Neutron matter, symmetry energy and neutron stars

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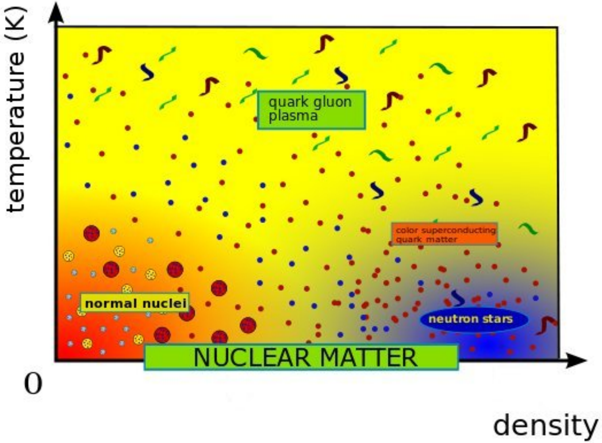
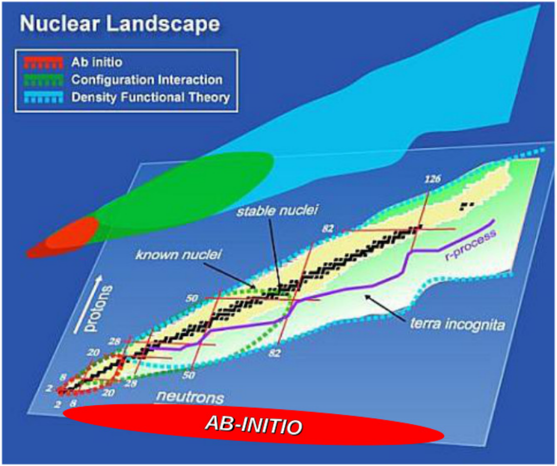
Homogeneous neutron matter



Inhomogeneous neutron matter



W. Nazarewicz – UNEDF

Outline

- The model and the method
- **Homogeneous neutron matter**
  - Three-neutron force and the equation of state of neutron matter
  - Symmetry energy
  - Neutron star structure
- **Inhomogeneous neutron matter: Skyrme vs ab-initio.**
  - Energy
  - Density and radii
- Conclusions

Nuclear Hamiltonian

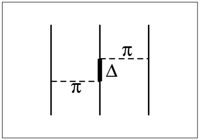
Model: non-relativistic nucleons interacting with an effective nucleon-nucleon force (NN) and three-nucleon interaction (TNI).

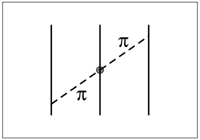
$$H = -\frac{\hbar^2}{2m}\sum_{i=1}^{A}\nabla_i^2 + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$

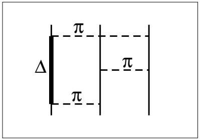
v_{ij} NN (Argonne AV8') fitted on scattering data. Sum of operators:

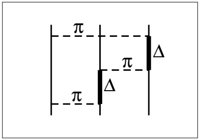
$$v_{ij} = \sum O_{ij}^{p=1,8} v^p(r_{ij}) \,, \quad O_{ij}^p = (1, \vec{\sigma}_i \cdot \vec{\sigma}_j, S_{ij}, \vec{L}_{ij} \cdot \vec{S}_{ij}) \times (1, \vec{\tau}_i \cdot \vec{\tau}_j)$$

Urbana–Illinois V_{ijk} models processes like









$+$ short-range correlations (spin/isospin independent).

Quantum Monte Carlo

Evolution of Schrodinger equation in imaginary time **t**:

$$\Psi(t) = e^{-(H-E_T)t}\Psi(0)$$

In the limit of $t \to \infty$ it approaches to the lowest energy eigenstate (not orthogonal to $\Psi(0)$).

