Nuclear structure IV: Nuclear physics and Neutron stars

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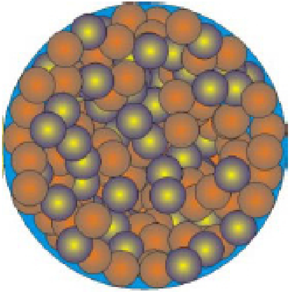
Fundamental questions in nuclear physics

Nuclear astrophysics:

- What's the relation between nuclear physics and neutron stars?
- What are the composition and properties of neutron stars?
- How do supernovae explode?
- How are heavy elements formed?

Nuclei and neutron stars



^{208}Pb, $\sim 10^{-15}$m, 10^{-25} kg

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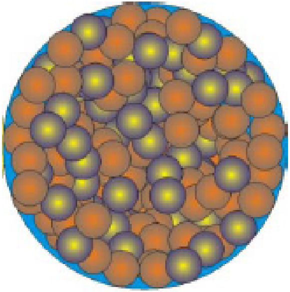

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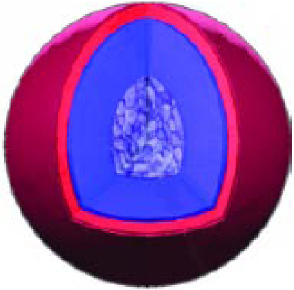
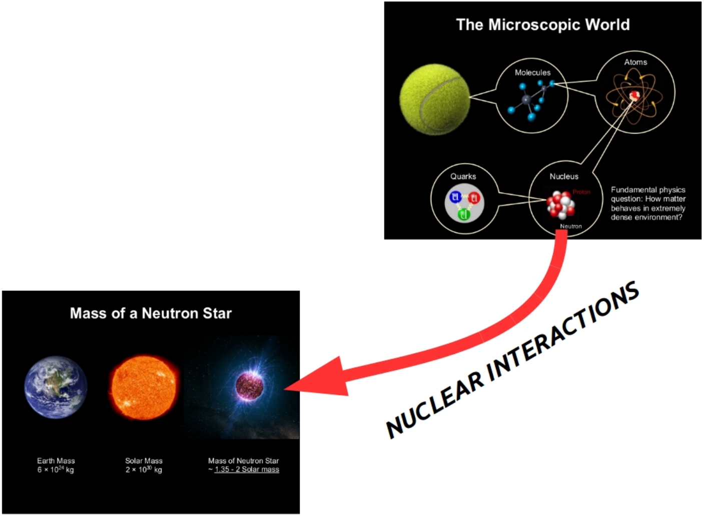


neutron star,
$\sim$ 10 Km, 10^{30} kg (2 $M_{\rm solar}$)



Can we really describe nuclei and neutron stars starting from the same forces???

Neutron matter and neutron star structure

TOV equations:

$$\frac{dP}{dr} = -\frac{G[m(r) + 4\pi r^3 P/c^2][\epsilon + P/c^2]}{r[r - 2Gm(r)/c^2]}\,, \qquad \frac{dm(r)}{dr} = 4\pi\epsilon r^2\,,$$

Boundary conditions: $P(r = 0) = P_c$ and $P(r = R_{\max}) = 0$ (surface).
An equation of state $P(\rho)$ is needed.

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Other useful quantities to know:

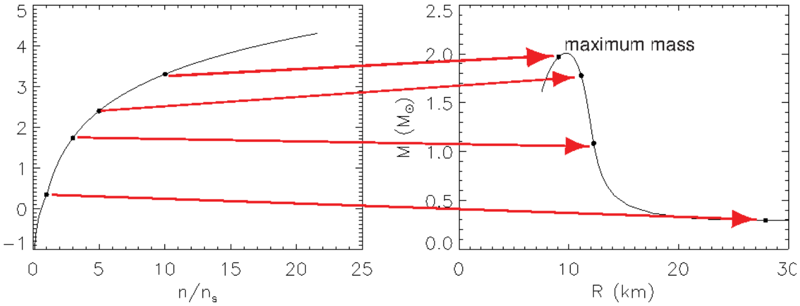
$\epsilon(\rho) = \rho\,[E(\rho) + m_N)]$ *energy density*

