Comments from a referee

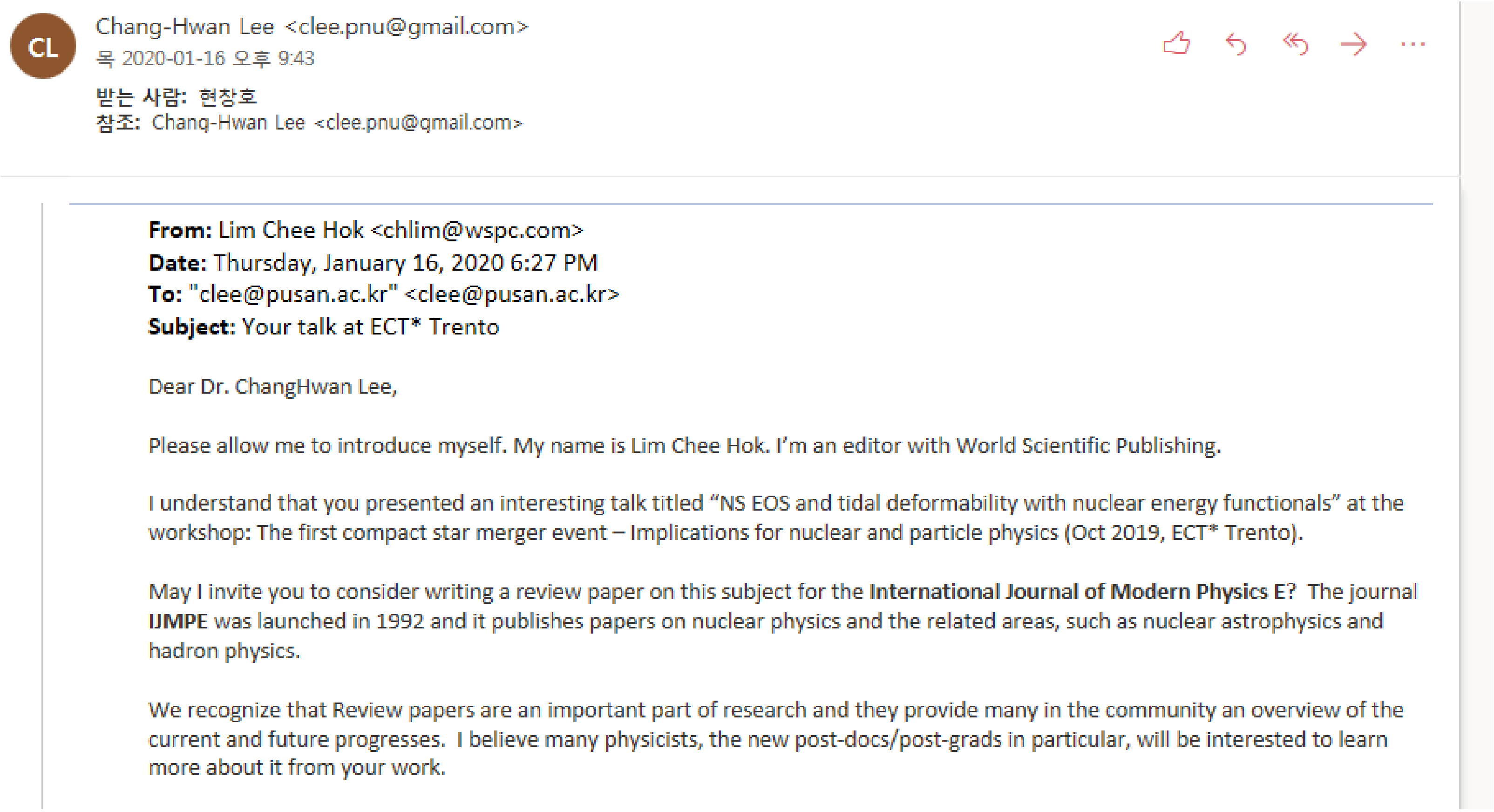
CENuM workshop

2020년 7월 3일

현창호

- 1월 International Journal of Modern Physics E로부터 중성자별에 관한 review article 의뢰를 받음

E-mail



CL

Chang-Hwan Lee <clee.pnu@gmail.com>
목 2020-01-16 오후 9:43

받는 사람: 현창호
참조: Chang-Hwan Lee <clee.pnu@gmail.com>

From: Lim Chee Hok <chlim@wspc.com>
Date: Thursday, January 16, 2020 6:27 PM
To: "clee@pusan.ac.kr" <clee@pusan.ac.kr>
Subject: Your talk at ECT* Trento

Dear Dr. ChangHwan Lee,

Please allow me to introduce myself. My name is Lim Chee Hok. I'm an editor with World Scientific Publishing.