Propagation performed by

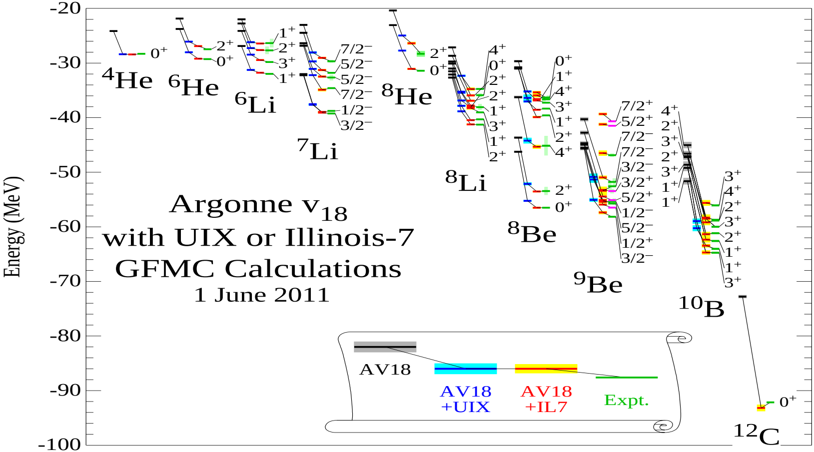
$$\psi(R,t) = \langle R|\psi(t)\rangle = \int dR' G(R,R',t)\psi(R',0)$$

For a given microscopic Hamiltonian, this method solves the ground–state within a systematic uncertainty of **1–2%** in a **non-perturbative way.**

GFMC: spin/isospin states included in the variational wavefunction.

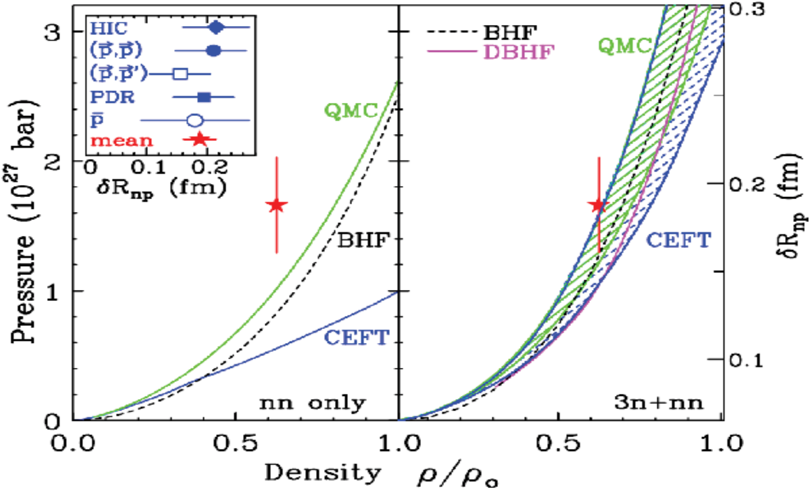
AFDMC: spin/isospin states are sampled.

Light nuclei spectrum computed with GFMC



Carlson, Pieper, Wiringa, many papers

Three-body force in neutron matter



Tsang *et al.*, arXiv:1204.0466

Neutron matter

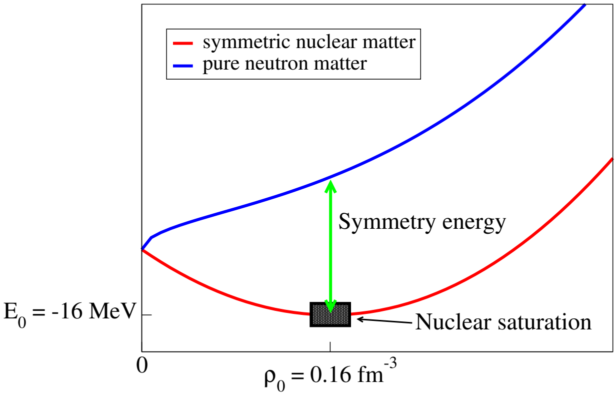
Assumptions:

- The two-nucleon interaction reproduces well (elastic) *pp* and *np* scattering data up to high energies ($E_{lab} \sim 600$MeV) in all channels.
- The three-neutron force ($T = 3/2$) very weak in light nuclei, while $T = 1/2$ is the dominant part (but zero in neutron matter). **Difficult to study in light nuclei.**
- In neutron matter the short-range repulsive part of three-body force is the dominant term.

