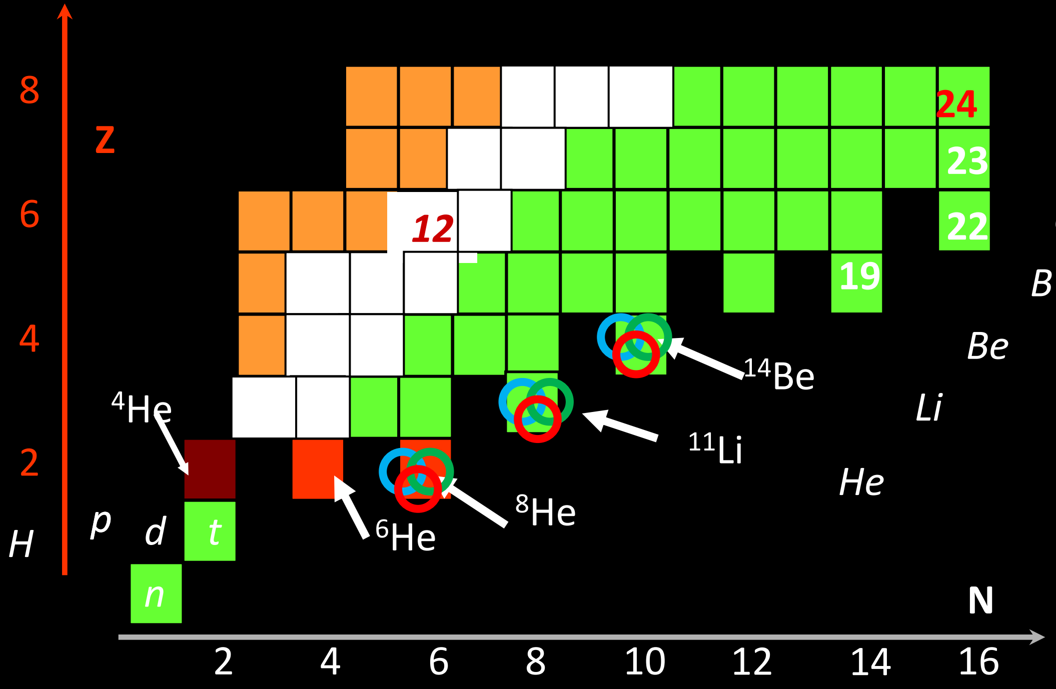
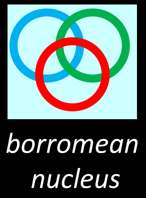
Nuclear matter radii
via elastic scattering on proton target




borromean nucleus

Motivations

Benchmark of nuclear interactions

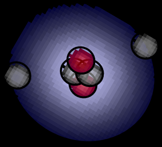
How to improve our description?

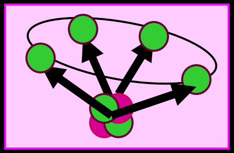
observables &Relevant probes?

Weakly-bound, large asymmetry
→ constraints on the models

Test cases: He and O isotopes

^{8}He, $^{18-22}$O



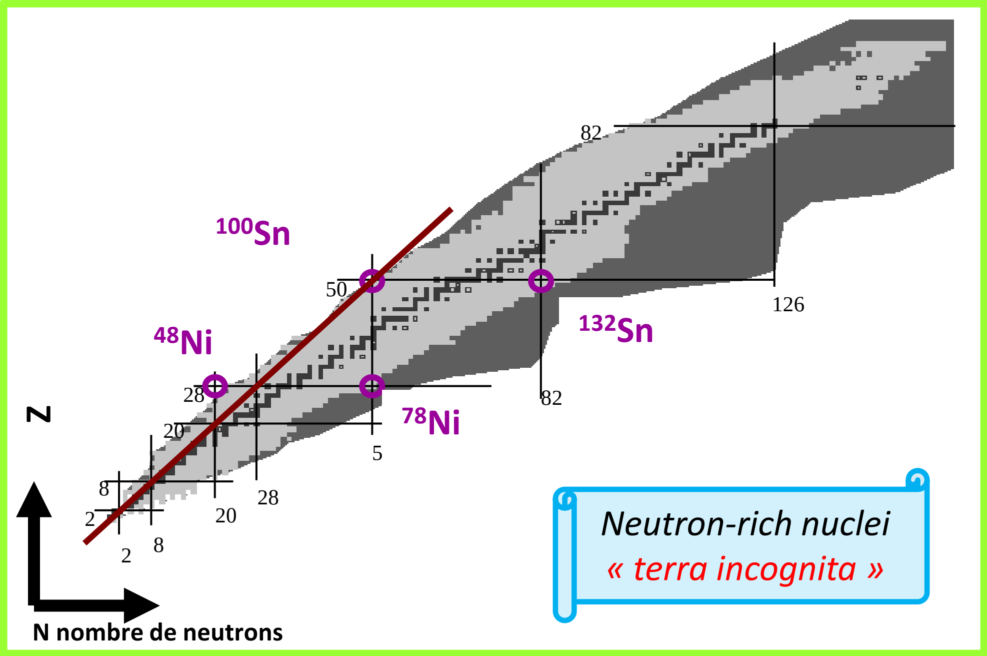


^{8}He drip-line nucleus
N/Z =3

Radii and binding energies in He and oxygen isotopes: a puzzle for nuclear forces

Dreaming of nuclear interactions…

How can we improve our knowledge on nuclear interactions ?



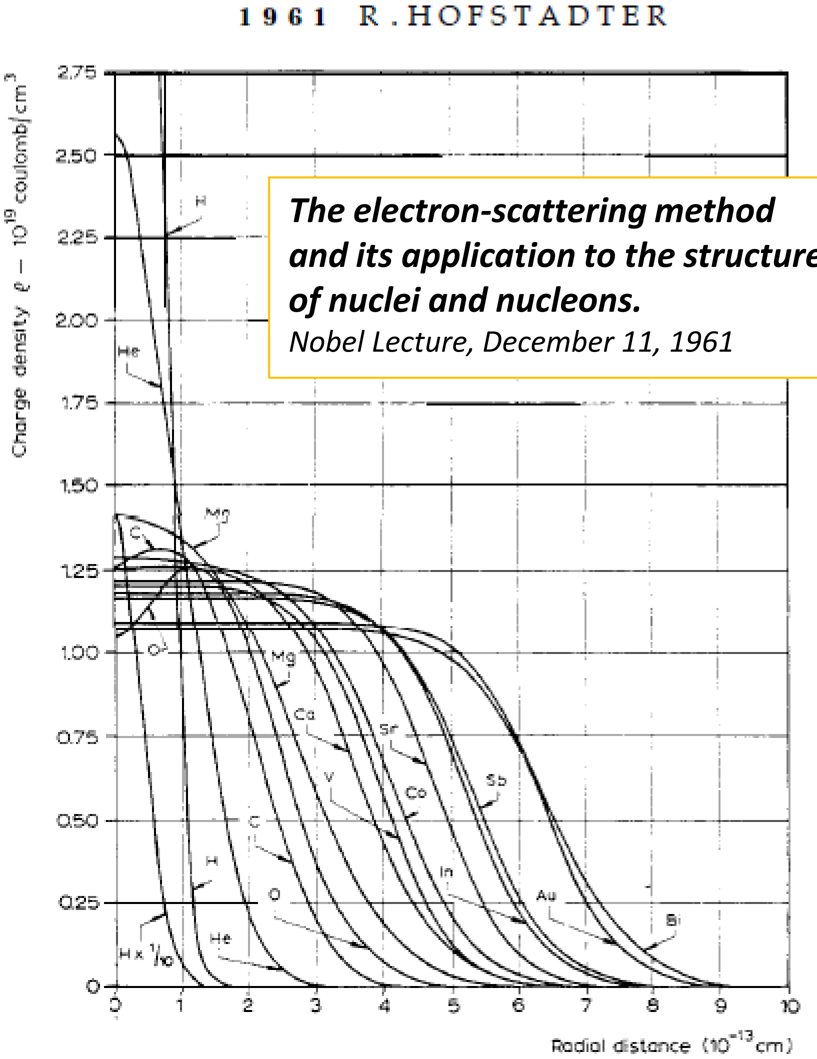
Neutron-rich nuclei
« terra incognita »

Verdi « *Sometimes the progress is to look back in the past.* ».

Dreaming of nuclear interactions, measuring densities

Voltaire, *Éléments de la philosophie de Newton* (1738) :
« L'homme n'est pas fait pour connaître la nature intime des choses ; il peut seulement calculer, mesurer, peser et expérimenter ».

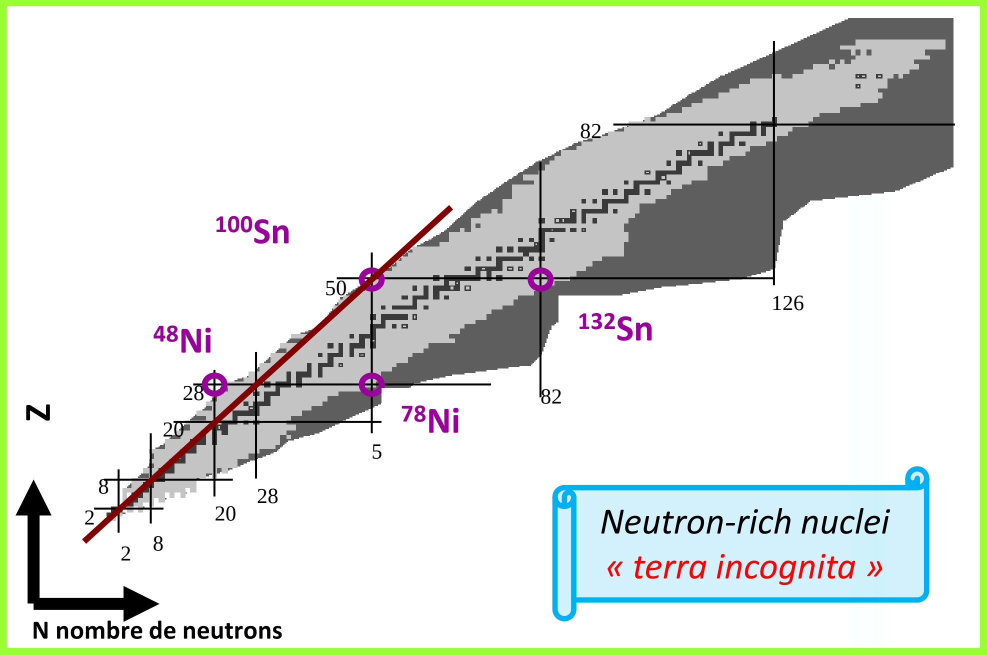
Micromégas et le nain Saturnien rencontrent des Terriens
Micromégas de M. de Voltaire.
1778 BnF



The electron-scattering method and its application to the structure of nuclei and nucleons.
Nobel Lecture, December 11, 1961

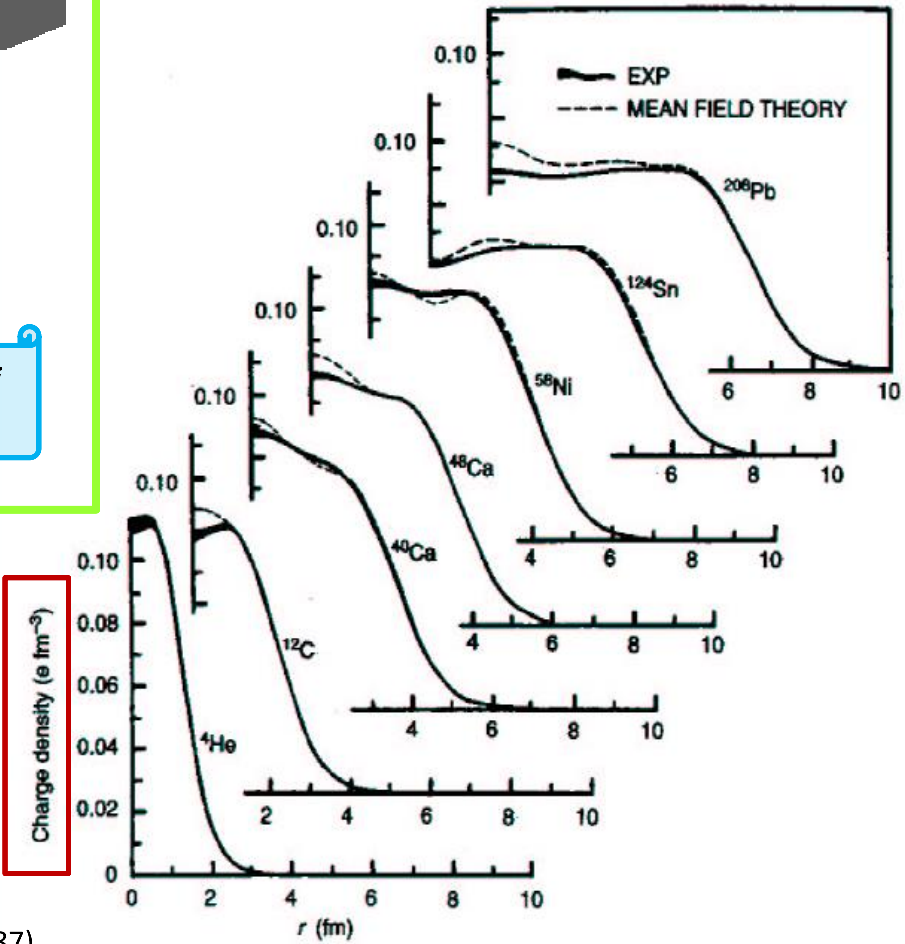
Dreaming of nuclear interactions…measuring densities

How can we improve our knowledge on nuclear interactions ?



