Nuclear Astrophysics Town Meeting

Working Group 1

Nuclear Theory for Nuclear Astrophysics

Conveners: Matthias Hempel, Nils Paar, Stefan Typel

Outline of Session

- **Overview**
- **Individual Contributions**
  - Dimiter Balabanski, Catalin Matei
  - Horst Lenske
  - Gabriel Martinez-Pinedo
  - Micaela Oertel
  - Nils Paar
  - Tomas Rodriguez
  - Armen Sedrakian
  - Aurora Tumino
  - Meng-Ru Wu
  - . . .
- **Discussion**

Nuclear Theory

- **Areas of Application**
  - Equation of State of Dense Matter
  - Properties of Atomic Nuclei
  - Nuclear Reactions
- **Methods**
  - ab initio approaches
  - interacting shell model
  - energy density functionals
- **Interface to Experiment**
  - error analysis of predictions
  - constraints for models
  - correlation of quantities
  - sensitivity to input
  - transfer of results

Methods for Structure Calculations

- **Ab Initio Approaches**
  - use of realistic interactions
    (potential models, meson exchange, chiral forces, RG evolved, . . .)
  - large variety of many-body methods
    (AMD/FMD, BHF/DBHF, SCGF, CBF, VMC, GFMC, AFDMC, NSCM, CC,
    MBPT, χEFT, nuclear lattice EFT, . . .)
- **Interacting Shell Model**
  - specific model space, nuclei close to magic shell closures
  - tailored interactions
- **Energy Density Functionals**
  - phenomenological interactions
  - mostly based on mean-field models (Skyrme, Gogny, relativistic)

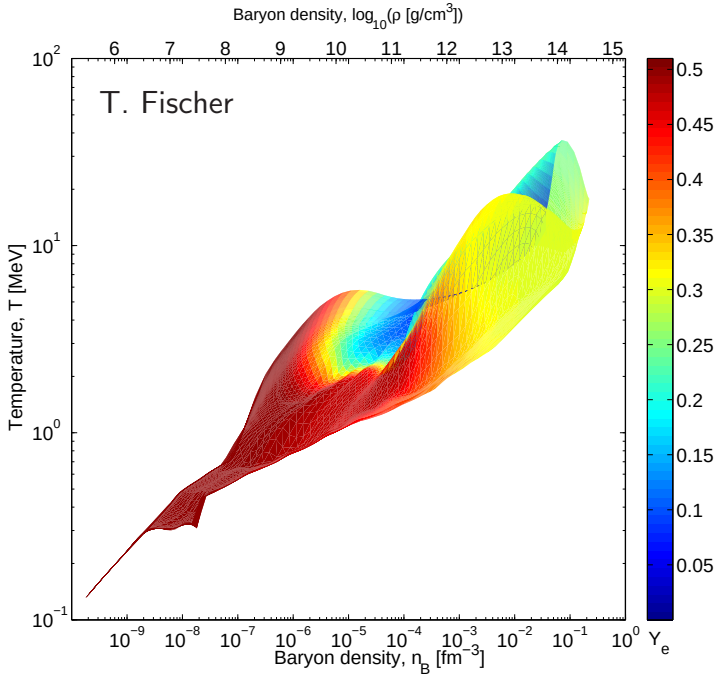
$\Rightarrow$ Nuclear Structure and Nuclear Matter

Interactions

- **In Ab Initio Calculations**
  - often fitted to NN scattering/properties of few-nucleon systems
  - two-body forces well constrained in vacuum
  - three-body forces much less constrained, but essential
  - two- and three-body forces not independent
  - connection to QCD?
  - error estimates in systematic approaches
  - effects of short-range repulsion $\Rightarrow$ high-momentum components
  - limitations? applicability (density, mass number, . . .)
- **General Problems**
  - in-medium modifications
  - uncertainties for hyperon-nucleon, hyperon-hyperon interactions, in particular at high densities ($\Rightarrow$ neutron star properties)
  - advantages/disadvantages of zero-range interactions

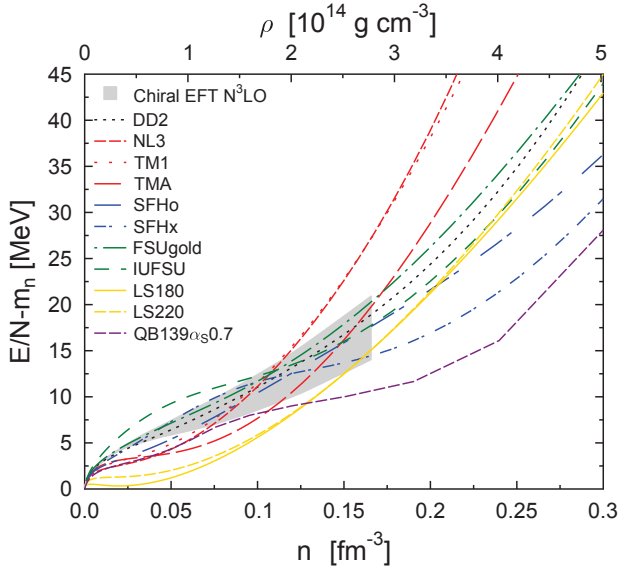
Equation of State of Dense Matter I

- **Neutron Star Matter**
  - large number of models
  - many excluded by $2\ M_\odot$ neutron star maximum mass constraint
- **General Purpose Equations of State**
  - cover large range in temperature, density, isospin asymmetry
  - development of unified models
    - single theoretical approach for homogeneous and inhomogeneous matter
    - relevant degrees of freedom? (clusters, hyperons, quarks, . . .)
    - phase transitions
- **future extensions**
  - consistent treatment of pairing
  - calculation of transport properties
  - . . . ?

