The PREX-CREX puzzle and energy density functional theory

Panagiota Papakonstantinou

Heavy-Ion Accelerator Research Institute
Institute for Basic Science
Daejeon, S. Korea

Overview

What I will not talk about and why

- Second RPA / Beyond mean field models
- Specific electric dipole modes

What I will talk about

- Density dependence of the symmetry energy
- The *KIDS* framework
- Studies of the curvature parameter
- CREX-PREX-a_D puzzle

What I will not talk about

1. Second RPA / Beyond mean field models

- Theory developments
  - 2009: Large-scale second-RPA calculations with realistic interactions
  - 2014: Thouless theorem and the stability condition reexamined and clarified
- Collaborations with experimentalists
  - Fine structure of giant resonances (quadrupole, dipole)

- Coming soon: Comparisons with the Equations of Motion Phonon Method

Next talk by F. Knapp

What I will not talk about

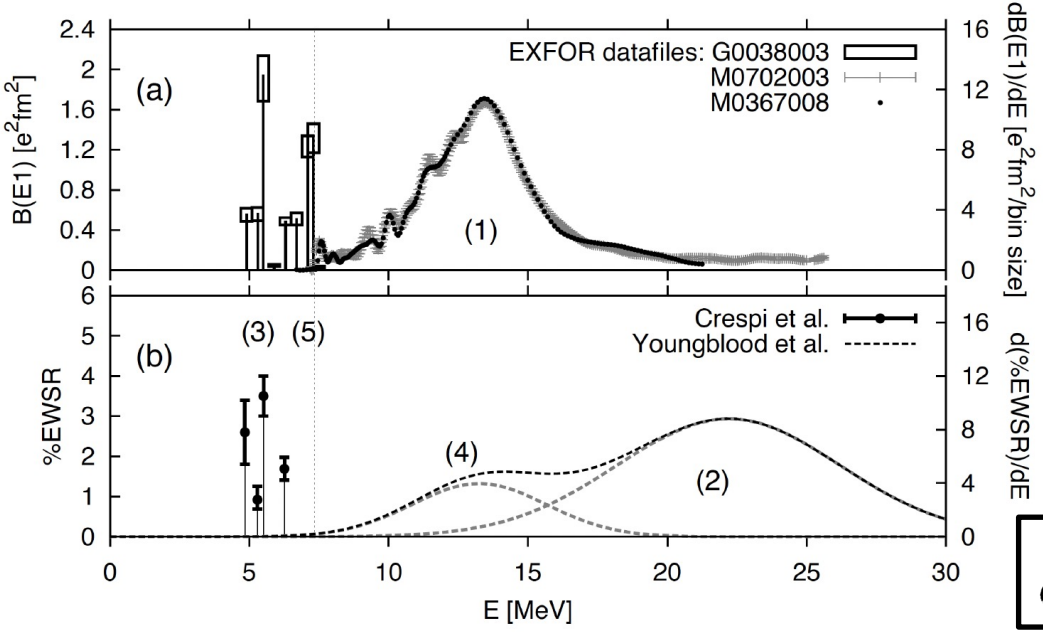
Work summarized in:

"Structures in the nuclear electric-dipole spectrum"
[PP, EXON2016 proceedings; arXiv:1711.10189]

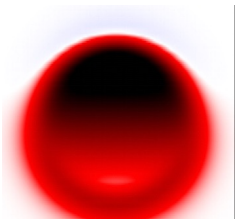
"Properties and significance of the Surface Dipole Mode
[PP, ARIS2014 proceedings; JPS Conf. Proc. 6, 030094; arXiv:1408.0894]

2. Specific electric dipole modes

- There seem to be **five** of them – counting is based on various data
- Here: ^{208}Pb



IS-LED:
Core-layer

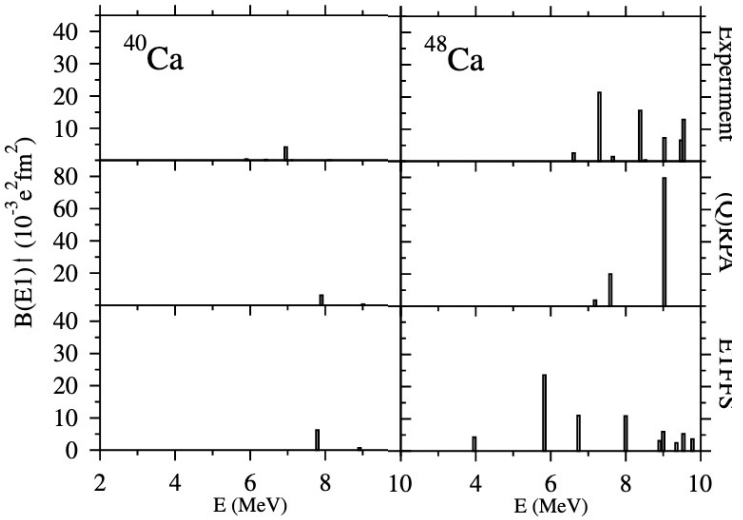


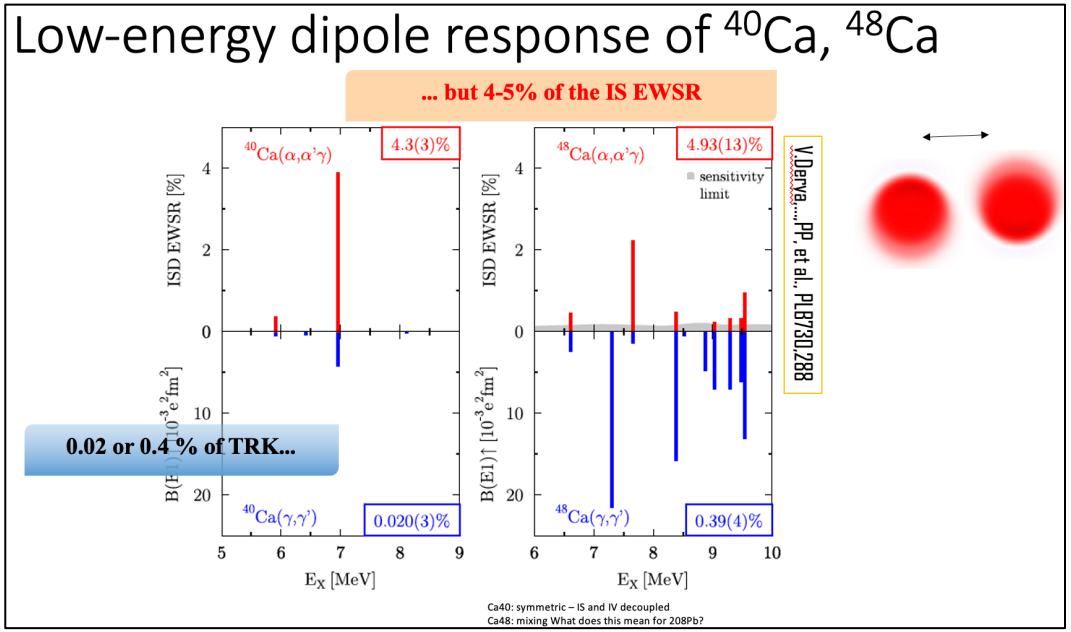
IS-GDR:
Compression

What I will not talk about

2. Specific electric dipole modes

- 2011 Prediction: one of these very weak electric-dipole transitions in 48Ca should be strong
- Confirmed – coauthored the paper with the experimental group

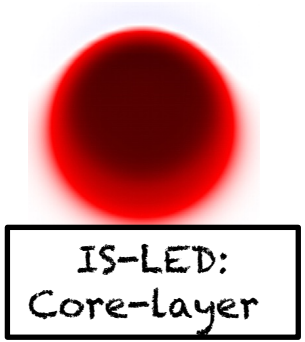




What I will not talk about

2. Specific electric dipole modes

- The IS-LED : An elementary mode of the extremely finite quantum liquid droplet
- Neutron skin has nothing to do with it. The diffuse surface does.



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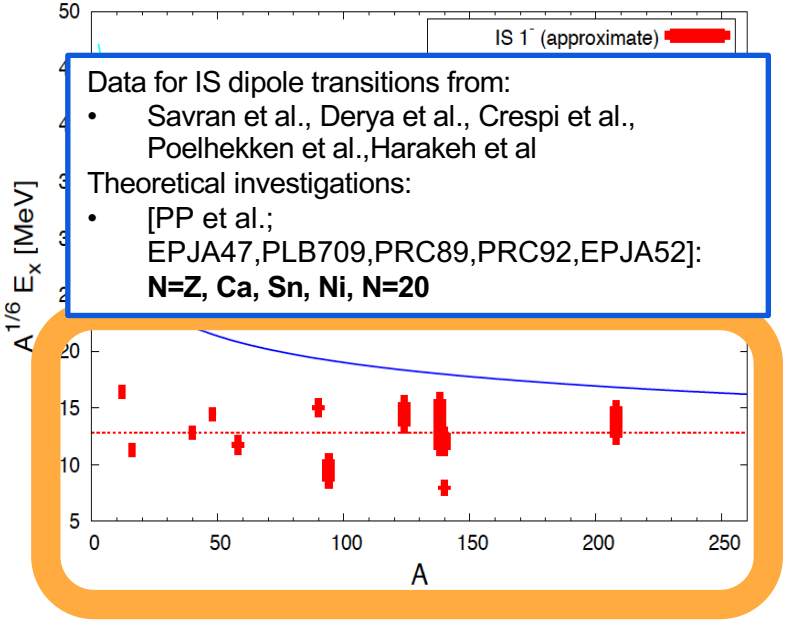


Data for IS dipole transitions from:

- Savran et al., Derya et al., Crespi et al., Poelhekken et al.,Harakeh et al

Theoretical investigations:

- [PP et al.; EPJA47,PLB709,PRC89,PRC92,EPJA52]: **N=Z, Ca, Sn, Ni, N=20**

This talk

Korea

IBS

Daegu

SKKU

Introduction

- Symmetry energy

Core grown-ups: H.Gil, C.H.Hyun, PP, ++

- KIDS framework for the nuclear equation of state and energy density functional

Symmetry energy within the KIDS framework

- A Bayesian analysis of isovector nuclear properties

With Jun Xu

- Correlation analysis with neutron star properties

With H.Gil, C.H.Hyun, et al.