I understand that you presented an interesting talk titled "NS EOS and tidal deformability with nuclear energy functionals" at the workshop: The first compact star merger event – Implications for nuclear and particle physics (Oct 2019, ECT* Trento).

May I invite you to consider writing a review paper on this subject for the **International Journal of Modern Physics E**? The journal **IJMPE** was launched in 1992 and it publishes papers on nuclear physics and the related areas, such as nuclear astrophysics and hadron physics.

We recognize that Review papers are an important part of research and they provide many in the community an overview of the current and future progresses. I believe many physicists, the new post-docs/post-grads in particular, will be interested to learn more about it from your work.

- 5월 말 투고

Cover page

International Journal of Modern Physics E

Neutron Star Equations of State and their Applications

--Manuscript Draft--

Manuscript Number:	
Full Title:	Neutron Star Equations of State and their Applications
Article Type:	Review Paper (invited)
Corresponding Author:	Chang-Hwan Lee Pusan National University Kumjeong-ku, KOREA, REPUBLIC OF
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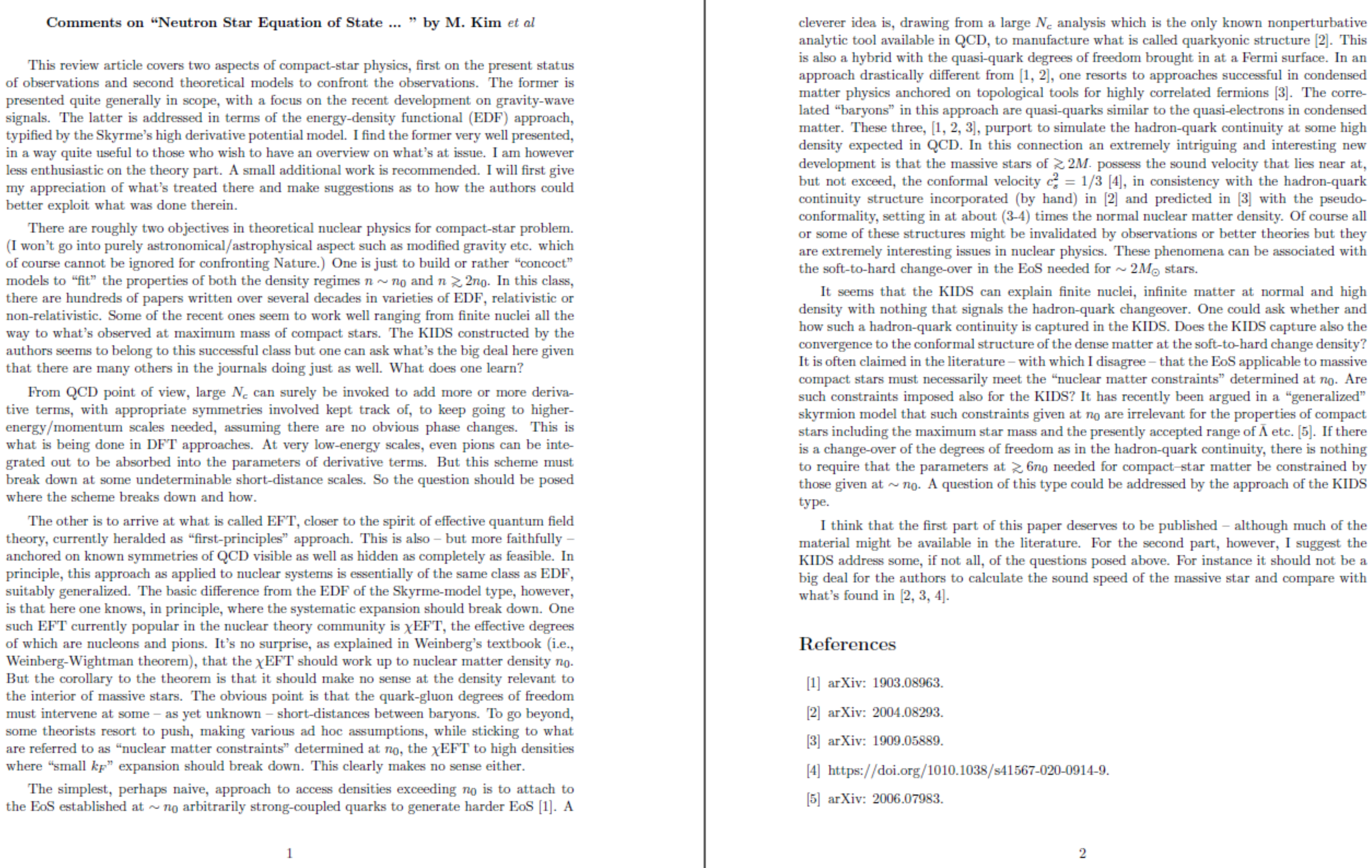
Abstract:	This article reviews the properties of neutron stars based on the recent multi-messenger observations including electromagnetic waves from the low-mass X-ray binaries and gravitational waves from the merger of neutron star binaries. Based on these observations, we investigate theoretical models for dense nuclear matter and discuss their implications to the neutron star observations such as mass, radius, cooling, and tidal deformability. We also discuss the uncertainties in the neutron star cooling, neutron star properties with Bayesian approaches, and an expansion scheme applied to the nuclear energy density functional theory.
Keywords:	neutron star equation of state; dense nuclear matter; low-mass X-ray binaries, gravitational-waves
Manuscript Classifications:	26.60.Dd Neutron star core; 26.60.Kp Equations of state of neutron-star matter
Author Comments:	