$P(\rho) = \rho^2\,\frac{\partial E}{\partial \rho}$ *pressure*

The total mass of the star is given by

$$M(R) = \int_0^R dr\,4\pi r^2 \epsilon(r)$$

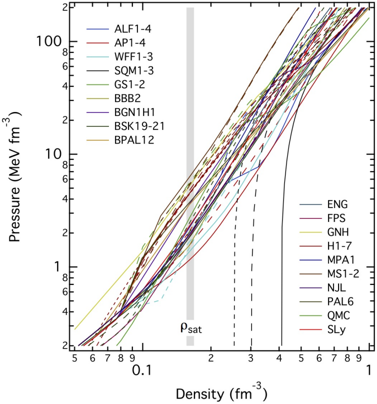
Neutron matter and neutron star structure



J. Lattimer

Equation of state of neutron matter

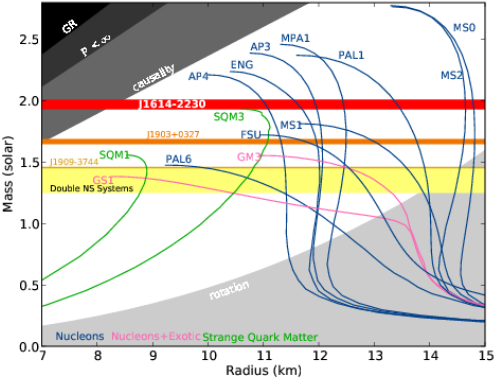
Many many EOS of neutron matter exist! Just "some":



Özel, Freire, arXiv (2016)

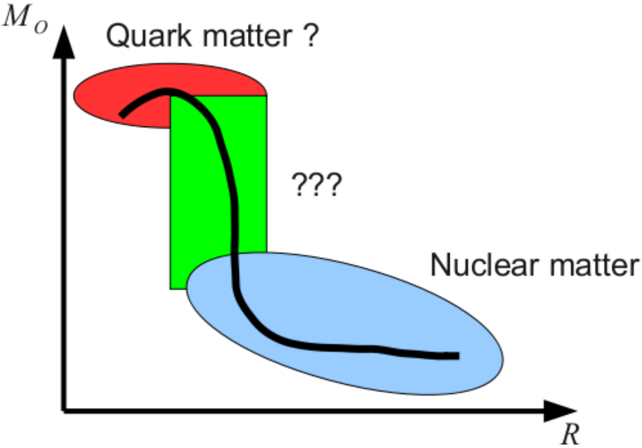
Which one(s) (if any) support neutron stars observations?

The main constrain: maximum mass.



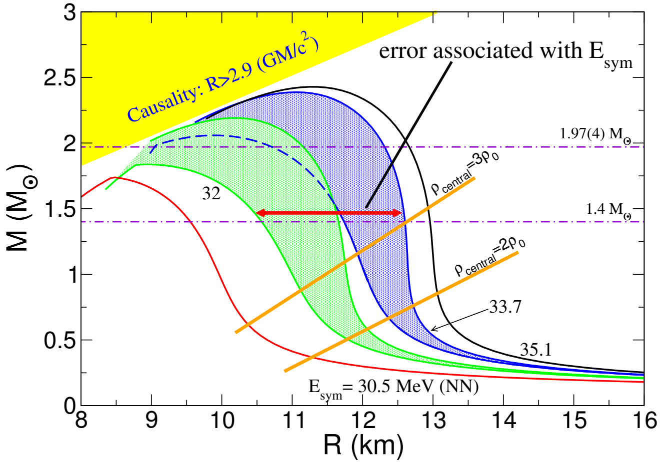
Demorest, *et al.*, Nature 467, 1081 (2010)

Neutron star structure test the EOS!