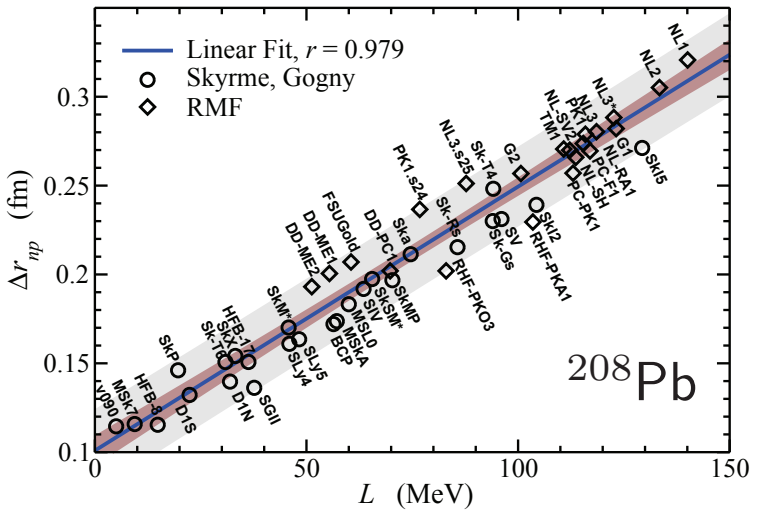


Equation of State of Dense Matter II

- **Constraints**
  - stiffness: flow in heavy-ion collisions, maximum neutron star mass $> 2\ M_\odot$,
  - neutron matter properties from theory
  - density dependence of symmetry energy
  - clustering in low-density matter
  - . . .
- **Correlations**
  - nuclear matter parameters (K, J, L)
    $\Leftrightarrow$ properties of nuclei
    – neutron skin thickness
    – pygmy and giant resonances
    – dipole polarizability
    – . . .
    model dependence?



T. Fischer et al., EPJA 50 (2014) 46



X. Viñas et al., EPJA 50 (2014) 27

Nuclear Structure

- **Most Relevant Quantities for Astrophysics**
  - masses, binding and separation energies
  - properties of excited states (single-particle, collective)
  - strength functions
  - level densities
- **Important Aspects**
  - correlations and clustering
  - deformation
  - beyond mean-field effects
  - restauration of symmetries
  - input for reaction models
- **Goals**
  - global, unified description of structure
  - quantification of errors
  - reliable extrapolation to exotic nuclei

Nuclear Reactions

- **Applications**
  - Big Bang and stellar nucleosynthesis, various processes (s, r, p, rp, νp, fission)
  - indirect methods
  - cosmochronometry
- **Specific Topics**
  - radiative capture/dissociation reactions
  - weak interaction reactions, half-lives, neutrino flavor oscillation, sterile neutrinos?
  - reliable microscopic theory of fission?
  - applicability of statistical methods
  - optical potentials
  - thermal and medium effects (e.g. electron screening)
- **Goals**
  - consistent description of structure and reactions
  - explanation of origin of elements and abundances
  - understanding of energy sources and transformation in cosmic history

Indirect Methods

- **Reaction Theory**
  - essential for analysis $\Rightarrow$ determination of wanted reaction cross sections from measured cross sections
- **Methods**
  - Asymptotic Normalization Coefficient (ANC) Method
    – effects of initial/final state interaction?
  - Coulomb Dissociation (CD) Method
    – higher-order & relativistic effects
    – Coulomb-nuclear interference
  - Trojan Horse Method (THM)
    – improvement of reaction theory

Beyond Nuclear Theory

- **Theory for Astrophysical Simulations**
  - hydrodynamics
  - general relativity
  - . . . ?
- **Data Repositories**
  - equations of state: CompOSE (`compose.obspm.fr`)
  - properties of nuclei, reaction rates: BRUSLIB (`www.astro.ulb.ac.be/bruslib/`)
  - reaction rates: NACRE I, II (`pntpm3.ulb.ac.be/Nacre/` & `www.astro.ulb.ac.be/nacreii/`), KADoNiS (`www.kadonis.org`), web pages of T. Rauscher (`nucastro.org`), . . .

  need for new European initiatives?
- **Computational Resources**
  - collaboration with simulation labs (e.g. KIT)
  - . . .