● 6월 18일 referee comment 받음



Comments on "Neutron Star Equation of State ... " by M. Kim *et al*

This review article covers two aspects of compact-star physics, first on the present status of observations and second theoretical models to confront the observations. The former is presented quite generally in scope, with a focus on the recent development on gravity-wave signals. The latter is addressed in terms of the energy-density functional (EDF) approach, typified by the Skyrme's high derivative potential model. I find the former very well presented, in a way quite useful to those who wish to have an overview on what's at issue. I am however less enthusiastic on the theory part. A small additional work is recommended. I will first give my appreciation of what's treated there and make suggestions as to how the authors could better exploit what was done therein.

There are roughly two objectives in theoretical nuclear physics for compact-star problem. (I won't go into purely astronomical/astrophysical aspect such as modified gravity etc. which of course cannot be ignored for confronting Nature.) One is just to build or rather "concoct" models to "fit" the properties of both the density regimes $n \sim n_0$ and $n \gtrsim 2n_0$. In this class, there are hundreds of papers written over several decades in varieties of EDF, relativistic or non-relativistic. Some of the recent ones seem to work well ranging from finite nuclei all the way to what's observed at maximum mass of compact stars. The KIDS constructed by the authors seems to belong to this successful class but one can ask what's the big deal here given that there are many others in the journals doing just as well. What does one learn?

From QCD point of view, large N_c can surely be invoked to add more or more derivative terms, with appropriate symmetries involved kept track of, to keep going to higher-energy/momentum scales needed, assuming there are no obvious phase changes. This is what is being done in DFT approaches. At very low-energy scales, even pions can be integrated out to be absorbed into the parameters of derivative terms. But this scheme must break down at some undeterminable short-distance scales. So the question should be posed where the scheme breaks down and how.