Symmetry energy

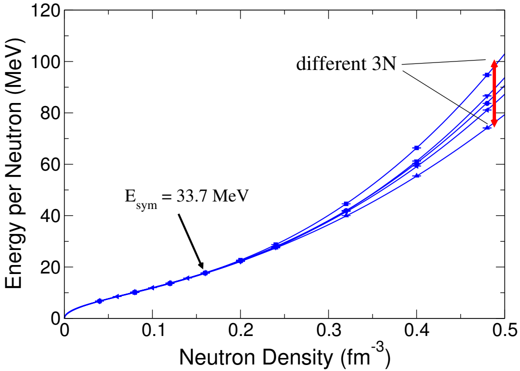
Nuclear matter EOS:

$$E(\rho, x) = E_{SNM}(\rho) + E^{(2)}_{sym}(\rho)(1-2x)^2 + \cdots \,, \quad \rho = \rho_n + \rho_p \,, \quad x = \frac{\rho_p}{\rho}$$



Neutron matter

We consider different forms of three-neutron interaction by only requiring a particular value of E_{sym} at saturation.

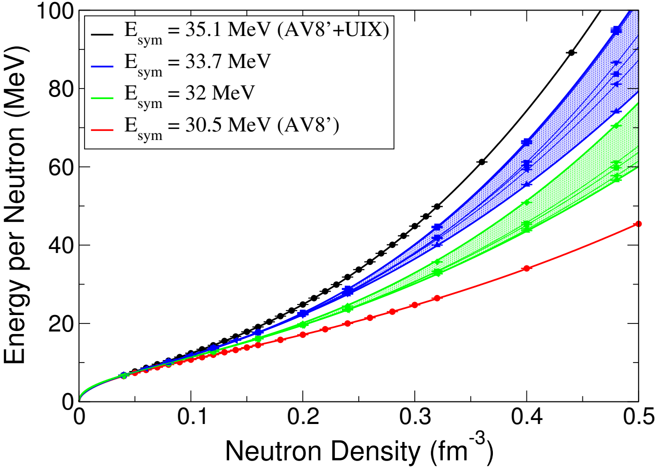


different 3N:

- $V_{2\pi} + \alpha V_R$
- $V_{2\pi} + \alpha V_R^{\mu}$ (several μ)
- $V_{2\pi} + \alpha \tilde{V}_R$
- $V_{3\pi} + \alpha V_R$
- ...

Neutron matter and symmetry energy

We then try to change the neutron matter energy at saturation:

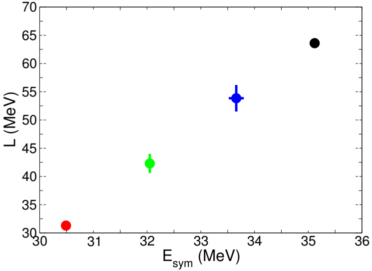


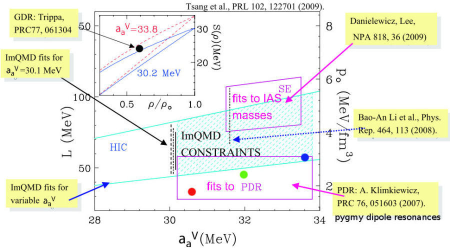
Gandolfi, Carlson, Reddy PRC (2012).

Neutron matter and symmetry energy

From the EOS, we can fit the symmetry energy around ρ_0 using

$$E_{sym}(\rho) = E_{sym} + \frac{L}{3}\frac{\rho - 0.16}{0.16} + \cdots$$





Tsang et al., PRL 102, 122701 (2009).

GDR: Trippa, PRC77, 061304

ImQMD fits for a_a^V=30.1 MeV

ImQMD fits for variable a_a^V

Danielewicz, Lee, NPA 818, 36 (2009)

Bao-An Li et al., Phys. Rep. 464, 113 (2008).

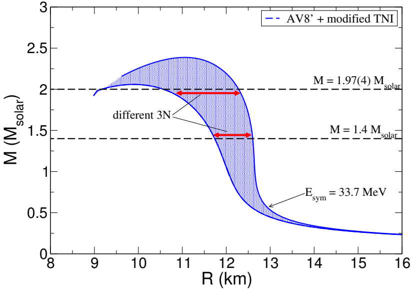
PDR: A. Klimkiewicz, PRC 76, 051603 (2007).