Neutron star radius sensitive to the EOS at nuclear densities.
Maximum mass depends mostly to the composition.

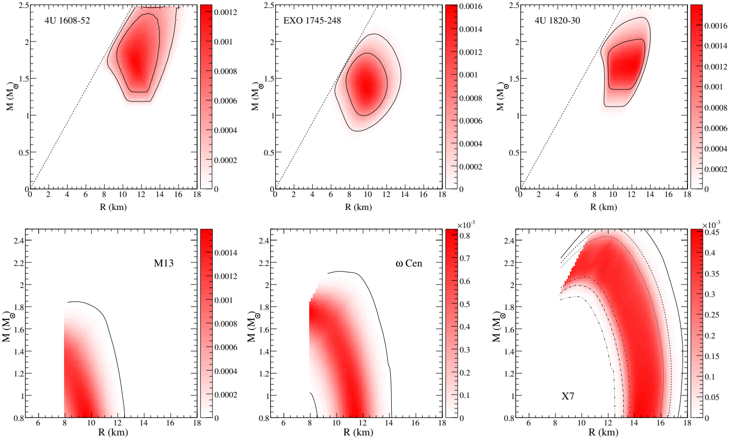
Neutron star structure



Gandolfi, Carlson, Reddy, PRC (2012).

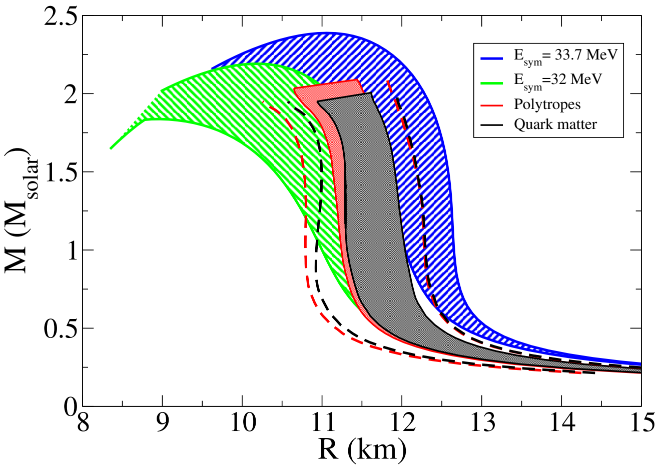
Accurate measurement of E_{sym} put a constraint to the radius of neutron stars, **OR** observation of M and R would constrain E_{sym}!

Neutron stars



Steiner, Lattimer, Brown, ApJ (2010)

Neutron star observations can be used to 'measure' the EOS and constrain E_{sym} and L. (Systematic uncertainties still under debate...)



Steiner, Gandolfi, PRL (2012), Gandolfi *et al.* EPJA (2014)

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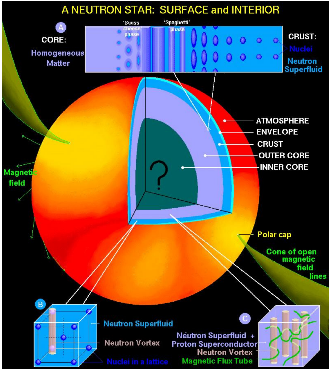
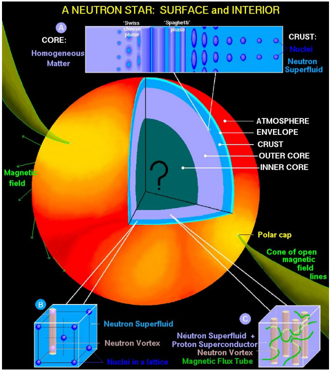
Neutron stars



D. Page

- Atmosphere: atomic and plasma physics
- Crust: physics of superfluids (neutrons, vortex), solid state physics (nuclei)
- Inner crust: deformed nuclei, pasta phase
- Outer core: nuclear matter
- Inner core: hyperons? quark matter? π or K condensates? ...?

