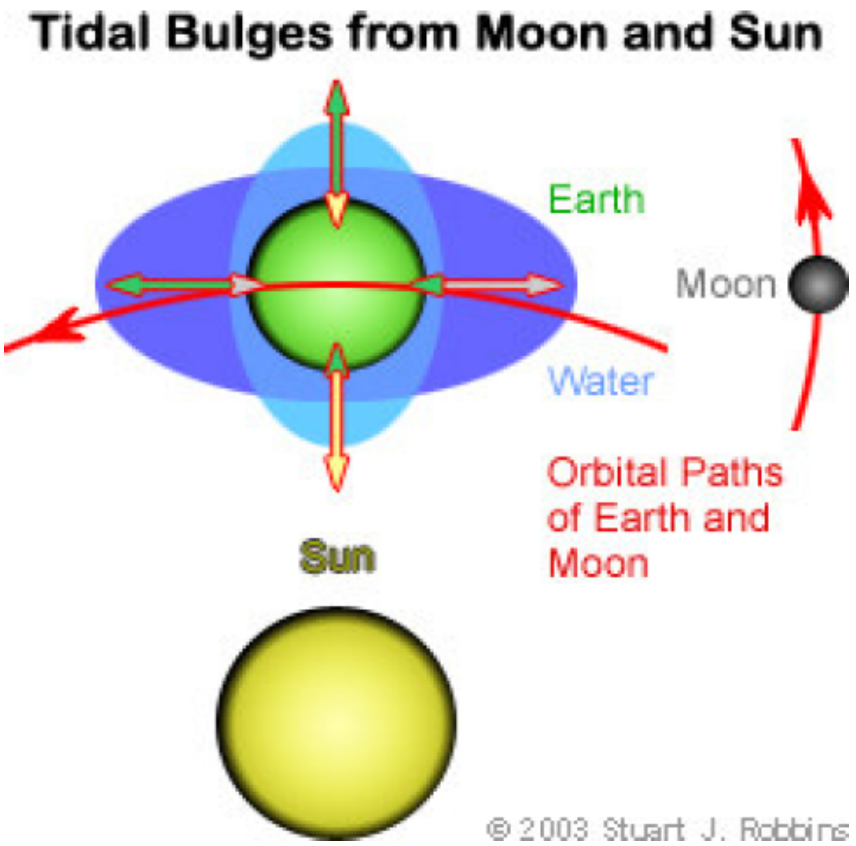
- If system is probed at low energies, fine details not resolved
- Use low-energy variables for low-energy processes
- Short-distance structure can be replaced by something simpler without distorting low-energy observables
- Physics interpretation can change with resolution!



The Hierarchy of Nuclear Forces in Chiral-EFT
2N forces
3N forces
4N forces
Leading Order
Q0
LO
Next-to Leading Order
Q2
NLO
Next-to-Next-to Leading Order
Q3
N2LO
+...
optimized 2014
derived 2000
derived 2002
Next-to-Next-to-Next-to Leading Order
Q4
N3LO
+...
+...
+...
derived 2003
derived 2011
derived 2007

