Colloquium at Texas A&M University, Commerce.
31 January 2019

Quark-Meson-Coupling Model for Finite Nuclei Nuclear Matter and beyond

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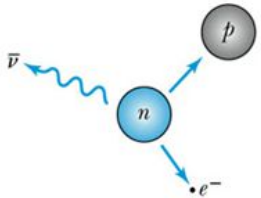
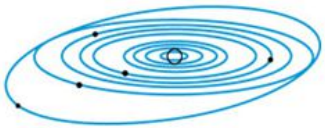
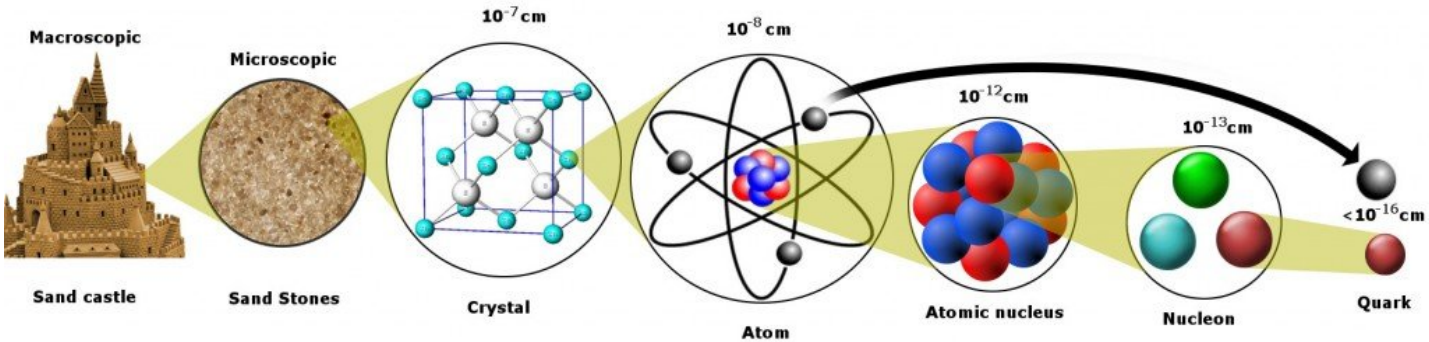
The Fundamental Interactions

Strong force	Electromagnetic force	Weak force	Gravitation
Gluons	Photon	W and Z bosons	Graviton?
Atomic nuclei Fission and fusion Quark structure of proton and neutron	Atoms and molecules Chemical reactions Light waves Electronics	Neutron decay Beta radioactivity Muon and tau decay Neutrino interactions	Solar system Galaxies Curved spacetime Black holes



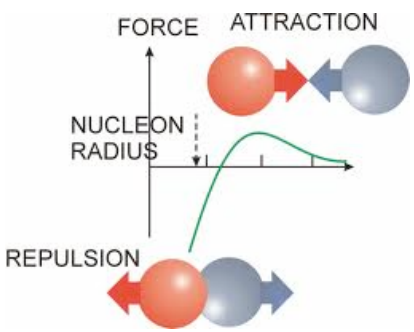




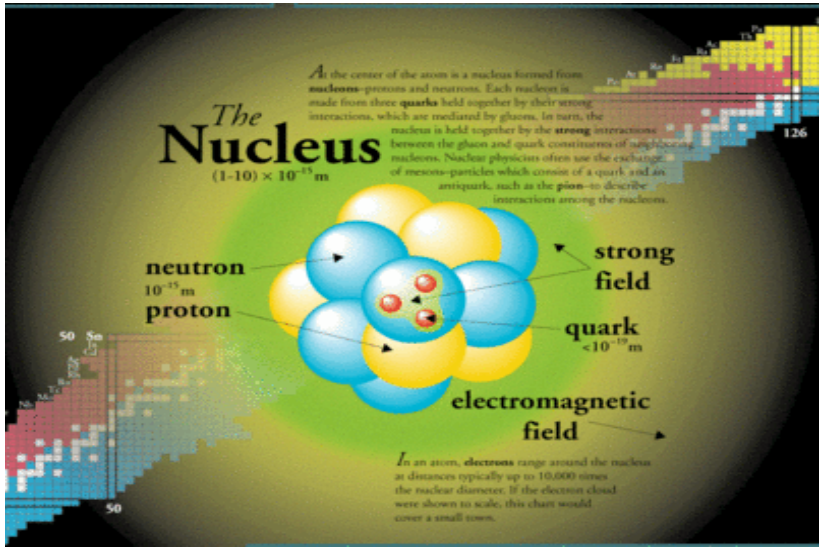


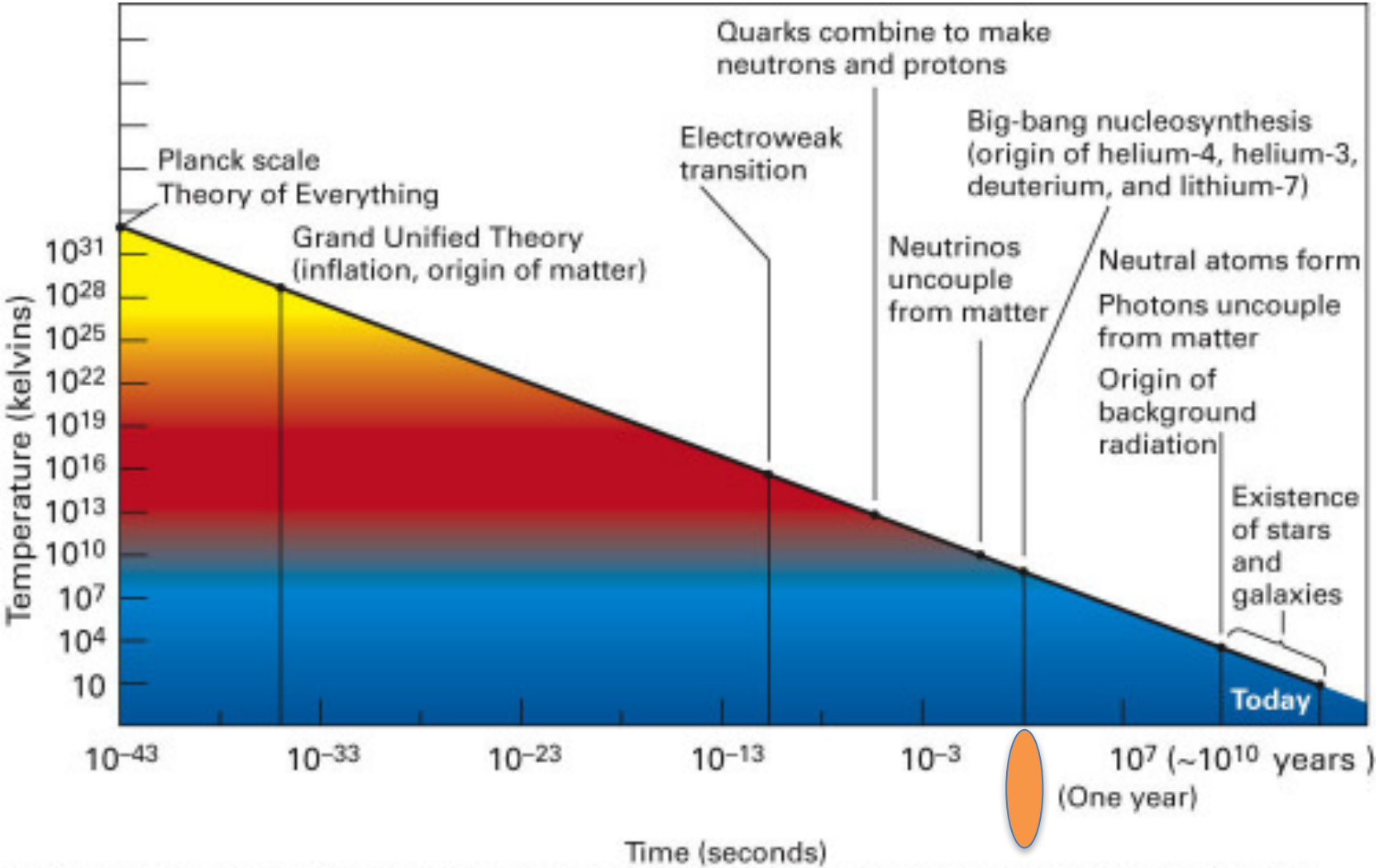
Nuclear force is not fundamental !!

Two nucleons:
nucleon-nucleon scattering
tractable with many parameters
no unique model as yet

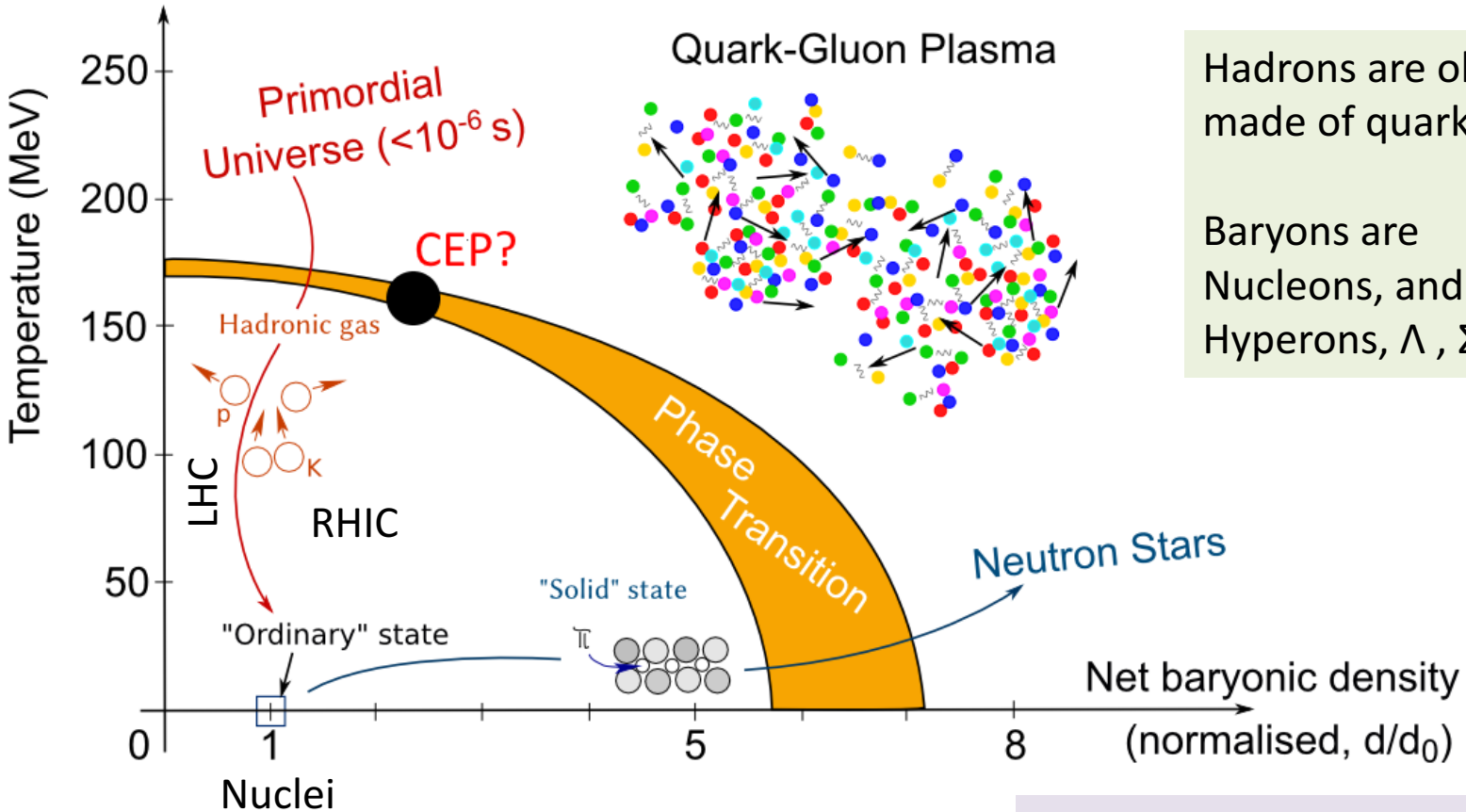


Many nucleons: force depends on density and momentum –
strong, electro-weak interactions play role as well as sub-nucleon structure





(Adapted from "Particle Accelerators Test Cosmological Theory" by David N. Schramm and Gary Steigman. © 1988 by Scientific American, Inc. All rights reserved. Drawn by Andrew Christie.)



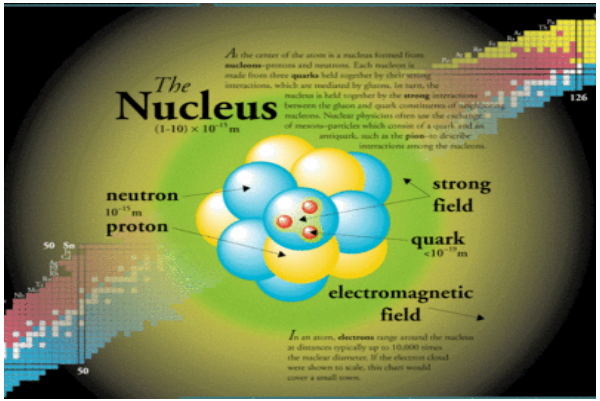
Hadrons are objects made of quarks

Baryons are Nucleons, and strange Hyperons, Λ , Σ, Ξ

d density normalized to nuclear density d_0= 0.16 fm^{-3}

NUCLEON-NUCLEON INTERACTION IN NUCLEAR MEDIUM:

NUCLEAR MANY-BODY PROBLEM (NMBP)



Forces and potentials derived from free nucleon systems do not work directly in finite nuclei

No exact direct solution of the NMBP possible – approximation have to be sought

Do we have enough constraints to uniquely determine parameters of existing theories?

Do we believe this is a relevant question?