The PREX-CREX-aD puzzle and the EoS of dilute matter

PP, in progress

Symmetry energy

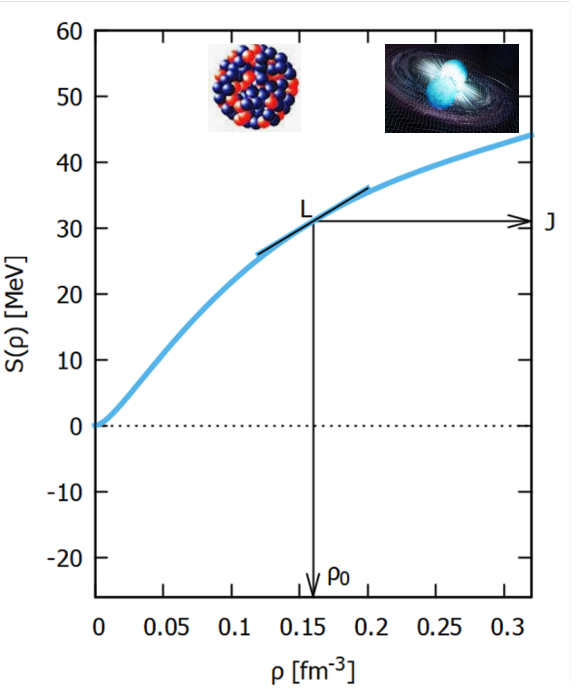
The energy it costs to change isospin-symmetric nuclear matter into neutron matter

Determines the physics of exotic nuclei and compact stars

By convention, the density dependence of the symmetry energy is encoded in a few parameters defined by a Taylor expansion:

$$S(\rho) = J + Lx + \tfrac{1}{2} K_{sym} x^2 + \tfrac{1}{6} Q_{sym} x^3 + \ldots \; ; x = (\rho-\rho_0)/3\rho_0$$

Namely its value J, slope L, curvature K_{sym}, skewness Q_{sym}, etc, at the nuclear saturation density ρ_0.

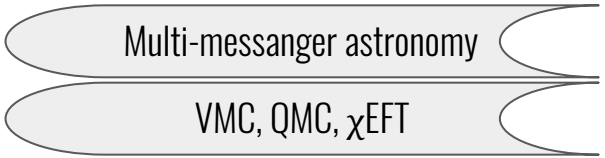


- Here we are discussing the EoS at zero temperature

Symmetry energy

Explored by examining:

- Low density: nuclear masses, density distributions (skins), collective excitations
- High density: Heavy-ion collisions, compact stars
- *Ab initio* calculations are also available



Rough estimates, frequently adjusted in light of new information:

- J=30-33 MeV (best known)
- L=40-70 MeV (conflicting results)
- K_{sym} = -400 - 0 MeV (very roughly)
- Q_{sym} = practically unconstrained

Some reviews:

Baldo&Burgio, ProgPartNuclPhys91,203 (2016)
Oertel et al., Rev.Mod.Phys.89,015007 (2017)
Roca-Maza&Paar, ProgPartNuclPhys101,96 (2018)

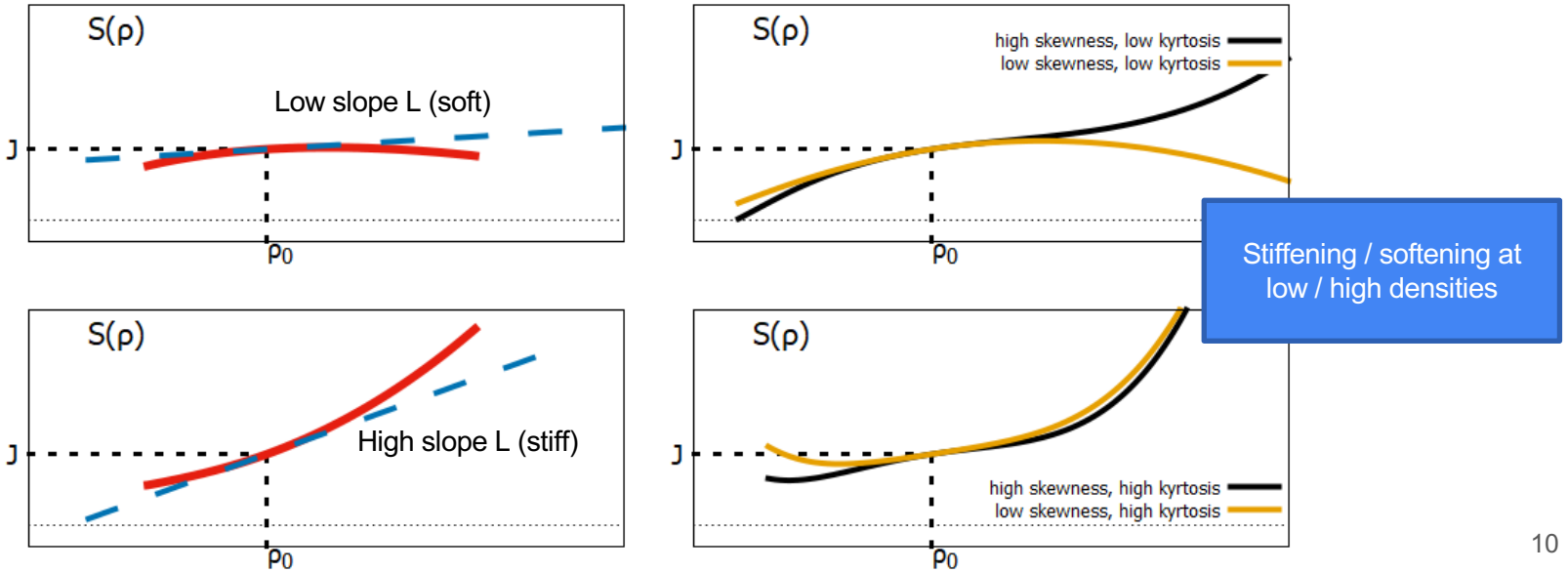
Some recent analyses:

Li et al., Universe 7, 182 (2021)
Thi et al., 2109.09675 (2021) +multiple others

Symmetry energy around saturation density

- Value J, slope L, curvature K_{sym}, skewness Q_{sym}, kyrtosis R_{sym}, …

$$S(\rho) = J + Lx + K_{\rm sym}x^2/2 + Q_{\rm sym}x^3/6 + R_{\rm sym}x^4/24\ldots$$

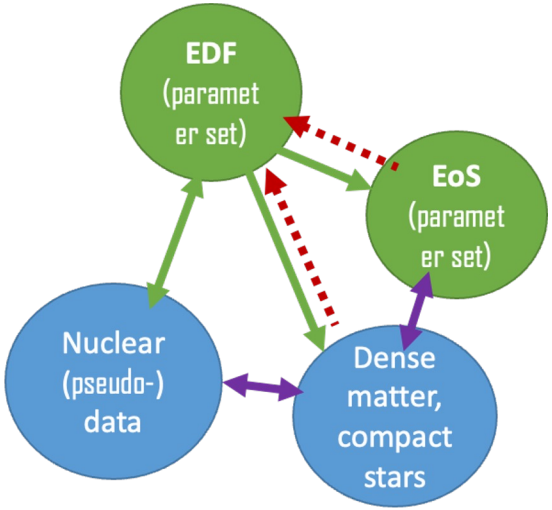


Connecting nuclear data and the EoS: EDFs

Connections are facilitated by phenomenological energy density functionals (EDFs) which describe nuclear structure. Usual way:

- ❑ Define the EDF
- ❑ Parameters can be fitted to data
- ❑ EoS can then be calculated
- ❑ The EDF serves as an extrapolation tool
- ❑ Prameters can be adjusted when new information is available on the EoS

Examples: Skyrme, Gogny, relativistic mean field



Connecting nuclear data and the EoS: EDFs

Problem:

Majority of EDFs fitted to data extrapolate to unrealistic EoSs

Dutra et al., Phys. Rev. C 85, 035201

Imposing realistic EoS parameters to EDFs can give strange nuclear results

Stevenson et al., AIP Conf. Proc.1529,262
Roca-Maza&Paar, ProgPartNuclPhys101,96

Overcome by:

KIDS - a versatile framework for the nuclear EoS and EDF

- ❑ Grounded in theory of interacting Fermi systems
- ❑ Optimal number of parameters eliminates model stiffness, overfitting
- ❑ In-medium effective mass decoupled from the EoS of homogeneous matter
  - No forced, unphysical correlations

KIDS EoS

For an **interacting Fermi system**, Brueckner theory and effective field theory suggest expansion of the energy per particle in terms of the Fermi momentum → **cubic root of density**

$$\mathcal{E}(\rho,\delta) = \mathcal{T}_{\rm FG}(\rho,\delta) + \sum_i c_i(\delta)\rho^{1+i/3} \qquad \delta \equiv (\rho_n - \rho_p)/\rho$$

The same then holds for the energy of symmetric matter

$$\mathcal{E}(\rho,0) = \mathcal{T}_{\rm FG}(\rho,0) + \sum_i \alpha_i\rho^{1+i/3}$$

and for the symmetry energy

$$S(\rho) = \mathcal{T}_{\rm sym,FG} + \sum_i \beta_i\rho^{1+i/3}$$

Three terms optimal

Four terms optimal

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KIDS EDF

KIDS EoS can be generated by an extended Skyrme functional with generalized density dependence → KIDS EDF. Generating potential:

$$
\begin{aligned}
v_{ij} \;=\; & (t_0 + y_0 P_\sigma)\delta(\mathbf{r}_i - \mathbf{r}_j) \\
& + \frac{1}{2}(t_1 + y_1 P_\sigma)[\delta(\mathbf{r}_i - \mathbf{r}_j)\mathbf{k}^2 + \mathbf{k}'^2\delta(\mathbf{r}_i - \mathbf{r}_j)] \\
& + (t_2 + y_2 P_\sigma)\mathbf{k}'\,\delta(\mathbf{r}_i - \mathbf{r}_j)\mathbf{k} \\
& + \frac{1}{6}\sum_{n=1}^{N-1}(t_{3n} + y_{3n} P_\sigma)\rho^{n/3}\delta(\mathbf{r}_i - \mathbf{r}_j) \\
& + iW_0\,\mathbf{k}'\times\delta(\mathbf{r}_i - \mathbf{r}_j)\,\mathbf{k}\cdot(\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j),
\end{aligned}
$$

notation:
instead of $t_i x_i$
we write y_i

Standard, fast Skyrme structure codes can be adapted and used

! The form is not arbitrary but grounded in the theory of correlated Fermi systems