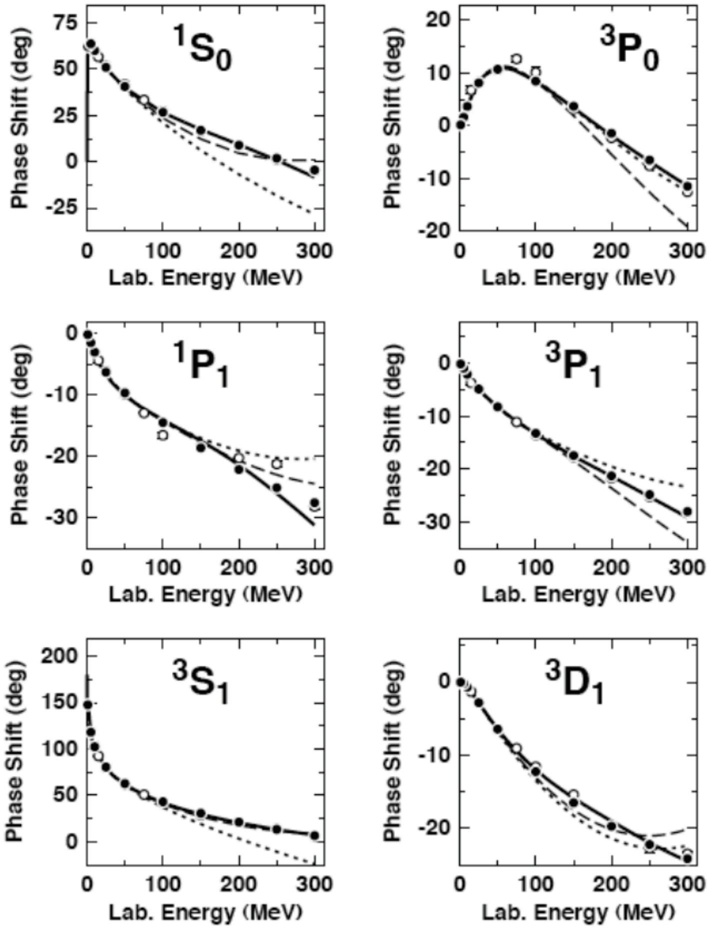
three-nucleon interactions

Three-body forces between protons and neutrons are analogous to tidal forces: the gravitational force on the Earth is *not* just the sum of Earth-Moon and Earth-Sun forces (if one employs point masses for Earth, Moon, Sun)



nucleon-nucleon interactions from chiral EFT

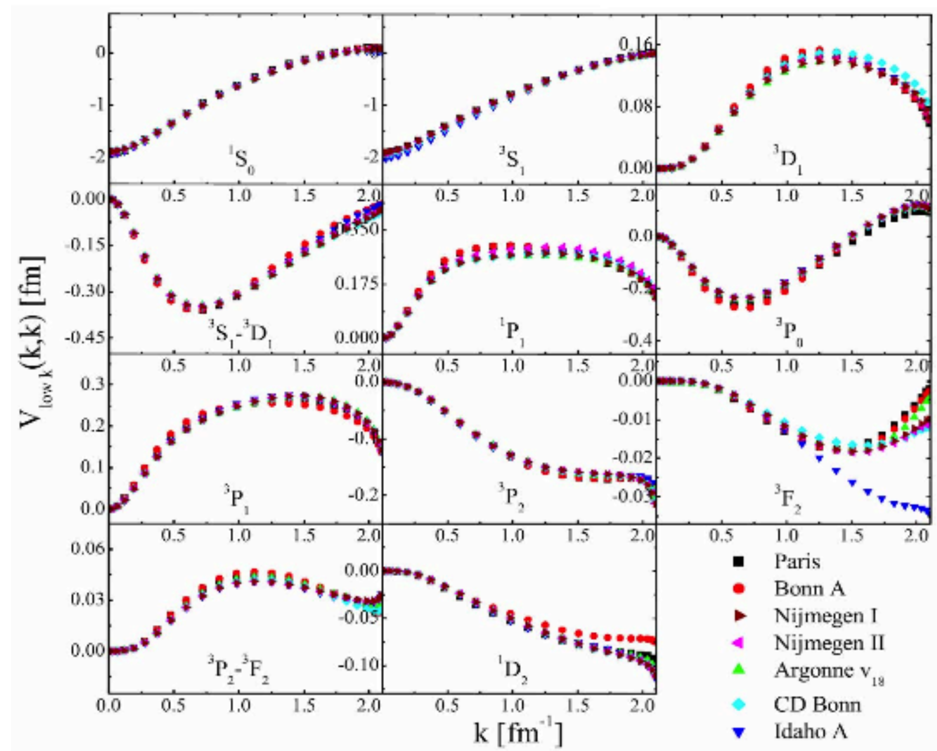
Effective-field theory potentials



N³LO: Entem et al., PRC68, 041001 (2003)
Epelbaum, Meissner, et al.

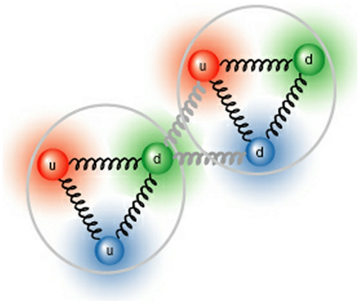
Renormalization group (RG) evolved nuclear potentials

$V_{low\text{-}k}$ unifies NN interactions at low energy



Bogner, Kuo, Schwenk, Phys. Rep. 386, 1 (2003)