The other is to arrive at what is called EFT, closer to the spirit of effective quantum field theory, currently heralded as "first-principles" approach. This is also – but more faithfully – anchored on known symmetries of QCD visible as well as hidden as completely as feasible. In principle, this approach as applied to nuclear systems is essentially of the same class as EDF, suitably generalized. The basic difference from the EDF of the Skyrme-model type, however, is that here one knows, in principle, where the systematic expansion should break down. One such EFT currently popular in the nuclear theory community is χEFT, the effective degrees of which are nucleons and pions. It's no surprise, as explained in Weinberg's textbook (i.e., Weinberg-Wightman theorem), that the χEFT should work up to nuclear matter density n_0. But the corollary to the theorem is that it should make no sense at the density relevant to the interior of massive stars. The obvious point is that the quark-gluon degrees of freedom must intervene at some – as yet unknown – short-distances between baryons. To go beyond, some theorists resort to push, making various ad hoc assumptions, while sticking to what are referred to as "nuclear matter constraints" determined at n_0, the χEFT to high densities where "small k_F" expansion should break down. This clearly makes no sense either.

The simplest, perhaps naive, approach to access densities exceeding n_0 is to attach to the EoS established at $\sim n_0$ arbitrarily strong-coupled quarks to generate harder EoS [1]. A cleverer idea is, drawing from a large N_c analysis which is the only known nonperturbative analytic tool available in QCD, to manufacture what is called quarkyonic structure [2]. This is also a hybrid with the quasi-quark degrees of freedom brought in at a Fermi surface. In an approach drastically different from [1, 2], one resorts to approaches successful in condensed matter physics anchored on topological tools for highly correlated fermions [3]. The correlated "baryons" in this approach are quasi-quarks similar to the quasi-electrons in condensed matter. These three, [1, 2, 3], purport to simulate the hadron-quark continuity at some high density expected in QCD. In this connection an extremely intriguing and interesting new development is that the massive stars of $\gtrsim 2M_\odot$ possess the sound velocity that lies near at, but not exceed, the conformal velocity $c_s^2 = 1/3$ [4], in consistency with the hadron-quark continuity structure incorporated (by hand) in [2] and predicted in [3] with the pseudo-conformality, setting in at about (3-4) times the normal nuclear matter density. Of course all or some of these structures might be invalidated by observations or better theories but they are extremely interesting issues in nuclear physics. These phenomena can be associated with the soft-to-hard change-over in the EoS needed for $\sim 2M_\odot$ stars.

It seems that the KIDS can explain finite nuclei, infinite matter at normal and high density with nothing that signals the hadron-quark changeover. One could ask whether and how such a hadron-quark continuity is captured in the KIDS. Does the KIDS capture also the convergence to the conformal structure of the dense matter at the soft-to-hard change density? It is often claimed in the literature – with which I disagree – that the EoS applicable to massive compact stars must necessarily meet the "nuclear matter constraints" determined at n_0. Are such constraints imposed also for the KIDS? It has recently been argued in a "generalized" skyrmion model that such constraints given at n_0 are irrelevant for the properties of compact stars including the maximum star mass and the presently accepted range of Λ etc. [5]. If there is a change-over of the degrees of freedom as in the hadron-quark continuity, there is nothing to require that the parameters at $\gtrsim 6n_0$ needed for compact–star matter be constrained by those given at $\sim n_0$. A question of this type could be addressed by the approach of the KIDS type.

I think that the first part of this paper deserves to be published – although much of the material might be available in the literature. For the second part, however, I suggest the KIDS address some, if not all, of the questions posed above. For instance it should not be a big deal for the authors to calculate the sound speed of the massive star and compare with what's found in [2, 3, 4].

References

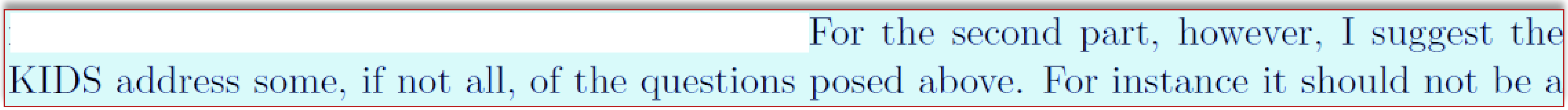
[1] arXiv: 1903.08963.

[2] arXiv: 2004.08293.

[3] arXiv: 1909.05889.

[4] https://doi.org/1010.1038/s41567-020-0914-9.

[5] arXiv: 2006.07983.