Astrophysics
Neutron stars
Supernovae
Nuclear synthesis
Star evolution
Early Universe
Gravity waves

Nuclear matter:
Cold and hot:
Symmetric
Asymmetric
Pure neutron

Nuclei and particles
Nuclear structure
Nuclear reactions
Fusion and fission
Heavy ion collisions:
Range of energies

Outline of the talk:

Two approaches to the problem:

1 Construction of models with **enough variable parameters** to reproduce experiment with less regard to physical content of the model

Examples: density dependent energy functional, realistic potentials, ab-initio models, one-boson-exchange relativistic models

2 Construction of models with **limited number of parameters** strongly constrained by theory and seek agreement with experiment by physical content

Example: Quark meson coupling model

Astrophysics and nuclear matter

Infinite dense matter:

System of an infinite number of interacting particles in an infinite volume with a finite ratio of a number of particles per unit volume.

No Coulomb force present – no surface effects –
- translational invariance

interior of neutron stars, core-collapse supernovae, possibly large heavy nuclei

Testing theories under simplified conditions

Phases of nuclear matter:

Symmetric (equal number of protons and neutrons)
Asymmetric (unequal)
Pure neutron

Symmetric matter has at density ρ_0 = 0.16 fm^{-3} :

Bound state (E/A)	=	-16 MeV
Symmetry energy $E/A(_{sym})-E/A(_{pn})$	=	30 - 32 MeV
Slope of the symmetry energy L	=	40 -100 MeV
Incompressibility: traditional K	=	240+/-30 MeV
NEW VALUE		250 – 315 MeV

Stone at al., PRC 89, 044316 (2014)

The Equation of State (EoS):

Ideal gas:

Ludwig Boltzmann
1844 - 1906

Average pressure :

$$p = \frac{1}{3}\frac{N}{V} m \bar{v}^2$$

N # of molecules of mass m in volume V

Average molecular kinetic energy :

$$\left\langle \frac{1}{2} m v^2 \right\rangle = \frac{3}{2} kT$$

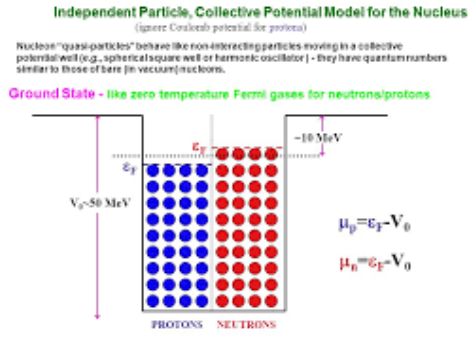
k Boltzmann constant, T temperature

Equation of State

$$p = \frac{NkT}{V} = \varepsilon(\rho, T)$$

ε total energy density of gas with number density $\rho = \frac{N}{V}$

Nuclear matter:



$$P = \varepsilon(\rho,T) \qquad \varepsilon(\rho,T) = \sum_f \left(\frac{E}{A}(\rho,T)\rho \right)_f \qquad \mu_B = (P+\varepsilon)/\rho$$

Two key points:

I. **The EoS is dependent on composition**
CONSTITUENTS + INTERACTIONS

II **E/A and ITS DENSITY DEPENDENCE**
must be determined by nuclear and/or particle models.

Realistic bare nucleon

20-60 adjustable parameters

Several thousands of data points:
Free nucleon-nucleon scattering and properties of deuteron

Used in nuclear matter calculations, shell model, ab-initio theories

NO DENSITY DEPENDENT FURTHER TREATMENT NEEDED TO USE IN NUCLEAR ENVIRONMENT

Phenomenological density dependence

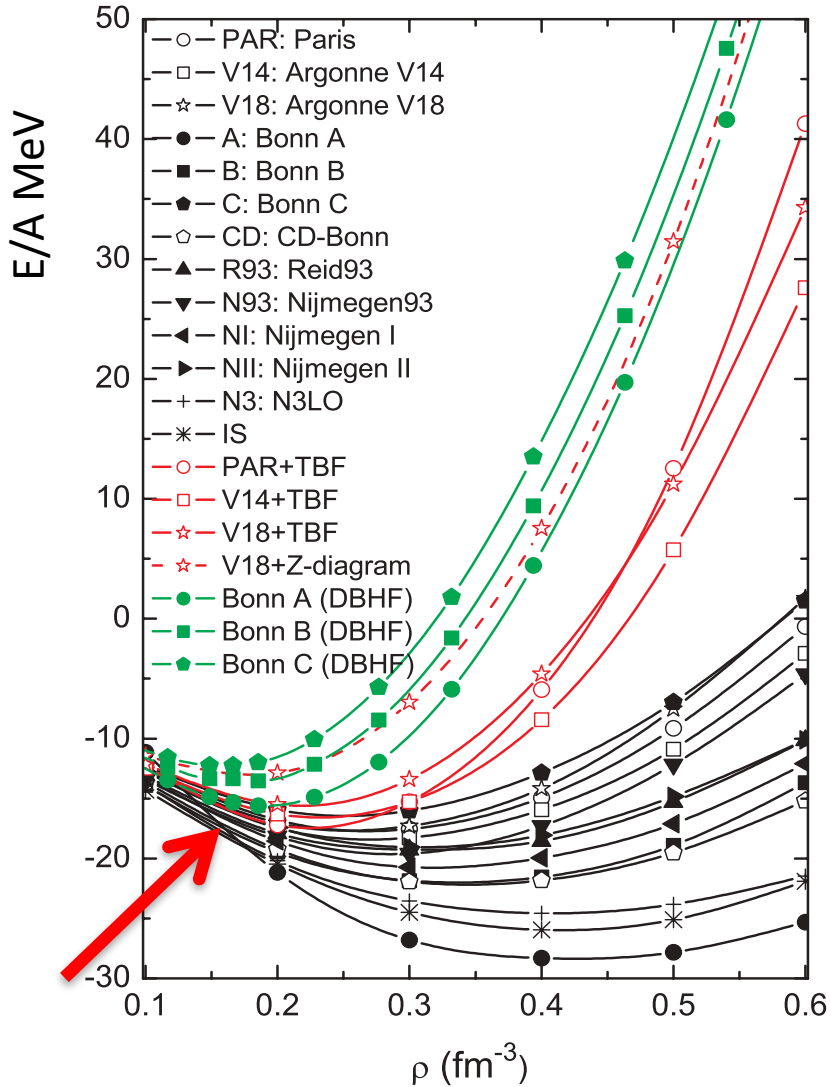
10-15 adjustable parameters

Several tens of data points:
Symmetric nuclear matter at saturation, Ground state properties of finite nuclei

Used in mean-field models non-relativistic Hartree-Fock

DENSITY DEPENDENCE INCLUDED IN AN EMPIRICAL WAY THROUGH PARAMETERS

Ab-initio techniques



BINDING ENERGY PER PARTICLE IN SYMMETRIC NUCLEAR MATTER

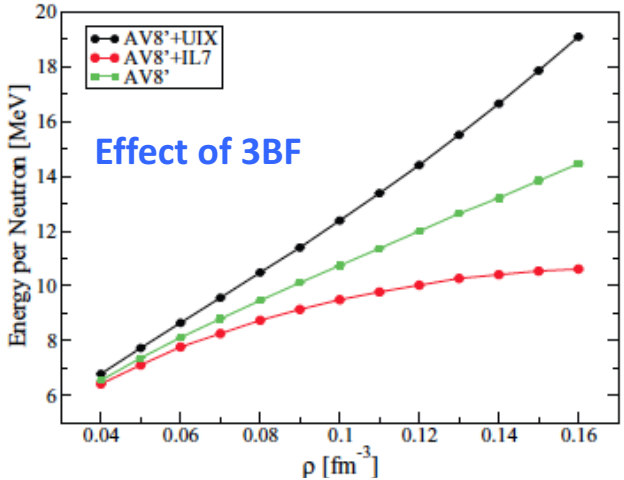
Li et al., PRC74, 047304 (2006)

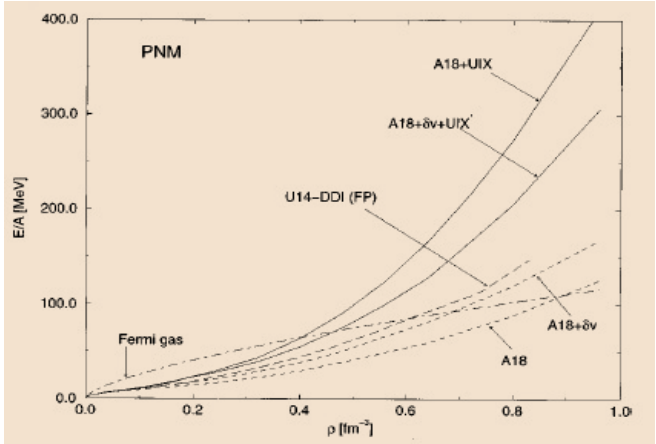
"Realistic" models obtained from free nucleon scattering and renormalized to nuclear medium.

NOT CALIBRATED TO SYMMETRIC NUCLEAR MATTER PARAMETERS.

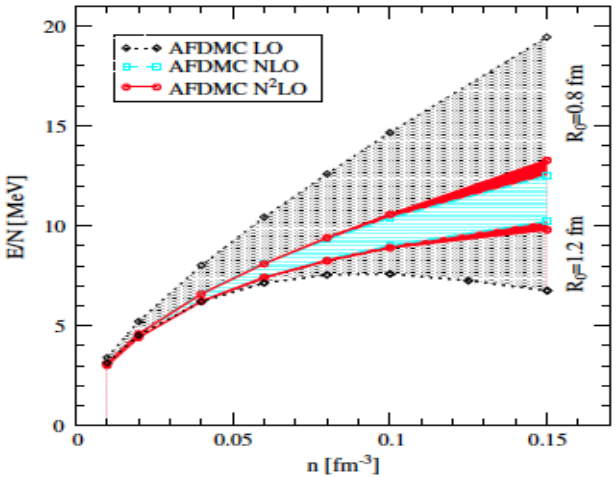
EoS of pure neutron matter as calculated in different models

Maris et al., PRC 87, 054318 (2013)

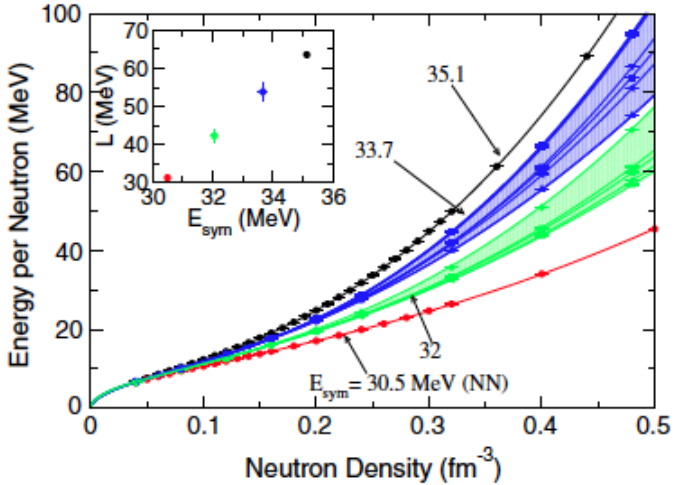




Akmal et al.,PRC58, 1084 (1998)



Gezerlis et al., PRL 111,032501 (2013)



J. Carlson et al. Rev. Mod. Phys. 87, 1065 (2015)

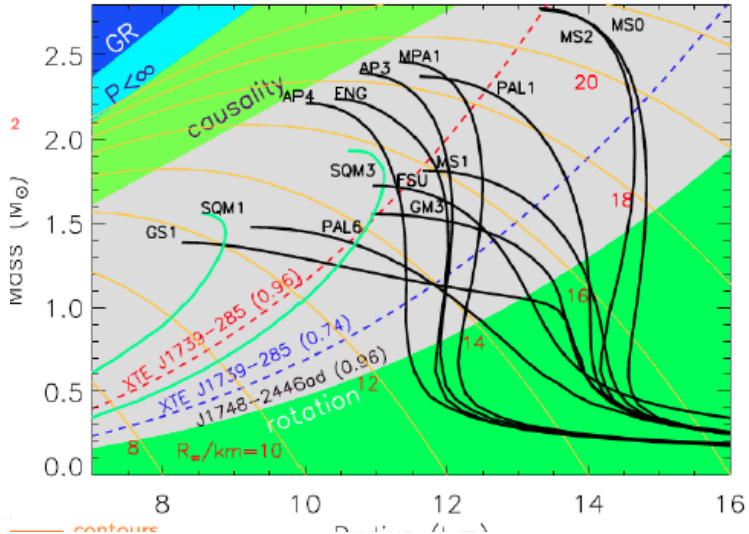
Neutron stars:

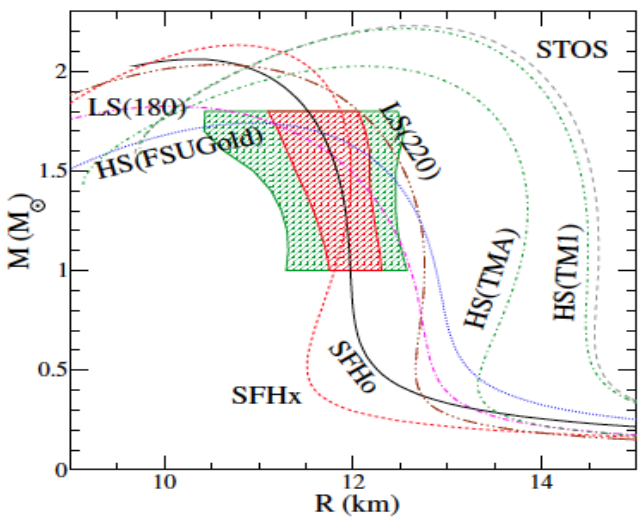
Masses are measured well – 2 solar mass
Radii are difficult and uncertain
Moments of inertia not available as yet
Gravitational waves signals not fully constraining