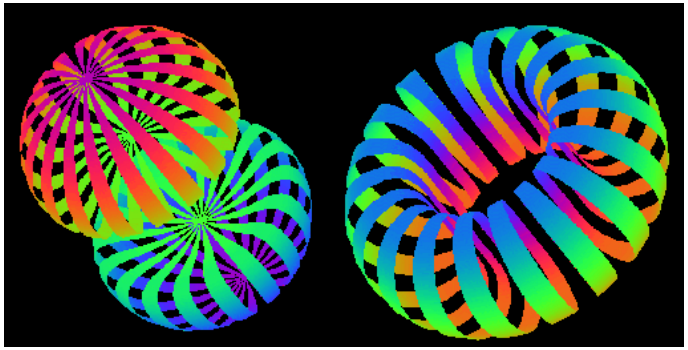
Deuteron

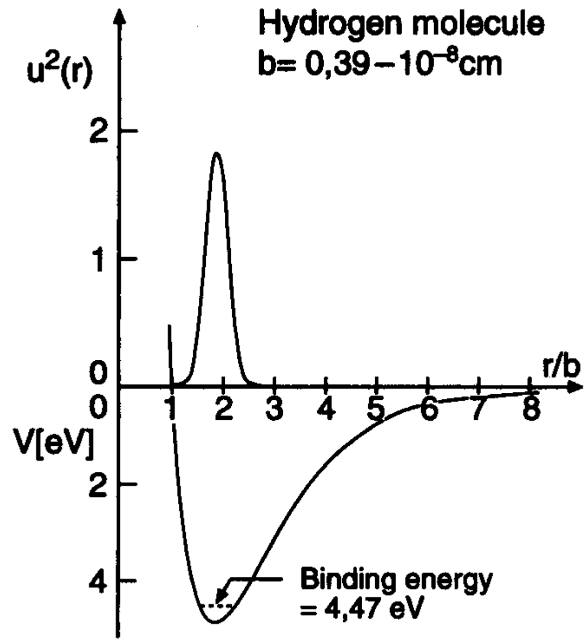


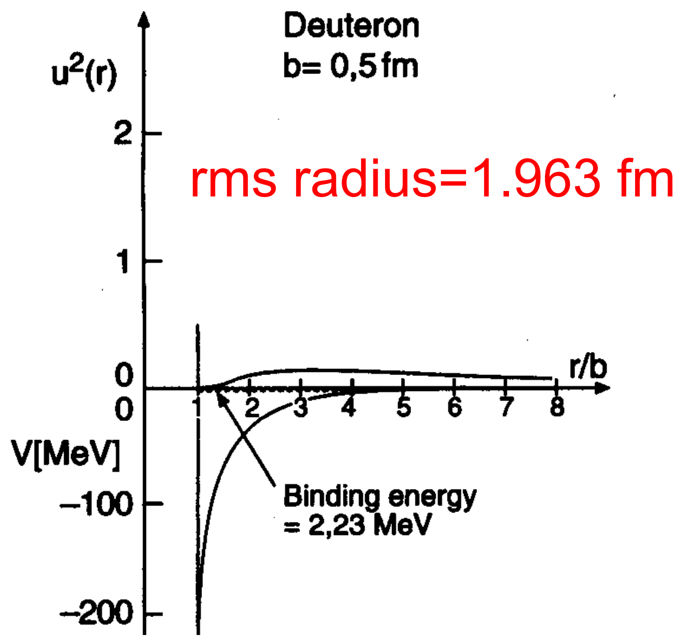
Binding energy	2.225 MeV
Spin, parity	1^+
Isospin	0
Magnetic moment	$\mu=0.857\ \mu_N$
Electric quadrupole moment	$Q=0.282\ e\ fm^2$