KIDS EoS to EDF: Proof of principle

EoS from Akmal-Pandharipande-Ravenhall pseudodata applied to nuclei

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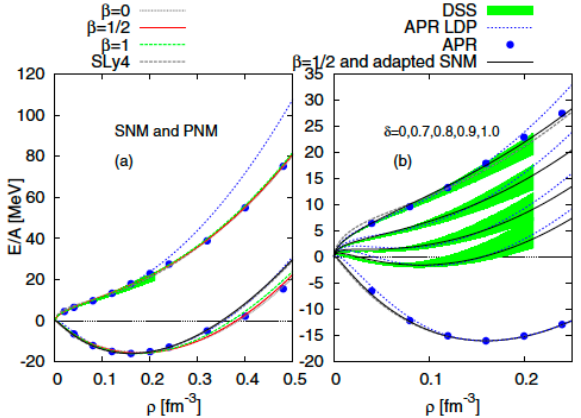

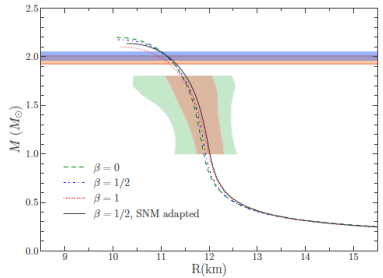

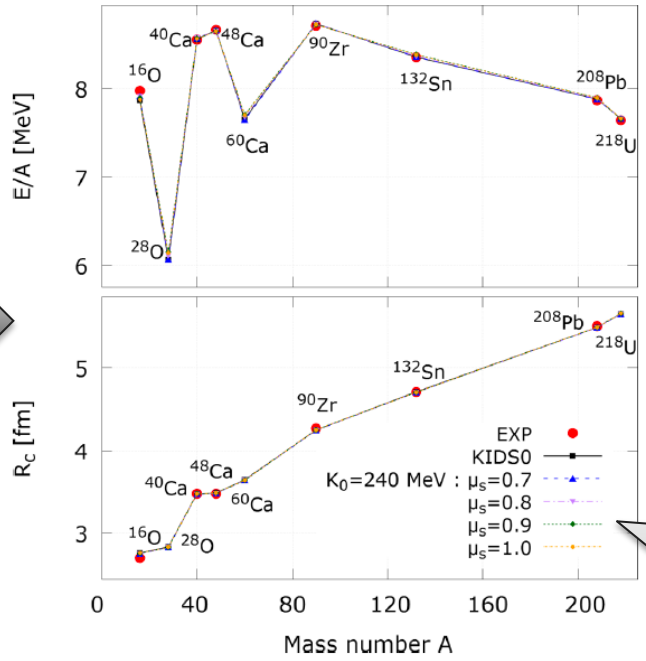

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And regardless of effective mass

KIDS EoS to EDF

See Appendix of
PHYSICAL REVIEW C **105**, 044305 (2022)

From standard EoS parameters (E_0, ρ_0 ,…,J,L,…,m*,…) to KIDS EoS parameters (α_i,β_i) to KIDS EDF parameters (t_i,y_i,…) is straightforward

$$c_i(\delta) = \alpha_i + \beta_i \delta^2$$

$$c_2(\delta) = \alpha_2 + \beta_2\delta^2 + C_{\rm eff} h_k \left[\left(\frac{1+\delta}{2}\right)^{5/3} + \left(\frac{1-\delta}{2}\right)^{5/3} \right] + D_{\rm eff} h_k \delta \left[\left(\frac{1+\delta}{2}\right)^{5/3} - \left(\frac{1-\delta}{2}\right)^{5/3} \right],$$

$$C_{\rm eff} = \frac{\hbar^2}{2m\rho_0}\left(\frac{m}{m_s^\star} - 1\right),$$
$$D_{\rm eff} = \frac{\hbar^2}{2m\rho_0}\left(\frac{m}{m_s^\star} - \frac{m}{m_v^\star}\right),$$

$$\begin{pmatrix} \alpha_0\rho_0 \\ \alpha_1\rho_0^{4/3} \\ \alpha_2\rho_0^{5/3} \\ \alpha_3\rho_0^2 \end{pmatrix} = \begin{pmatrix} 20 & -19/3 & 1 & -1/6 \\ -45 & 15 & -5/2 & 1/2 \\ 36 & -12 & 2 & -1/2 \\ -10 & 10/3 & -1/2 & 1/6 \end{pmatrix} \begin{pmatrix} E_0 - (\frac{\hbar^2}{2m} + C_{\rm eff}\rho_0) h_k (\rho_0/2)^{2/3} \\ -(2\frac{\hbar^2}{2m} + 5C_{\rm eff}\rho_0) h_k (\rho_0/2)^{2/3} \\ K_0 + (2\frac{\hbar^2}{2m} - 10C_{\rm eff}\rho_0) h_k (\rho_0/2)^{2/3} \\ Q_0 + (-8\frac{\hbar^2}{2m} + 10C_{\rm eff}\rho_0) h_k (\rho_0/2)^{2/3} \end{pmatrix}$$

$$t_0 = \tfrac{8}{3}\alpha_0, \quad t_{3i} = 16\alpha_i \ (\text{for } i = 1, 2, 3),$$
$$y_0 = -\tfrac{1}{2}t_0 - 4\beta_0, \quad y_{3i} = -\tfrac{1}{2}t_{3i} - 24\beta_i \ (\text{for } i = 1, 2, 3),$$

$$\begin{pmatrix} \beta_0\rho_0 \\ \beta_1\rho_0^{4/3} \\ \beta_2\rho_0^{5/3} \\ \beta_3\rho_0^2 \end{pmatrix} = \begin{pmatrix} 20 & -19/3 & 1 & -1/6 \\ -45 & 15 & -5/2 & 1/2 \\ 36 & -12 & 2 & -1/2 \\ -10 & 10/3 & -1/2 & 1/6 \end{pmatrix} \begin{pmatrix} E_{\rm sym}^0 - [\sigma(\frac{\hbar^2}{2m} + C_{\rm eff}\rho_0) + \varphi D_{\rm eff}\rho_0] h_k \rho_0^{2/3} \\ L - [\sigma(2\frac{\hbar^2}{2m} + 5C_{\rm eff}\rho_0) + 5\varphi D_{\rm eff}\rho_0] h_k \rho_0^{2/3} \\ K_{\rm sym} + [\sigma(2\frac{\hbar^2}{2m} - 10C_{\rm eff}\rho_0) - 10\varphi D_{\rm eff}\rho_0] h_k \rho_0^{2/3} \\ Q_{\rm sym} + [\sigma(-8\frac{\hbar^2}{2m} + 10C_{\rm eff}\rho_0) + 10\varphi D_{\rm eff}\rho_0] h_k \rho_0^{2/3} \end{pmatrix}.$$

$$\begin{pmatrix} t_1 \\ y_1 \\ t_2 \\ y_2 \end{pmatrix} = \frac{2}{3} \begin{pmatrix} 2 & 0 & -8 & 0 \\ -1 & -3 & 4 & 12 \\ 6 & -12 & 8 & -16 \\ -3 & 15 & -4 & 20 \end{pmatrix} \begin{pmatrix} C_{\rm eff} \\ D_{\rm eff} \\ -G_S/2 \\ G_V/2 \end{pmatrix}$$

$$\mathcal{E}(\rho,0) = \mathcal{T}_{\rm FG}(\rho,0) + \sum_i \alpha_i \rho^{1+i/3}$$

$$S(\rho) = \mathcal{T}_{\rm sym,FG} + \sum_i \beta_i \rho^{1+i/3}$$

Differenciate these at saturation to obtain K_0, Ksym etc

$$c_i(\delta) = \alpha_i + \beta_i \delta^2$$

$$c_2(\delta) = \alpha_2 + \beta_2\delta^2 + C_{\rm eff} h_k \left[\left(\frac{1+\delta}{2}\right)^{5/3} + \left(\frac{1-\delta}{2}\right)^{5/3} \right] + D_{\rm eff} h_k \delta \left[\left(\frac{1+\delta}{2}\right)^{5/3} - \left(\frac{1-\delta}{2}\right)^{5/3} \right],$$

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$$\begin{pmatrix} E_0 - (\frac{\hbar^2}{2m} + C_{\rm eff}\rho_0) h_k (\rho_0/2)^{2/3} \\ -(2\frac{\hbar^2}{2m} + 5C_{\rm eff}\rho_0) h_k (\rho_0/2)^{2/3} \\ K_0 + (2\frac{\hbar^2}{2m} - 10C_{\rm eff}\rho_0) h_k (\rho_0/2)^{2/3} \\ \dots \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 & \dots \\ 3 & 4 & 5 & \dots \\ 0 & 4 & 10 & \dots \\ \dots & \dots & \dots & \dots \end{pmatrix} \begin{pmatrix} \alpha_0\rho_0 \\ \alpha_1\rho_0^{4/3} \\ \alpha_2\rho_0^{5/3} \\ \dots \end{pmatrix}$$

Just invert this matrix
(and similar for Symmetry Energy)

Curvature parameter of the symmetry energy

Selected results from:

- ❑ Bayesian analysis of isoscalar and isovector nuclear properties
- ❑ Correlation analysis of nuclear properties and neutron-star properties

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Jun Xu, PP

Recent puzzles to be addressed

- Why is Tin so soft?
- The GMR energy of Sn isotopes roughly 1MeV lower than expected
- The GMR energy of Sn and other nuclei cannot be described with the same compression modulus
- We will explore both K_0 and Q_0 and extract correlations under the constraint of ^{208}Pb GMR and ^{120}Sn GMR