For the second part, however, I suggest the KIDS address some, if not all, of the questions posed above. For instance it should not be a

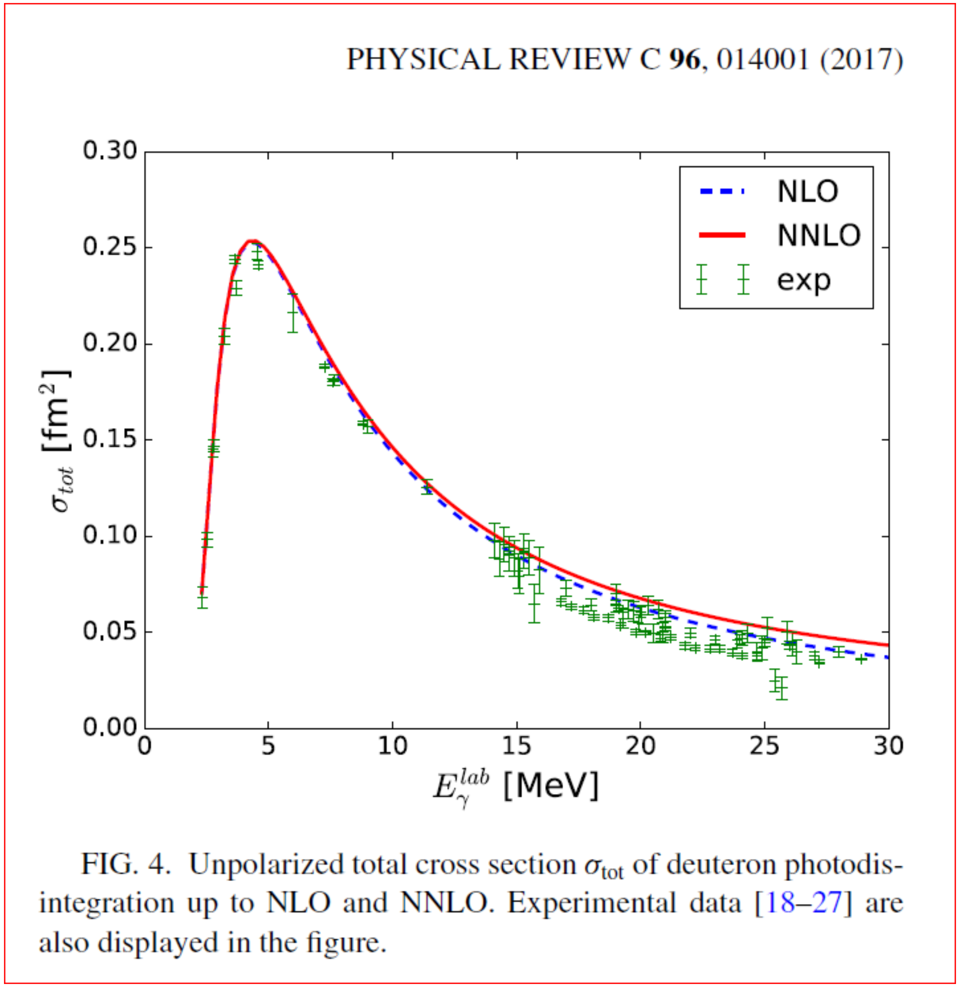
Key questions

- So the questions should be posed where the scheme breaks down and how?
- One could ask whether and how such a hadron-quark continuity is captured in the KIDS
- …such constraints given at the saturation density are irrelevant for the properties of compact stars including the maximum star mass and the presently accepted range of tidal deformability etc

Where the scheme breaks down and how?

- Answer: NO idea
- May be understood by trial and error
- Lesson from pionless EFT in two-nucleon low-energy phenomenology
- Pionless EFT
  - Pion integrated out: no meson exchange, interactions represented in terms of contact terms only
  - Applicable, in principle, for processes in which momentum is smaller than the pion mass
  - $p \sim 150$ MeV, $p^2/2m_N \sim 10$ MeV: pionless theory is breaking down at energies larger than 10 MeV
  - However…