Models yield only mass as function of radius
Composition of the star uncertain but crucial for determination of the EoS

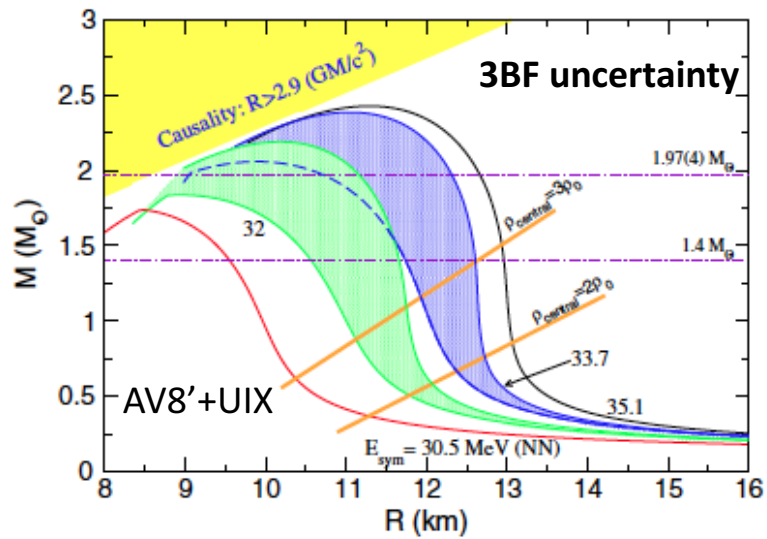
EOS CRITICALLY DEPENDENT ON NUCLEAR/PARTICLE MODELS

From J.M.Lattimer





Steiner et al., ApJ774:17 (2013)

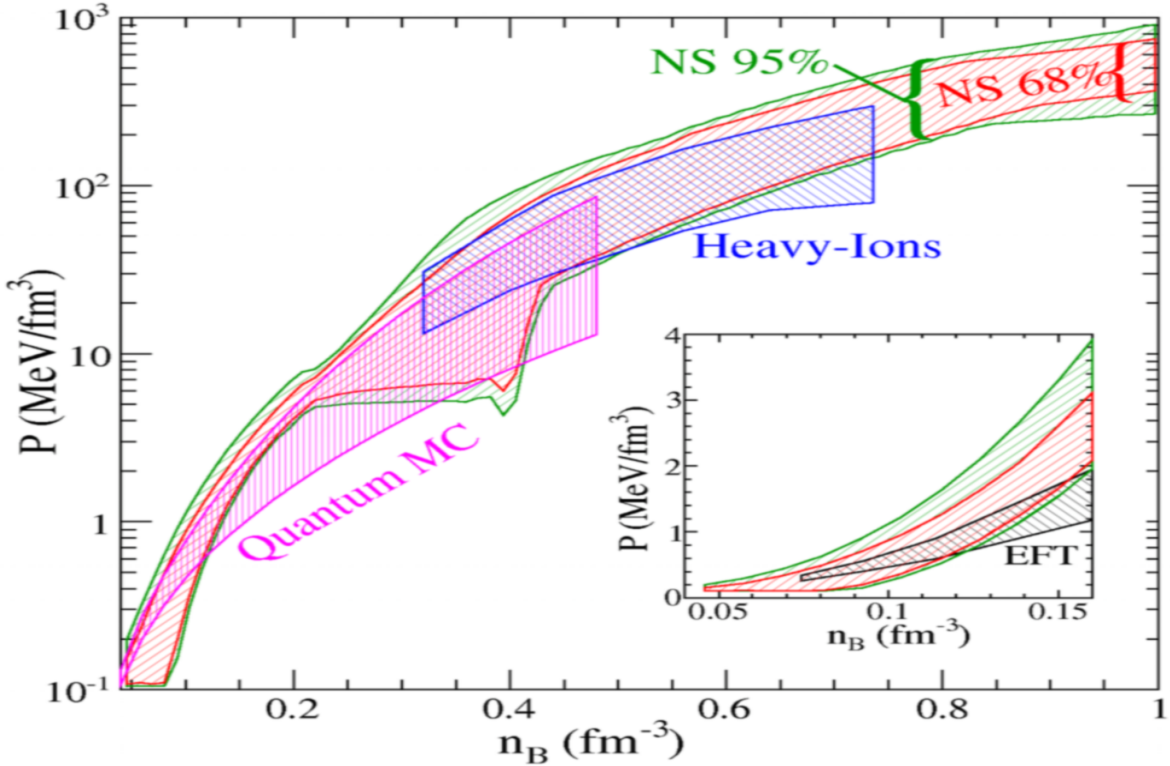


J. Carlson et al. Rev. Mod. Phys. 87, 1065 (2015)

Empirical approach – polytropic EoS: $P(n_B)=Kn_B^{\Gamma}$

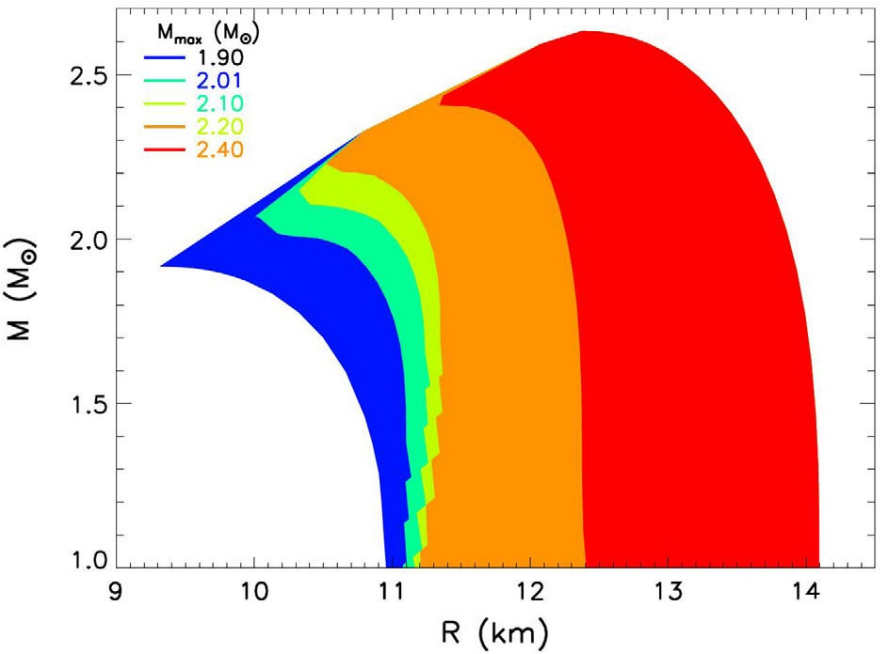
Combination of models and observation data

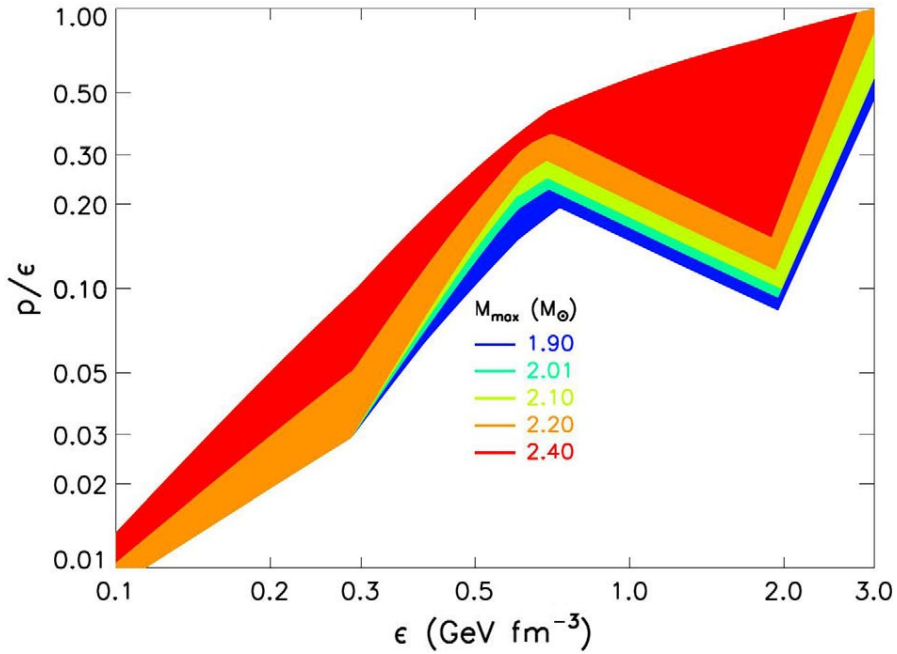
Assumptions: There is only one EoS of high density matter



Steiner et al., ApJ Letters 765, L5 (2013)

Latest models models (right panel) of the EoS calibrated on data from the gravitational wave observation of the GW170817 NS merger
(Zhao and Lattimer, Phys. Rev. D98, 063020 (2018))





Binary tidal deformability $\tilde{\Lambda}$,

Finite nuclei

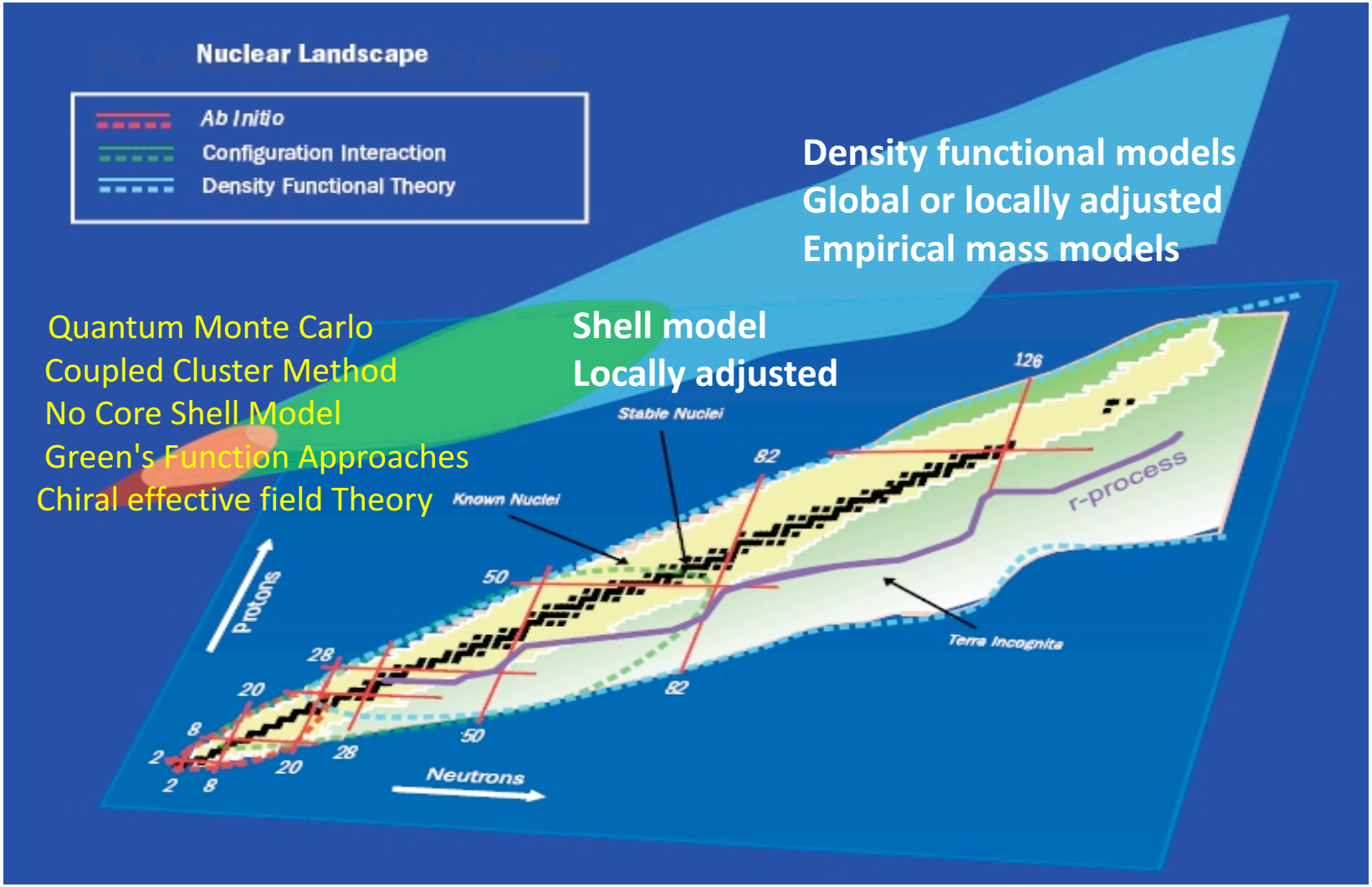


Figure adapted from SCIDAC report

Example:

Skyrme non-relativistic energy functional (total energy of the system includes density dependence

Designed to model:

Ground state properties of finite nuclei: binding energies, radii, shapes, electromagnetic moments, low amplitude collective excitations (giant resonances), single-particle states in nuclear ground state

Derived properties: neutron skin, particle separation energies, particle driplines