- Why is the neutron skin of ^{208}Pb so thick?
  - Especially in view of the recent CREX measurement (thin-skinned ^{48}Ca)
- PREX incompatible with dipole polarizability a_D measurement and with CREX in Skyrme and RMF
- We will explore J,L,Ksym and extract correlations under the constraints of neutron skin, IVGDR energy and a_D in ^{208}Pb and ^{120}Sn

Bayesian analysis

- Default values and prior ranges, data

	Default value	Prior range
ρ_0 (fm^{-3})	0.16	
E_0 (MeV)	−16	
K_0 (MeV)	240	200–300
Q_0 (MeV)	−373	−800–400
$E^0_{\rm sym}$ (MeV)	33	25–35
L (MeV)	49	0–120
$K_{\rm sym}$ (MeV)	−156	−400–100
$Q_{\rm sym}$ (MeV)	583	0–1000
$m^\star_s/m$	0.82	
$m^\star_v/m$	0.7	0.5–1
G_S (MeV fm^5)	132	
G_V (MeV fm^5)	5	
W_0 (MeV fm^5)	133	

	$E_{\rm ISGMR}$ (MeV)	E_b (MeV)	R_c (fm)
^{208}Pb	14.17 ± 0.28 & 13.9 ± 0.1	−7.867452 ± 3%	5.5010 ± 3%
^{120}Sn	15.7 ± 0.1	−8.504548 ± 3%	4.6543 ± 3%

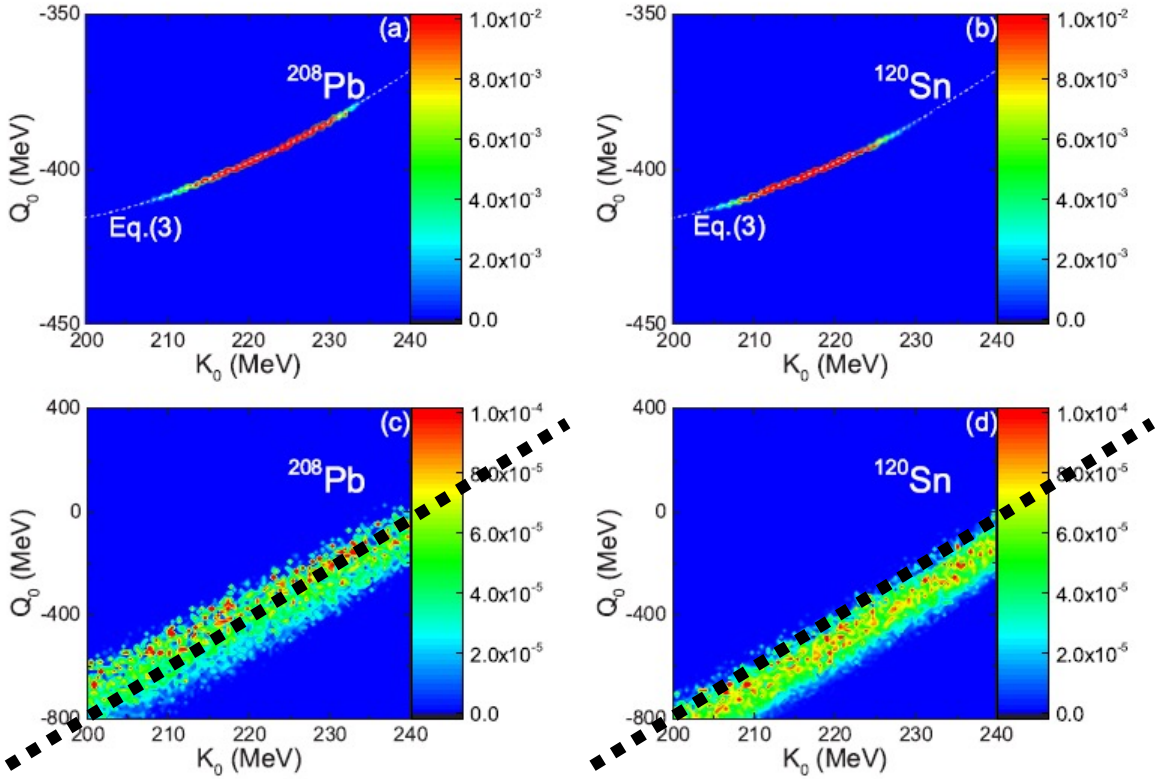
	Δr_{np} (fm)	E_{-1} (MeV)	α_D (fm^3)
^{208}Pb	0.283 ± 0.071	13.46 ± 0.10	19.6 ± 0.6
^{120}Sn	0.150 ± 0.017	15.38 ± 0.10	8.59 ± 0.37

Isoscalar properties

- Skyrme models:

$$Q_0 = -3(3\alpha+1)\frac{3}{5}\left(\frac{3\pi^2}{2}\right)^{2/3}\frac{\hbar^2}{2m}\rho_0^{2/3} + 45(\alpha+1)E_0 + (3\alpha+2)K_0.$$

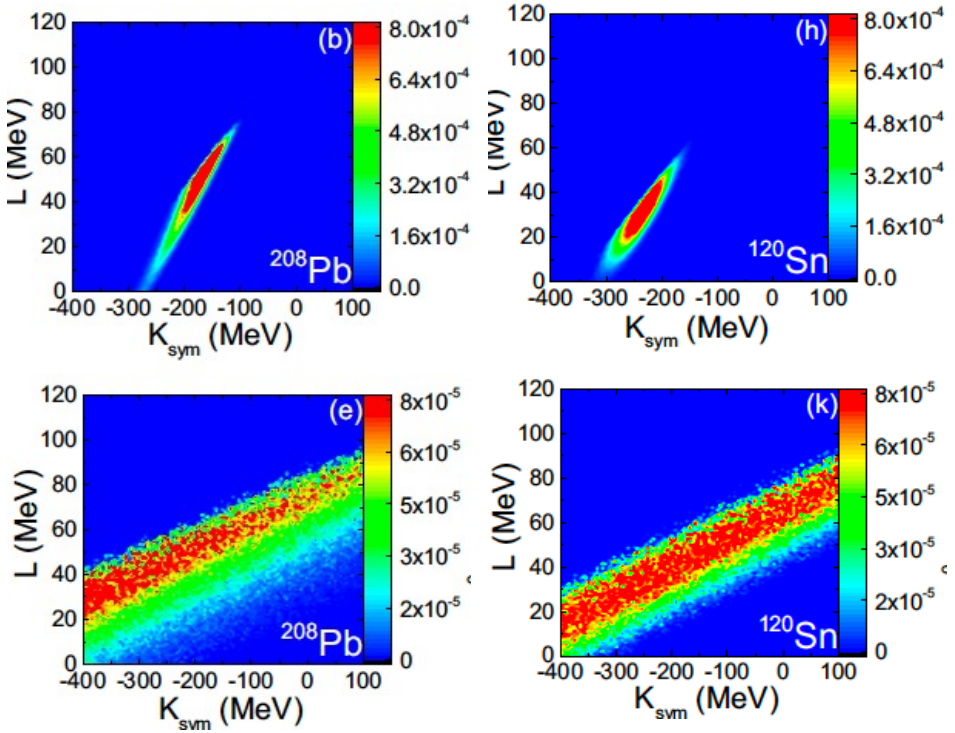
- KIDS: independent



Bayesian analysis of isovector nuclear properties

Ksym vs L

Skyrme:



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KIDS:

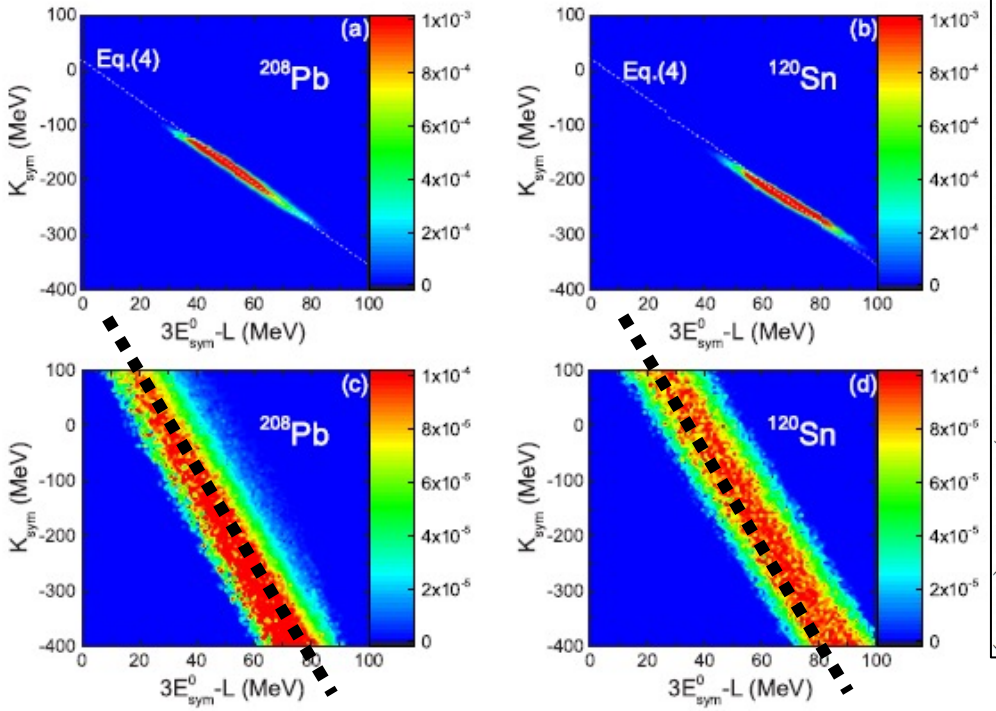
Broader PDFs

K_{sym} unconstrained

Bayesian analysis of isovector nuclear properties

Ksym vs 3J-L

Skyrme:



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KIDS:

Broader PDFs

K_{sym} unconstrained

Bayesian analysis of isovector nuclear properties

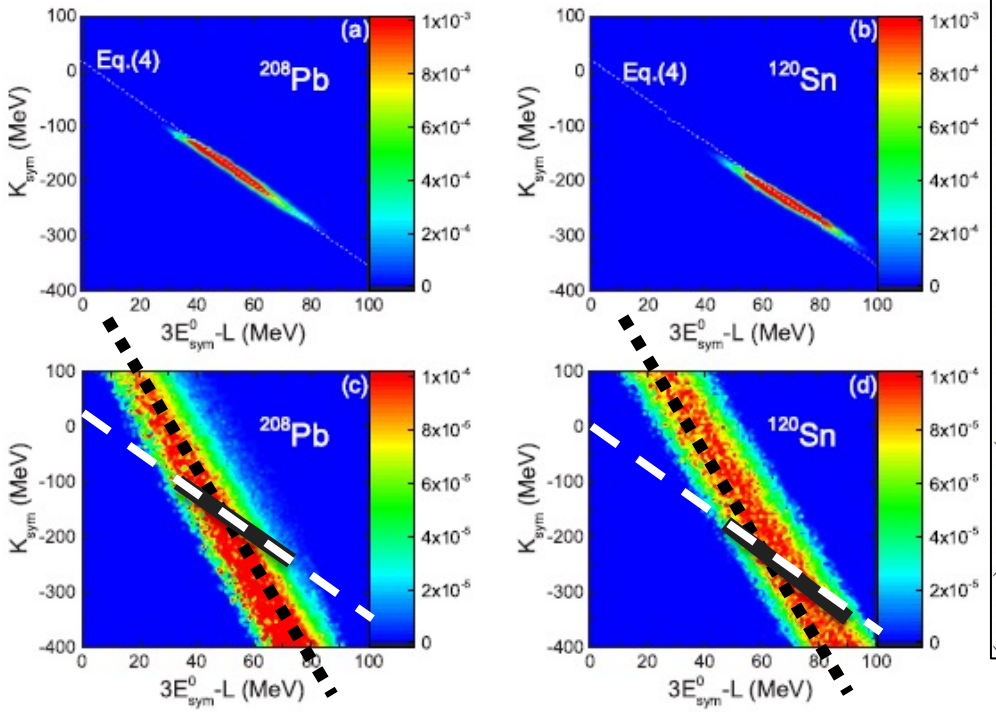
$$K_{\rm sym} = (2-3\alpha)\frac{2}{3}\left(\frac{3\pi^2}{2}\right)^{2/3}\frac{\hbar^2}{2m}\rho_0^{2/3}$$
$$\times\left[-3\left(\frac{m}{m_v^\star}-1\right)+4\left(\frac{m}{m_s^\star}-1\right)\right]$$
$$-3(1+\alpha)\left(3E_{\rm sym}^0-L\right)$$
$$+(1+3\alpha)\frac{1}{3}\left(\frac{3\pi^2}{2}\right)^{2/3}\frac{\hbar^2}{2m}\rho_0^{2/3}.$$

Skyrme:

KIDS:

Broader PDFs

K_{sym} unconstrained



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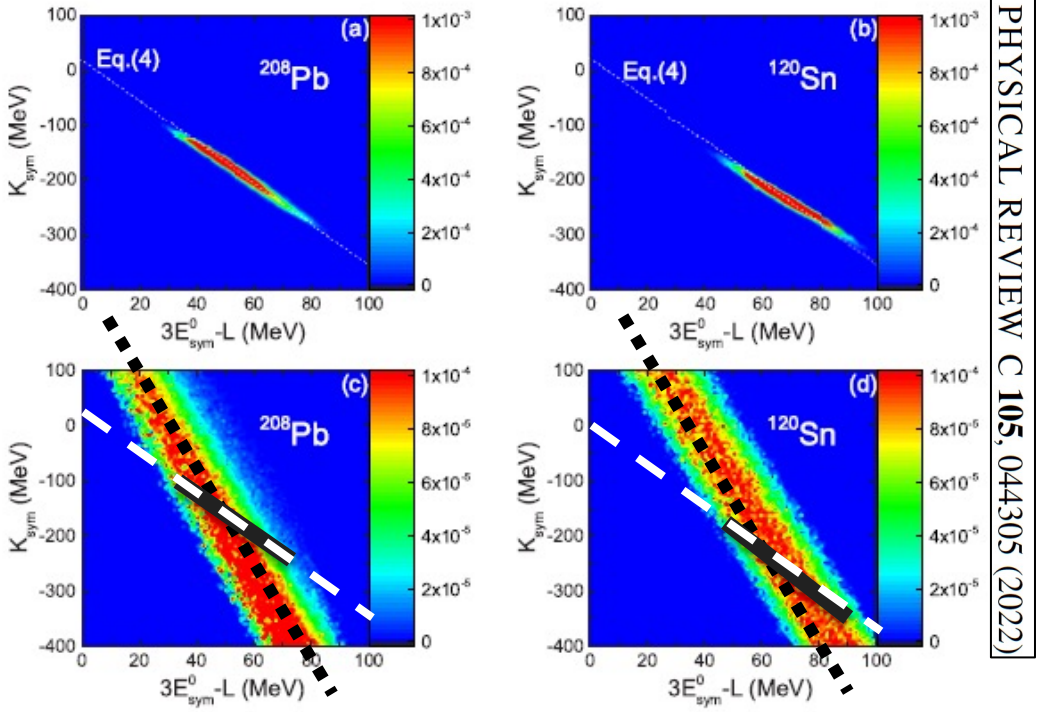
Bayesian analysis of isovector nuclear properties

$$K_{\rm sym} = (2-3\alpha)\frac{2}{3}\left(\frac{3\pi^2}{2}\right)^{2/3}\frac{\hbar^2}{2m}\rho_0^{2/3} \times\left[-3\left(\frac{m}{m_v^\star}-1\right)+4\left(\frac{m}{m_s^\star}-1\right)\right] -3(1+\alpha)\left(3E_{\rm sym}^0-L\right) +(1+3\alpha)\frac{1}{3}\left(\frac{3\pi^2}{2}\right)^{2/3}\frac{\hbar^2}{2m}\rho_0^{2/3}.$$

Skyrme:



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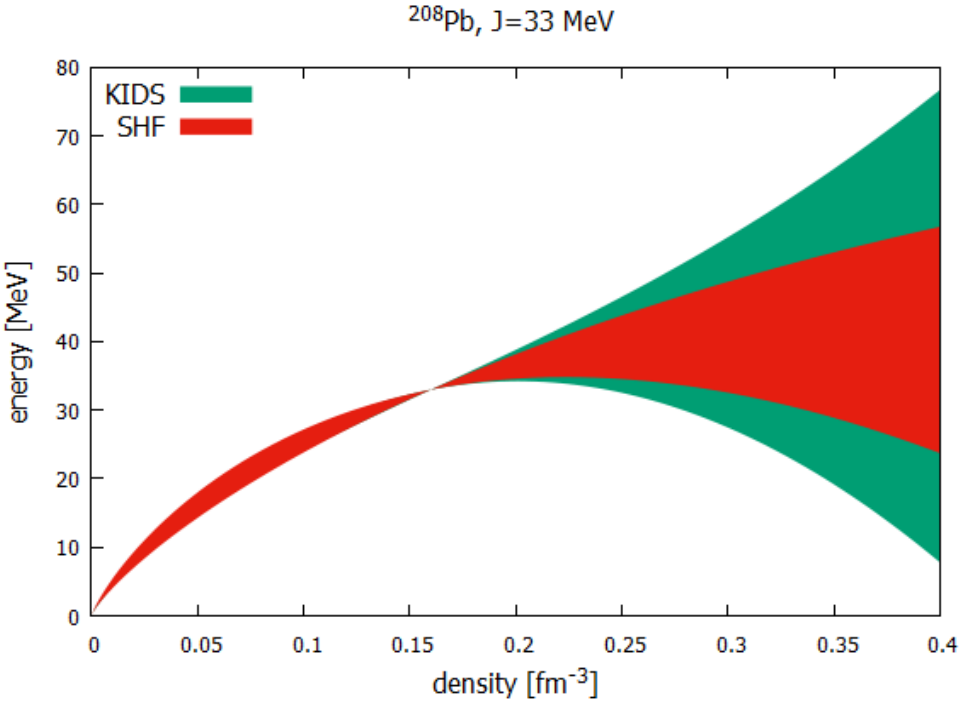
Standard EDFs are **constrictors**

KIDS:

Corresponding EoS domains (Illustration)

KIDS model allows for

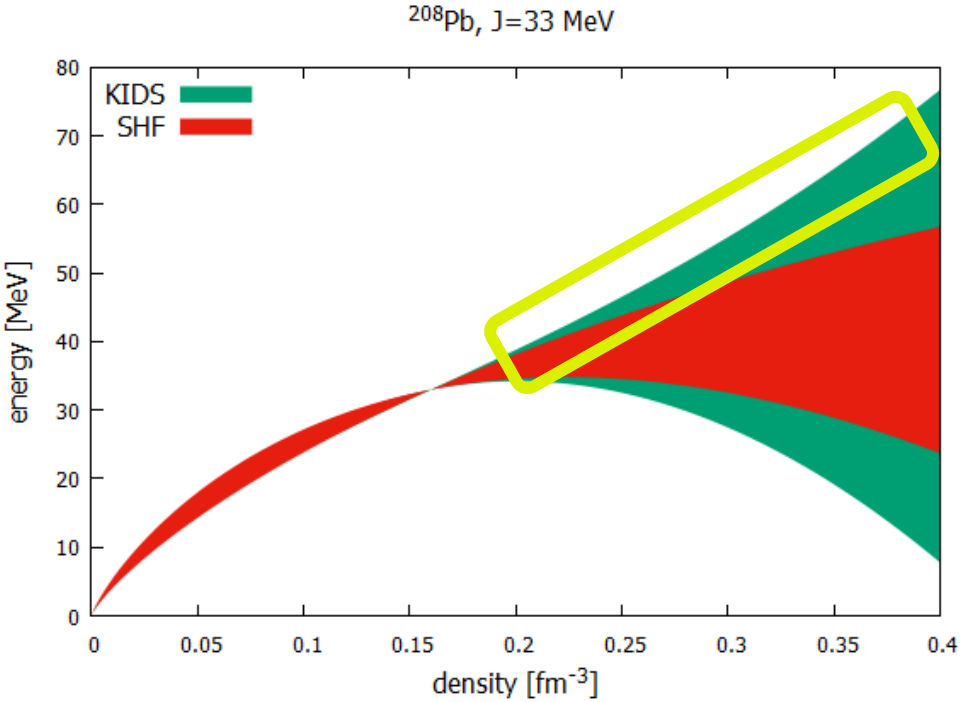
- Broader extrapolation regime
- Inflection point: *soft-to-stiff transition,* important for description of dense matter
- Possible decoupling of dilute and dense regimes