$$|\psi_d\rangle = 0.98|{}^3S_1\rangle + 0.20|{}^3D_1\rangle$$

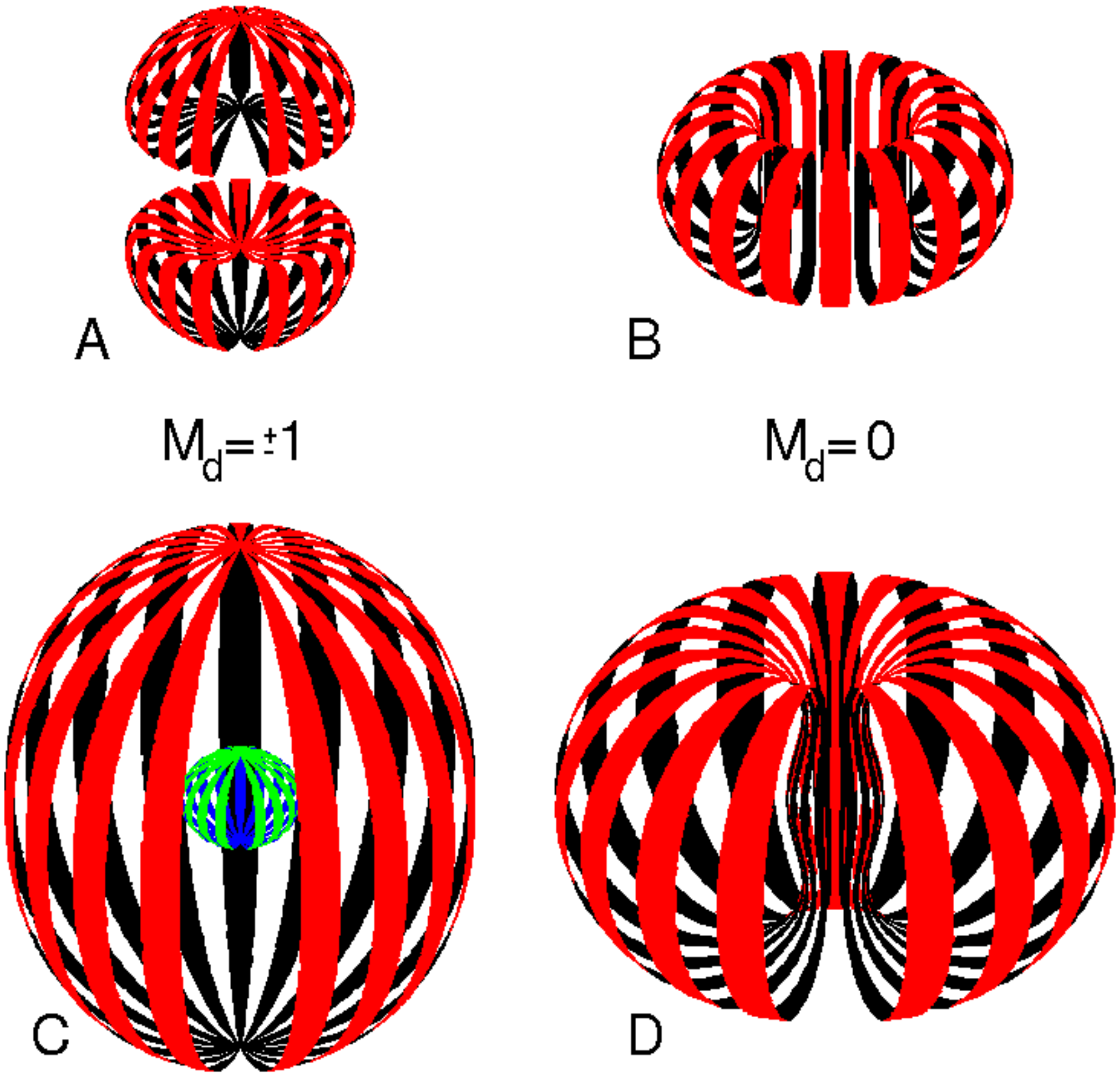
D-wave produced by tensor force!