Properties of nuclear matter

Tony Hilton Royle Skyrme
1922 - 1987

PHENOMENOLOGICAL DENSITY DEPENDENT POTENTIAL: THE SKYRME INTERACTION

$$\mathcal{E}_{\rm Sk} = \mathcal{E}_{\rm Sk,even} + \mathcal{E}_{\rm Sk,odd}\ , \tag{6a}$$

$$\begin{aligned}
\mathcal{E}_{\rm Sk,even} = \quad & C_0^{\rho}\,\rho_0^2 && + \quad C_1^{\rho}\,\rho_1^2 \\
& + C_0^{\rho,\alpha}\,\rho_0^{2+\alpha} && + \quad C_1^{\rho,\alpha}\,\rho_1^2\rho_0^{\alpha} \\
& + C_0^{\Delta\rho}\,\rho_0\Delta\rho_0 && + \quad C_1^{\Delta\rho}\,\rho_1\Delta\rho_1 \\
& + C_0^{\nabla J}\,\rho_0\nabla\cdot\boldsymbol{J}_0 && + \quad C_1^{\nabla J}\,\rho_1\nabla\cdot\boldsymbol{J}_1 \\
& + C_0^{\tau}\,\rho_0\tau_0 && + \quad C_1^{\tau}\,\rho_1\tau_1 \\
& + C_0^{J}\,\boldsymbol{J}_0^2 && + \quad C_1^{J}\,\boldsymbol{J}_1^2
\end{aligned} \tag{6b}$$

$$\begin{aligned}
\mathcal{E}_{\rm Sk,odd} = \quad & C_0^{\sigma}\,\boldsymbol{\sigma}_0^2 && + \quad C_1^{\sigma}\,\boldsymbol{\sigma}_1^2 \\
& + C_0^{\sigma,\alpha}\,\boldsymbol{\sigma}_0^2\rho_0^{\alpha} && + \quad C_1^{\sigma,\alpha}\,\boldsymbol{\sigma}_1^2\rho_0^{\alpha} \\
& + C_0^{\Delta\sigma}\,\boldsymbol{\sigma}_0\Delta\boldsymbol{\sigma}_0 && + \quad C_1^{\Delta\sigma}\,\boldsymbol{\sigma}_1\Delta\boldsymbol{\sigma}_1 \\
& + C_0^{\nabla J}\,\boldsymbol{\sigma}_0\cdot\nabla\times\boldsymbol{j}_0 && + \quad C_1^{\nabla J}\,\boldsymbol{\sigma}_1\cdot\nabla\times\boldsymbol{j}_1 \\
& - C_0^{\tau}\,\boldsymbol{j}_0^2 && - \quad C_1^{\tau}\,\boldsymbol{j}_1^2 \\
& - \tfrac{1}{2}C_0^{J}\boldsymbol{\sigma}_0\cdot\boldsymbol{\tau}_0 && - \quad \tfrac{1}{2}C_1^{J}\boldsymbol{\sigma}_1\cdot\boldsymbol{\tau}_1
\end{aligned} \tag{6c}$$

P.-G. Reinhard, Phys. Scr. 91, 023002 (2016).

Parameters adjustable to experiment:
t0, t1, t2, t3, t4, t5, x0, x1, x2, x3, x4, x5, α, β, γ

$$C_0^\rho = \tfrac{3}{8}t_0 + \tfrac{3}{48}t_3\rho^\alpha, \tag{A30a}$$

$$C_1^\rho = -\tfrac{1}{4}t_0\left(\tfrac{1}{2}+x_0\right) - \tfrac{1}{24}t_3(1+x_3)\rho^\alpha, \tag{A30b}$$

$$C_0^s = -\tfrac{1}{4}t_0\left(\tfrac{1}{2}-x_0\right) - \tfrac{1}{24}t_3\left(\tfrac{1}{2}-x_3\right)\rho^\alpha, \tag{A30c}$$

$$C_1^s = -\tfrac{1}{8}t_0 - \tfrac{1}{48}t_3\rho^\alpha, \tag{A30d}$$

$$C_0^\tau = \tfrac{3}{16}t_1 + \tfrac{1}{4}t_2\left(\tfrac{5}{4}+x_2\right) + \tfrac{3}{16}t_4\rho^\beta + \tfrac{1}{4}t_5\left(\tfrac{5}{4}+x_5\right)\rho^\gamma, \tag{A30e}$$

$$C_1^\tau = -\tfrac{1}{8}t_1\left(\tfrac{1}{2}+x_1\right) + \tfrac{1}{8}t_2\left(\tfrac{1}{2}+x_2\right) - \tfrac{1}{8}t_4\rho^\beta\left(\tfrac{1}{2}+x_4\right) + \tfrac{1}{8}t_5\rho^\gamma\left(\tfrac{1}{2}+x_5\right), \tag{A30f}$$

$$C_0^T = -\tfrac{1}{8}\Big[t_1\left(\tfrac{1}{2}-x_1\right) - t_2\left(\tfrac{1}{2}+x_2\right) + t_4\rho^\beta\left(\tfrac{1}{2}-x_4\right) - t_5\rho^\gamma\left(\tfrac{1}{2}+x_5\right)\Big], \tag{A30g}$$

Infinite number of combinations of the parameters that give good agreement with experiment

NUCLEAR MATTER PROPERTIES FROM MEAN FIELD MODELS WITH DENSITY DEPENDENT SKYRME EFFECTIVE INTERACTION:

1. 240 non-relativistic models based on the Skyrme interaction - density dependent effective nucleon-nucleon force dependent on up to 15 adjustable parameters were recently tested against the most up-to-date constraints on properties of nuclear matter:

5 satisfied all the constraints M. Dutra et al., PRC 85, 035201 (2012)
BUT ONLY 2 OF THEM (SQMC(700) and KDEv1)
ALSO WORK SATISFACTORILY) IN FINITE NUCLEI!!!
P. Stevenson et al., arXiv:1210.1592 (2012)

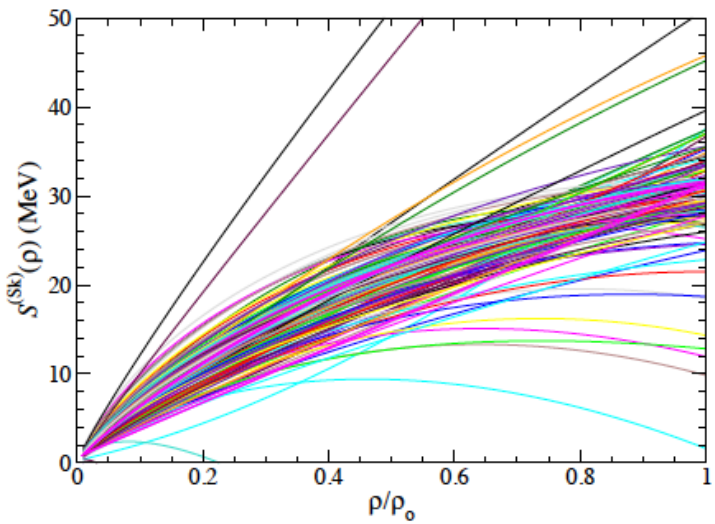
TABLE VI. Parameters of the Skyrme interactions consistent with the macroscopic constraints. and t_{3i} is in MeV fm$^{3+3\sigma_i}$. x_0, x_1, x_2, x_{3i}, and σ_i are dimensionless. For all parametrizations $t_4 = x_4$

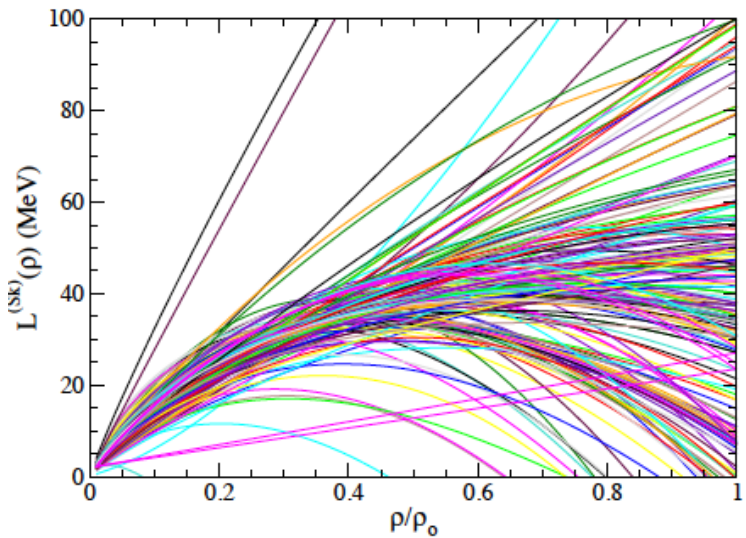
Skyrme	t_0	t_1	t_2	t_{31}	t_{32}	t_{33}	x_0	x_1	x_2
GSkI	−1855.5	397.2	264.6	13858.0	−2694.1	−319.9	0.12	−1.76	−1.81
GSkII	−1856.0	393.1	266.1	13842.9	−2689.7	–	0.09	−0.72	−1.84
KDE0v1	−2553.1	411.7	−419.9	14603.6	–	–	0.65	−0.35	−0.93
LNS	−2485.0	266.7	−337.1	14588.2	–	–	0.06	0.66	−0.95
MSL0	−2118.1	395.2	−64.0	12875.7	–	–	−0.07	−0.33	1.36
NRAPR	−2719.7	417.6	−66.7	15042.0	–	–	0.16	−0.05	0.03
Ska25s20	−2180.5	281.5	−160.4	14577.8	–	–	0.14	−0.80	0.00
Ska35s20	−1768.8	263.9	−158.3	12904.8	–	–	0.13	−0.80	0.00
SKRA	−2895.4	405.5	−89.1	16660.0	–	–	0.08	0.00	0.20
SkT1	−1794.0	298.0	−298.0	12812.0	–	–	0.15	−0.50	−0.50
SkT2	−1791.6	300.0	−300.0	12792.0	–	–	0.15	−0.50	−0.50
SkT3	−1791.8	298.5	−99.5	12794.0	–	–	0.14	−1.00	1.00
Skxs20	−2885.2	302.7	−323.4	18237.5	–	–	0.14	−0.26	−0.61
SQMC650	−2462.7	436.1	−151.9	14154.5	–	–	0.13	0.00	0.00
SQMC700	−2429.1	371.0	−96.7	13773.6	–	–	0.10	0.00	0.00
SV-sym32	−1883.3	319.2	197.3	12559.5	–	–	0.01	−0.59	−2.17

EXAMPLES OF RESULTS OF THE SYMMETRY ENERGY OF NUCLEAR MATTER USING DIFFERENT SKYRME MODELS

Energy per particle $E(\rho,\delta) = E_0(\rho,\delta=0) + S(\rho)\delta^2, \quad \delta = (\rho_n - \rho_p)/\rho$

Symmetric nuclear matter: $S(\rho) = S(\rho_0) - L\dfrac{(\rho_0 - \rho)}{3\rho_0}$ $\qquad S(\rho_0) \approx a_{Sym} \approx 30$ MeV





Santos et al., arXiv:1507.05856v1 (2015)

AB-INITIO: (eg. MR-iM-SRG, Coupled clusters, No-core shell model, Green's function models, Quantum Monte Carlo etc.

Techniques based on Effective field theory – include only nucleon-pion interaction.

Advantage: Provide ground-state and excited states properties (include correlations in the mean field) calculate interaction + operators, estimate errors

Disadvantages: Dependence on cut-off parameters, uncertainty in 3-body forces, computationally expensive to include higher orders in theories and to apply to heavier nuclei.

ALREADY MULTIPLE MODELS EXIST

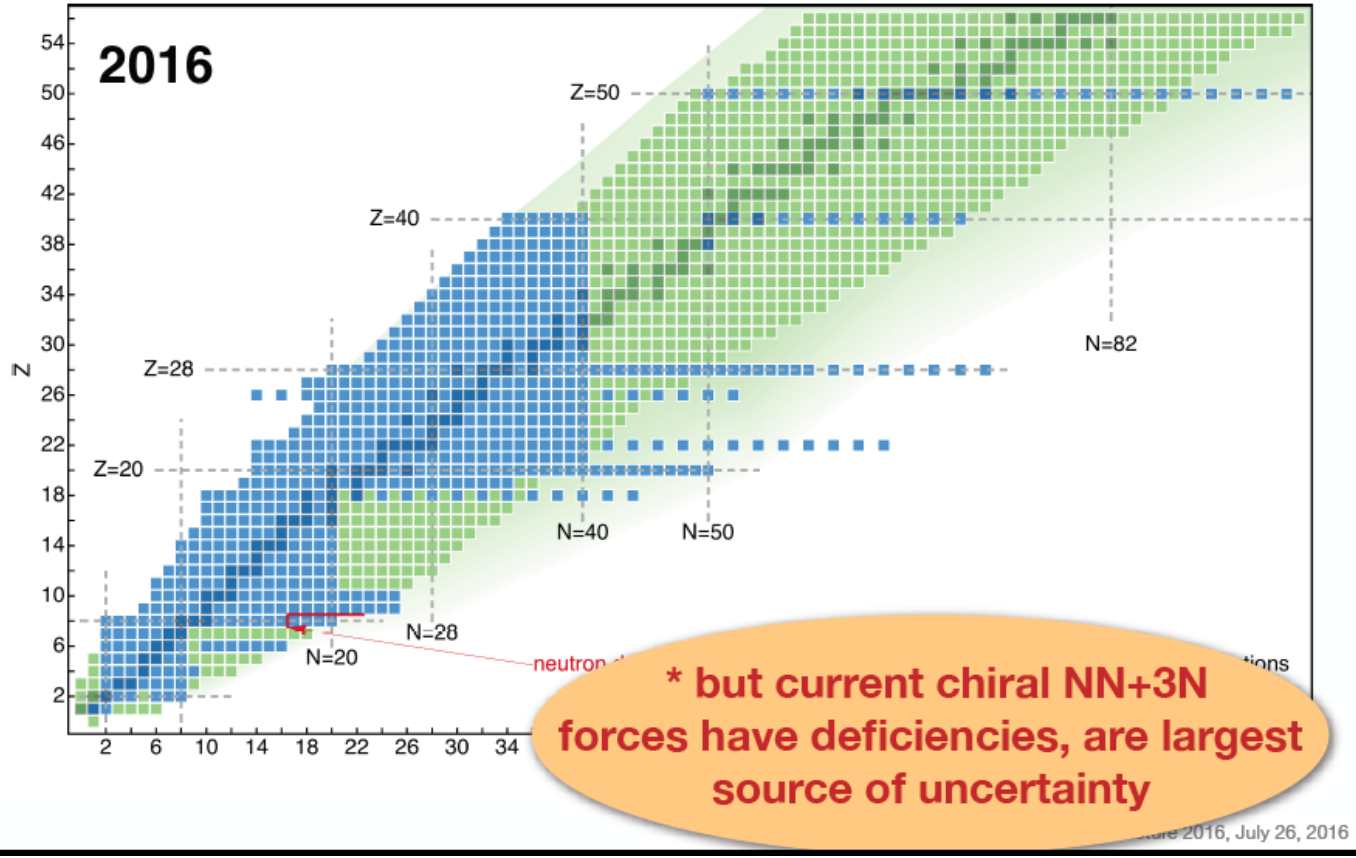
S. Bogner, R. Furnstahl, and A. Schwenk, Prog. Part. Nucl. Phys. 65 (2010) 94