Corresponding EoS domains (Illustration)

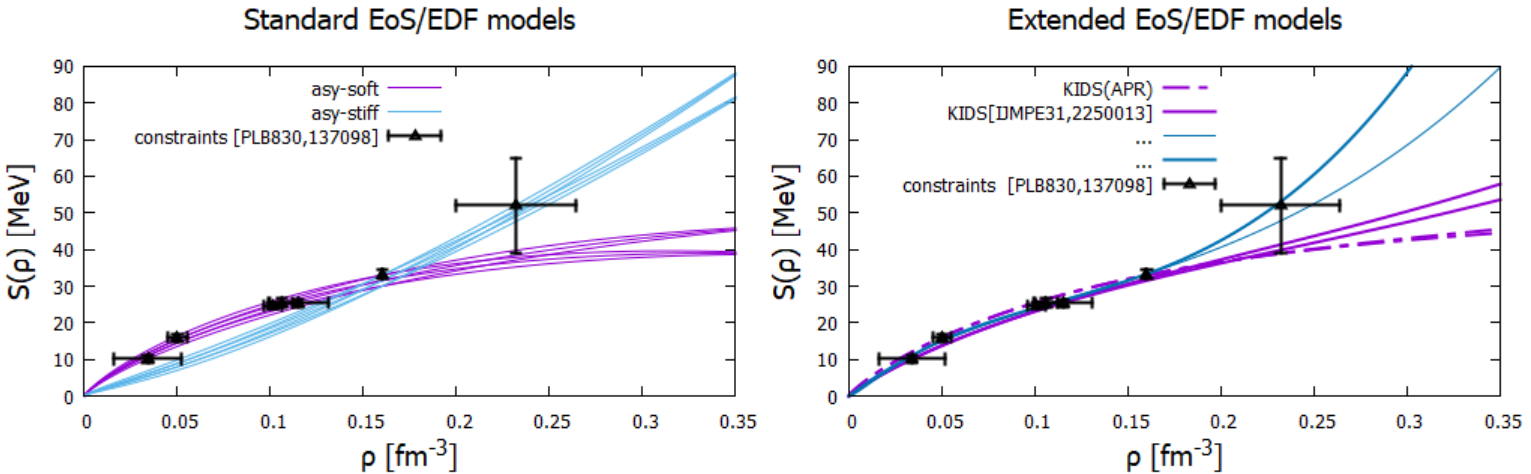
KIDS model allows for

- Broader extrapolation regime
- Inflection point: *soft-to-stiff transition,* important for description of dense matter
- Possible decoupling of dilute and dense regimes



Inflection point of symmetry energy

- Standard EoS/EDF models (Skyrme, RMF) are either soft or stiff
- However, dense-matter constraints require an inflection point at high density, reflecting possible phase change → extensions (KIDS)



Nuclei and neutron stars

PHYSICAL REVIEW C **103**, 034330 (2021)

International Journal of Modern Physics E
Vol. 31, No. 1 (2022) 2250013 (24 pages)

Explored (K_0,J,L,K_{sym}) parameter space

- Assume standard saturation point, $\rho_0 = 0.16 fm^{-3}$; $\varepsilon_0 = -16 MeV$
- Explore in total: (9x9x7x9=5103 sets)

  K_0:[220,260]MeV, step:5MeV; J:[30,34]MeV, step:0.5MeV ;

  L:[40,70]MeV, step:5MeV; K_τ: [-420,-260]MeV, step:20MeV
- **Select best-performing EoSs for nuclear mass and size**:
  - Imposed constraint : ADPD(13)<0.3%
  - Roughly 7% of the sets survive

$$\mathrm{ADPD}(N) \equiv \frac{1}{N}\sum_{i=1}^{N}\left|\frac{O_i^{\mathrm{exp}} - O_i^{\mathrm{cal}}}{O_i^{\mathrm{exp}}}\right|$$

- **Next, select against neutron star mass radius relation**

Nuclei and neutron stars

Observation:

- ❑ Correlation between Ksym and neutron star radius

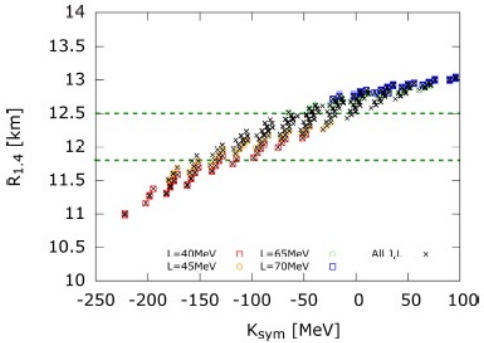
Selection:

- ❑ 11.8 < $R_{1.4}$ < 12.5 km (=Common range of current constraints)

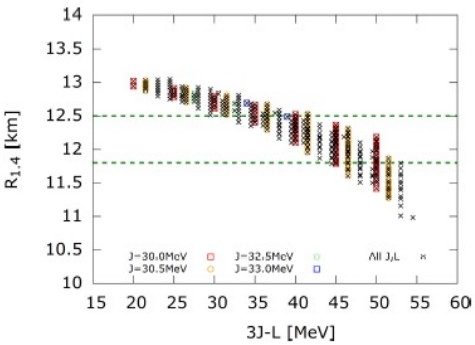
Result:

- ❑ -200 MeV < K_{sym} < 0
- ❑ Inflection point at around twice saturation density

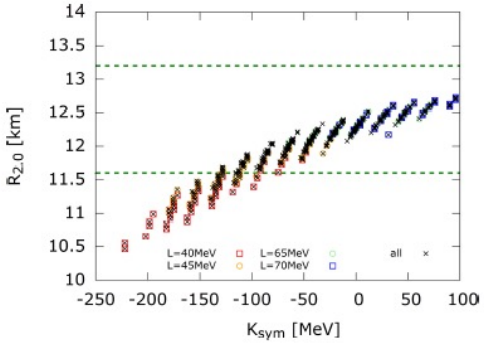
International Journal of Modern Physics E
Vol. 31, No. 1 (2022) 2250013 (24 pages)

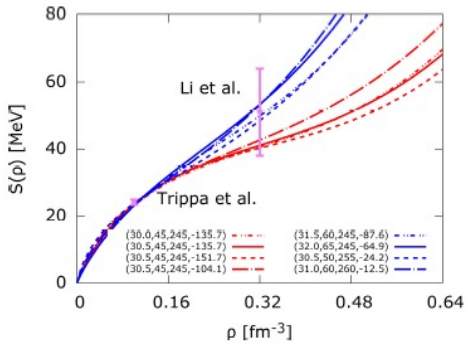


(a)



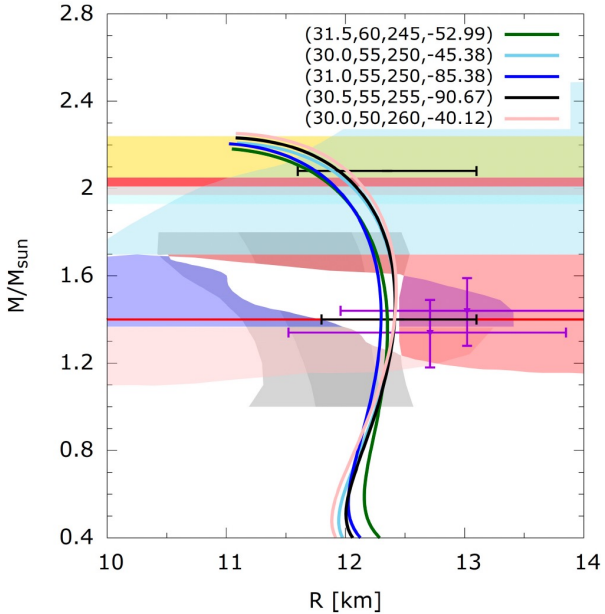
(b)



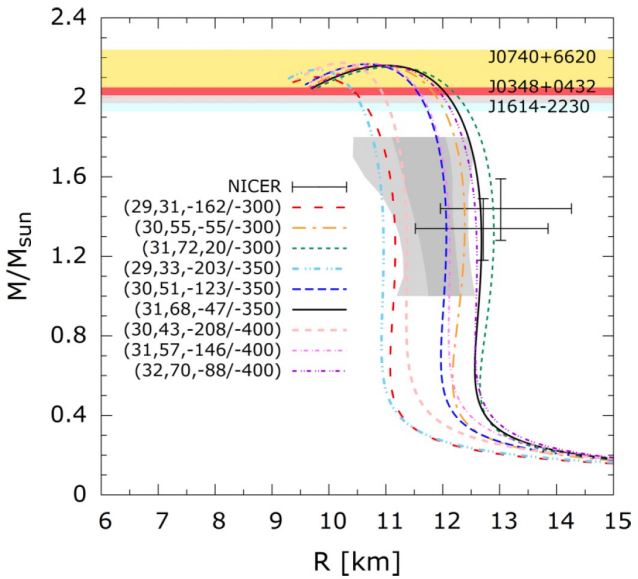


Mass-radius relations

EoS examples which satisfy basic nuclear data and neutron star constraints



Gil et al., IJMP31,2250013



Gil et al., PRC103,034330

Current constraints suggest conservatively

$-200\ \text{MeV} < K_{sym} < 0$

Nuclei and neutron stars

- Strong correlation of both L and K_{sym} with neutron star radius
- No correlation of K_{sym} with neutron skin thickness
- Some anticorrelation between K_τ and skin (stronger than L's?)
- No correlation between neutron skin thickness and neutron star radius