Neutron-rich nuclei
« terra incognita »

Building blocks of our knowledge on nuclei
→ charge distributions

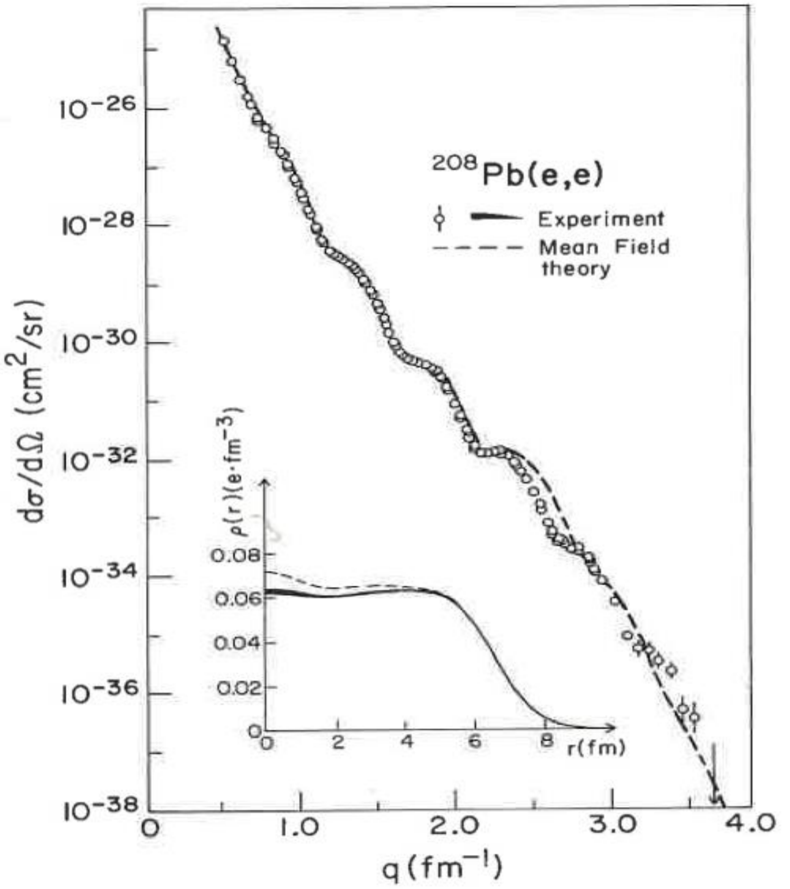


Comparison between model calculations
& experimental nuclear densities

B. Frois, C. N. Papanicolas,
Ann. Rev. Nucl. Part. Sci. **37**, 133 (1987).

From (e,e) form factors → ρ_{ch}, ρ_p

Goals for Nuclear matter densities: charge density profiles for RI as done for stable nuclei



$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_{Mott}} \left|F(q)\right|^2$$

$$F(\vec{q}) = \int d^3r \rho_{ch}(\vec{r}) e^{i\vec{q}\vec{r}}$$

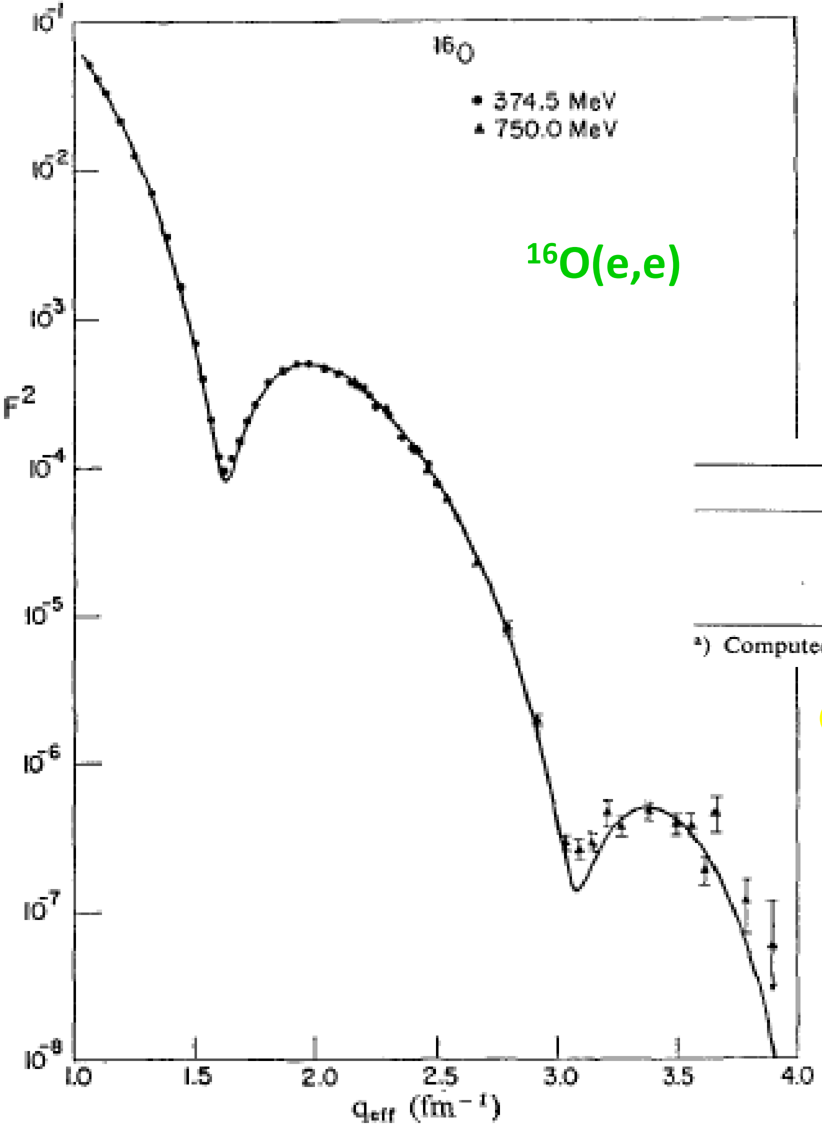
Extraction of densities
(e,e) scattering observables←→ nuclear density fit
I. Assuming various density shapes,
with parameters fitted on (e,e) data
II. Parameterization from theory
III. Model-independent (FB expansion,…)
functions for the nuclear densities

Tables encoding the knowledge on nuclear densities since the 50^{ies} -Observables

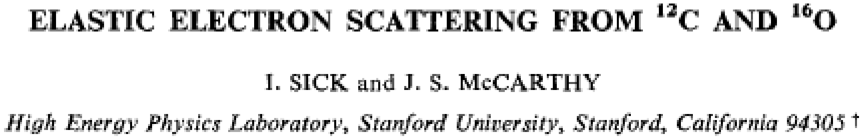
H.De Vries, C. W.De Jager, and C.De Vries,
At. Data Nucl. Data Tables 36 (1987) 495-536
Nuclear charge density distribution parameters from electron elastic scattering

B. Frois, C. N. Papanicolas,
Ann. Rev. Nucl. Part. Sci. **37**, 133 (1987).

^{16}O(e,e) scattering measurements to extract charge density profiles



^{16}O(e,e)



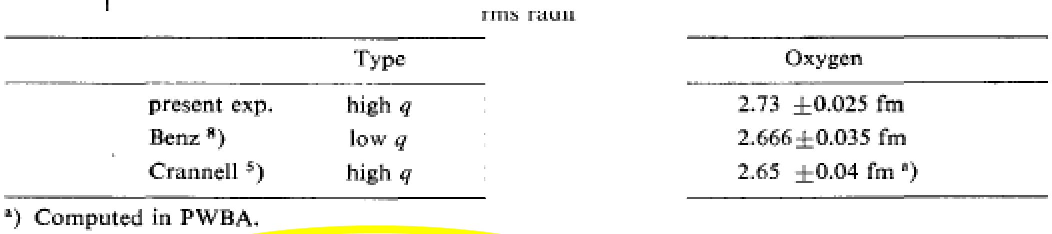
ELASTIC ELECTRON SCATTERING FROM ^{12}C AND ^{16}O

I. SICK and J. S. McCARTHY

High Energy Physics Laboratory, Stanford University, Stanford, California 94305 †

Nucl. Phys. ***A 150*** (1970) 631-654

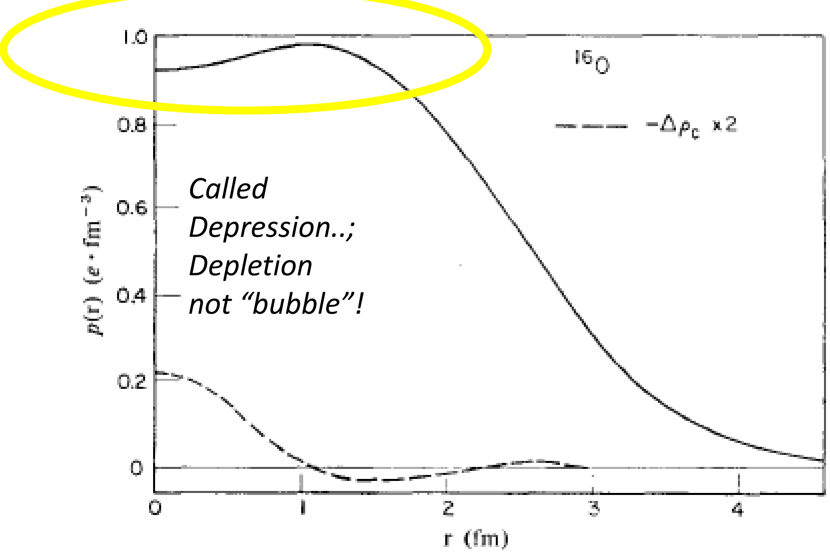
$$\rho(r) \propto \frac{1+Wr^2/C^2}{1+\exp\left(\frac{r-C}{z}\right)},$$



rms radii

	Type	Oxygen
present exp.	high q	2.73 ±0.025 fm
Benz [8])	low q	2.666±0.035 fm
Crannell [5])	high q	2.65 ±0.04 fm [a])

[a]) Computed in PWBA.



Called Depression..; Depletion not "bubble"!

Dreaming of nuclear densities,measuring radii

Observables, sizes and densities — Back to basics

(e,e) and (p,p) → ρ_p and ρ_m → ρ_n

Elastic and inelastic electron scattering
→ Determination of nuclear **charge** sizes and shapes

From (e,e) **for stable nuclei**
form factors→**ρ_{ch}, ρ_p**

^{18}O(e,e)

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_{Mott}} |F(q)|^2$$

$$F(\vec{q}) = \int d^3r \rho_{ch}(\vec{r}) e^{i\vec{q}\vec{r}}$$

For exotic nuclei: up to now, only **r_{ch}**
Few cases, cf data from laser spectroscopy
F(q) → ρ_{ch} ?
Electron-ion: SCRIT at RIKEN.
On-going projects for **RI-electron collisions:**
→ Physics cases in NuPECC LRP 2017
→ Future e-RI colliders; Elise@FAIR

$$\rho(r) = \langle \Psi_{gs} | \delta(\vec{r} - \vec{r'}) | \Psi_{gs} \rangle$$

Elastic and inelastic proton scattering
to probe details of the densities ρ_{m},
and to infer **ρ_n** properties

^{18}O(p,p)

From (p,p)
form factors →ρ_m

$$\frac{d\sigma}{d\Omega} = \frac{m_i m_f}{(2\pi\hbar^2)^2} \frac{k_f}{k_i} \left| \langle \varphi_f | V | \varphi_i \rangle \right|^2$$

$$U(\rho_p, \rho_n, E_p) = \lambda_v V(\rho, E_p) + i \lambda_w W(\rho, E_p)$$

Optical Model Potential microscopic analysis
E, ρ ({ρ_p, ρ_n}) density-dependent nucleon-nucleus pot.
JLM local microscopic complex OMP
from g-matrix calculations
E_p ~10-160 MeV extended to 200 MeV (CEA-DAM)
J.P. Jeukenne, A. Lejeune, C. Mahaux, PRC ***16****, 80 ('77)*

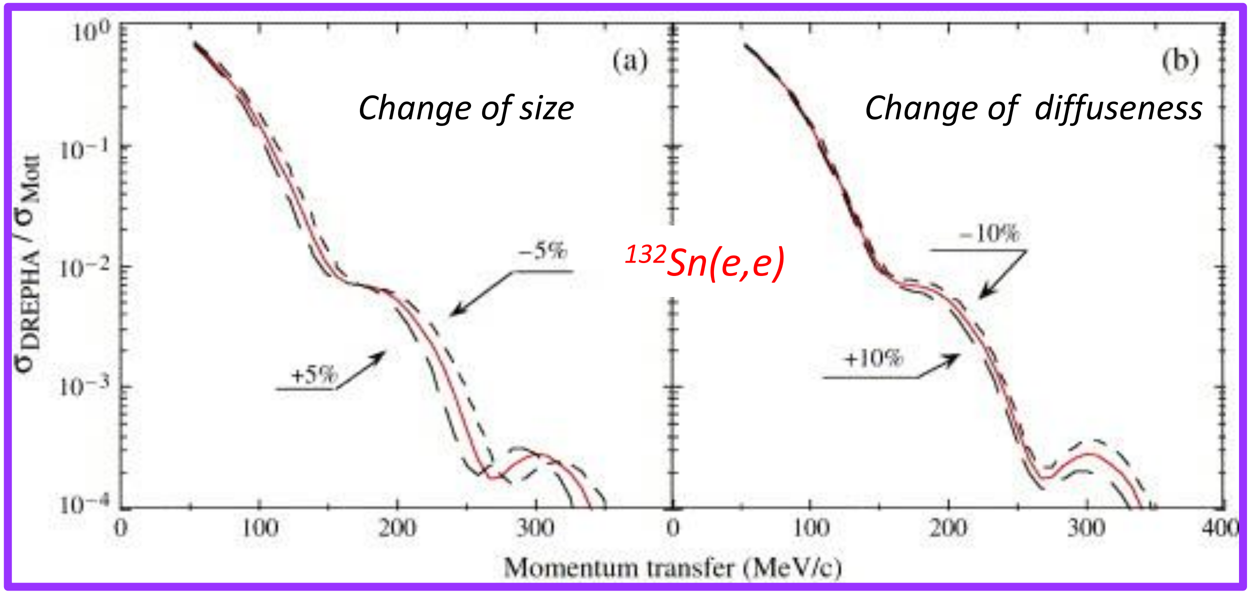
Neutron-rich RI beams (p,p) →test the validity of calculated ρ_p ,ρ_m, ρ_n
and check possible **neutron-skin via exp/theory comparison**
N.B. We DO NOT EXTRACT ρ_m but radii

(e,e) scattering measurements ; sensitivity to the shape of the density

Observables-Deduced quantity	**Reactions**	**I [s^{-1}] L [$cm^{-2}s^{-1}$]**
r.m.s. matter radii	(p,p) *at small q*	I =10^4 (light)
Matter density with 3 parameters ρ_m	(p,p) *2^{nd} min.*	I = 10^{5-6} (medium-heavy)
r.m.s. charge radii	(e,e) *at small q*	L: 10^{24} (light)
Charge density with 2 parameters ρ_{ch}	(e,e) *First min.*	10^{24-28} (light-heavy)
Charge density with 3 parameters ρ_{ch}	(e,e) *2^{nd} min.*	10^{26-29} (medium-heavy)
Neutron skin density from ρ_m and ρ_{ch}	**(p,p) and (e,e)**	**(p,p) : 10^6/s** **e: 10^{28} 10^{29}**

NuPECC
www.nupecc.org
Long Range Plan 2017
"Perspectives in Nuclear Physics" ; 2016 Subgroup Nuclear Structure Question 4

Works by Hofstadter et al. (1950s)
Ee ~150 MeV
N_{beam} ~ 1nA (~10^9 /s)
~10^{28} /cm²/s