R. Machleidt and D. R. Entem, Phys. Rept. 503, (2011) 1

H. Hergert et al., Phys. Rept. 621 (2016)165

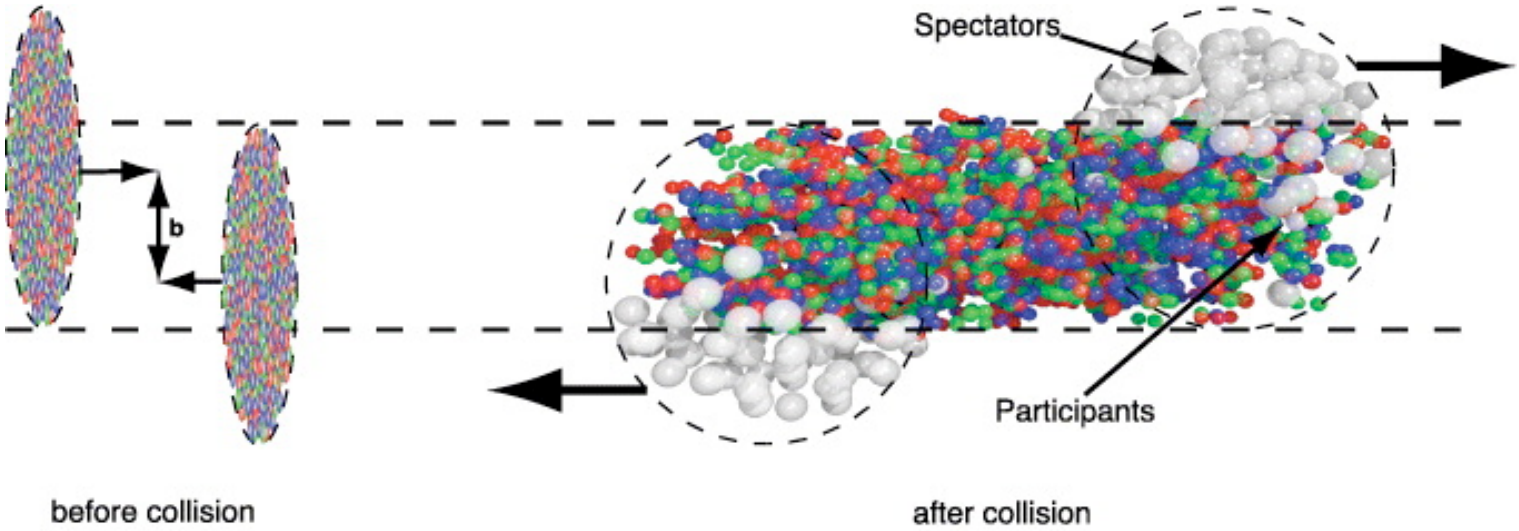
G. R. Jansen et al., Phys. Rev. Lett. 113 (2014) 142502

Progress in *Ab Initio* Calculations



Courtesy of Heiko Hergert, NS 2016, Knoxville TN

Heavy Ion Collisions



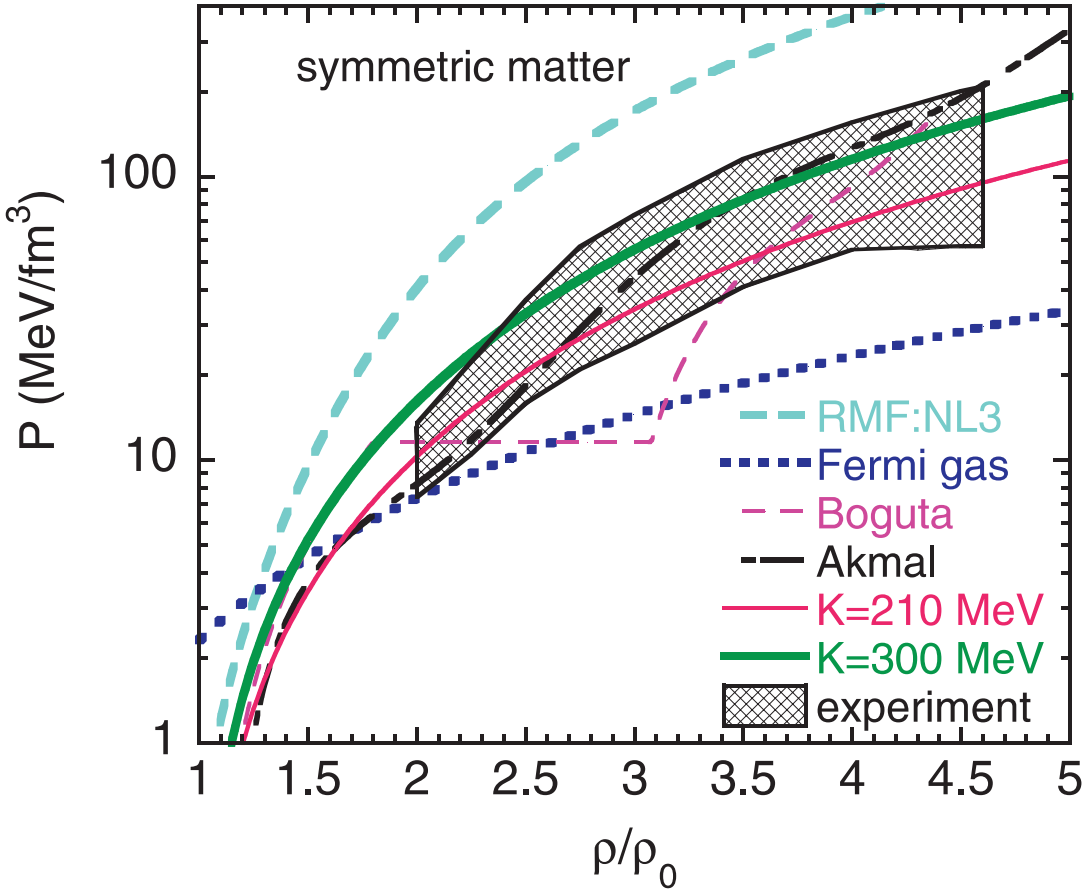
Heavy Ion collisions:

GSI, MSU, Texas A&M, RHIC, LHC existing
FAIR (GSI), NICA (Dubna, Russia) planned

Measurement: Beam energy 35 A MeV – 5.5 A TeV
Collisions (Au,Au), (Sn,Sn) , (Cu,Cu)
but also (p,p) for a comparison
Transverse and Elliptical particle flow

Calculation: Transport models -- empirical mean field potentials
Fit to data → energy density → P (ε) → the EoS
(extrapolation to equilibrium, zero temperature, infinite matter) (e.g Danielewicz et al., Science 298, 2002, Bao-An Li et al., Phys.Rep. 464, 2008)

Quantum Molecular Dynamics
(e.g. Yingxun Zhang, Zhuxia Li, Akira Ono)



Determination of the Equation of State of Dense Matter

Paweł Danielewicz,[1,2] Roy Lacey,[3] William G. Lynch[1*]

Science 298, 1592 (2002)

Transport models with parameters fitted to data on elliptical and transverse flow

Matter in HIC and compact objects have different EoS:

Central A-A collision:

Strongly beam energy dependent
Beam energy < 1GeV/ A:

Temperature: < 50 MeV
Energy density: ~ 1 -2 GeV/fm^3
Baryon density < ρ_0
Time scale to cool-down: 10^{-22-24} s
No neutrinos

Strong Interaction: (S, B and L conserved)
Time scale 10^{-24} s

NEARLY SYMMETRIC MATTER

Inelastic NN scatterings,
N,N*, Δ's
LOTS of PIONS
strangeness
less important (kaons)

? (Local)EQUILIBRIUM?

Proto-neutron star:

(progenitor mass dependent)
~ 8 – 20 solar mass

Temperature: < 50 MeV
Energy density: ~ 1 GeV/fm3
Baryon density ~ 2-3 ρ_s
Time scale to cool-down: 1 -10 s
Neutrino rich matter

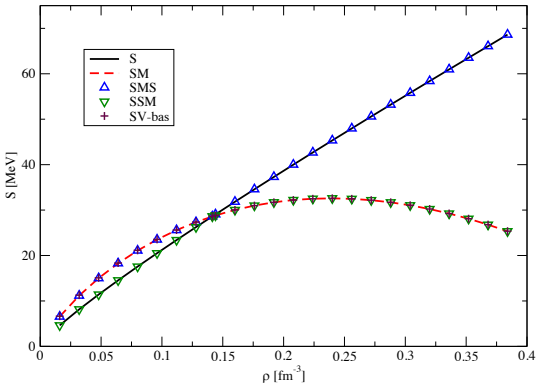
Strong +Weak Interaction: (B and L con)
Time scale 10^{-10} s (ρ and T dependent)

HIGHLY ASYMMETRIC MATTER

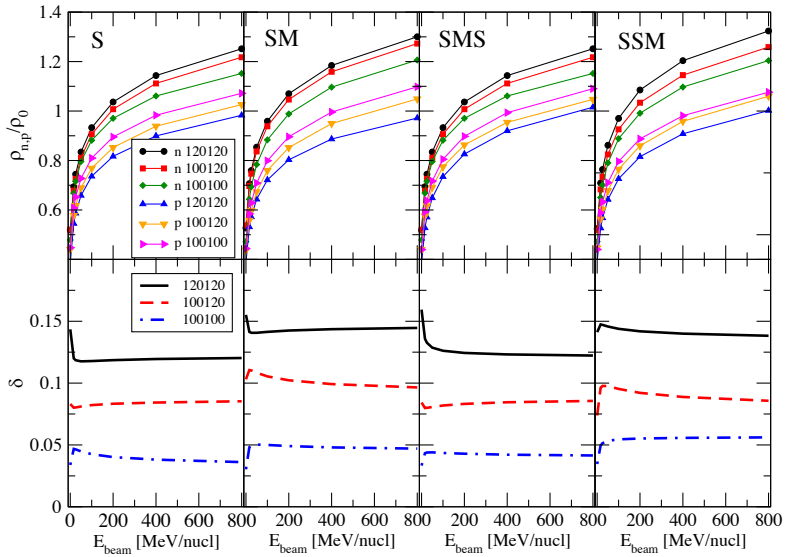
Higher T: strangeness produced in
in weak processes
Lower T: freeze-out
N, strange baryons and mesons,
NO PIONS, leptons

EQUILIBRIUM

Transport model results for maximum proton and neutron density and is isospin asymmetry δ in a collision od Sn nuclei as a function of the lab beam energy up to 800 MeV/nucl



Four models for density dependence of the symmetry energy S, SM, SMS, SSM



Three observations: (i) The maximum density does exceed 1.4 ρ_0

(ii) The isospin asymmetry has does not increase with beam energy

- the system retains memory of the original asymmetry

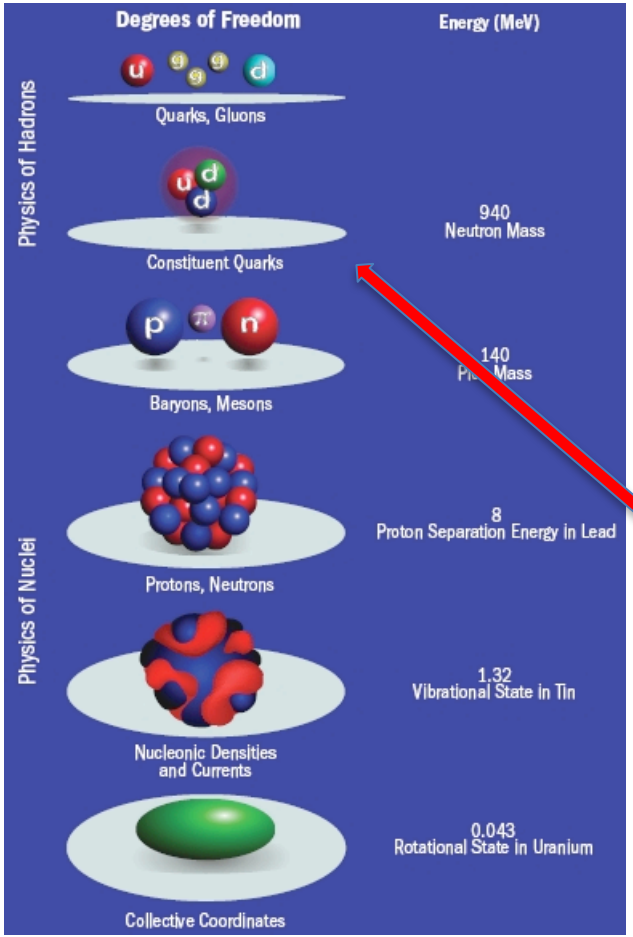
(iii) The observables are only weakly dependent on S(ρ)

JRS, P. Danielewicz and Y. Iwata, PRC 96, 014612(2017)

New Physics (still on a phenomenological level)?

Quark-Meson-Coupling instead Nucleon-Meson Coupling?