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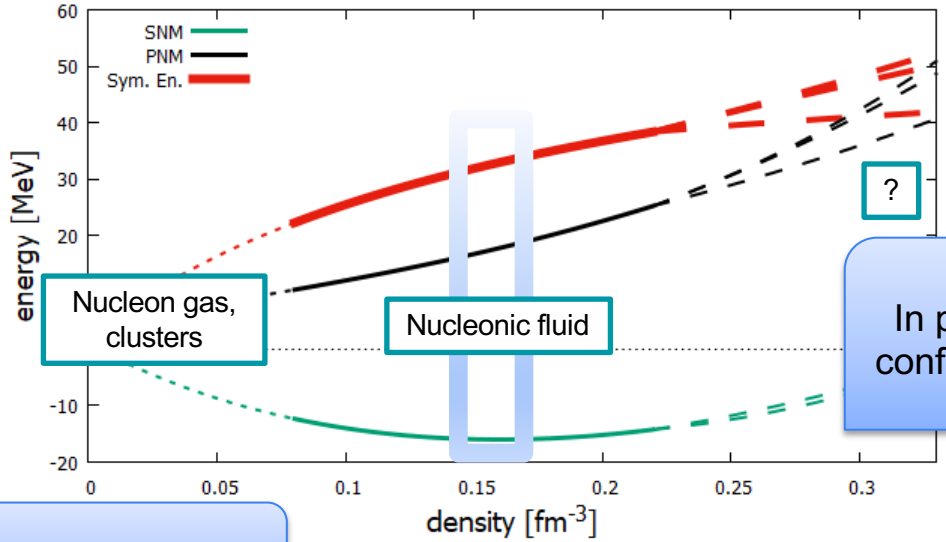
Nuclear and NS data

Nuclear data only

	K_0	J	L	$3J-L$	K_{sym}	K_τ	ΔR_{np}	$R_{1.4}$	$R_{2.0}$
K_0	1	−0.51	−0.24	*0.10*	0.35	0.50	−0.58	0.24	0.46
J	−0.39	1	0.56	−0.35	*−0.06*	−0.52	0.62	0.22	*0.01*
L	0.24	0.45	1	**−0.96**	0.50	−0.27	0.65	0.79	0.65
$3J-L$	−0.34	−0.27	**−0.98**	1	−0.60	0.14	−0.54	−0.84	−0.75
K_{sym}	0.56	*0.09*	0.83	−0.88	1	0.69	−0.29	**0.90**	**0.91**
K_τ	0.62	−0.30	0.34	−0.44	0.80	1	−0.85	0.33	0.43
ΔR_{np}	−0.53	0.56	0.35	−0.26	−0.20	−0.70	1	*0.09*	*−0.05*
$R_{1.4}$	0.52	0.21	**0.91**	**−0.93**	**0.96**	0.66	*−0.02*	1	**0.97**
$R_{2.0}$	0.63	*0.09*	0.85	**−0.90**	**0.96**	0.69	−0.11	**0.99**	1

Remarks

Away from saturation regime, different phases may require different modeling



In progress: interpolations to conformal limit in dense matter

In progress: PREX vs CREX

KIDS and the PREX-CREX-aD puzzle

- KIDS predictions for the neutron skin when the parameters are constrained on gross nuclear propertiees (masses, charge radii) and neutron-star properties, generally can agree with CREX but underestimate PREX
- The extended form of KIDS and the analysis of the curvature parameter leave open the possibility to reconcile them (The posterior probability densities show overlaps)
- One has yet to show that a single EDF model can accommodate both measurements within 1σ each.
- It is possible to accommodate them within their 90% confidence level [Zhang&Chen,arXiv:2207.03328]. It is not mandated that we must accommodate them more stringently. But it is a useful exercise and it would be of great significance if it succeeds.

What does it take for PREX&CREX to be reconciled?

I will search for KIDS parameter sets which reproduce both measurements within their respective error bars as well as the basic nuclear properties (<1%) (19 data)

First attempt: Vary all six low-order parameters within fiducial ranges:

ρ_0 = 0.155-0.161fm^{-3}, -E_0=15.5-16.1MeV, K_0=190-250,MeV

J=30-34MeV, L=40-70MeV, -K_τ=250-500MeV

varied in 4-10 equidistant steps each.

- Gradient terms: -C_{12}=64,66,68 MeV fm^5, D_{12}=2.5 MeV fm^5 .
- Spin-orbit coupling: W_0=129,130, …,135 MeV fm^5
- Effective masses: m*/m=0.82, κ=0.22

I found no successful combination of parameters

What does it take for PREX&CREX to be reconciled?

I will search for KIDS parameter sets which reproduce both measurements within their respective error bars as well as the basic nuclear properties (<1%)

Second attempt: Extend the formalism so that I can vary freely up to 5+5 EoS parameters :

- Will include variations in skewness and kyrtosis of both symmetric matter and symmetry energy (Q_0, R_0, Q_{sym}, R_{sym}). I span the space as follows:

  ρ_0 = -0.16 fm^{-3}, E_0=-16 MeV, K_0=220,240 MeV, J=32,33MeV, L=40-70MeV, C_{12}=-66 MeV fm^5, D_{12}=2.5 MeV fm^5 , m*/m=0.82, κ=0.22 W_0=133 MeV fm^5 and

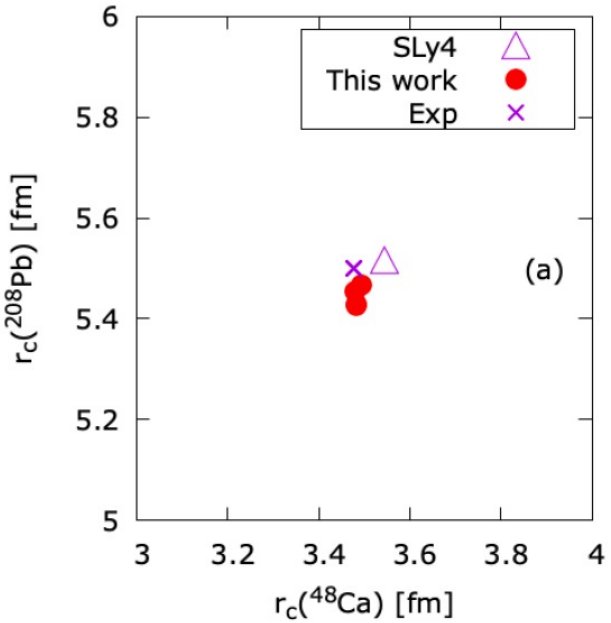
  Q_0, Q_{sym} varied widely in steps of 500MeV

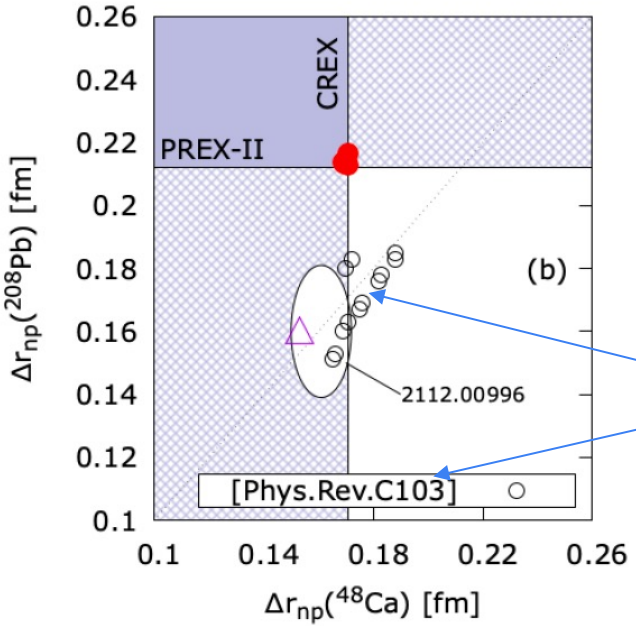
  R_0, R_{sym} varied widely in steps of 2GeV

I found four successful combinations of parameters

What does it take for PREX&CREX to be reconciled?

Second attempt: Results for charge radii and neutron skin with successful EoSs





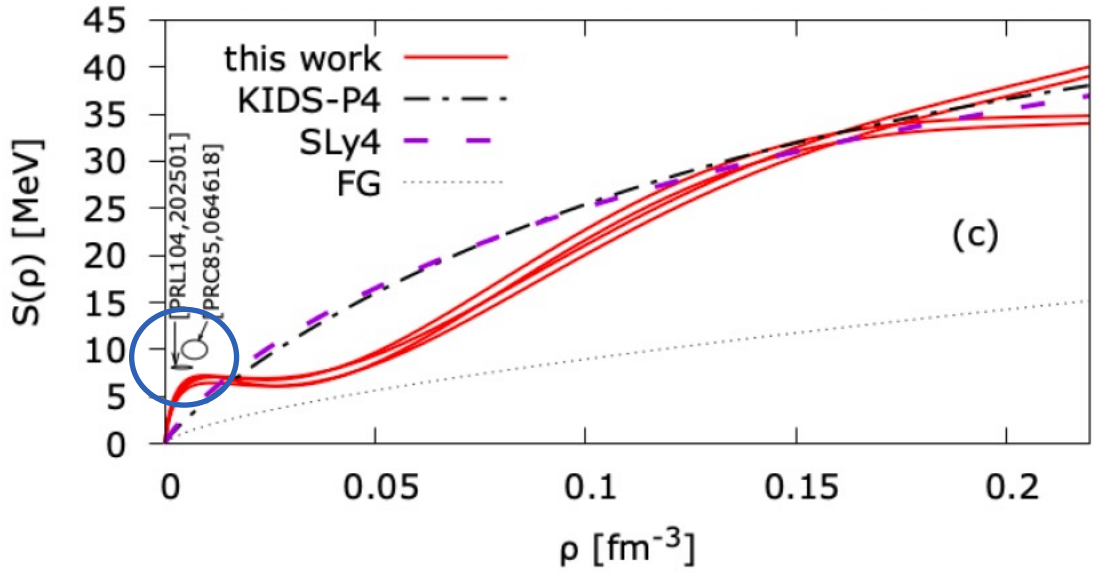
PP, NWT39 Proceedings
[arXiv:2210.02696]

Previous predictions from representative KIDS EoS/EDFs reproducing basic nuclear and NS data

What does it take for PREX&CREX to be reconciled?