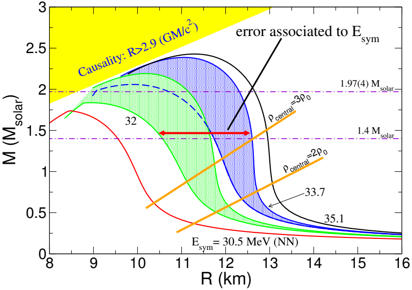
pygmy dipole resonances

Very weak dependence to the model of 3N force for a given E_{sym}.

Neutron star structure

EOS used to solve the TOV equations.



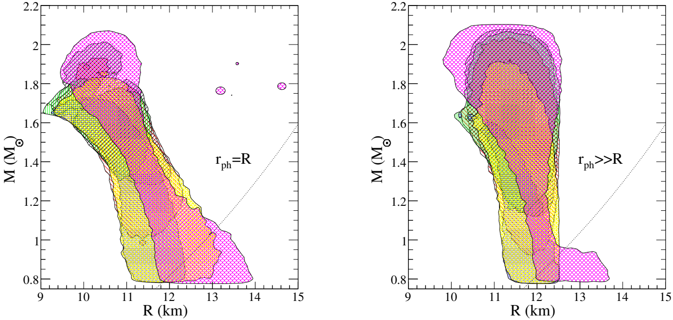


Accurate measurement of E_{sym} would put a constraint to the radius of neutron stars, **OR** observation of M and R would constrain E_{sym}!

$M = 1.97\,M_{solar}$ recently observed – Nature (2010).

Neutron stars

Observations of the mass-radius relation of neutron stars are becoming available:



Steiner, Lattimer, Brown, ApJ (2010)

Neutron star matter model

Neutron star matter model:

- $\rho < \rho_t , \quad \rho_t = 0.28 \ldots 0.48 \text{ fm}^{-3}$

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

$$E_{sym} = a + b + 16 \, , \quad L = 3(a\alpha + b\beta)$$

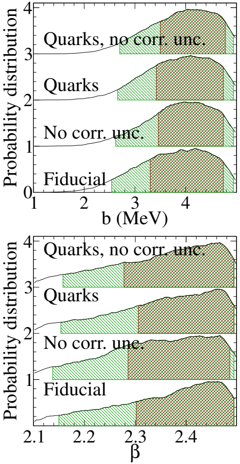
Note:

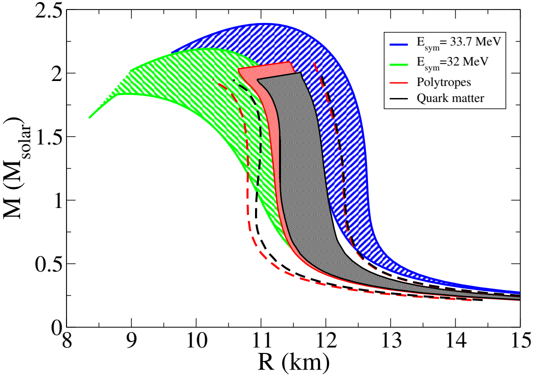
a and α sensitive to the 2-neutron force.
b (and β) is strongly related to 3-neutron force.

- $\rho > \rho_t$,

Polytropes or Polytrope+Quark matter (Alford et al.)

Neutron star matter model

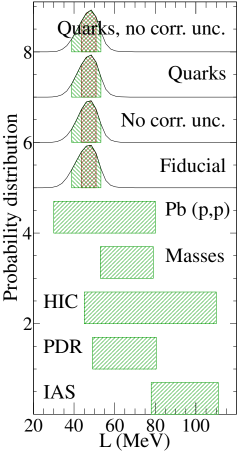




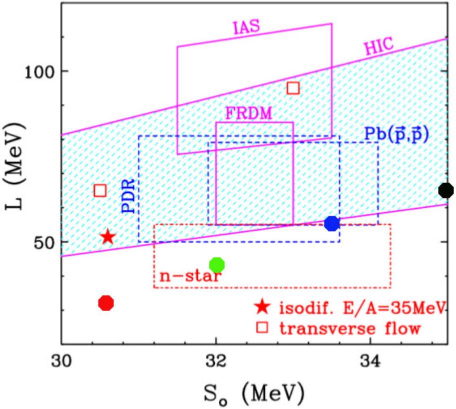
Steiner, Gandolfi, PRL (2012)

New constraints to 3-neutron force (to combine with NN)!!