Energy scales in hadron and Nuclei



FUNDAMENTAL QUESTIONS:

1. **Is the nucleon immutable?**
2. **When immersed to a nuclear medium with applied scalar field with strength of order of half of its mass is it really unchangeable?**
3. **Is this effect relevant to nuclear structure?**

Replace interaction between nucleons

↓

By interaction between valence quarks in individual non-overlapping nucleons

Look for the modification of the quark dynamics in a nucleon due to presence of other nucleons

ACCOUNT FOR THE MEDIUM EFFECT

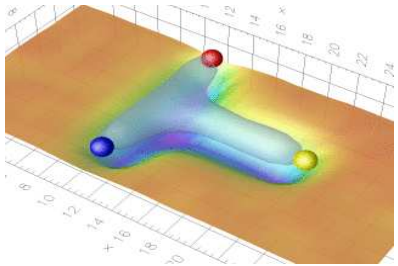
Quark-Meson-Coupling Model
(many-body effective Hamiltonian)

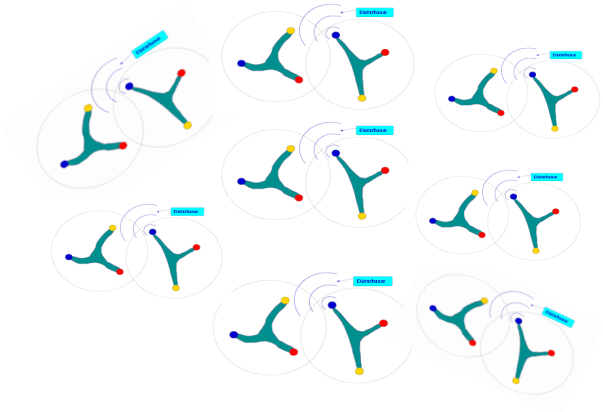
History:

Original: Pierre Guichon (Saclay), PLB 200, 235 (1988)

Several variants developed in Japan, Europe, Brazil, Korea, China

Latest: JRS, Guichon, Reinhard and Thomas, PRL 116, 092501 (2016)





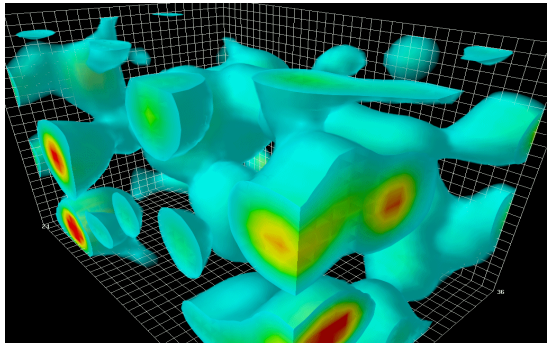
Exchange

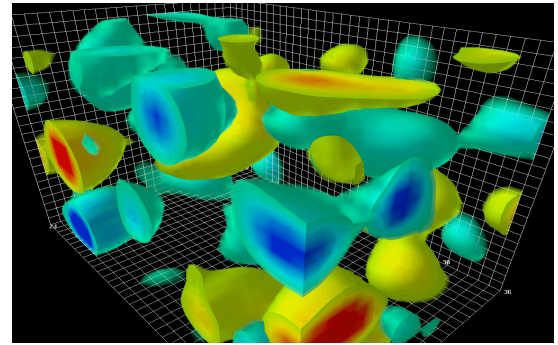
σ, ω, ρ

Lattice QCD simulations of the structure of a nucleon

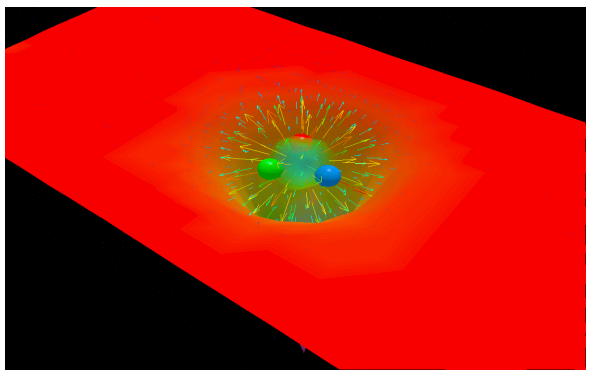
Bissey, PRD76, 114512 (2007)

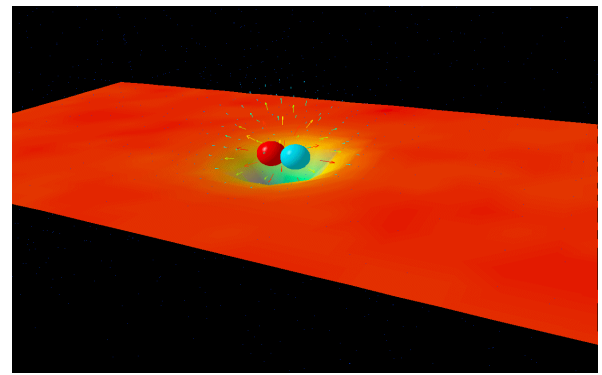
Schematic illustration of a multi-baryon system: baryons can appear close enough to to exchange mesons between quarks through disturbance in the QCD vacuum *(Guichon)*





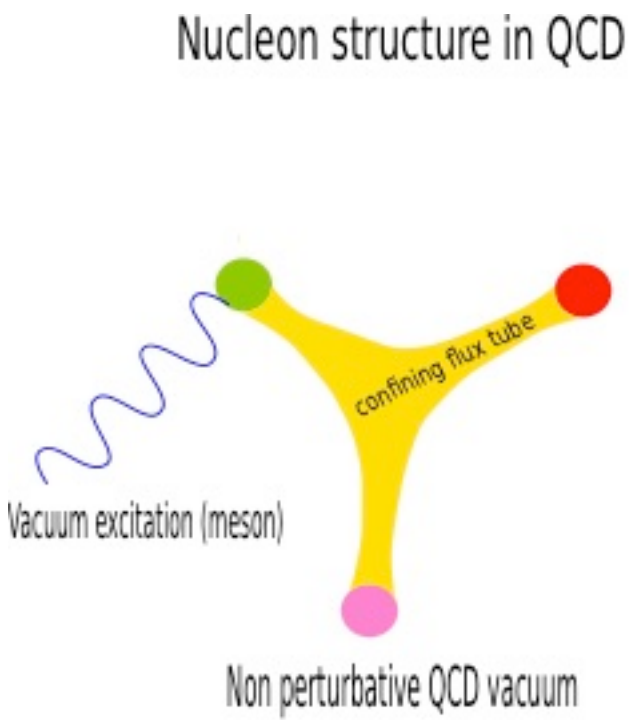
Typical structure of gluon-field configurations, averaged over time, describing the the vacuum properties of QCD (action density – left), charge density (right)

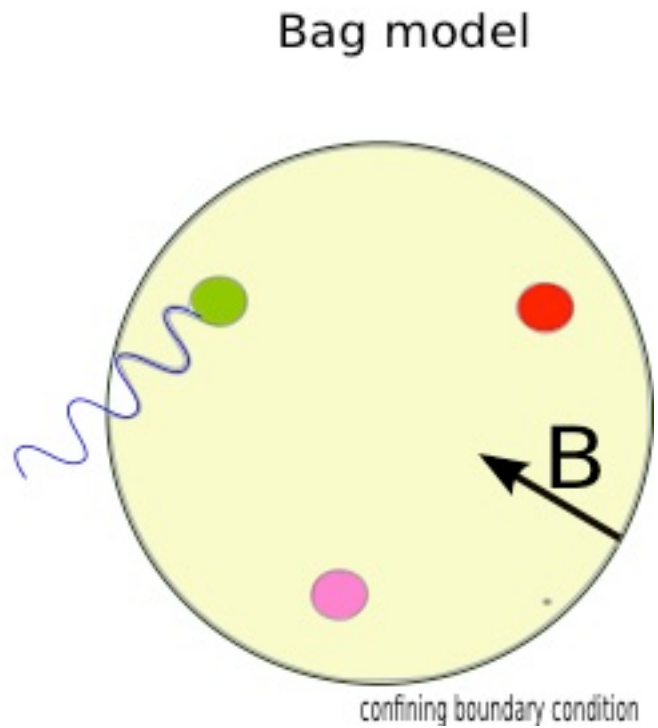




QCD vacuum fluctuations are expelled from the interior region of a baryon like the proton is animated at left and a quark-antiquark pair at the right

http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/index.html





Guichon, JRS, Thomas Prog.Part.Nucl.Phys. 2018

OUTLINE OF THE QMC MODEL

Guichon et al., Nucl.Phys. A772,1,(2006), Guichon and Thomas PRL93, 132502 (2004)
Guichon, Stone,Thomas: Progress in Particle and Nuclear Physics 100 (2018) 262–297

1. Take a baryon in medium as an MIT bag (with one qluon exchange) immersed in a mean density dependent scalar field $\bar{\sigma}$

2 Approximate the solution of the bag equations by a dynamical nucleon effective mas

$$M_N^*(\sigma) = M_N - g_{\sigma N}\bar{\sigma} + \frac{d}{2}(g_{\sigma N}\bar{\sigma})^2$$

The last term represents the response of a nucleon to the scalar field with *d* being the scalar polarizability – the origin of MANY- BODY forces in QMC (no additional parameters – d is calculated) $d = 0.0044 + 0.211 * R_B - 0.0357 R_B^2$

3. The nucleon meson coupling constants relate to the quark meson couplings as

$$g_{\sigma N} = 3g_\sigma^q \int_{Bag} d\vec{r}\ \bar{q}q(\vec{r}), \qquad g_{\omega N} = 3g_\omega^q, \qquad g_{\rho N} = g_\rho^q$$

where q is the valence quark wave function for a free bag.

4. **Solve self-consistently for the meson fields using the condition**

$$\partial E / \partial \bar{\sigma} = 0 \qquad \partial E / \partial \bar{\omega} = 0 \qquad \partial E / \partial \bar{\rho} = 0$$

5. **Construct a quantized Hamiltonian/Lagrangian for a given system (non-rel) for finite nuclei and relativistic for nuclear matter.**

These depend only on nucleon dynamics and are solved by standard Hartree-Fock methods to determine observables of interest.

-density dependence of the energy density functional is microscopically
- calculated
- multi-body forces are automatically included
-exchange terms are always included
- spin-orbit term appears naturally in both NR and R models
- proton and neutron s.p. potentials are calculated – no need for fitting.

Parameters (very little maneuvering space) :

I. 3 nucleon-meson coupling constants in vacuum $g_{\sigma N}, g_{\omega N}, g_{\rho N}$
We define (for convenience)

$$G_{\sigma N} = g_{\sigma N}^2 / m_\sigma^2 \qquad G_{\omega N} = g_{\omega N}^2 / m_\omega^2 \qquad G_{\rho N} = g_{\rho N}^2 / m_\rho^2$$

II. Meson masses: ω, ρ, π keep their physical values
650 MeV < M_σ < 700 MeV

III. Bag radius (free nucleon radius):
1 fm (limited sensitivity within change +/- 20%)

All other parameters either calculated within the model or fixed by symmetry

I. **Nuclear matter parameters used in the fit:**

$$-17 \text{ MeV} < E_0 < -15 \text{ MeV}$$
$$0.15 \text{ fm} < \rho_0 < 0.17 \text{ fm}^{-3}$$
$$28 \text{ MeV} < J < 34 \text{ MeV}$$
$$L > 22 \text{ MeV}$$
$$250 \text{ MeV} < K_0 < 350 \text{ MeV}$$

+

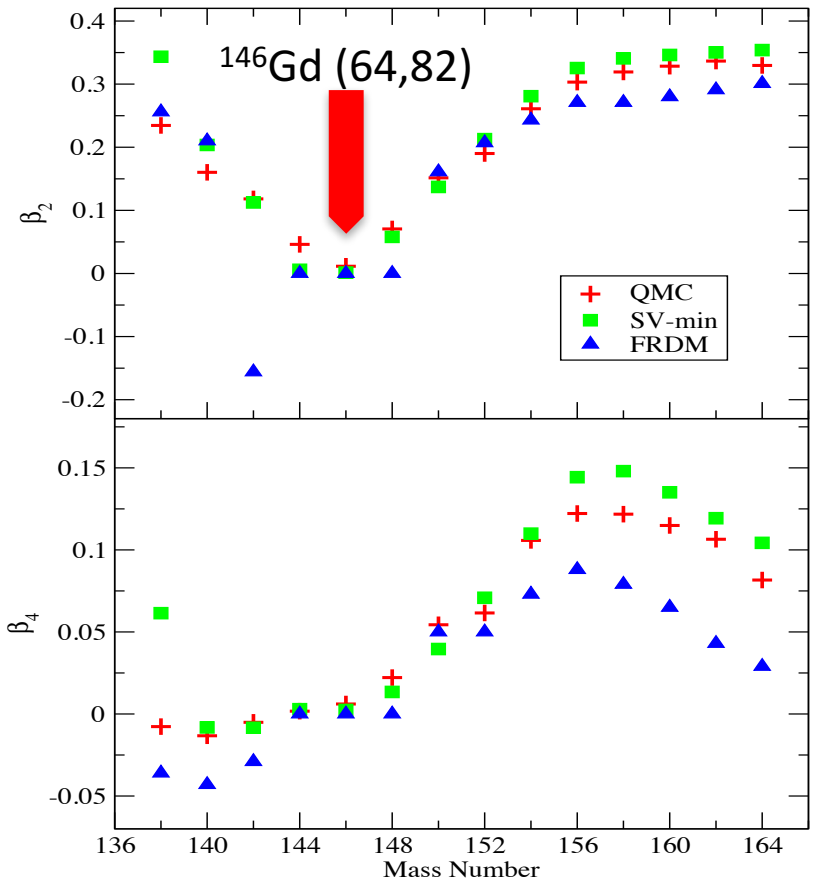
II. **HF+BCS model including constrained calculation at fixed quadrupole moment Q_{20}**
(two more parameters – proton and neutron pairing strengths)

Calculated: **ground state binding energies, axial and octupole deformations, two-neutron separation energies, electromagnetic properties, single-particle energies, pairing gaps, neutron skin, spin-orbit splitting**