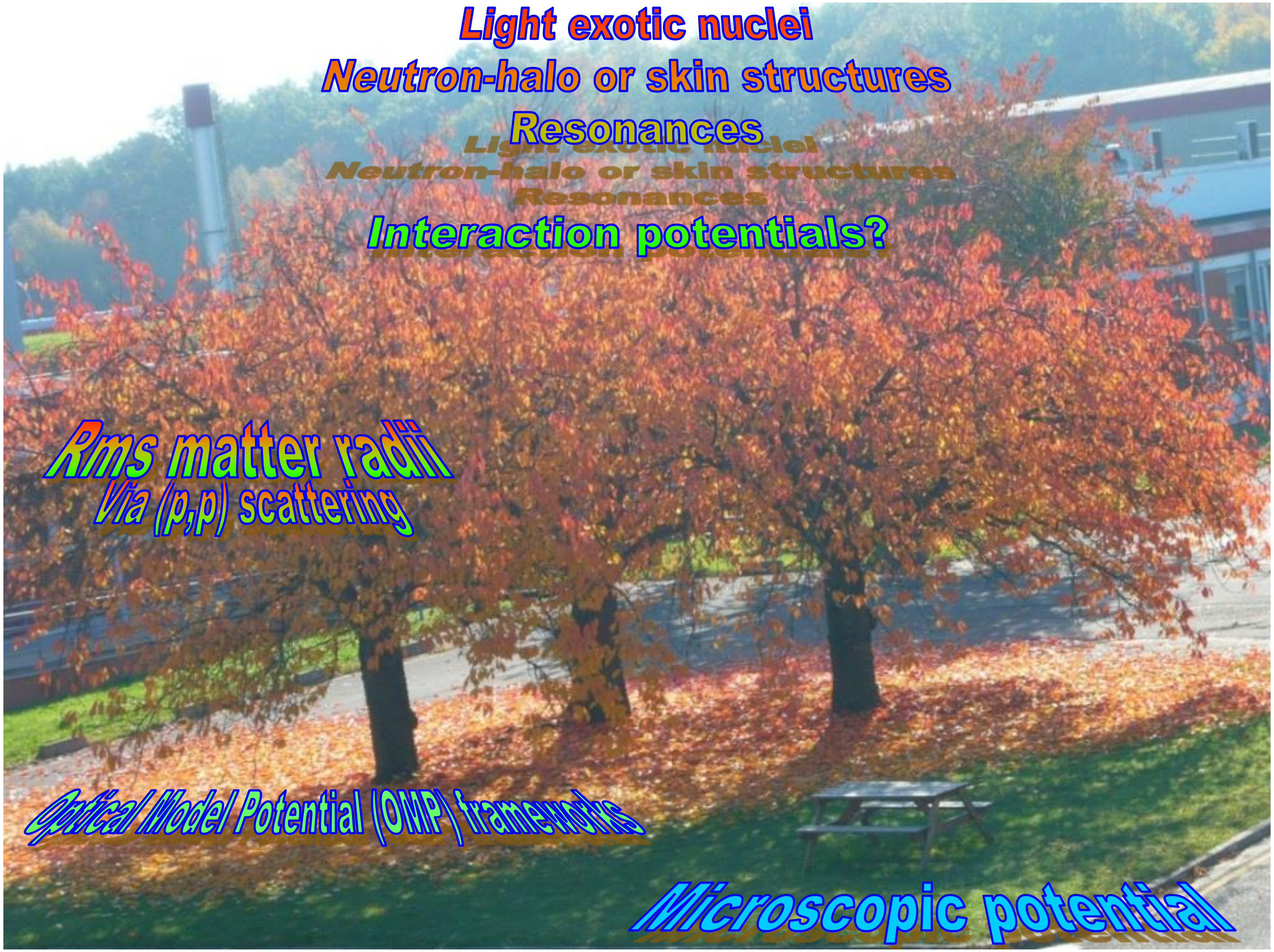


T. Suda and M. Wakasugi, PPNP. 55, 417 ('05)

http://esnt.cea.fr/Phocea/Page/index.php?id=58

Electron-radioactive ion collisions: theoretical and experimental challenges 25-27 April 2016

Matter radii



Light exotic nuclei

Neutron-halo or skin structures

Resonances

Interaction potentials?

Rms matter radii

Via (p,p) scattering

Optical Model Potential (OMP) frameworks

Microscopic potential

Energy dependence of the interaction

$$V = V_0 + V_\sigma \sigma_1 \cdot \sigma_2 + V_\tau \tau_1 \cdot \tau_2 + V_{\sigma\tau} \; \sigma_1 \cdot \sigma_2 \; \tau_1 \cdot \tau_2$$

Isoscalar terms

ΔT=0

ΔS=0 ΔS=1

Isovector terms

ΔT=1

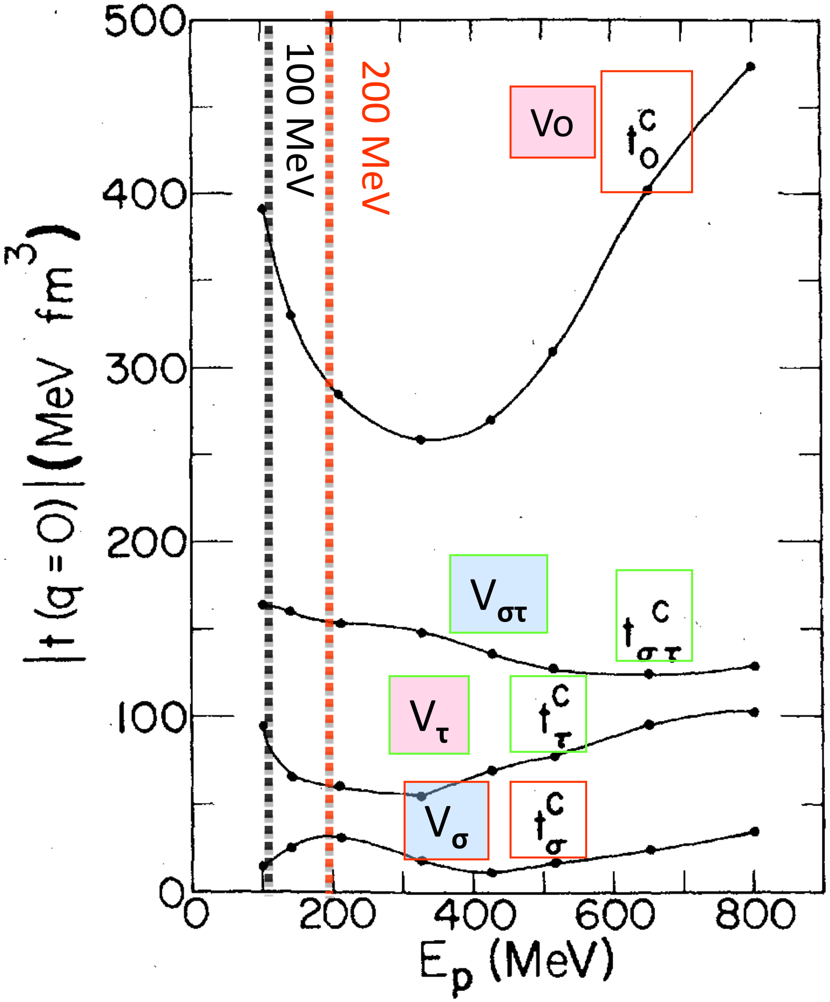
Δ S=0 ΔS=1

Isoscalar [ΔT=0], isovector [ΔT=1],
spin-flip [ΔS=0] non-spin-flip [ΔS=1]

Non-spin-flip transition strengths decreases as the energy increases (up to 400 MeV), while those for spin-flip transition remain unchanged.))

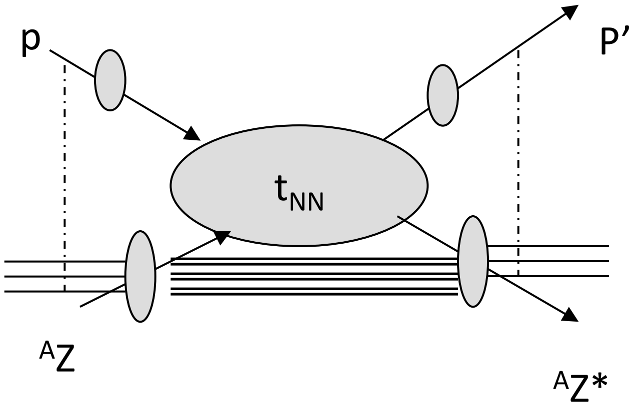
Spin transitions are much weakly populated in the isoscalar channel than in the isovector channel.

Energy dependence of the *NN* t-matrix: t(q=0)
*W.G. Love and F.A. Franey, PRC **24**, 1073 (1981).*



Calculations of the (p,p') reactions – structure and potential inputs

An optical potential OMP proton+nucleus is needed as input of the reaction code



→ **Phenomenological approach, global OMP**
KD 02 : Global parametrization
A.J.Koning and J.P.Delaroche, NP***A731*, 231** ('03).

→ **Microscopic approach requires:**
+Structure inputs
Wave functions >> Densities (gs and transition)
HFB SLy4 and others
HFB calculations D1S QRPA calculations (CEA-BIII) et al
Tests of Shell Model wave functions

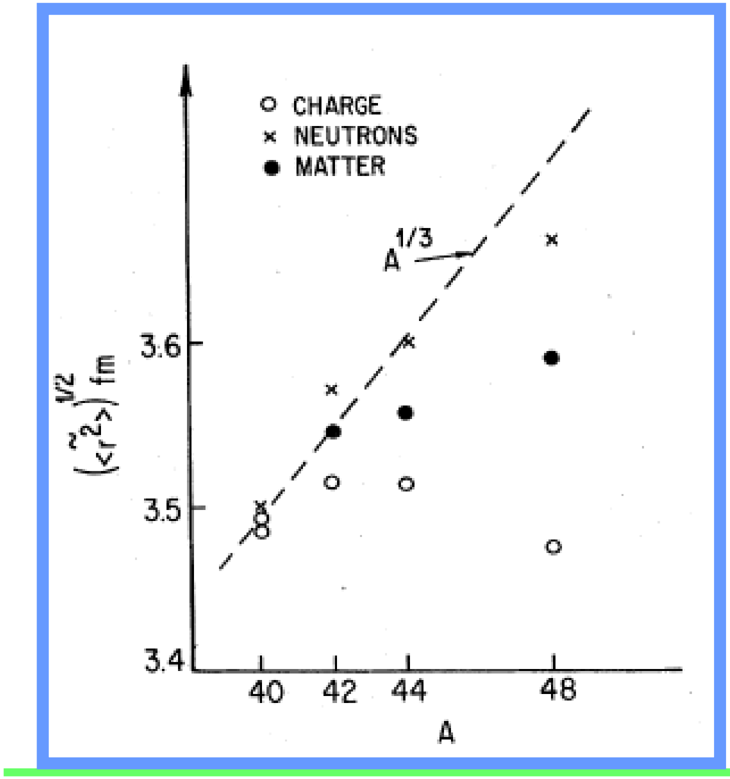
+ proton-nucleus nuclear interactions - effective interaction eg g-matrix I M3Y (Ep ~20-200 MeV) :
G.Bertsch et al., NPA284(1977)399. BDM3Y and CDM3Y families D. T Khoa and W vOertzen

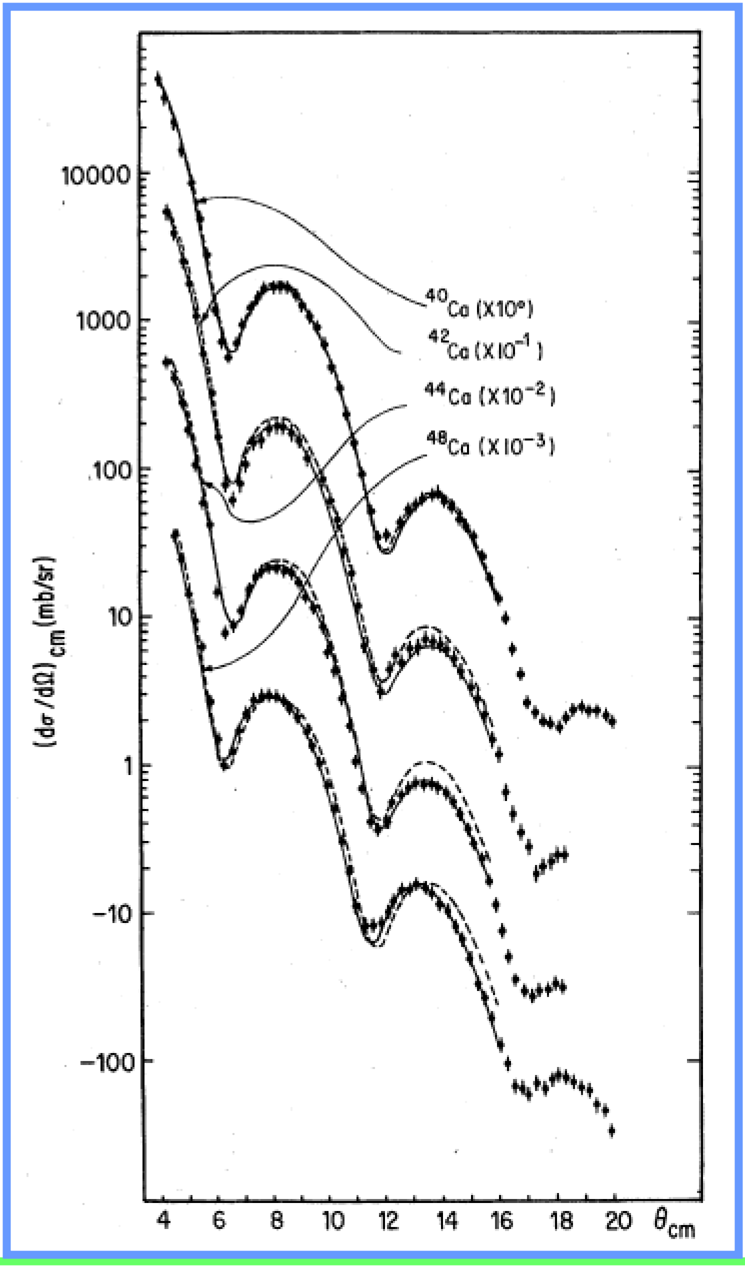
+ JLM local microscopic complex potential from g-matrix calculations for Ep ~10-160 MeV,
extended to 200 MeV (CEA-Bruyères, E. Bauge et al.)

+ F&L: **Nucleon-nucleon t-matrix (Ep ~200-500 MeV)** M.A.Franey and W.G.Love, PRC **31,** 488 (1985).
+ non-local g-matrix potential approach: cf M Dupuis et al BIII PRC **73**, 014605 (2006)
H. F. Arellano and H. V. von Geramb, Phys. Rev. C **66**, 024602 (2002).
H Arellano, M.Girod, full-folding OMP,HFB Gogny PRC **76**, 034602 (2007)
Calculation code: dwba DWBA91 : J Raynal ; CC approach ECIS07

Observables, high-energy proton-nucleus cross sections

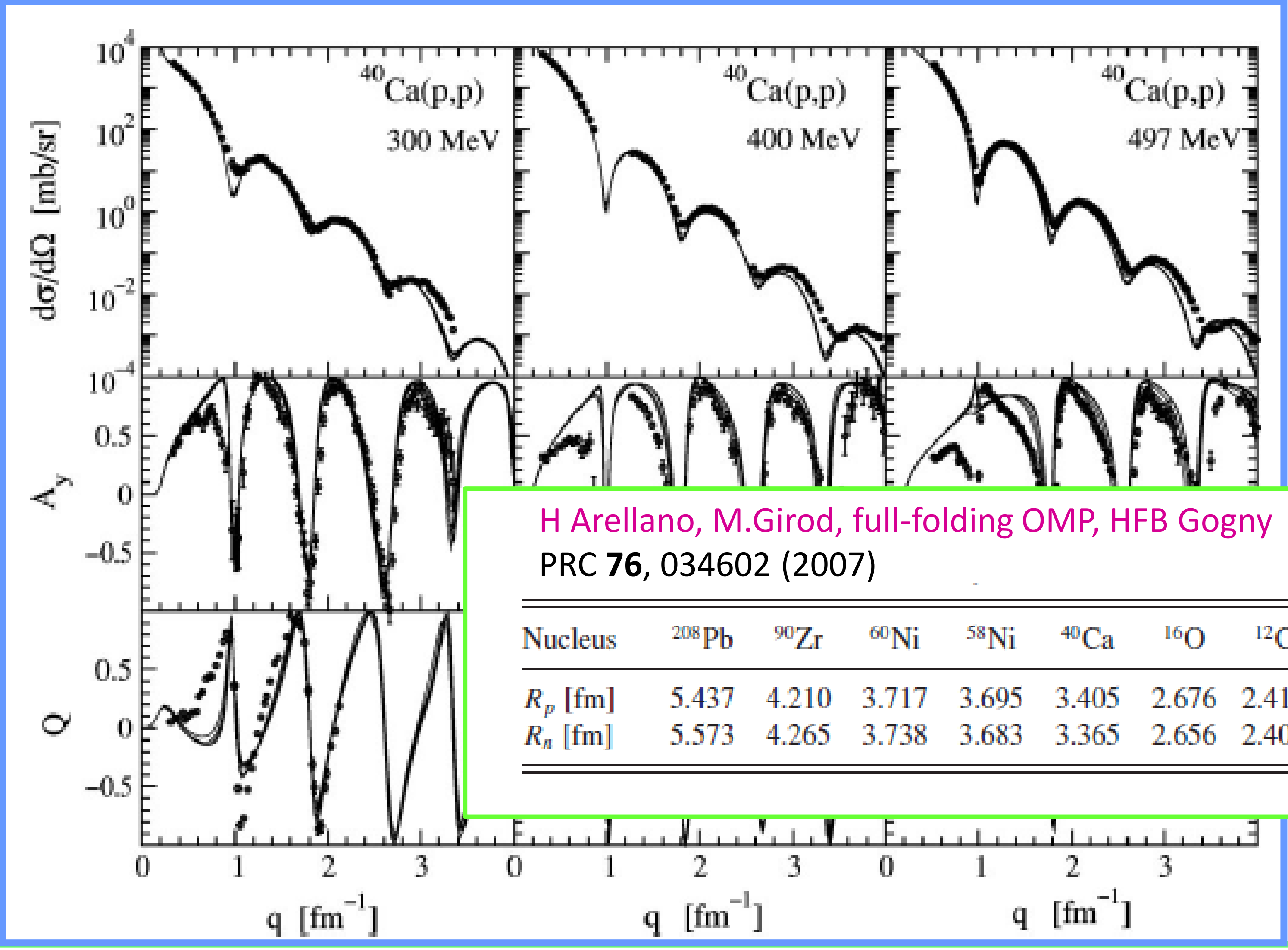
G. J. Igo Rev. Mod.Phys.**50**, pp.523-560 (1978)
Some recent intermediate and high-energy proton-nucleus research
Fig.31. Data Ca+p at 1.044 GeV
Alkhazov et al., 1976
Tests:
-n density identical to the known p (charge) density
-n density adjusted for the best fit to the data