Neutron stars



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Let's discuss **only one** possible scenario: hyperons

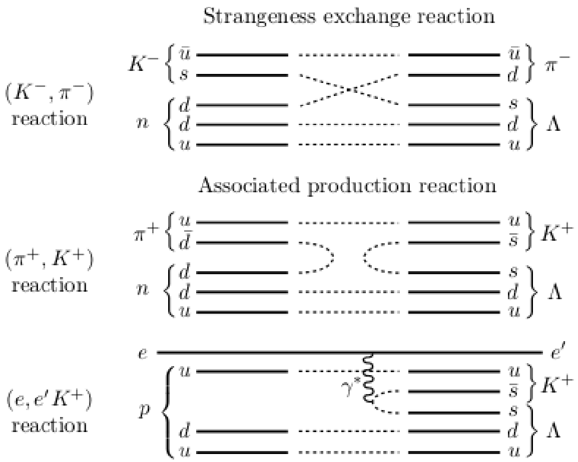
High density neutron matter

If chemical potential large enough ($\rho \sim 2 - 3\rho_0$), heavier particles form, i.e. Λ, Σ, ...

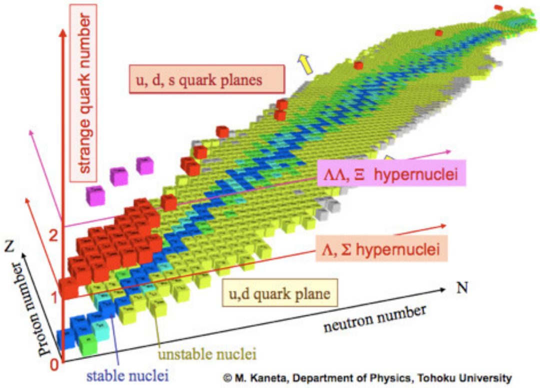
For example: it might be energetically convenient to change a neutron(ddu) into a Λ(uds).

Hypernuclei

In order to infer the hyperon-nucleon interactions, hypernuclei can be created in experiments!



Nuclei and hypernuclei



Few thousands of binding energies for normal nuclei are known.

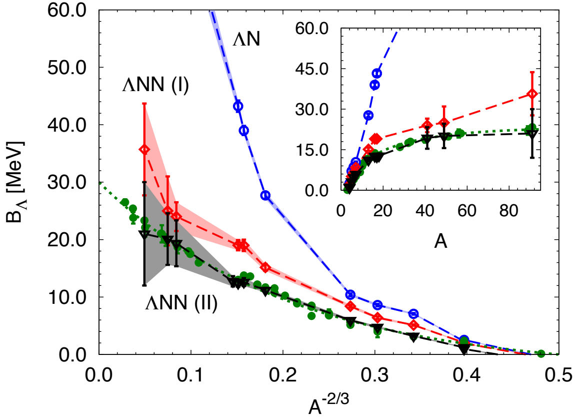
Only few tens for hypernuclei.

Hypernuclei and hypermatter:

$$H = H_N + \frac{\hbar^2}{2m_\Lambda}\sum_{i=1}^{A}\nabla_i^2 + \sum_{i<j} v_{ij}^{\Lambda N} + \sum_{i<j<k} V_{ijk}^{\Lambda NN}$$

Λ-binding energy calculated as the difference between the system with and without Λ.

$v^{\Lambda N}$ and $V^{\Lambda NN}$(I) are phenomenological (Usmani).



Lonardoni, Pederiva, Gandolfi, PRC (2013) and PRC (2014).

$V^{\Lambda NN}$ (II) is a new form where the parameters have been fine tuned.

As expected, the role of ΛNN is crucial for saturation.