The parameter set is UNIQUE for each model Hamiltonian

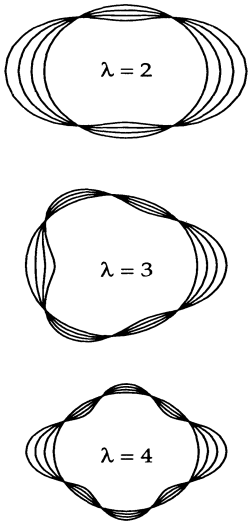
Details in JRS, Guichon, Reinhard and Thomas, PRL 116, 092501 (2016)

Quadrupole deformation of even-even Gd isotopes across the isotopic chain



$$R(\theta,\phi,t) = R_0\left(1 + \sum_{\lambda=0}^{\infty}\sum_{\mu=-\lambda}^{\lambda} \alpha^*_{\lambda\mu}(t)\, Y_{\lambda\mu}(\theta,\phi)\right)$$

Deformation parameters

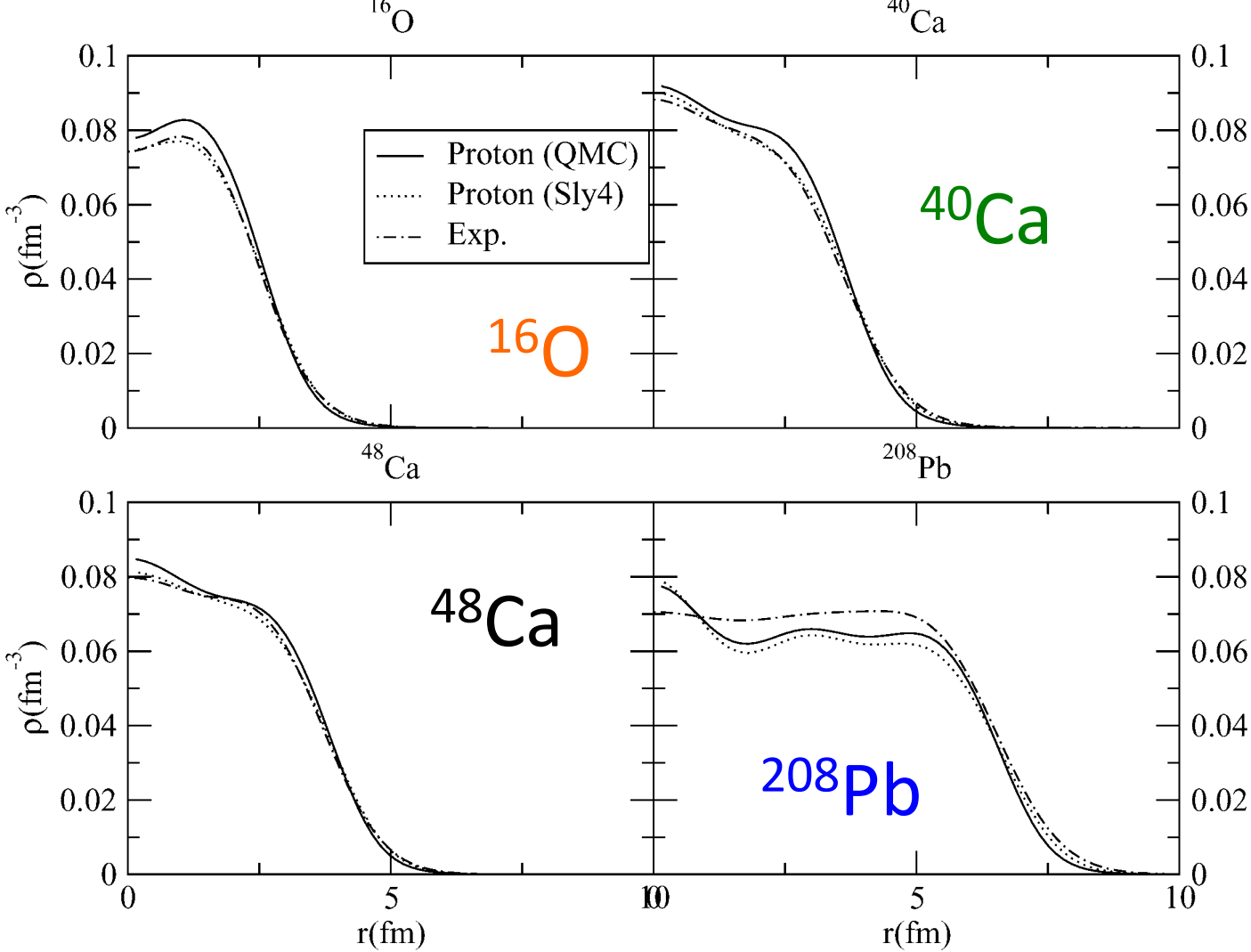


β_2 quadrupole

β_3 octupole

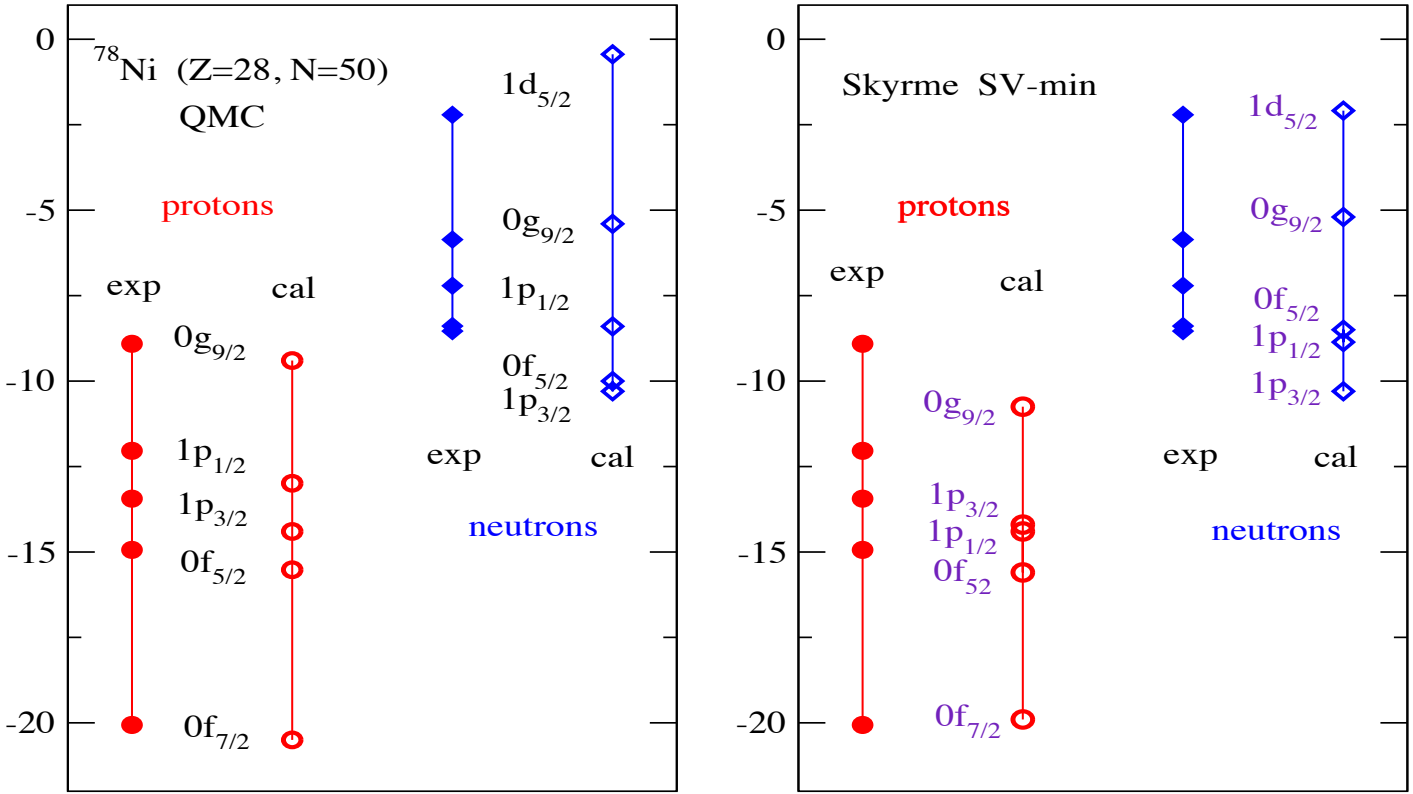
β_4 hexadecapole

SV-min Klupfel et al. (11 parameters)
Phys. Rev. C **79**, 034310 (2009)
FRDM Moller et al., ADNDT, 59, 185 (1995)



QMC proton density distribution compared with experiment and Skyrme SLy4

Spectrum of single-particle energies in the ground state of ^{78}Ni



Data taken from Grawe et al., Rep.Prog.Phys. 70, 1525 (2007)

Ground state binding energy for selected SHE nuclei

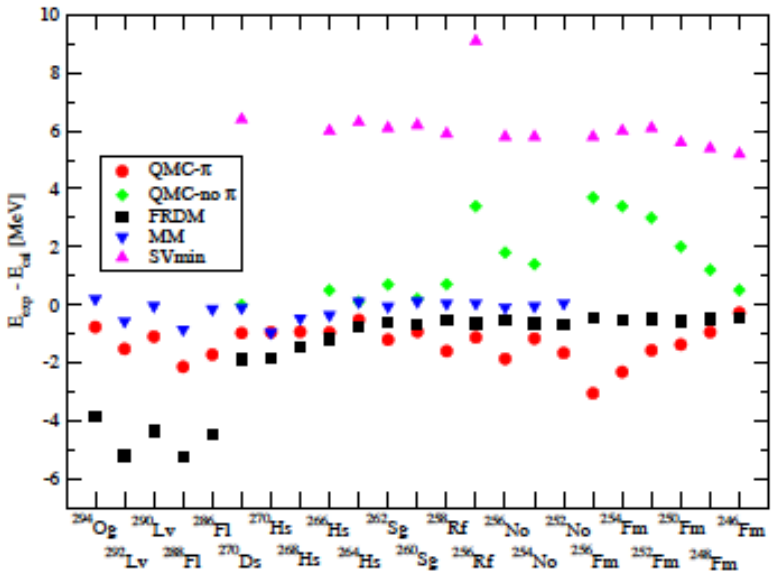


Figure 1. (Color online). Ground state binding energies of selected 'benchmark' even-even superheavy nuclei. The experimental data were taken from [27, 28].

Theory:

Skyrme SV-min
P. Klupfel et al.
Phys. Rev. C **79**, 034310 (2009)

Finite Range Droplet Model (FRDM)
P. Moller et al., ADNDT, 59, 185 (1995)

Micro-macro model (MM)
I.Muntian et al., Atomic Nuclei, 66,1015(2003)
Acta Phys.Pol B 34, 2073 (2003

Experiment:

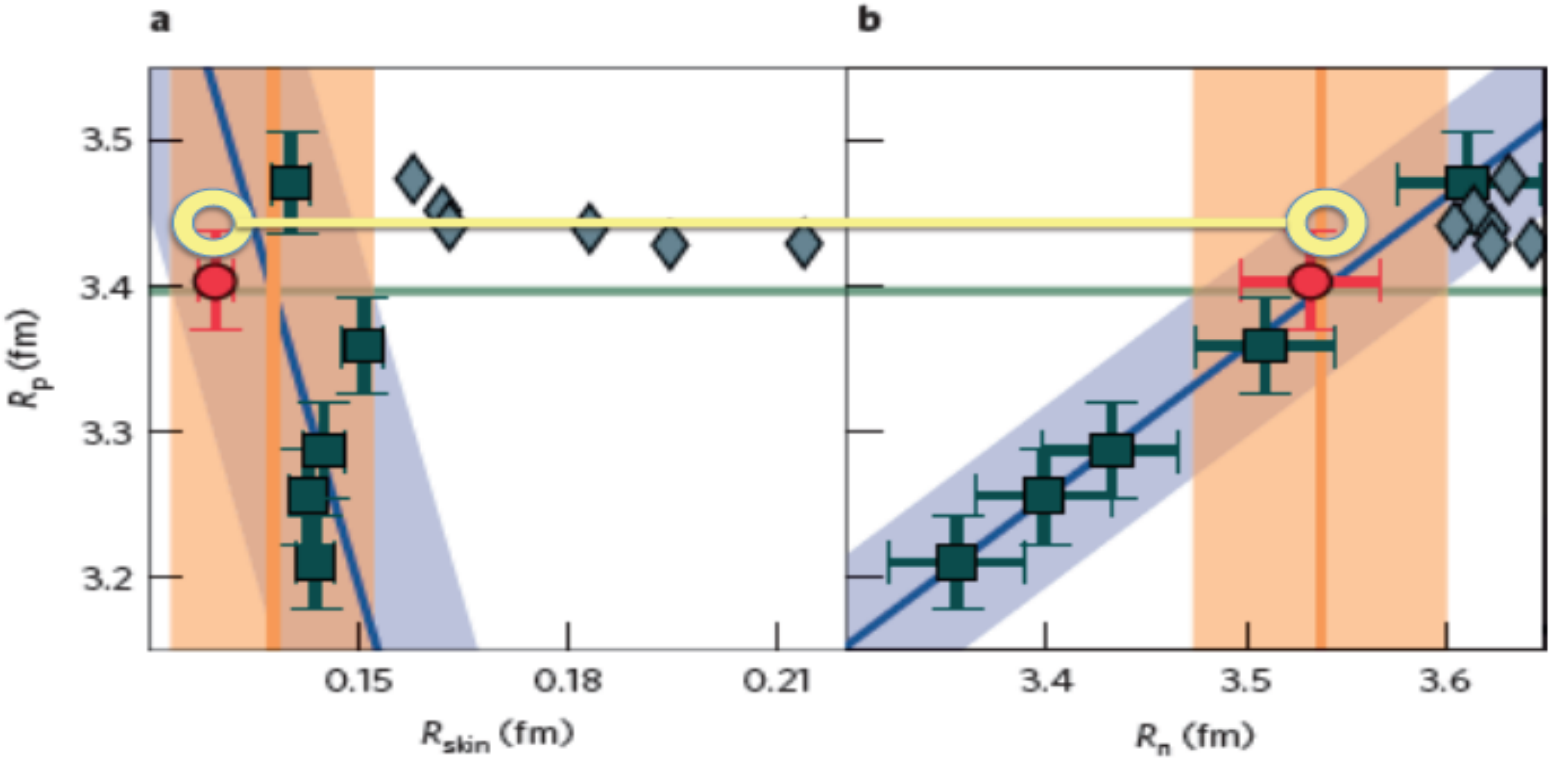
H.J.Huang et al., Chinese Phys. C41, 030002 and 030003 (2017)