Second attempt: The correponding EoSs have huge skewness and kyrtosis. Are they physical?

PP, NWT39 Proceedings [arXiv:2210.02696]



PRL **104,** 202501 (2010) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 21 MAY 2010

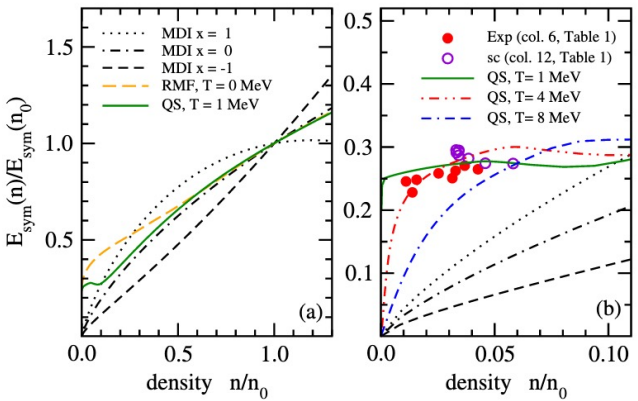
Symmetry Energy of Dilute Warm Nuclear Matter

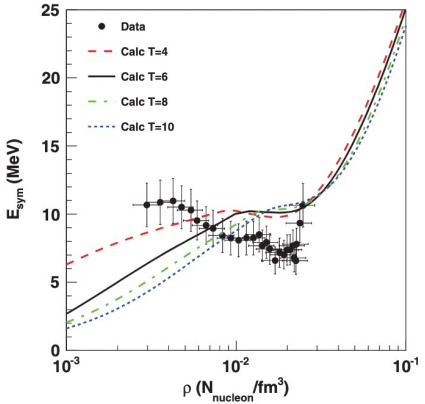
J. B. Natowitz,[1] G. Röpke,[2] S. Typel,[3,4] D. Blaschke,[5,6] A. Bonasera,[1,7] K. Hagel,[1] T. Klähn,[5,8] S. Kowalski,[1] L. Qin,[1] S. Shlomo,[1] R. Wada,[1] and H. H. Wolter[9]

PHYSICAL REVIEW C **85**, 064618 (2012)

Nuclear matter symmetry energy at $0.03 \leqslant \rho/\rho_0 \leqslant 0.2$

R. Wada,[1,2] K. Hagel,[2] L. Qin,[2] J. B. Natowitz,[2] Y. G. Ma,[3] G. Röpke,[4] S. Shlomo,[2] A. Bonasera,[2,5] S. Typel,[6] Z. Chen,[1,2] M. Huang,[1,2] J. Wang,[1,2] H. Zheng,[2] S. Kowalski,[7] C. Bottosso,[2] M. Barbui,[2] M. R. D. Rodrigues,[2] K. Schmidt,[2] D. Fabris,[8] M. Lunardon,[8] S. Moretto,[8] G. Nebbia,[8] S. Pesente,[8] V. Rizzi,[8] G. Viesti,[8] M. Cinausero,[9] G. Prete,[9] T. Keutgen,[10] Y. El Masri,[10] and Z. Majka[11]



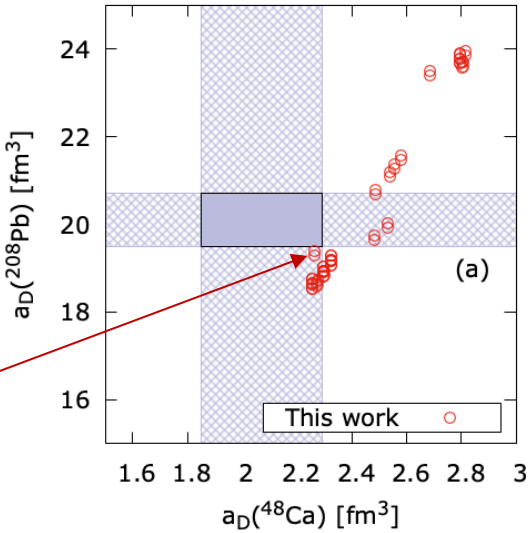


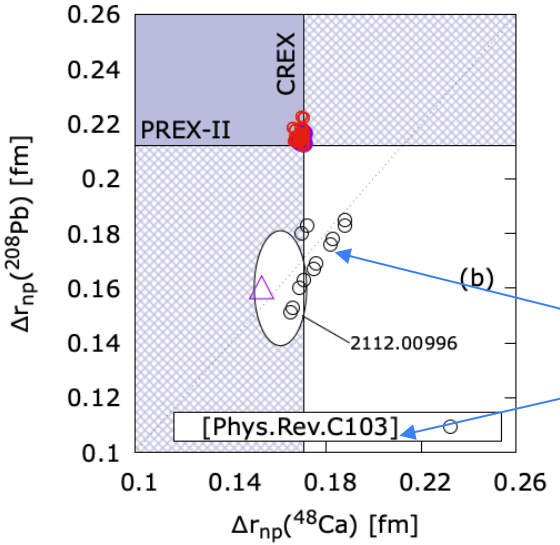
What does it take for PREX,CREX, a_D to be reconciled?

a_D of ^{48}Ca and ^{208}Pb was too large

Some more ongoing attempts in large parameter spaces (these plots are **one day old**)

Next, I also plot the EoS for one of these points (chosen blindly for lack of time)

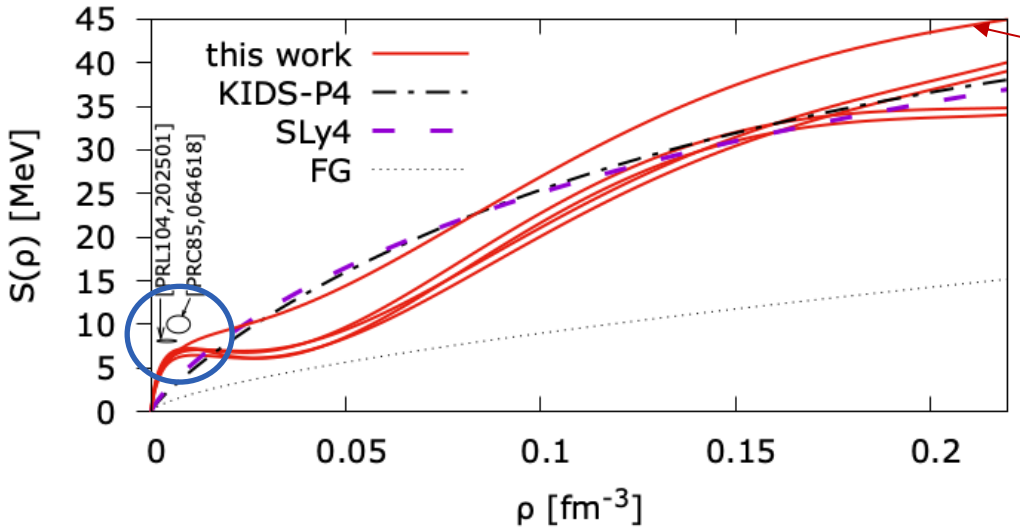




Previous predictions from representative KIDS EoS/EDFs reproducing basic nuclear and NS data

What does it take for PREX,CREX, $\mathbf{a_D}$ to be reconciled?

One of the latest EoSs with best a_D is shown here along with the previously shown ones:

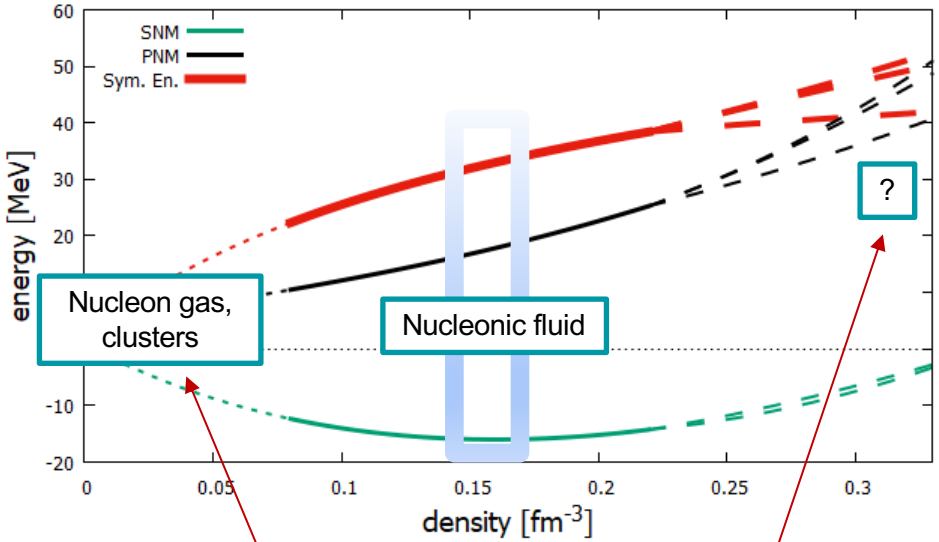


From the latest point (see previous slide)

An unorthodox but not necessarily unphysical behavior is required at low density

Remarks

Away from saturation regime, different phases may require different modeling



different density regimes (different phases or degrees of freedom) may require different functional forms which need to be interpolated.

Summary

- In order to extract information about the nuclear equation of state from collective excitations we rely on **energy density functional theory**
- Traditional Skyrme and RMF models have shown severe limitations
- I presented the versatile and physically motivated **KIDS** framework for the equation of state and energy density functional and its applications to constraining the **curvature parameter** of the symmetry energy based on gross nuclear and neutron star data; obtained conservatively **$-200\ \mathrm{MeV} < K_{sym} < 0$**
- I showed correlation studies suggesting a decoupling of low- and high-density regimes
- I stretched the model to its limits in order to examine whether CREX, PREX, and the dipole polarizability can be reconciled. It appears so – if we accept that different density regimes (different phases or degrees of freedom) require different functional forms which need to be interpolated.

You, too, are welcome to play with KIDS !

Thank you!

Supported by the Rare Isotope Science Project of Institute for Basic Science funded by Ministry of Science, ICT and Future Planning, and by NRF of Korea (Grant No. 2013M7A1A1075764)