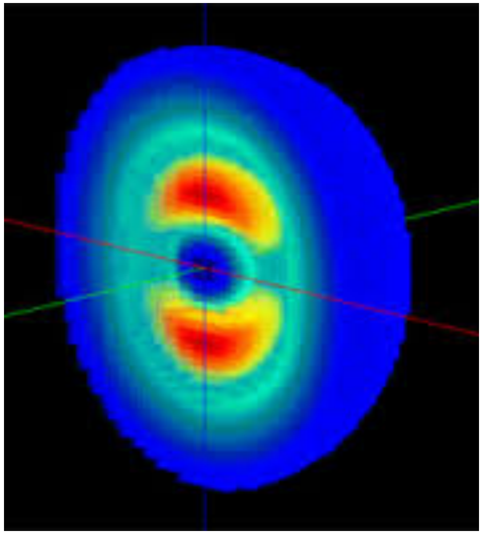




Deuteron Shapes with V_{18}

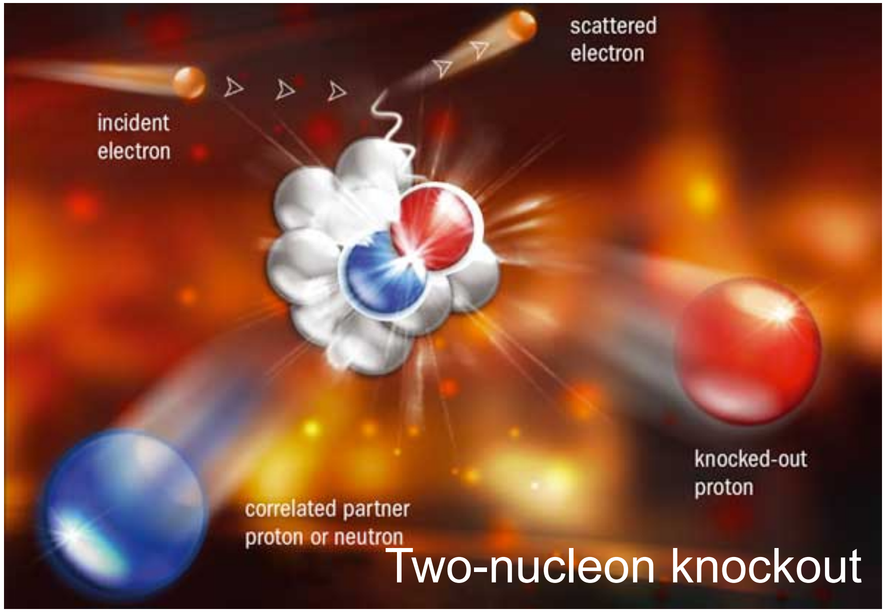


Jlab data

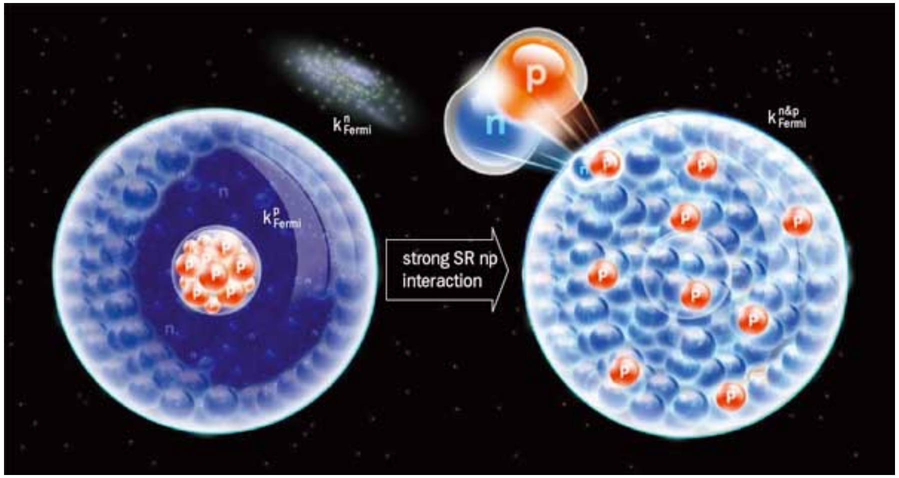


http://www.phy.anl.gov/theory/movie-run.html

Short Range Correlations and Tensor Force

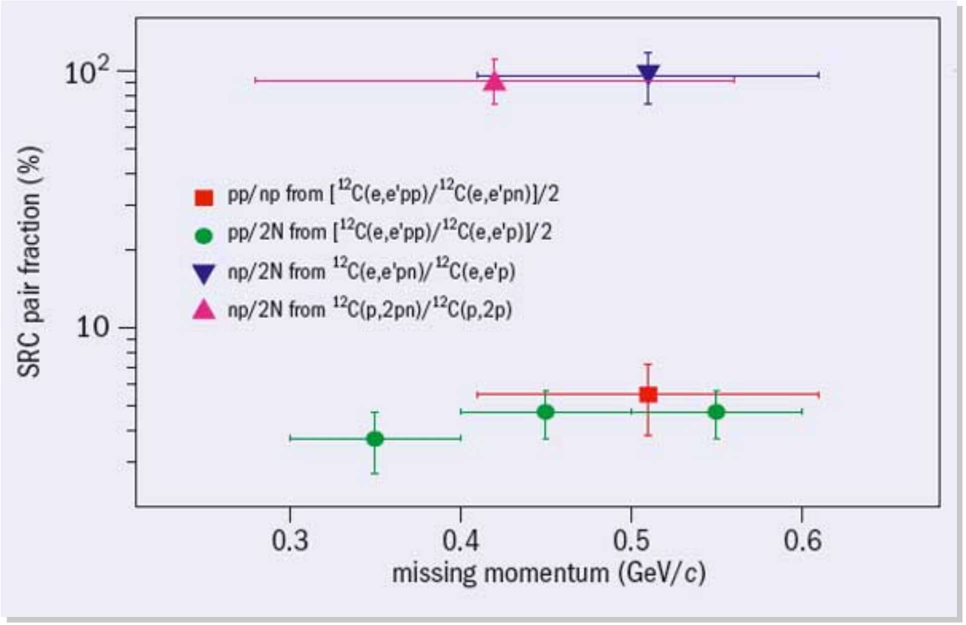


http://cerncourier.com/cws/article/cern/34919
http://cerncourier.com/cws/article/cern/37330



Dominance of proton–neutron pairs at intermediate range (c.o.m. momenta around 400 MeV/c)

Science 320, 1475 (2008)



Theory explains the pn pair dominance in terms of the tensor force:

Phys. Rev. Lett. 98, 132501 (2007)