Physics of even-even superheavy nuclei with 96 < Z < 110 in the Quark-Meson-Coupling Model

J.R. Stone, K. Morita, P. A. M. Guichon, A. W. Thomas

https://arxiv.org/abs/1901.06064

Correlation of neutron skin, point proton and neutron radii in ^{48}Ca



From Hagen et al., Nat.Phys. 12, 186 (2016)

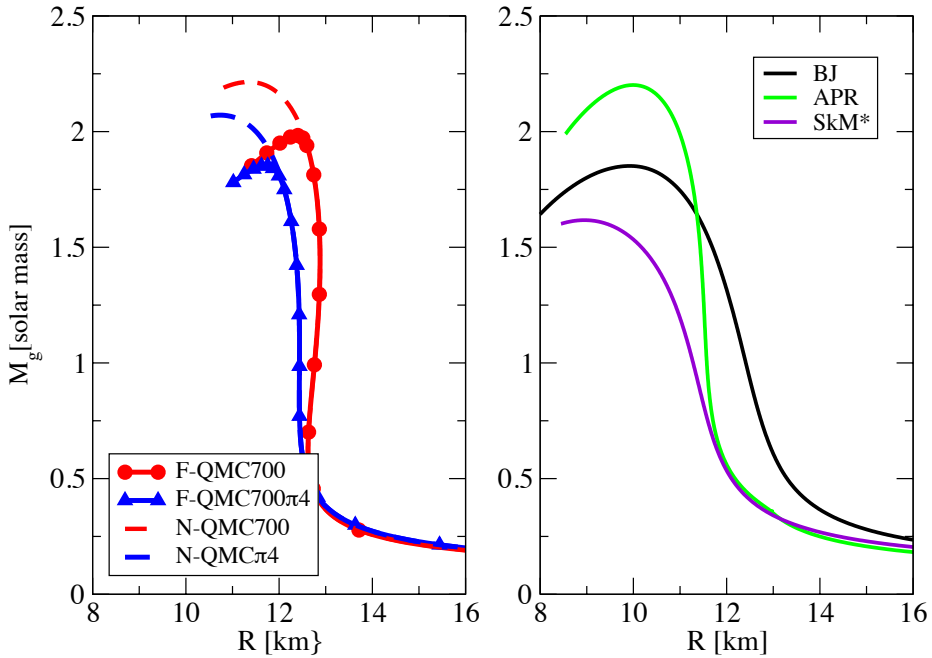
Red circles: $NNLO_{sat}$ PRC 91, 051301(R) (2015)

Blue squares: Ch-Int. PRC 83, 031301 (2011)

Grey diamonds: DFT PRC 85, 041302 (2012)

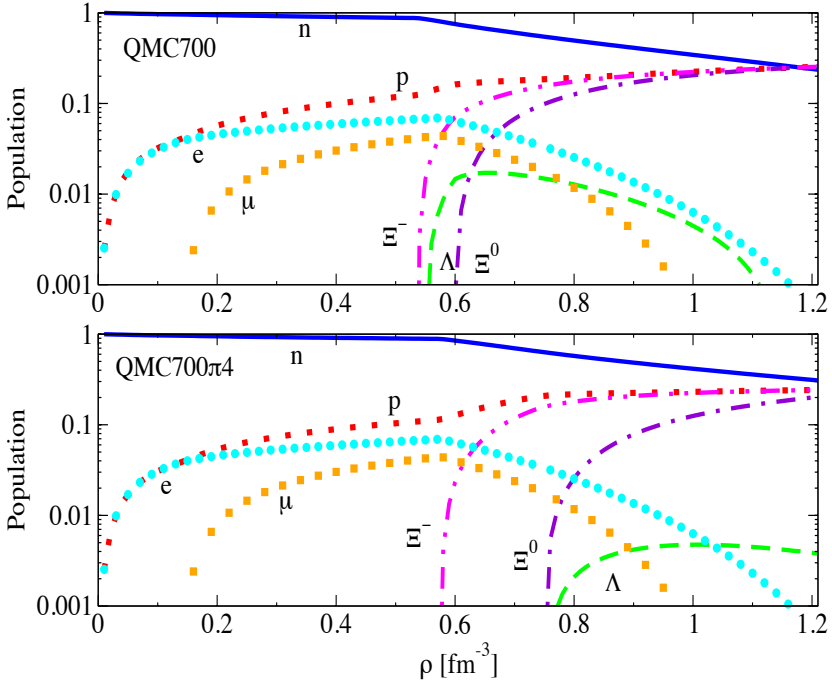
Yellow symbols: QMC(π)

Mass-radius of a neutron star prediction by the QMC model (relativistic version)



2 M_{solar} mass neutron star with full hyperon octet predicted 3 years before its observation – no hyperon puzzle

Composition of matter in a neutron star core as calculated in the QMC model (nucleon-hyperon interaction calculated in a mean field approximation)



Existence of Λ - hypernuclei

Existence of cascade-hypernucleus

Non-Existence of bound Σ hypernuclei

The first evidence of a deeply bound state of Ξ--14N system"K.Nakazawa et al.,Prog. Theor. Exp. Phys. (2015), 033D02

Stone, Guichon, Matevosyan, Thomas, NPA 792, 341 (2007)

Concluding remarks

1. Current low energy nuclear physics faces a number of challenges

1. We introduce the Quark-Meson-Meson Coupling model based on structure of the nucleon. The model has a small number of well constrained parameters – UNIQUE SET PER HAMILTONIAN

3. The formalism works for any baryons without increased number of parameters

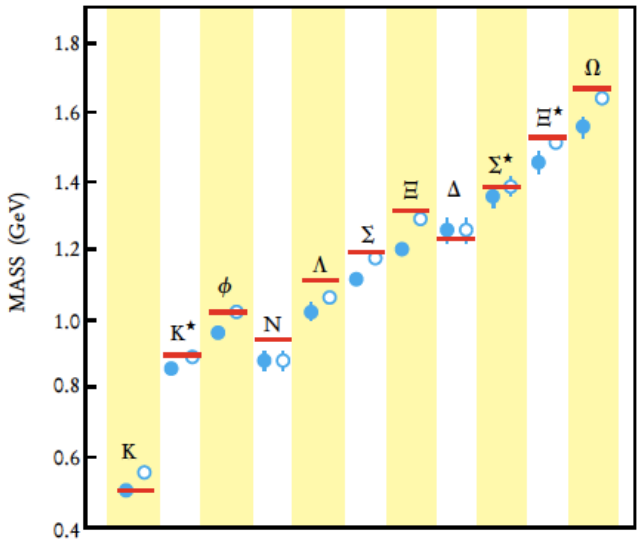
4. The model is consistent when applied to nuclear matter, finite nuclei, hyperonic physics and compact objects

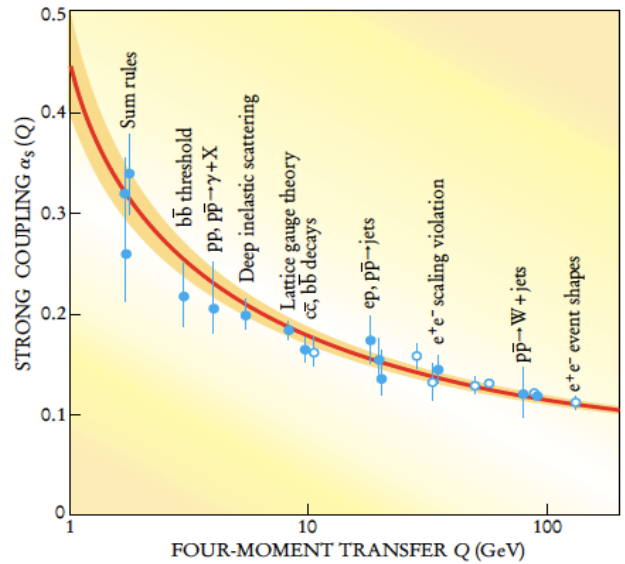
5. Is there an independent experimental confirmation of a medium effect a dynamical structure of a baryon? EMC ?

6. **What is the way forward?**

Lattice QCD

increasingly successful numerical experiment
for free systems





Quantum Chromodynamics (QCD): Complete description of the strong interaction

Parameters: Coupling constant g and quark masses

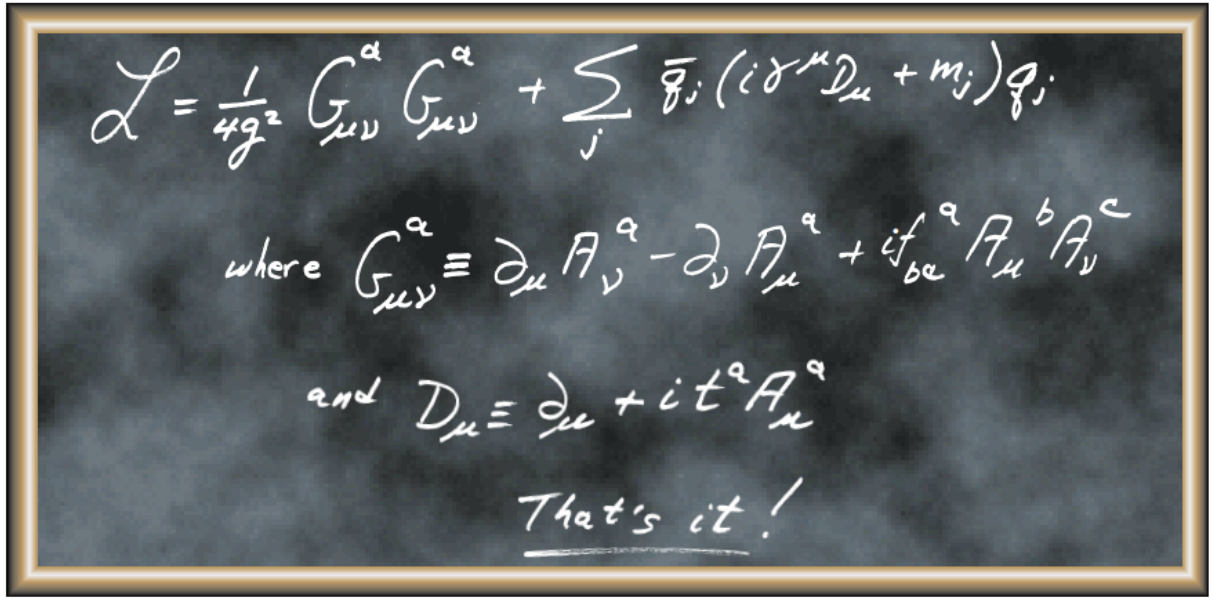


FIGURE 1. THE QCD LAGRANGIAN $\mathcal{L}$ displayed here is, in principle, a complete description of the strong interaction. But, in practice, it leads to equations that are notoriously hard to solve. Here m_j and q_j are the mass and quantum field of the quark of jth flavor, and A is the gluon field, with spacetime indices μ and ν and color indices a, b, c. The numerical coefficients f and t guarantee SU(3) color symmetry. Aside from the quark masses, the one coupling constant g is the only free parameter of the theory.

Frank Wilczek, Physics Today, August 2000

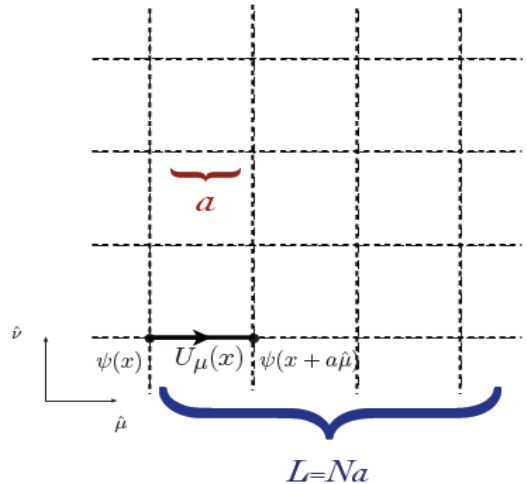
The Lattice

Ken Wilson (1974)

- **Quark fields reside on sites** $\psi(x)$
- **Gauge fields on the links** $U_\mu(x) = e^{-iagA_\mu(x)}$
- **Approximate the full QCD path integral by Monte Carlo methods**

$$\langle \mathcal{O} \rangle = \frac{1}{Z} \int \mathcal{D}A\mathcal{D}\bar{\psi}\mathcal{D}\psi\, \mathcal{O}[A, \bar{\psi}, \psi]\, e^{-S[A,\bar{\psi},\psi]}$$

$$\Rightarrow \quad \langle \mathcal{O} \rangle \simeq \frac{1}{N_{\rm conf}} \sum_i^{N_{\rm conf}} \mathcal{O}([U^{[i]}])$$



With field configurations U_i distributed according to $e^{-S[U]}$

Put it on a supercomputer

TWO PROBLEMS: THE EXPONENTIAL WEIGHTING FACTOR OSCILLATES AT FINITE CHEMICAL POTENTIALS

OVERLAP PROBLEM (PLEASE GOOGLE FOR DETAILS)

Courtesy James Zanotti

Thanks to:

My co-authors Pierre Guichon and Tony Thomas

P.-G. Reinhard for implementation of the QMC model in the Skyax 2D code

and

Chris Dűllmann for valuable comments and suggestions concerning experimental data and future prospects of SHE.