Observables, high-energy proton-nucleus cross sections

Extension of the full-folding optical model for nucleon-nucleus scattering with applications up to 1.5 GeV
H. F. Arellano and H. V. von Geramb, Phys. Rev. C **66**, 024602 (2002)



H Arellano, M.Girod, full-folding OMP, HFB Gogny
PRC **76**, 034602 (2007)

Nucleus	^{208}Pb	^{90}Zr	^{60}Ni	^{58}Ni	^{40}Ca	^{16}O	^{12}C
R_p [fm]	5.437	4.210	3.717	3.695	3.405	2.676	2.419
R_n [fm]	5.573	4.265	3.738	3.683	3.365	2.656	2.402

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(p,p’) analysis within OMP frameworks

^{16}O(p,p) at 200 MeV CEA-DAM BIII

Fully microscopic optical model for NA scattering off doubly closed-shell nuclei.

→ relevance of the *g*-matrix method to build microscopic OMP at medium energies,

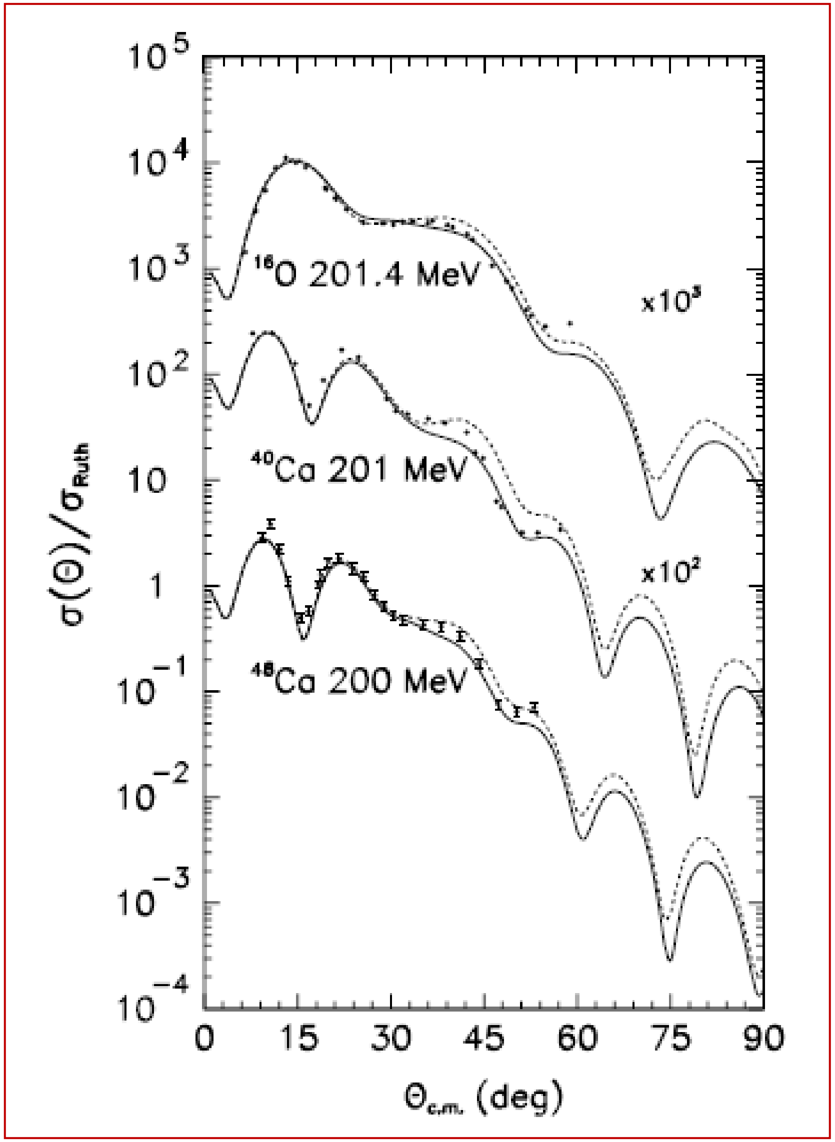
→ emphasizes the need to include nucleon-phonon coupling

Solid curves: correlated description of gs

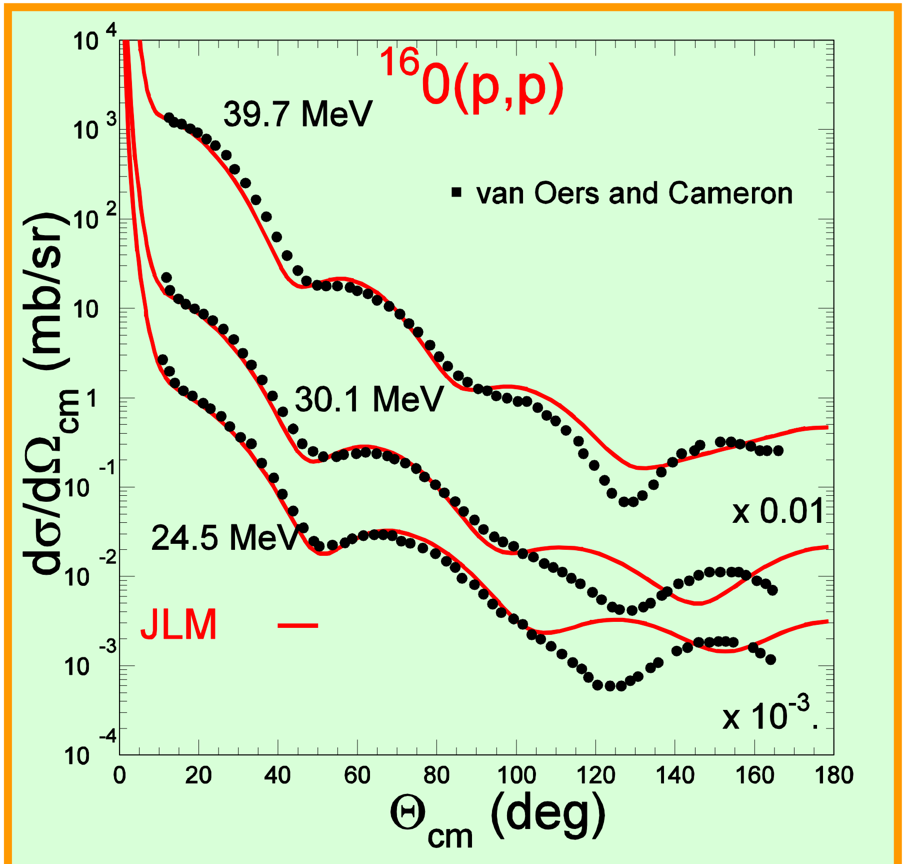
Dashed curves: uncorrelated

M. Dupuis, S. Karataglidis, E. Bauge,
J. P. Delaroche, and D. Gogny, PRC **73**, 014605 (‘06)

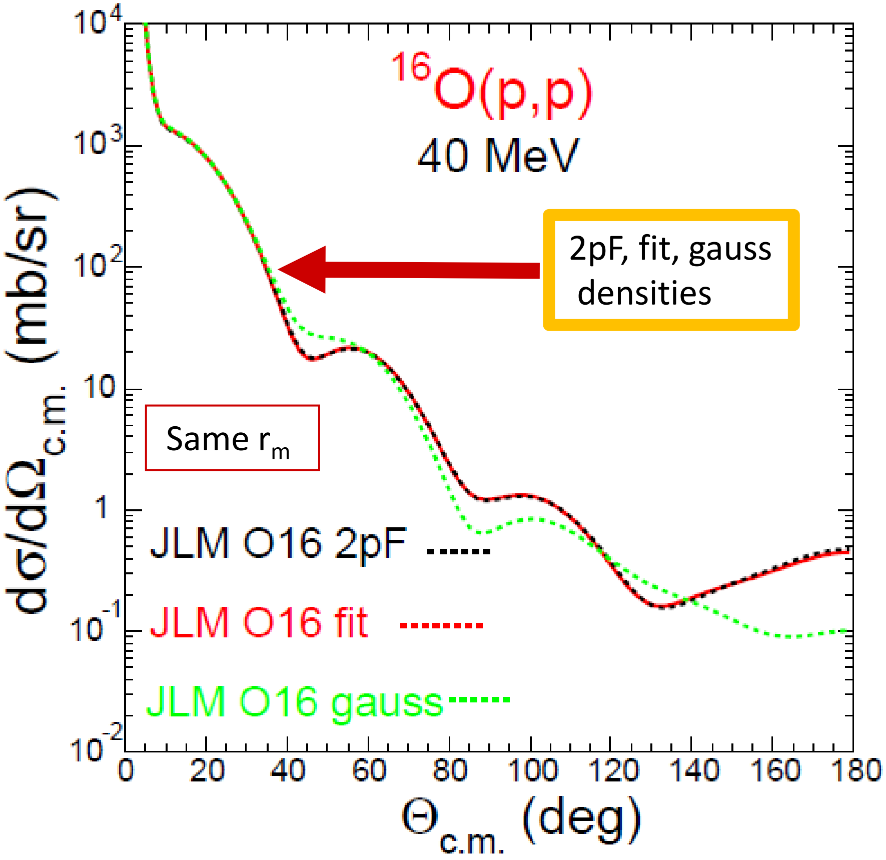
M.Dupuis EPJA **53:111** (2017)
Microscopic description of elastic and direct inelastic nucleon scattering off spherical nuclei



Proton Elastic Scattering: microscopic OMP analysis to extract rms radii



JLM calc. ^{16}O+p : V. Lx, HDR report



Other examples of JLM analysis
^{10,11,12}C (p,p') PRC **72**, 014308 ('05)
JLM lighter nuclei: λ_w= **0.8**

^{16}O experimental density (e,e); *Sick 1970*
At. Nucl. data tables, De Vries et al. (1987)
r_{ch}= 2.730 (25) fm → r_p exp 2.59 (7) fm
r_m = 2.57 fm (p,p) analysis

The sensitivity of (p,p) to r_m is ~±0.1 fm

Previous analysis: coupling effects observed for ^{6,8}He(p,p)

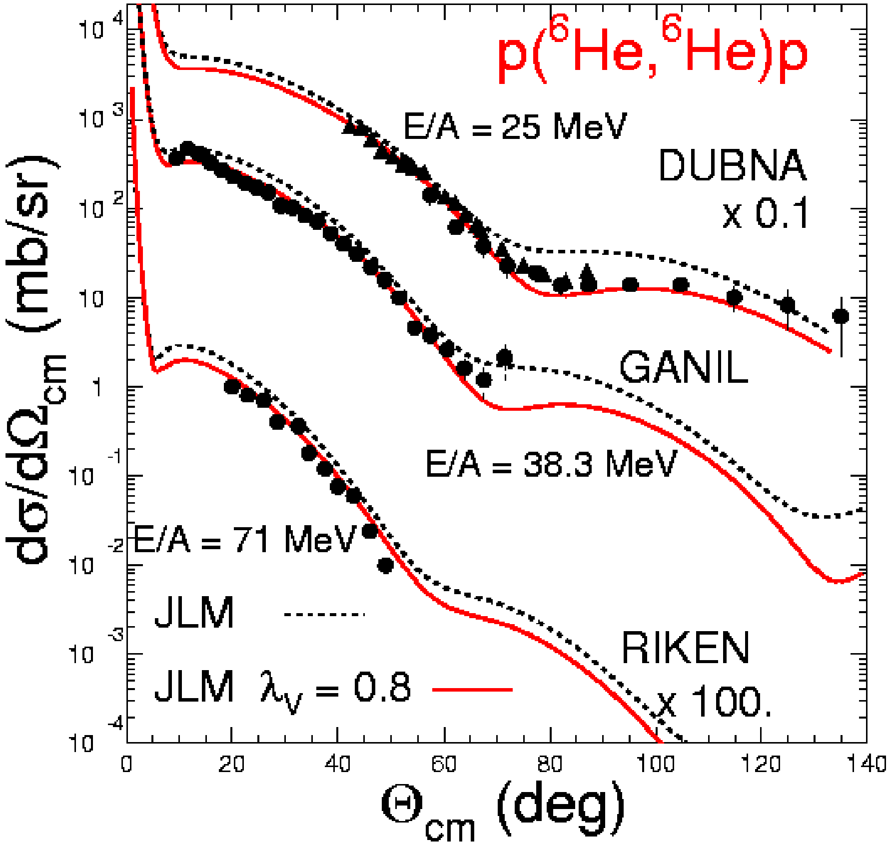
The JLM microscopic nucleon-nucleus optical potential
J.P. Jeukenne, A. Lejeune and C. Mahaux, PRC **16**, 80 ('77)

$$U_{JLM}(^{8}He+p) = \lambda_V V + i\, \lambda_W W$$

$\lambda_V = 0.8$; $\lambda_w = 0.8$

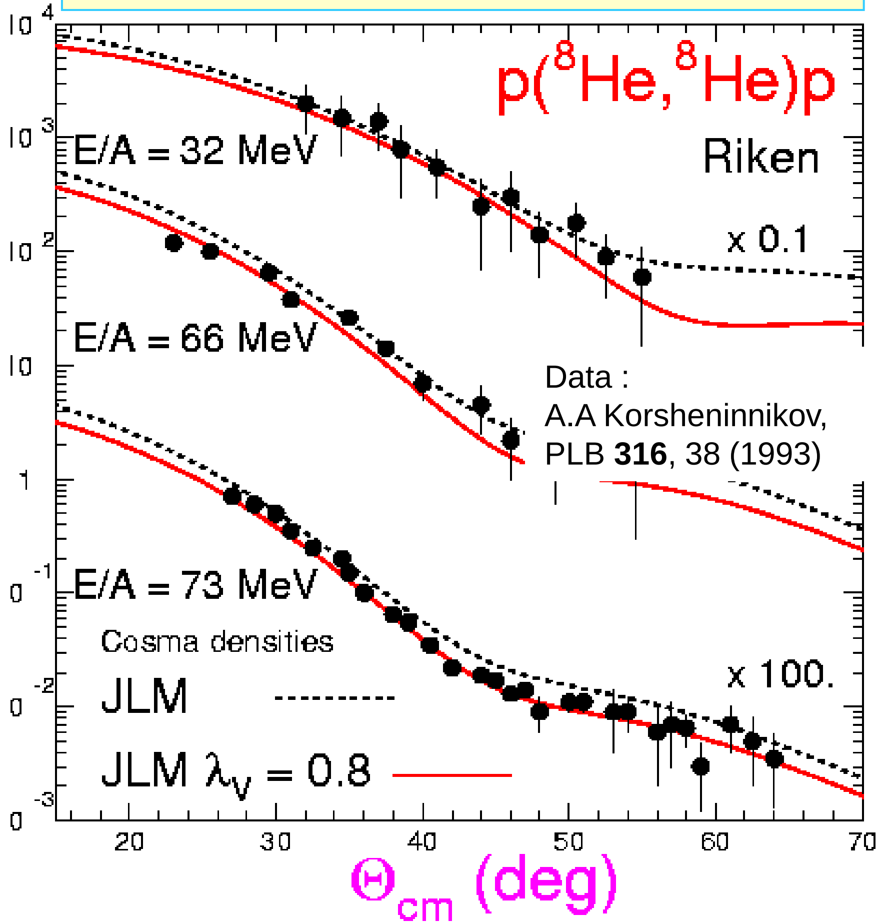
Reduction of the real part: repulsive surface term
(from VCP virtual coupling potential)