Neutron stars: symmetry energy



Steiner, Gandolfi, PRL (2012)



Tsang *et al.*, arXiv:1204.0466

Neutron drops

Now let's study **inhomogeneous neutron matter.**

We confine neutrons by adding an external potential:

$$H = -\frac{\hbar^2}{2m}\sum_{i=1}^{A}\nabla_i^2 + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \sum_i V_{ext}(r_i)$$

V_{ext} is a Wood-Saxon or Harmonic well:

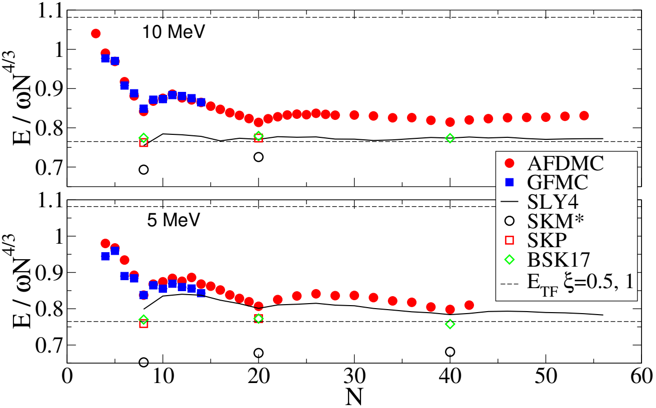
$$V_{WS} = -\frac{V_0}{1 + exp[(r - R)/a]}$$

$$V_{HO} = \frac{1}{2} m\omega^2 r^2$$

$\Longrightarrow$ different geometries and densities.

Neutron drops, harmonic oscillator well

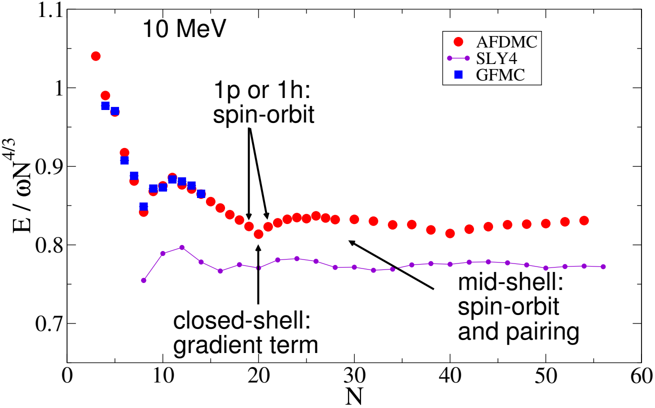
External well: harmonic oscillator with $\hbar\omega$=5, 10 MeV.



Skyrme systematically overbind neutron drops.

Neutron drops, harmonic oscillator well

Fixing Skyrme force:

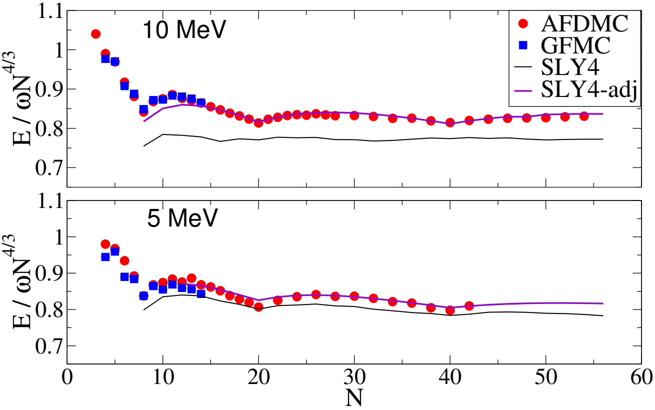


The correction is very similar in all the Skyrme forces we considered.

Neutron drops, adjusted Skyrme force

Note: bulk term of Skyrme fit neutron matter.