Total cross section of dγ → np

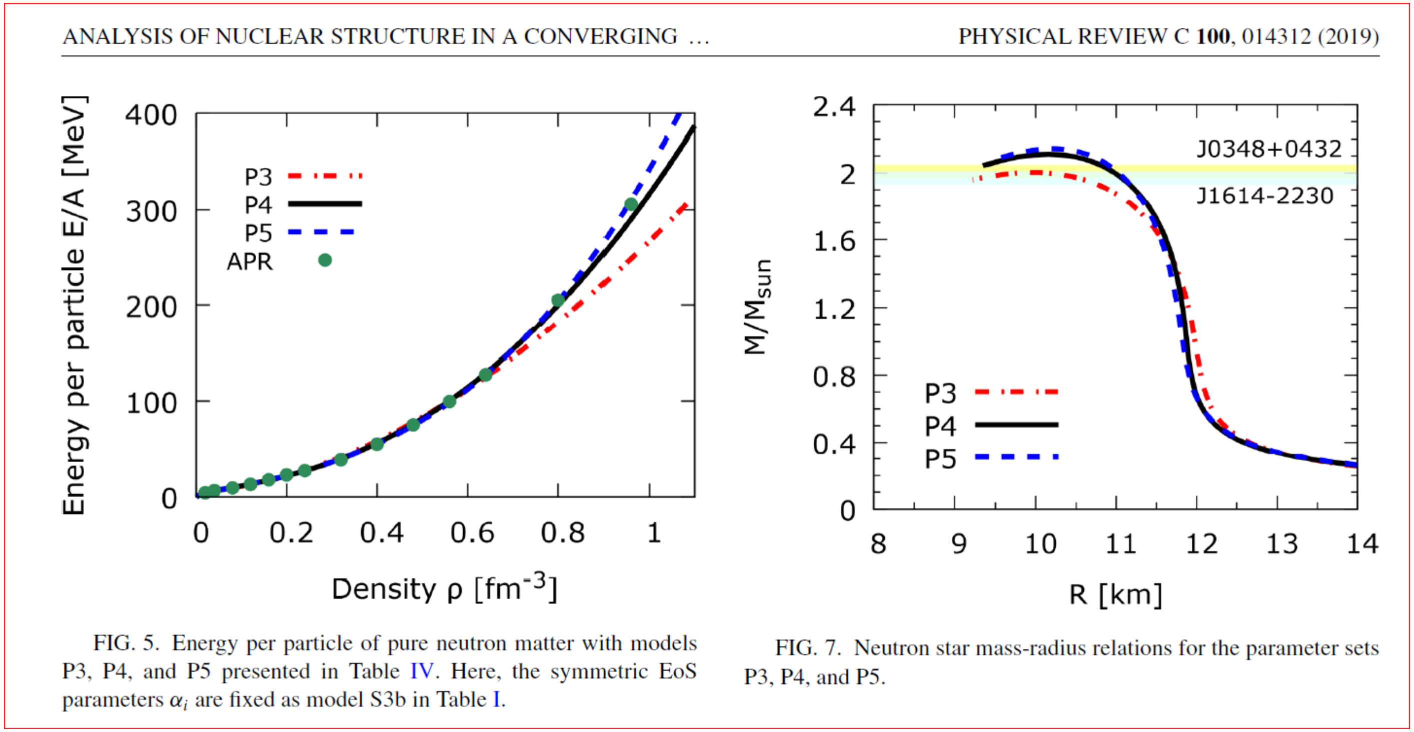


PHYSICAL REVIEW C **96**, 014001 (2017)

FIG. 4. Unpolarized total cross section σ_{tot} of deuteron photodisintegration up to NLO and NNLO. Experimental data [18–27] are also displayed in the figure.

- In principle theory breaks down at E_γ<20 MeV
- NLO is working well above 20 MeV
- NNLO is still marginal above 20 MeV

KIDS EDF



ANALYSIS OF NUCLEAR STRUCTURE IN A CONVERGING … PHYSICAL REVIEW C **100**, 014312 (2019)

FIG. 5. Energy per particle of pure neutron matter with models P3, P4, and P5 presented in Table IV. Here, the symmetric EoS parameters α_i are fixed as model S3b in Table I.

FIG. 7. Neutron star mass-radius relations for the parameter sets P3, P4, and P5.