GANIL data + JLM analysis:
VLx et al., PLB **517**,18 ('01)



Dubna data :
R. Wolski et al.,
PLB **467**, 8 (1999)

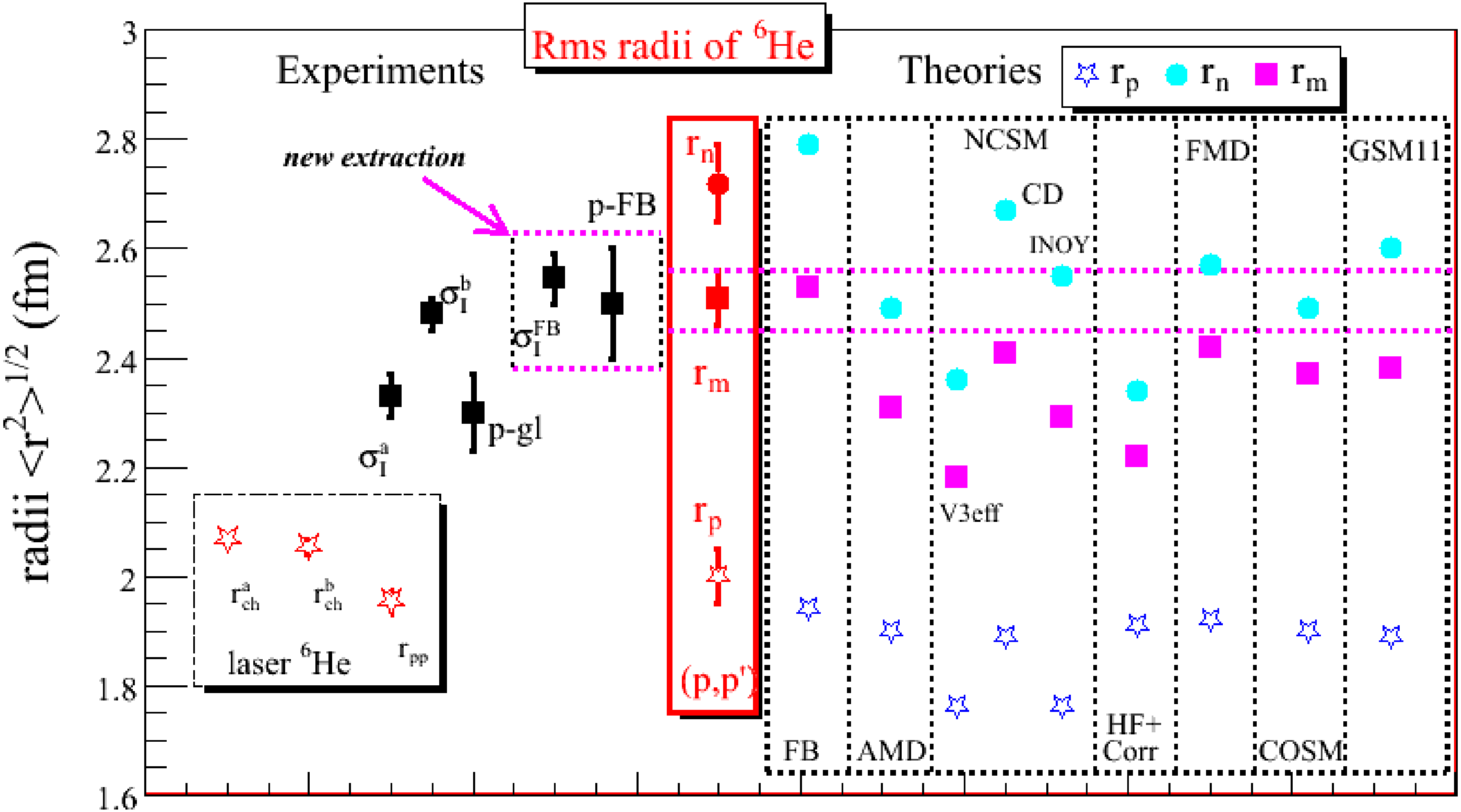
Riken Data : A.A
Korsheninnikov,
NPA**617**, 45 (1997)



Data :
A.A Korsheninnikov,
PLB **316**, 38 (1993)

Halo/skin Densities: matter rms 2.5 ± 0.1 fm

Experiment versus theories for proton and matter Rms radii



Laser L.B. Wang et al., PRL 93, 142501 (2004).
P. Mueller et al., PRL 99, 252501 (2007).
M. Brodeur et al., PRL. 108, 052504 (2012).

(p,p') analysis:VLx, N. Alamanos, ***EPJA 51**, 91 (2015)*
Weakly-bound structures of the exotic ^{6,8}He Cf ref therein

AMD-m56 K. En'yo PRC **76** ('07)
FMD T. Neff, H. Feldmeier, NPA **738,** 357 (2004)
HF+corr H.Sagawa et al PLB **286** (1992)
COSM T. Myo et al, PRC **76** ('07); PRC **80** (09)
GSM11 G. Papadimitriou PRC **84** ('11)

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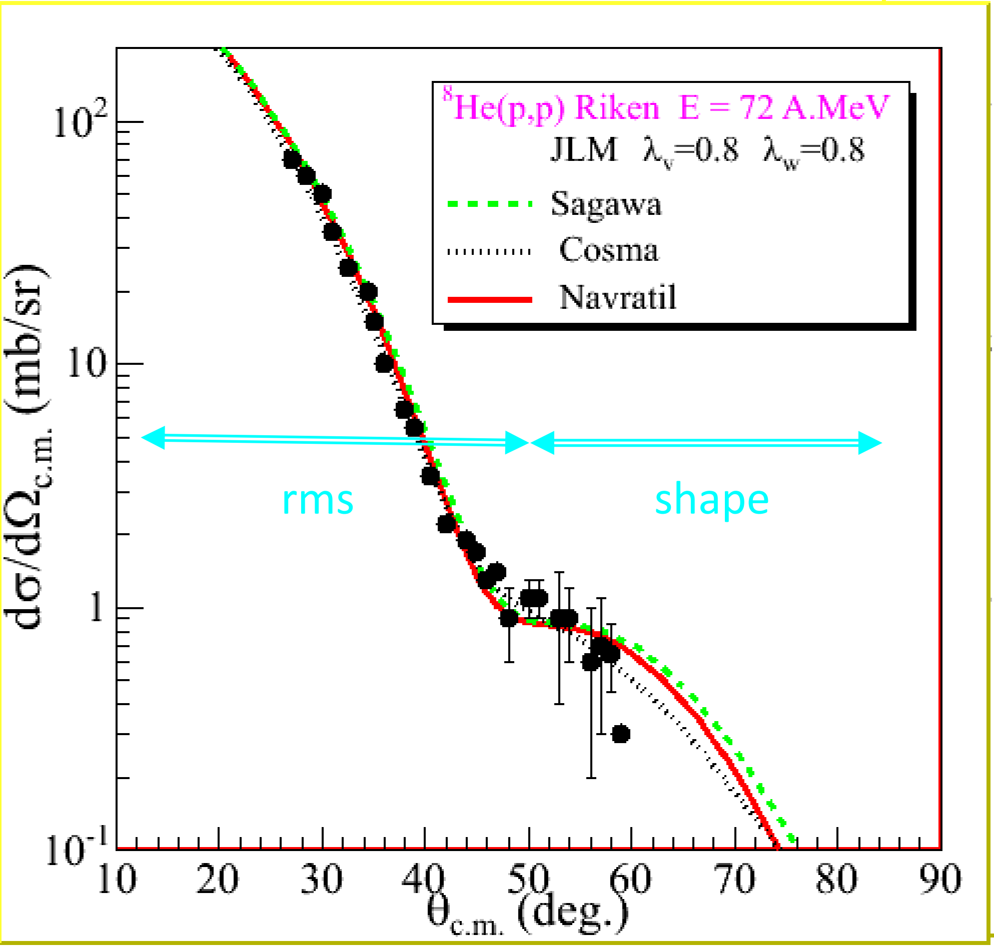
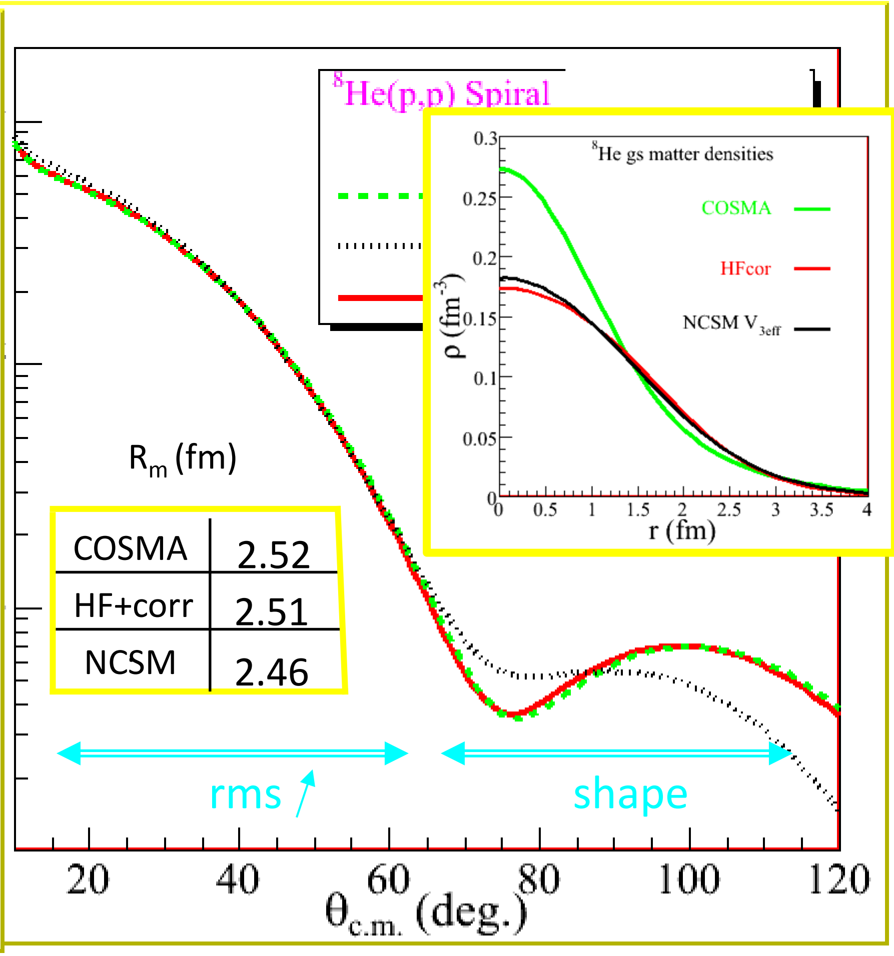
Nuclear matter radii via (p,p) scattering

Analysis of elastic ^{8}He(p,p) within optical model framework

$$U_{JLM}(^8He+p) = \lambda_V V + i\,\lambda_W W$$

Reduction of the real part due to a repulsive surface term generated by couplings $\lambda_V = 0.8$; $\lambda_w = 0.8$



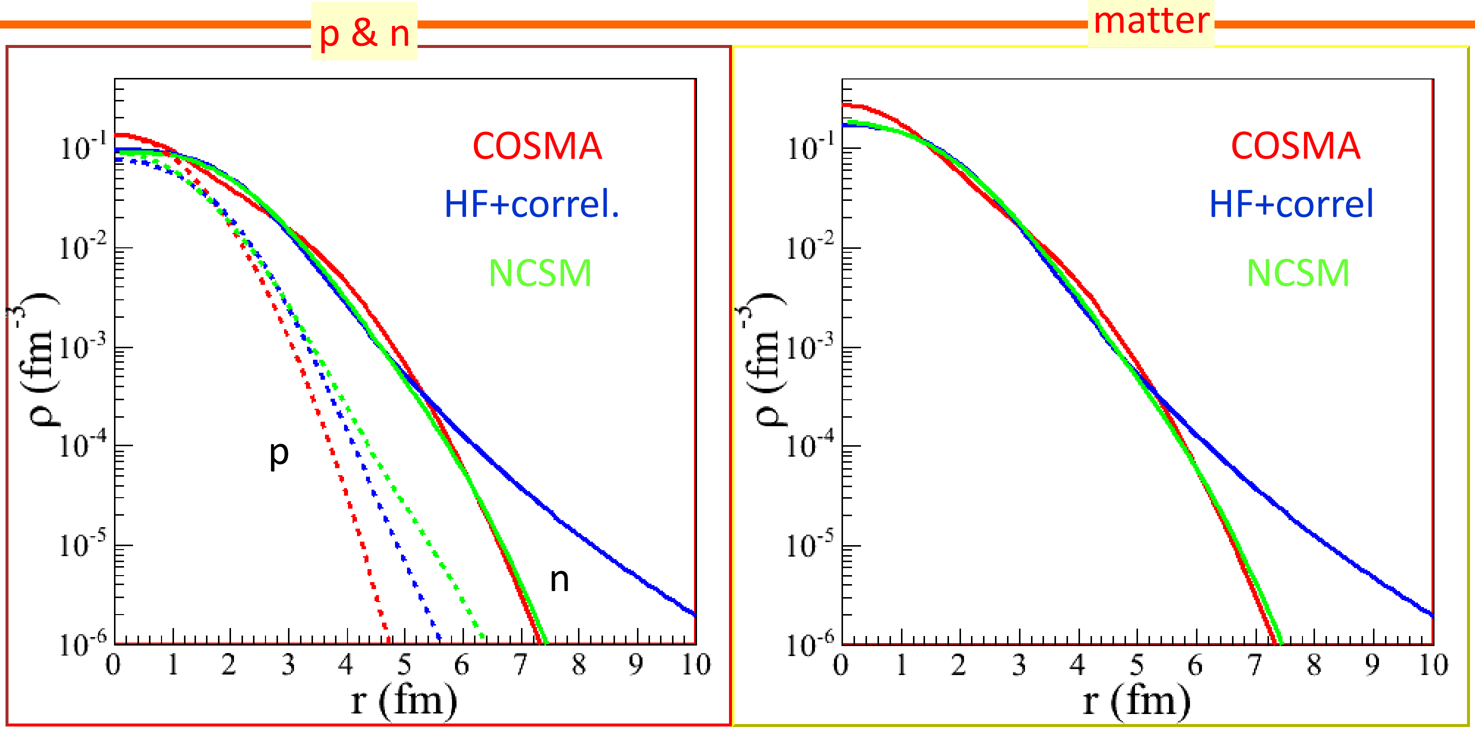


R_m (fm)

COSMA	2.52
HF+corr	2.51
NCSM	2.46

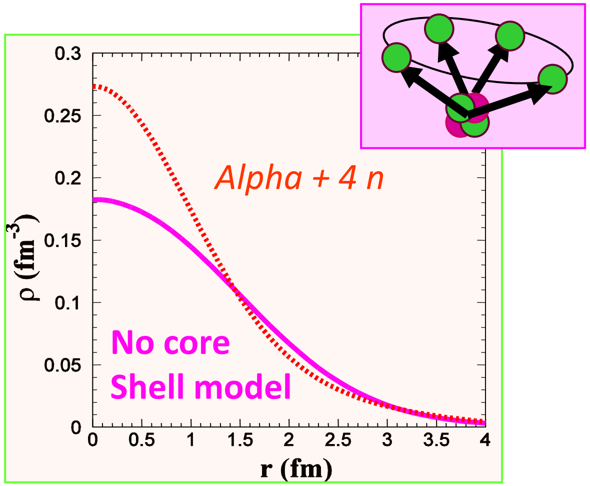
V. Lapoux and N. Alamanos, EPJA **51** 91 (2015).