Hyper-neutron matter

Neutrons and Λ particles:

$$\rho = \rho_n + \rho_\Lambda \,, \qquad x = \frac{\rho_\Lambda}{\rho}$$

$$E_{\rm HNM}(\rho, x) = \Big[E_{\rm PNM}((1-x)\rho) + m_n\Big](1-x) + \Big[E_{\rm P\Lambda M}(x\rho) + m_\Lambda\Big]x + f(\rho, x)$$

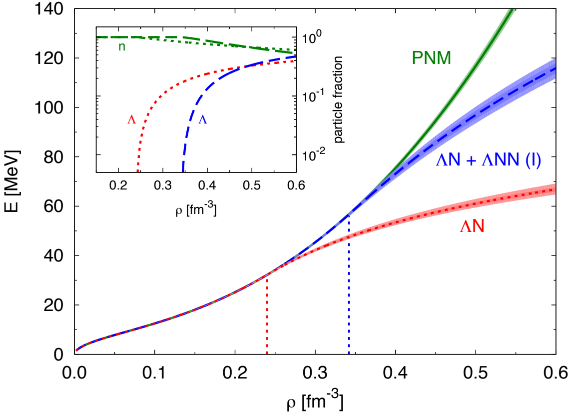
where $E_{P\Lambda M}$ is the non-interacting energy (no $v_{\Lambda\Lambda}$ interaction),

$$E_{PNM}(\rho) = a\left(\frac{\rho}{\rho_0}\right)^\alpha + b\left(\frac{\rho}{\rho_0}\right)^\beta$$

and

$$f(\rho, x) = c_1\frac{x(1-x)\rho}{\rho_0} + c_2\frac{x(1-x)^2\rho^2}{\rho_0^2}$$

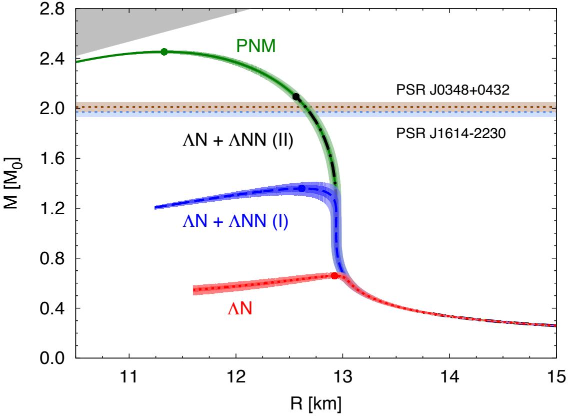
EOS obtained by solving for $\mu_\Lambda(\rho, x) = \mu_n(\rho, x)$



Lonardoni, Lovato, Pederiva, Gandolfi, PRL (2015)

No hyperons up to $\rho = 0.5$ fm^{-3} using ΛNN (II)!!!

Λ-neutron matter



Lonardoni, Lovato, Pederiva, Gandolfi, PRL (2015)

Drastic role played by ΛNN. Calculations can be compatible with neutron star observations.

Note: no $v_{\Lambda\Lambda}$, no protons, and no other hyperons included

Hyperons

Understanding hyperon-nucleon interactions is crucial, but very few experimental data available:

- $\sim$ 4500 NN scattering data available, $\sim 30\ \Lambda N$
- few thousands of binding energies for nuclei known. Only few tens for hypernuclei.

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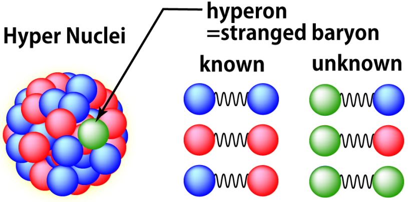

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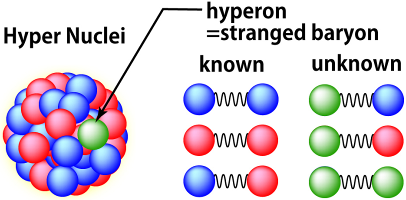
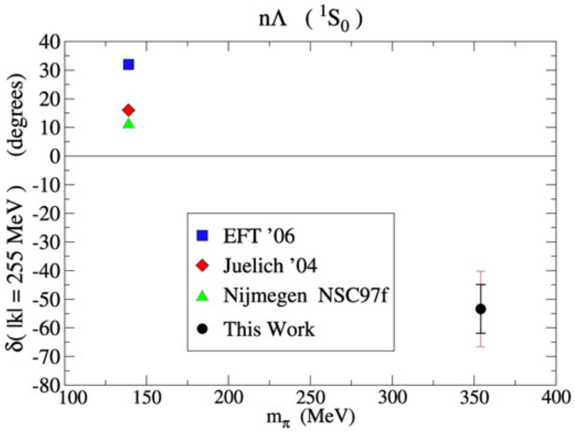