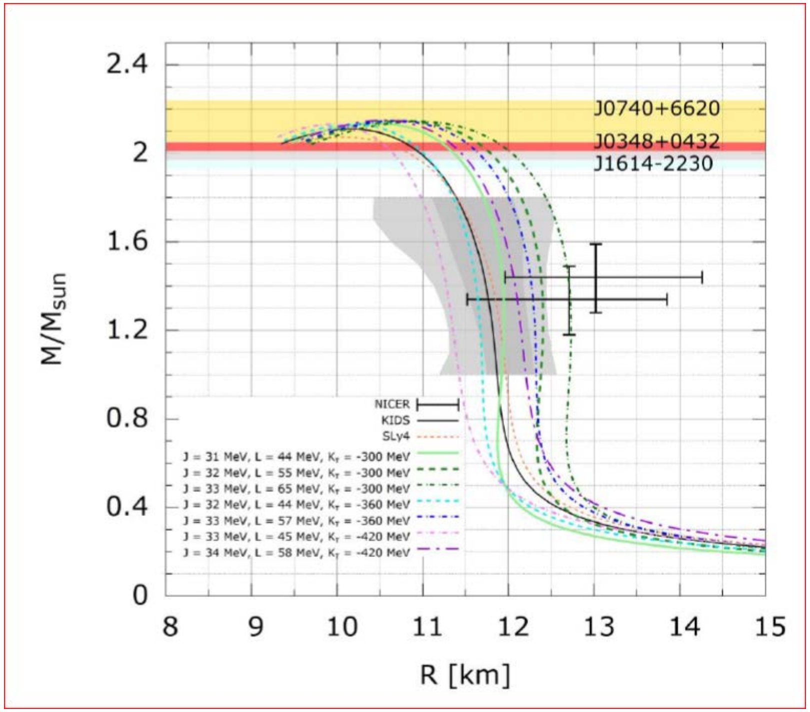
- 3, 4, 5 denote the number of terms
- APR: input data that determine the model parameters
- Seem that the behavior above 0.6 (or 0.8)fm^{-3} affects the observable little
- Convergence range (or uncertainty) could be identified, but does not mean that EoS is correct

Constraints given at the saturation density are irrelevant for the properties of compact star

- Very probably NO
- Most prominent uncertainties at the saturation density
  - **Symmetry energy**
  - **Effective mass**

Symmetry energy

- Neutron star



K_τ	-300			-360		-420		-375.1	-322.8
(J,L)	(31,44)	(32,55)	(33,65)	(32,44)	(33,57)	(33,45)	(34,58)	KIDS-ad2	SLy4
M_{max}	2.136	2.145	2.143	2.130	2.147	2.131	2.148	2.110	2.074
R	10.45	10.76	10.95	10.19	10.92	9.919	10.54	10.15	10.07
$R_{1.4}$	11.94	12.39	12.71	11.62	12.27	11.28	12.08	11.79	11.82
$\Lambda_{1.4}$	361.3	456.5	530.3	292.6	411.9	230.0	358.5	307.5	312.9