Densities of ^{8}He: to be tested via (p,p) scattering



p & n

matter



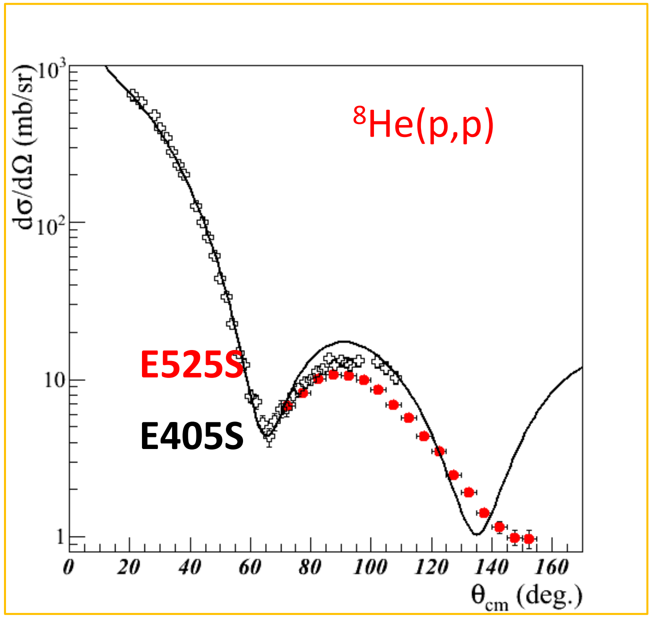
COSMA: M.V. Zhukov, A.A Korsheninnikov and M.H Smedberg, PRC 50 (1994) R1

HF+Correlations: H. Sagawa, PLB 286 (1992) 7

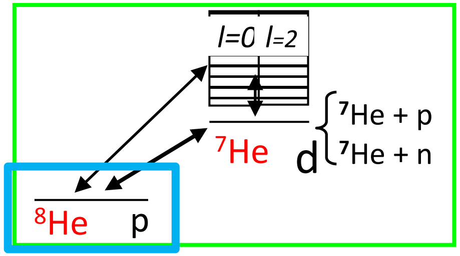
NCSM P. Navratil, priv. Co.+ PRC (98)

^{8}He	Rms (fm)		
	Proton	Neutron	Matter
COSMA 5-body	1.69	2.74	2.52
HF+corr Sagawa	1.95	2.67	2.51
NCSM, Navrátil	2.00	2.59	2.46

Comparisons EXP-theory for all the data sets of ^{8}He+p



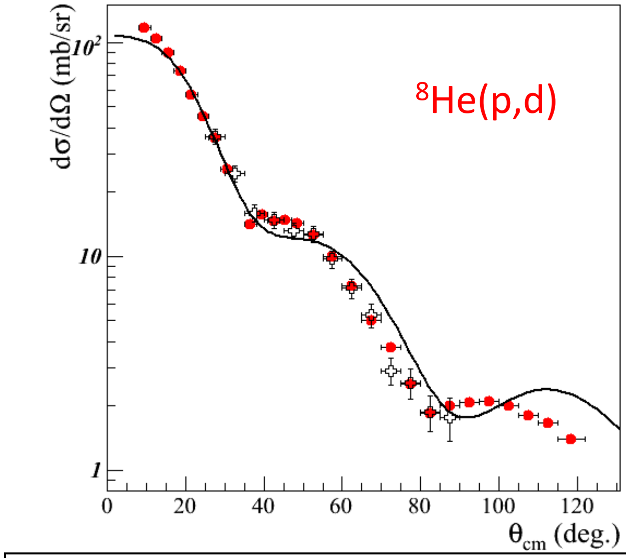
Pick-up effects on the
^{8}He(p,p) .Data +CRC:
PLB **619**, 82 (2005)

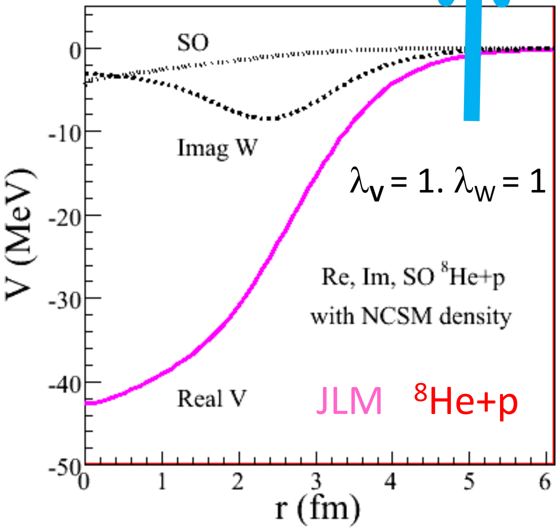


Effective coupling potential obtained from CRC with JLM

$U_E = V_{00} + VCP$

$[\lambda_v V + i\,\lambda_W W]$+PotCRC





$\lambda_V = 1.05$
λ_W **= 0.2**

"Remaining" W:
CC, CRC, CN effects

EPJA **51: 91** (2015)

E525S data (MUST2) and CRC calculations (N. Keeley) + OMP JLM (V.L.) PLB **718,** 441 ('12)

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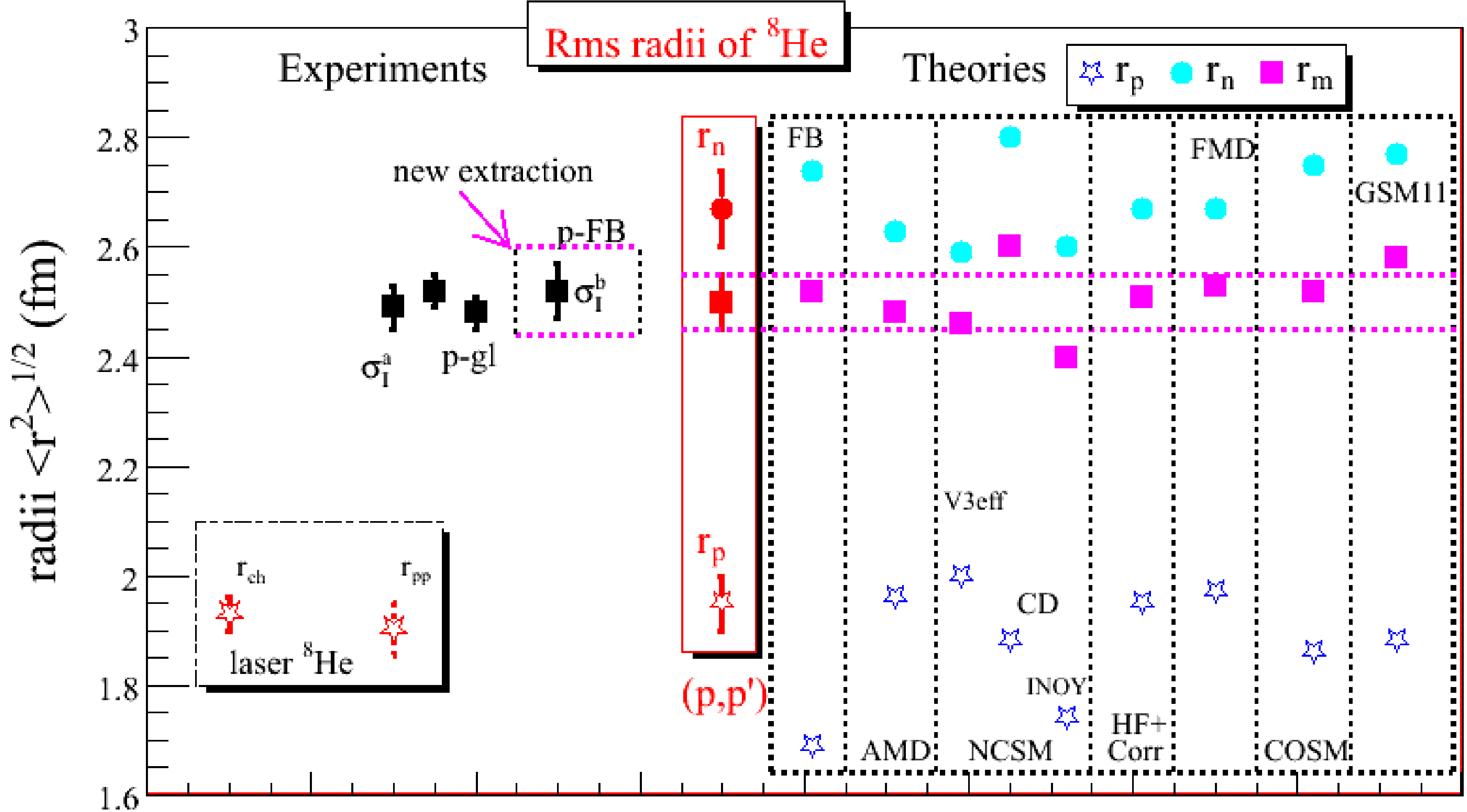
Experiment versus theories for proton and matter radii

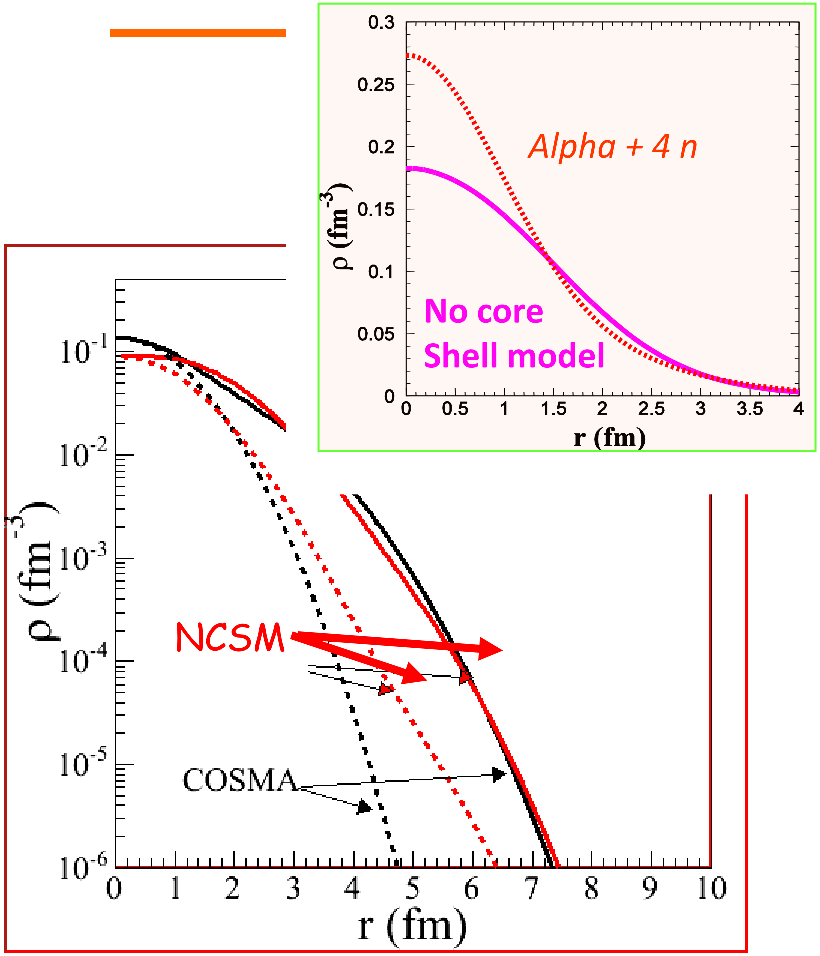
(p,p') analysis *EPJA* ***51****, 91 (2015) - cf ref therein for exp/theory*



Laser L.B. Wang et al., PRL 93, 142501 (2004). P. Mueller et al., PRL 99, 252501 (2007). M. Brodeur et al., PRL. 108, 052504 (2012).