Hyperons

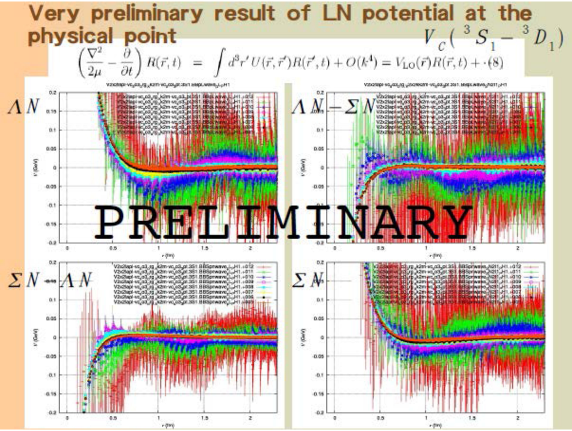
Future, more ΛN experiments and/or Lattice QCD.
Example: phase-shifts calculated with Lattice QCD.



Beane *et al.*, Nuclear Physics A794, 62 (2007)

Hyperons

Future, more ΛN experiments and/or Lattice QCD. Example: attempt to extract the potential with Lattice QCD:



HAL QCD collaboration.

Stay tuned...

Remember, hyperons in dense matter is only **one possible** scenario. Very active field...

Summary of this lecture before the general summary:

- Neutron star structure from the EOS
- Maximum mass and radii
- Hyperons and dense matter

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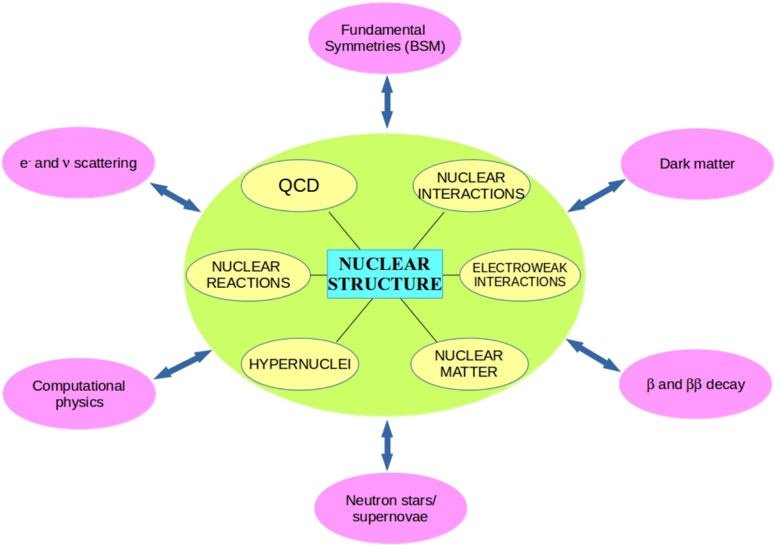
Wrap up...


Fundamental Symmetries (BSM)
e⁻ and ν scattering
Dark matter
QCD
NUCLEAR INTERACTIONS
NUCLEAR REACTIONS
NUCLEAR STRUCTURE
ELECTROWEAK INTERACTIONS
HYPERNUCLEI
NUCLEAR MATTER
Computational physics
β and ββ decay
Neutron stars/ supernovae

Last lesson...

The last but very important lesson.

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Always acknowledge the funding agencies!!!

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NUCLEI Nuclear Computational Low-Energy Initiative

www.computingnuclei.org

U.S. DEPARTMENT OF ENERGY


"That's all Folks!"