Symmetry energy

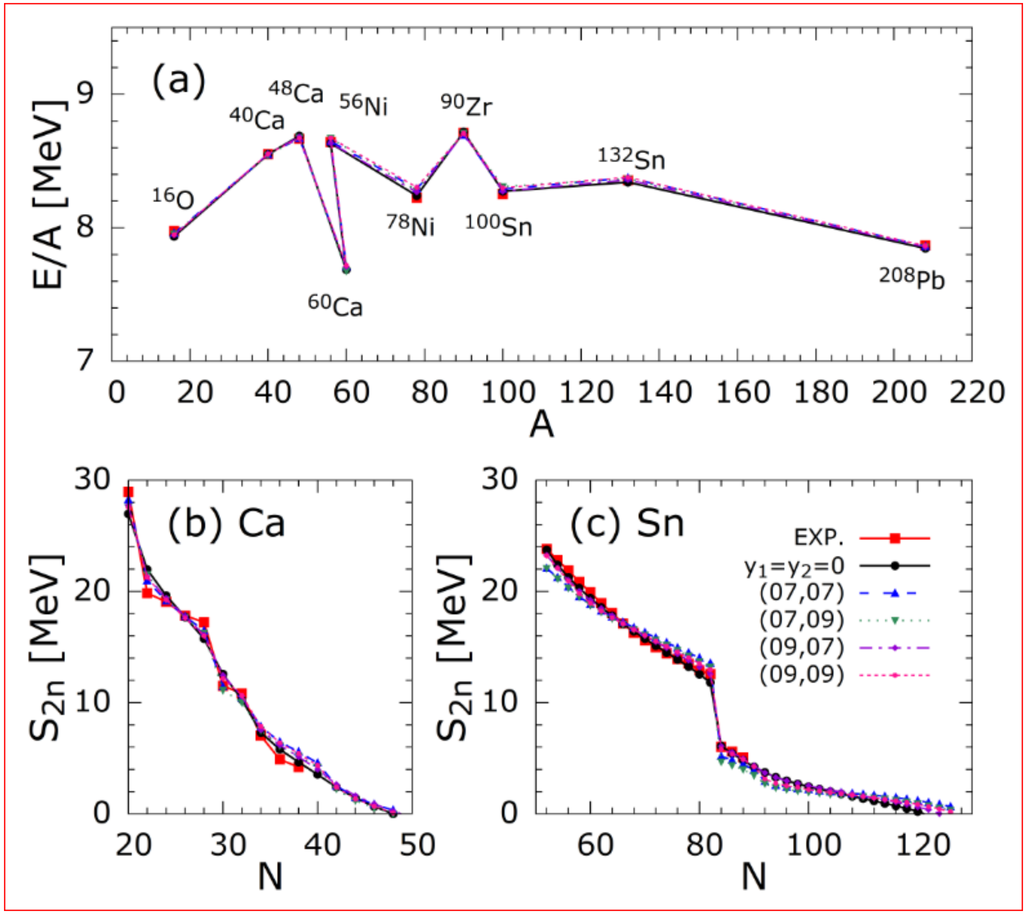
- Neutron drip line

K_τ	-300			-360		-420			-375.1	-322.8
(J,L)	(31,44)	(32,55)	(33,65)	(32,44)	(33,57)		(33,45)	(34,58)	KIDS-ad2	SLy4
O	18	18	18	20	20		20	20	18	20
Ca	46	46	46	48	48		48	50	48	46
Ni	62	62	60	62	62		62	64	62	60
Zr	88	88	86	90	92		96	96	90	82
Sn	122	122	122	122	124		122	122	122	126
Pb	184	184	184	184	184		184	184	184	184
χ^2_{tot} $[10^{-4}]$	**0.934**	**1.001**	**1.032**	**1.099**	**1.326**		**1.545**	**1.830**	**1.143**	**1.223**

  - **$\Delta n=0$: Pb**
  - **$\Delta n=2$: O, Sn**
  - **$\Delta n=4$: Ca, Ni**
  - **$\Delta n=10$: Zr**
- For specific nuclei, dependence on the symmetry energy critical

Effective mass m*

- In the KIDS model, m* is determined (or controlled) after the nuclear matter EoS is fixed, so it does not affect the compact star properties
- On the other hand m* affects many observables relevant to the structure of nuclei, and nuclear reactions



- Binding energy, S_{2n} of Ca: independent of m*
- S_{2n} of Sn: m* sensitive
- Not always, but for some nuclei, neutron drip line can be sensitive to m*

Whether and how such a hadron-quark continuity is captured in the KIDS

- NO problem to consider the hadron-quark transition: just follow the methods in the papers
- A project is in progress
- Requirements
  - Nuclear EoS at densities far above the saturation should be precise
  - EoS for matter including exotic degrees of freedom, e.g. hyperons or quarks should be less uncertain than now
- KIDS is a candidate with which the uncertainty of nuclear EoS at supra saturation densities can be controlled and reduced
- Uncertainty at the saturation should be under control prior to extrapolating to high densities

Conclusion

- Don’t know
    - Where theory breaks down
    - When hyperons, or quarks, or something else will appear
- To get reasonable prediction, it is crucial
    - To reduce uncertainties in the nuclear EoS
    - To reduce uncertainties in the exotica
- During the mission of CENuM
    - Reduce the uncertainty in the symmetry energy: J~3%, L~10%
    - Keep search for observables with which uncertainty goal is achieved
    - Keep tuned to the neutron star observation: GW, NICER, Bursts, …
- Hadron-quark transition
    - Less uncertain EoS for nucleons and quarks
    - Applications to astrophysics, heavy ion collisions and etc
    - **Top priority intra-CENuM collaboration**