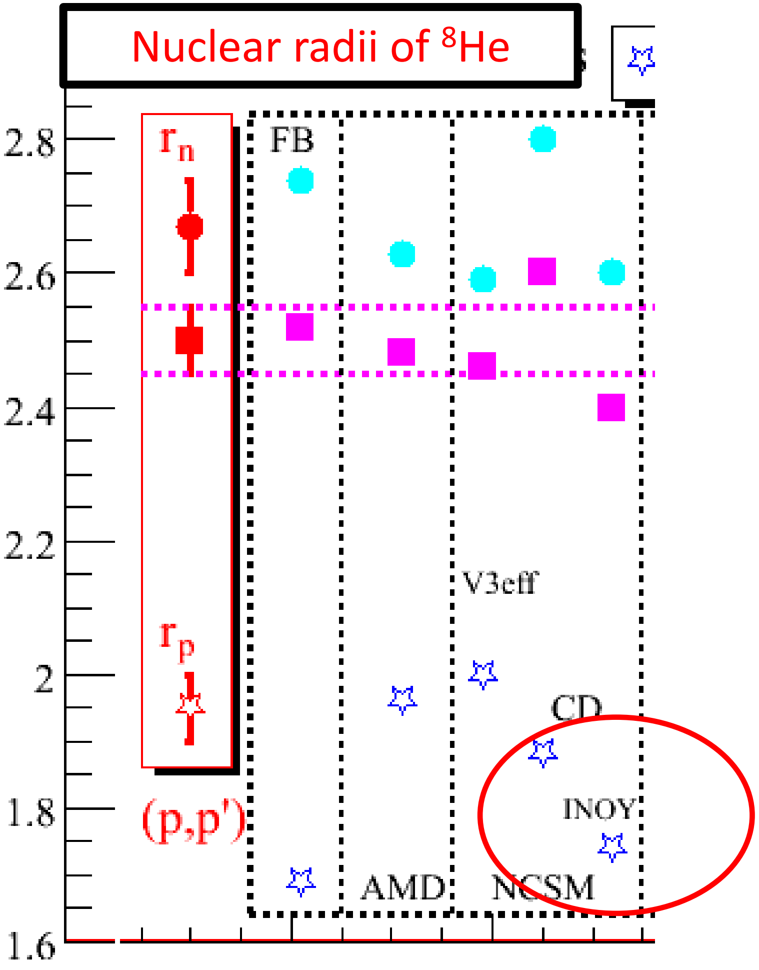
p-gl G.D. Alkhazov et al., PRL 78, 2313 (1997).
p-FB J. Tostevin, J. Al-Khalili, NPA 616, 418c ('97). PRC 57, 1846 ('98)
σ A. Ozawa, T Suzuki, I. Tanihata NPA **693**, 32 (2001)

AMD-m56 K. En'yo PRC **76** ('07)
FMD T. Neff, H. Feldmeier, NPA **738,** 357 (2004)
HF+corr H.Sagawa et al PLB **286** (1992)
COSM T. Myo et al, PRC **76** ('07); PRC **80** (09)
GSM11 G. Papadimitriou PRC **84** ('11)



P. Navratil, priv. co
NCSM (No Core Shell Model) (*V3eff 4hw, 13MeV*)

Nuclear radii of ^{8}He

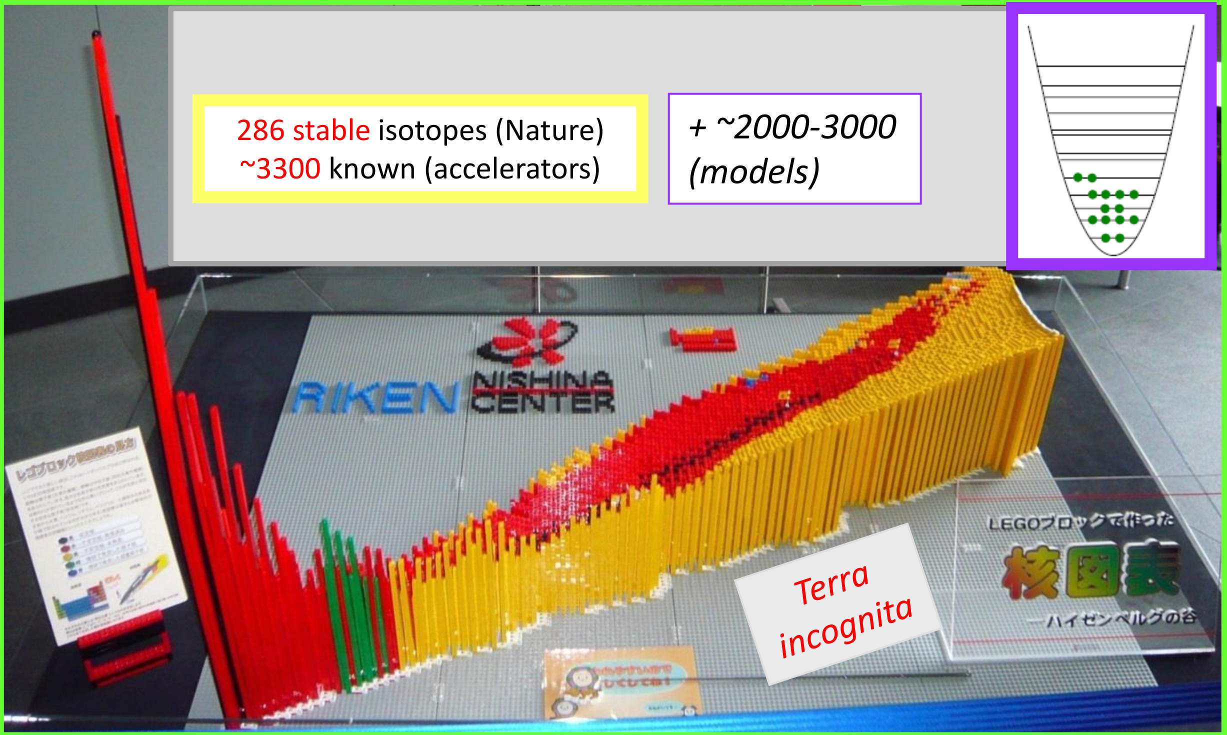


Attraction of the protons outside from the Alpha core:
p-n interaction stronger with NCSM than with COSMA

Comparison Experiment- *ab-initio* calculations to test interactions between nucleons

Matter radii of Oxgen isotopes

experiment

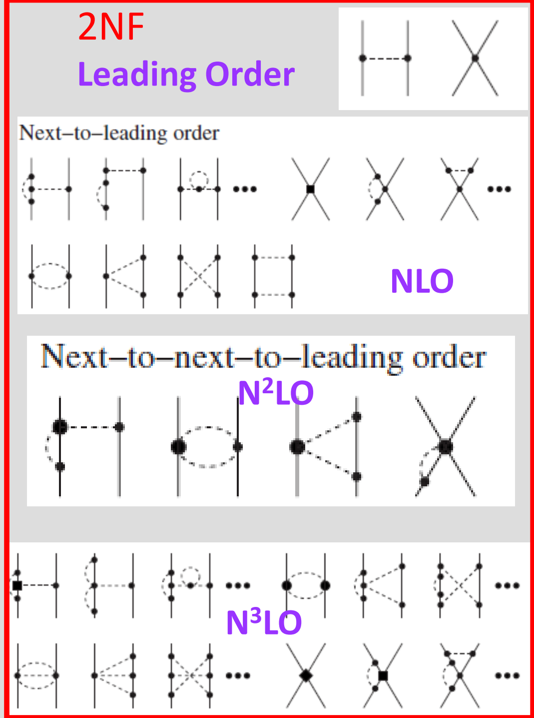


286 stable isotopes (Nature)
~3300 known (accelerators)

+ ~2000-3000 (models)

Terra incognita

ab-initio



2NF
Leading Order

Next–to–leading order

NLO

Next–to–next–to–leading order
N^2LO

N^3LO

3NF Leading order
+ NLO +N^2LO

Weakly-bound systems, large asymmetry
→ constraints on the models

Observables?

Masses ←→ Binding energies

Sizes ←→Nuclear rms radii r_{ch}, r_m

Oxygen isotopes radii via (p,p)

Work group. DPhN: Vittorio Somà, V.lx (exp) + theorists: C. Barbieri, H. Hergert, J.D. Holt, S. R. Stroberg

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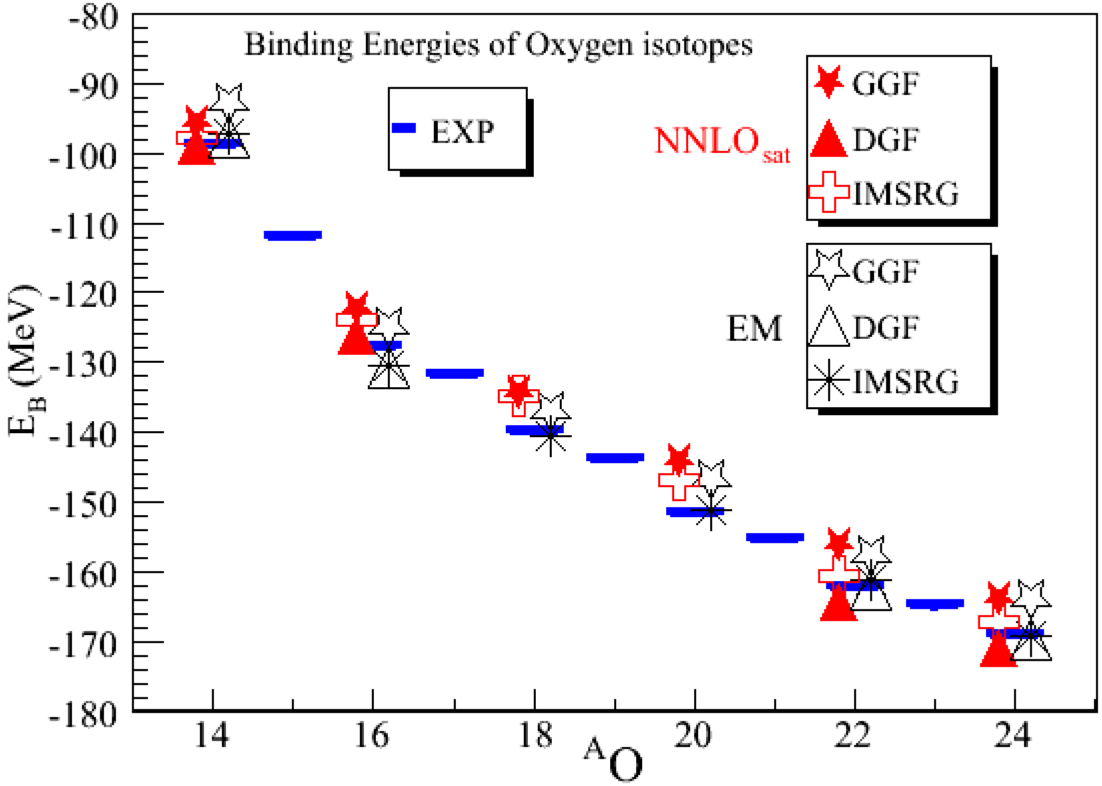
Ab initio calculations of the binding energies - tests of two chiral interactions

2 methods using microscopic interactions
V. Somà, C.Barbieri, R. Stroberg, H. Hergert, J.D. Holt *PRC 84 ('11), PRC 87 ('13) PRL 110 ('13) …*
self-consistent Green's function (SCGF) | *in-medium similarity renormalisation group* (IM-SRG).
2 potentials :
-Classical chiral potential **EM** *D. R. Entem and R. Machleidt, Phys. Rev C* ***68****, 041001 (2003)*
with standard adjustment of coupling constants (on data for *A = 2,3,4*)
-New one, different strategy **NNLO$_{sat}$** (constants also adjusted on ^{12}C et ^{16}O r_{ch} E_B). *PRC* ***91****, 051301 (2015)*



Consistent results
Experiment-theory
Up to ^{24}O

Binding energies are tested for various methods, interactions…

Nuclear radii ?

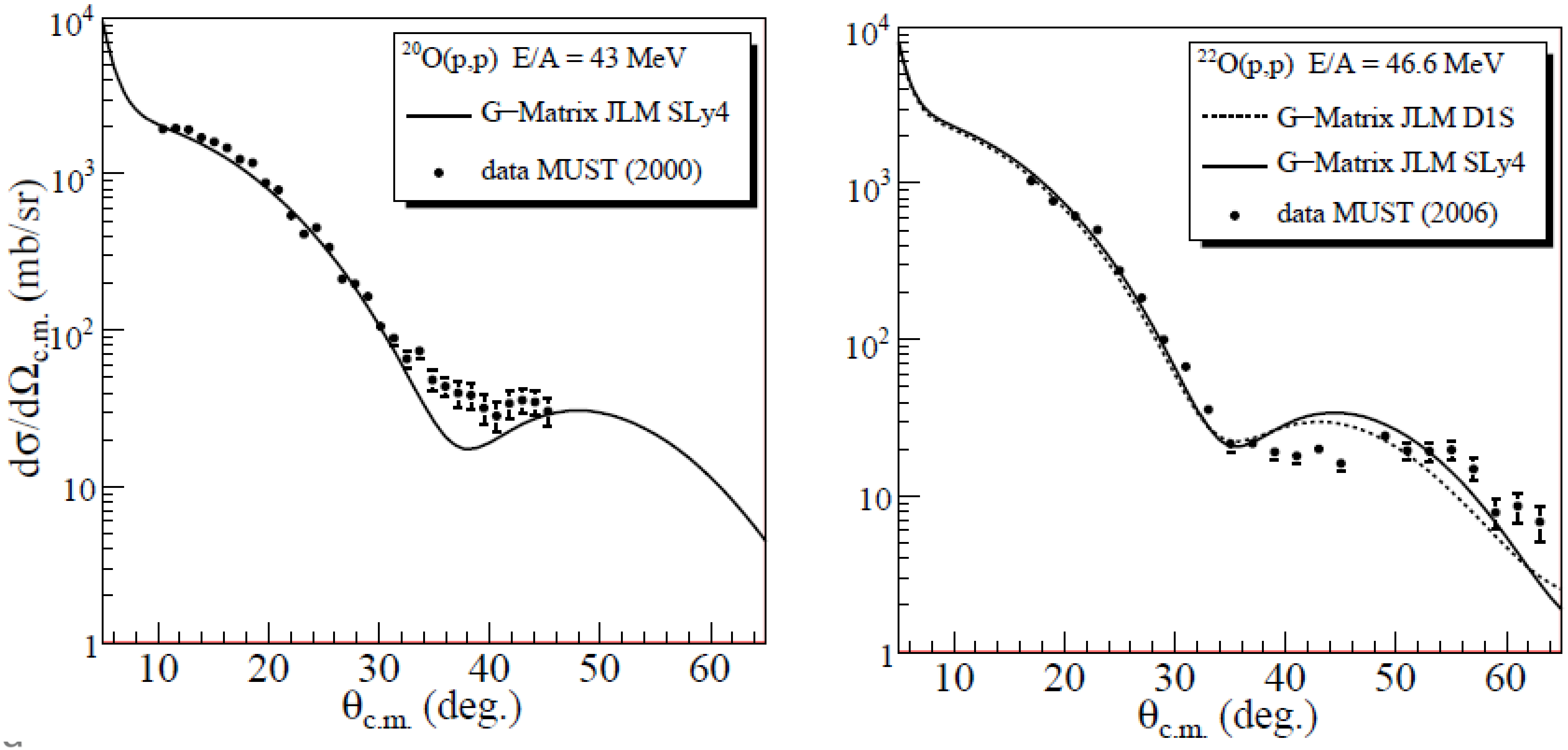
PRL **112**, 052501 (2016) , *V. L, V. Somà, C. Barbieri, H. Hergert J.D. Holt, S.R. Stroberg*

Evaluation of the experimental rms matter radii

Observables for nuclei: stable, **(e,e)** → ρ_{ch} → ρ_p **; (p,p)** → ρ_m
Exotic weakly-bound nuclei, (p,p) analysis → evaluation of r_m radii
Experimental methods MUST1 & 2 ; ex: ^{6,8}He(p,p) EPJA 51, 91 (2015)
(data MUST@GANIL) ^{18,20}O PLB **490**, 45 ('00) ; ^{22}O PRL **96,** 012501 ('06).
U(ρ,E) JLM analysis ^{18,20,22}O(p,p): **this work** *(V.L)* **; first step:** D1S+SLy4 test densities

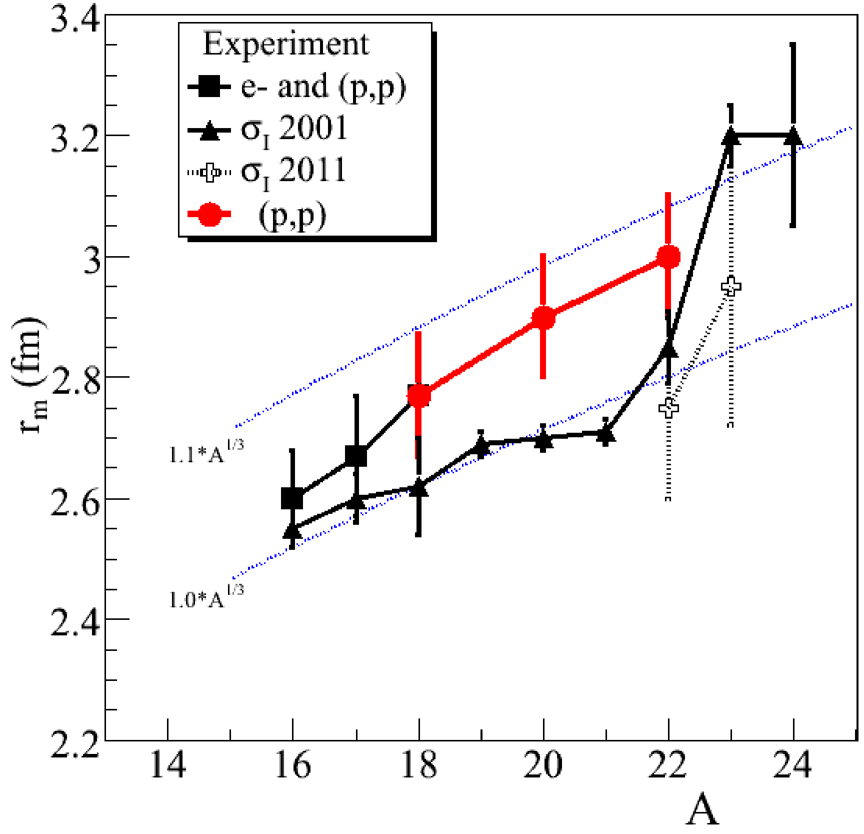
^{20}O(p,p)