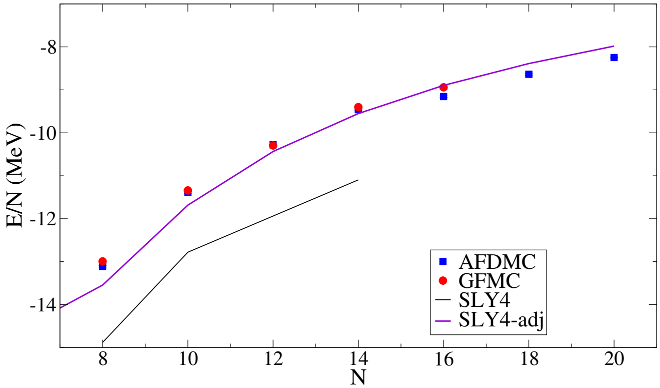
We add the **missing repulsion** by adjusting the gradient term $G_d[\nabla \rho_n]^2$, the pairing and spin-orbit terms.



Gandolfi, Carlson, Pieper, PRL (2011).

Neutron drops, adjusted Skyrme force

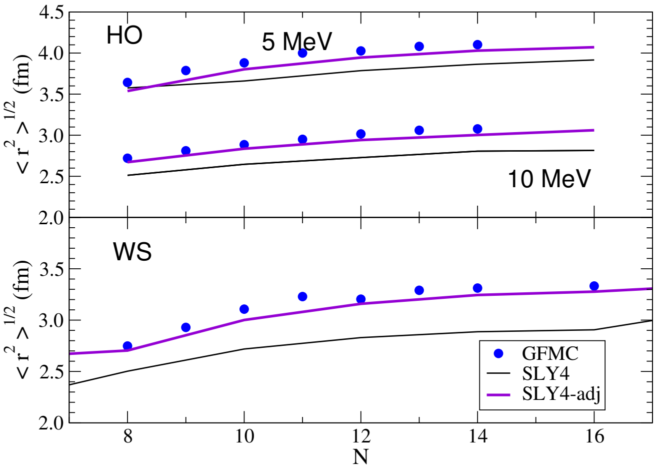
Neutrons in the Wood-Saxon well are also better reproduced by the adjusted SLY4.



Gandolfi, Carlson, Pieper, PRL (2011).

Neutron drops: radii

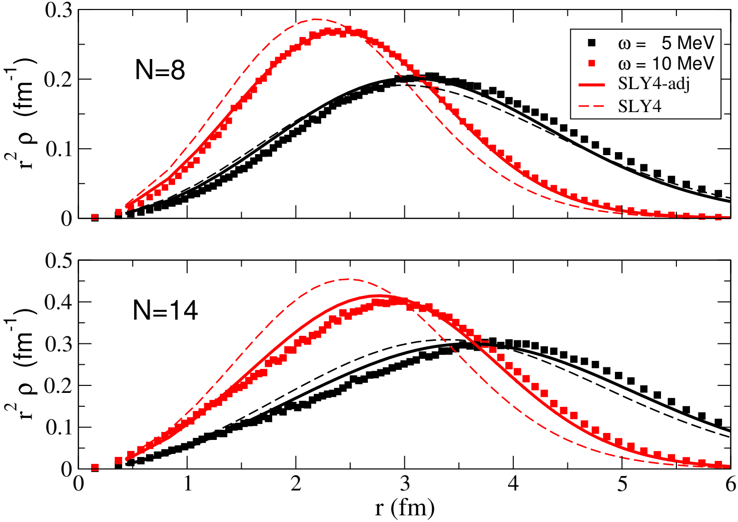
Correction to radii using the adjusted-SLY4.



Gandolfi, Carlson, Pieper, PRL (2011).

Neutron drops: radial density

Neutron radial density:



Gandolfi, Carlson, Pieper, PRL (2011).

Gradient term

Where is the gradient term important?

Just few examples:

- Medium large neutron-rich nuclei
- Phases in the crust of neutron stars
- Isospin-asymmetry energy of nuclear matter

Conclusions

- Effect of three–neutron forces to high-density neutron matter; the systematic uncertainty due to 3N is relatively small.
- E_{sym} strongly constrain L. Weak dependence to the model of 3N.
- Uncertainty of the radius of neutron stars mainly due E_{sym} rather than 3N.
- Neutron star observations becoming competitive with terrestrial experiments.
- Skyrme can be better constrained by ab-initio calculations.

Thanks for the attention