^{22}O(p,p)



^{18,20,22}O(p,p) JLM analysis: PRL **112**, 052501 (2016)

Experimental values of the matter radii

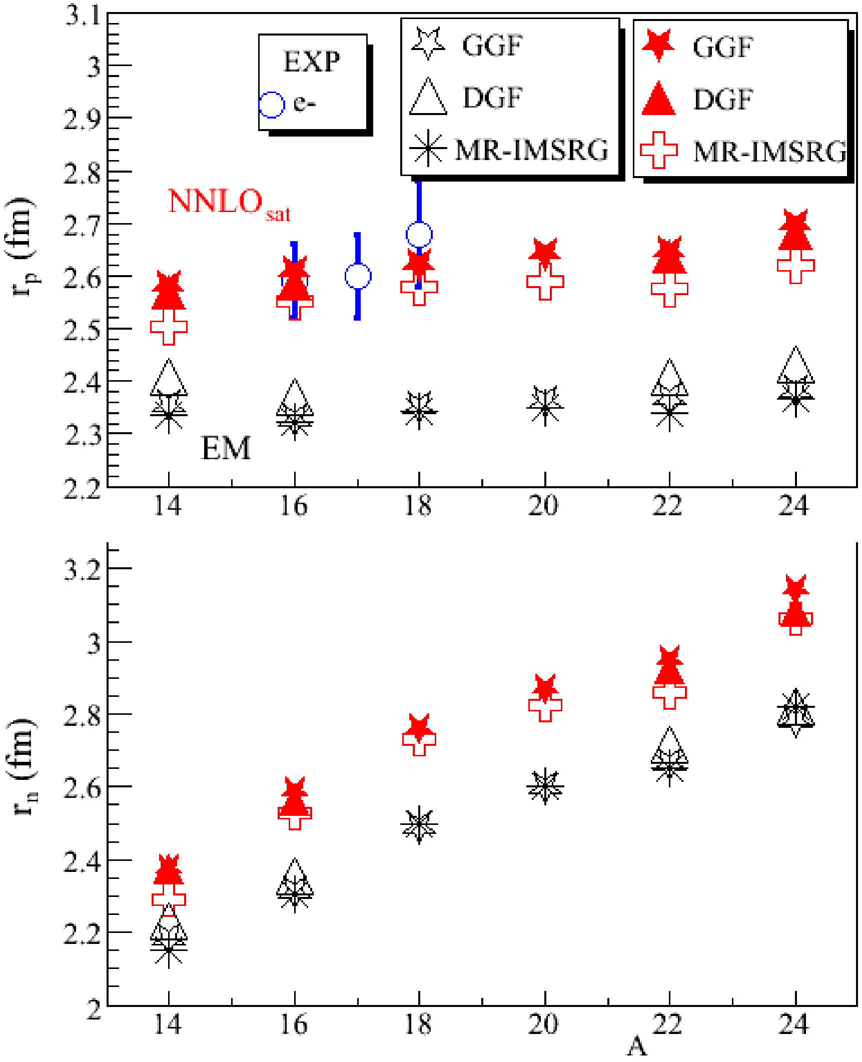


A	16	17	18	20	22
r_p	2.59 (7)	2.60 (8)	2.68 (10)		
r_m (σ_I)	2.54 (2)	2.59 (5)	2.61 (8)	2.69(3)	2.88(6)
r_m (p,p)	2.60 (8)	2.67 (10)	2.77 (10)	2.9 (1)	3.0 (1)

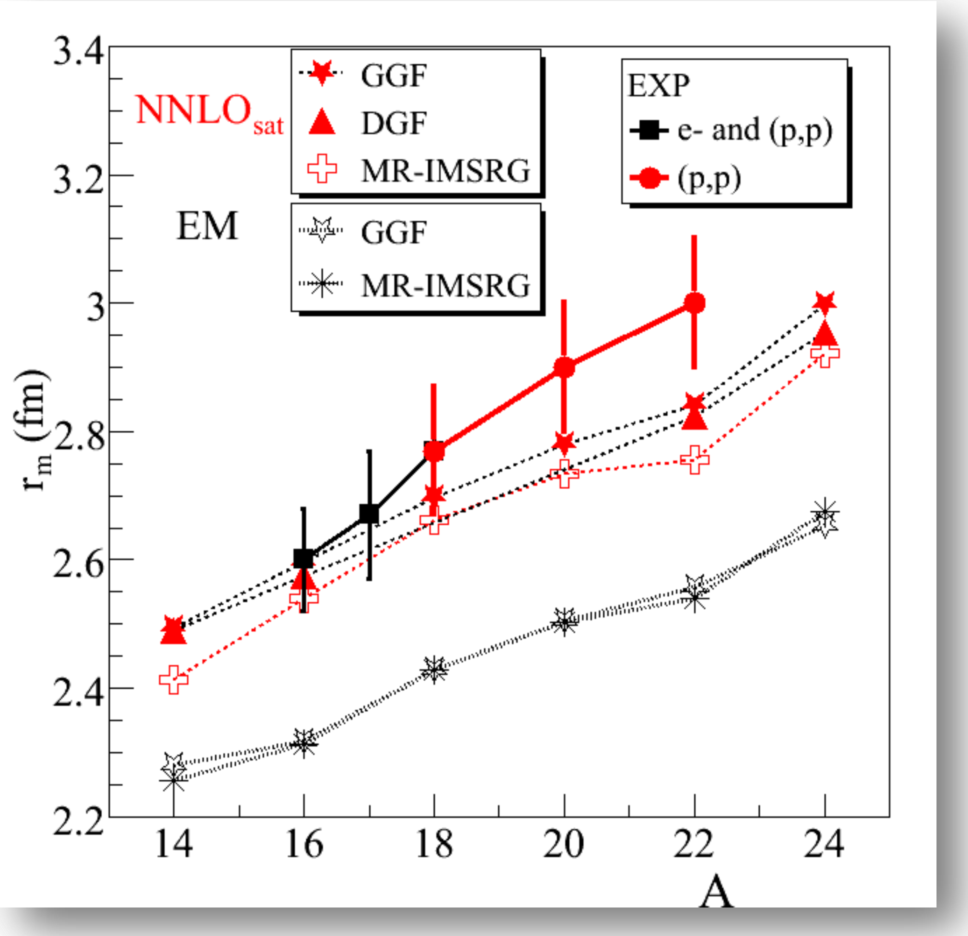
Observables for exotic nuclei :
From reaction analysis of ^{20,22}O(p,p)
(*data MUST@GANIL*)
evaluation of r_m radii for $^{16-22}$O Vlx (HDR)

Data
σ_I *A. Ozawa, T Suzuki,*
*I Tanihata NPA **693**, 32 (2001);*
new: *R Kanungo et al*
*PRC **84**, 061304 (R) (2011)*
(p,p) JLM analysis: this work

Calculated versus experimental proton, neutron and matter radii



State-of-the-art *ab initio* calculations: V. Somà, C. Barbieri, H. Hergert J.D. Holt, S.R. Stroberg



PRL **112**, 052501 (2016)
V. Lapoux, V. Somà, C. Barbieri,
H. Hergert J.D. Holt, S.R. Stroberg

Possible explanations?
Missing terms in the (N^{2}LO, N^{3}LO) developments of the EFT chiral forces…

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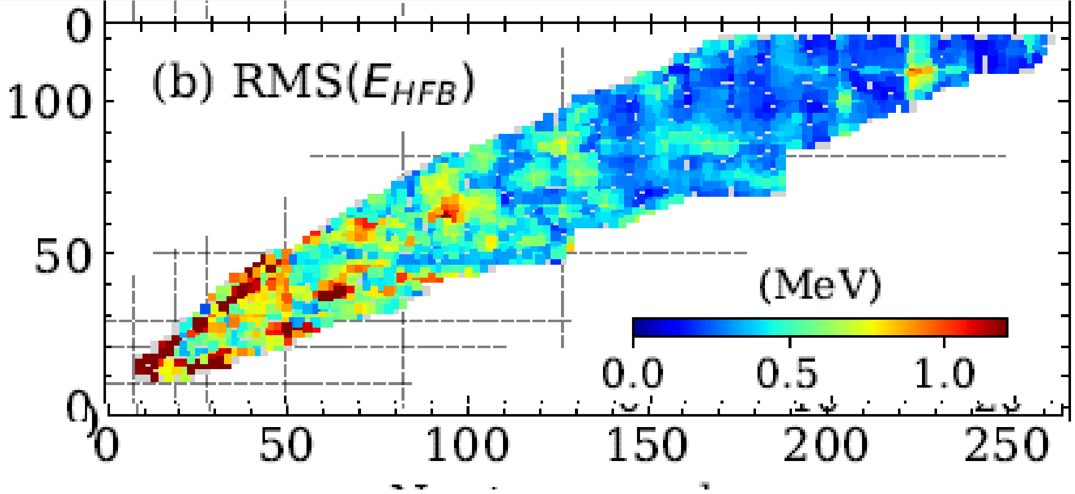
Nuclear chart Website (available during 2020) nucleAI.cea.fr

- → Egs, Rm, Rch, spectra, PES,… for various interactions
- → Z,N Plots for calculated observables
- → Comparison between exp-theory, theory-theory



"…we propose a general method to perform fast-scale many-body predictions applied to Nuclear Structure using Multi-Task Deep Learning. (…) **We demonstrate that deep neural networks trained on Hartree-Fock-Bogoliubov variables can predict physical observables such as nuclear spectra with a good accuracy and a 10 speed-up factor relative to other usual approaches…"**

Taming nuclear complexity
with a committee of deep neural networks
To be submitted to PRL
R.D.Lasseri (CEA,ESNT), D. Regnier (ENS Paris-Saclay), J.-P. Ebran (CEA DAM), A. Penon (Magic LEMP, Orsay).

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Experiment- theory *ab-initio* calculations of matter radii r_m

Summary

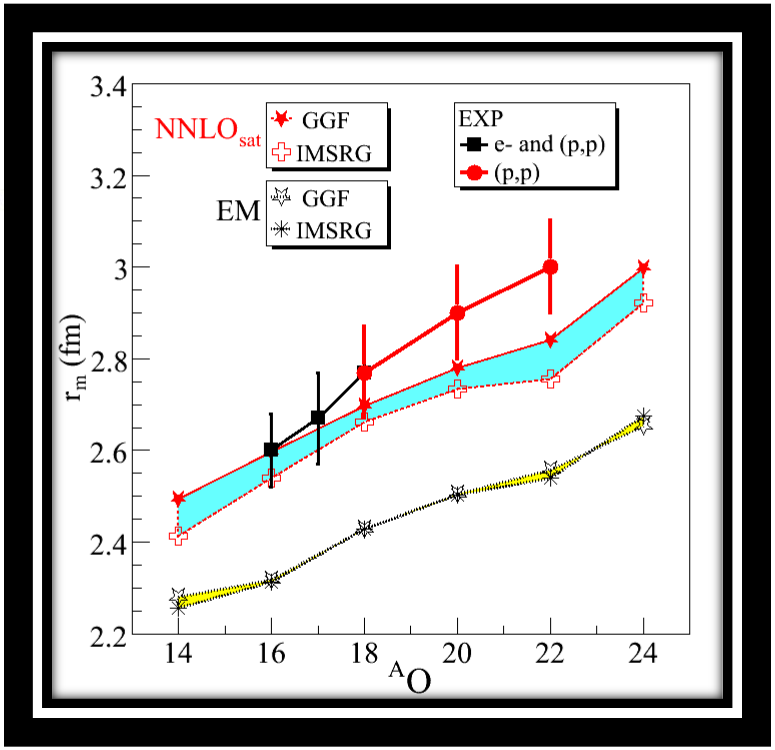
State-of-the-art *ab-initio* calculations
Various technics, 2 interactions : EM, NNLO_{sat}
→E_B **and matter radii**

(p,p) microscopic OMP analysis →r_m
- from (e,e) & (p,p) *data for stable nuclei*
- exotic from (p,p) MUST-GANIL data

Conclusions

→ Crucial role played by the r_m observable for the test of the interaction is underlined

Using matter radii as benchmarks for theories
Evolution of the choices of interactions?



PRL **117**, 052501 (2016)

Perspectives

→Improvements of the reliability of *ab initio* calculations for properties towards driplines, beyond Z = 8, selecting fundamental **observables like radii.**

More reliable calculations of radii also needed

→To have quantitative evaluation of the properties of very-neutron nuclei, today not accessible experimentally nor in far future

→ To reach quantitative estimate of reaction rates with microscopic structure inputs

→ key benchmark-necessary step to build an unified model for structure & reactions.

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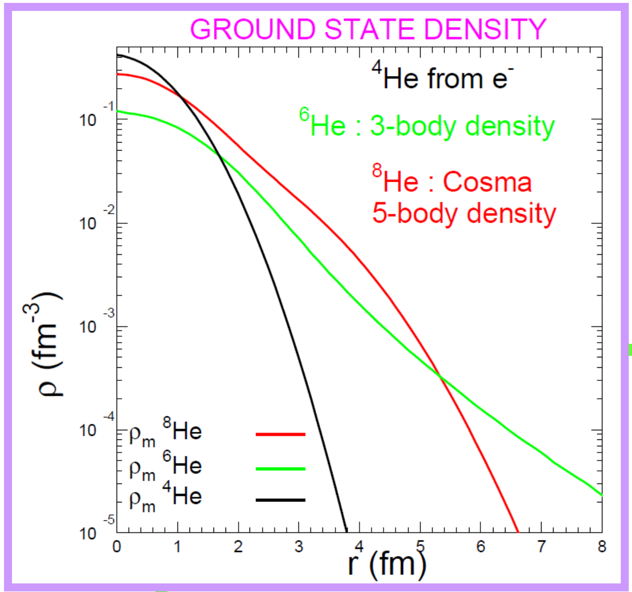
Comments



Long-term goals for experimental nuclear densities: charge &matter profiles for RI as done for stable nuclei

Limitations due to achievable luminosity;
physics cases limited to radii, for nuclei close to the valley of stability

Ab-initio results are compared to exp. charge & matter radii
There are some troubles in the force…or in the concept
Look also at EDF results
which are encoding the nuclear properties in an effective way

Soon (2020): website nucleAI.cea.fr to compare EDF calculations (with various interactions) and theory versus exp. → *Nuclear observables Eb,Rch, spectroscopy…*
-Perspectives for combined e-& (p,p) scattering?
→We need to look back at the (e,e)& (p,p) data using modern structure &reaction model calculations to extract the nuclear densities
→Check the limits of RI nuclei reached via both techniques

Questions: evaluation of the exp. data for rms radii + uncertainties related to the microscopic interaction used for the (p,p) reaction models, whatever the nucleon energy? In the case of the radioactive exotic nuclei, how to deal with the weak-binding effects?

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