iRiS 중이온가속기연구소 Institute for Rare Isotope Science

Symmetry energy in dilute and dense matter

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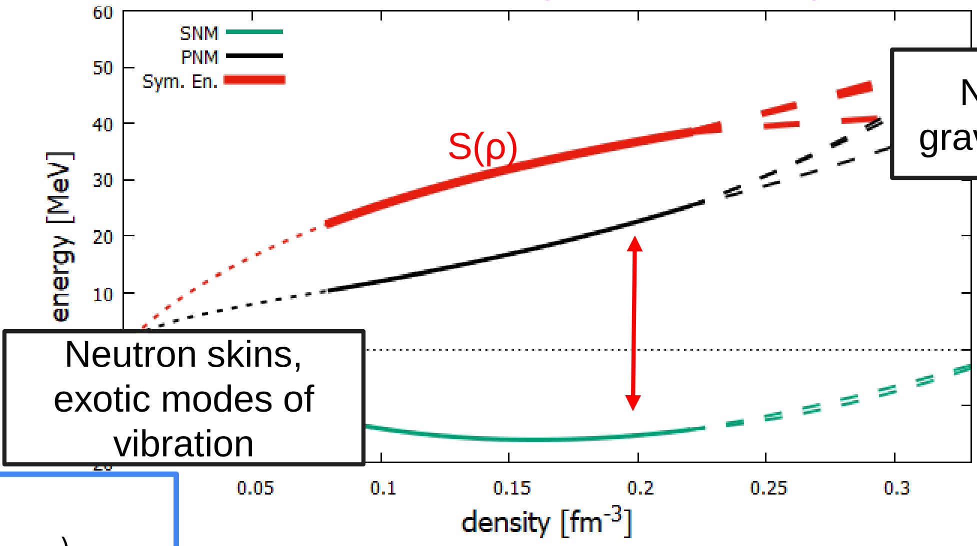
Contents

- Density dependence of symmetry energy :: properties of neutron rich nuclear systems

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



Rough estimates:
- J=30-33 MeV (best known)
- L=40-70 MeV
- K_{sym} = -200 - 0 MeV
- Q_{sym} = practically unconstrained

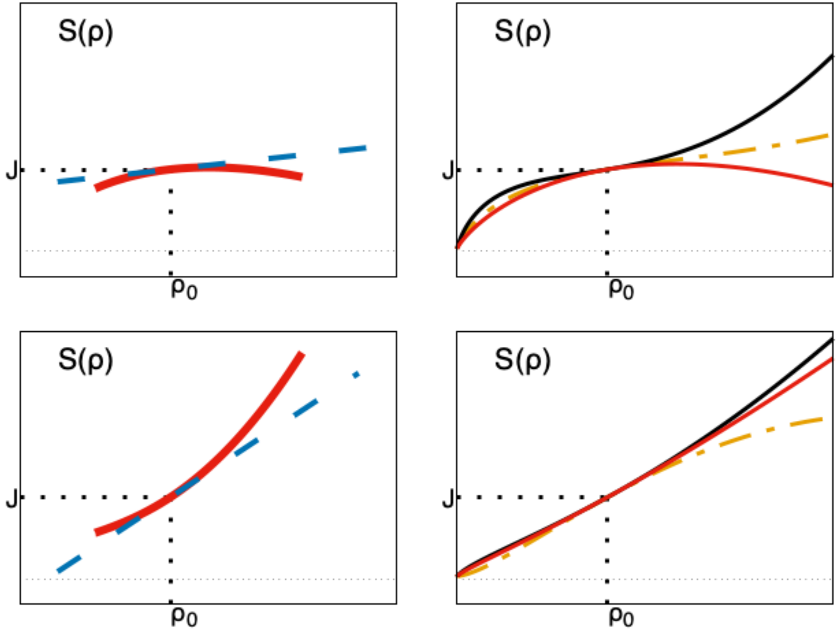
Some reviews:
Baldo&Burgio, ProgPartNuclPhys91,203 (2016)
Oertel et al., Rev.Mod.Phys.89,015007 (2017)
Roca-Maza&Paar, ProgPartNuclPhys101,96 (2018)
Related analyses:
Li et al., Universe 7, 182 (2021)
Thi et al., Universe 7, 373 (2021)
+multiple others

- Symmetry energy coefficients

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

Soft: low slope L

Stiff: high slope L



Soft with high K_{sym}

Soft, Skyrme/RMF type

Stiff, Skyrme/RMF type

Stiff with low K_{sym}

01 Introduction

Connecting nuclear data and the equation of state: energy density functionals

Dutra et al, PRC85,035201
Stevenson et al., AIP Conf.Proc 1529,262
Roca-Maza&Paar, ProgPartNuclPhys101,96

- Problem:

  Majority of EDFs fitted to data extrapolate to unrealistic EoSs

  Imposing realistic EoS parameters to EDFs can give strange nuclear results

- Overcome by:

  KIDS - a versatile framework for the nuclear EoS and EDF

  - Grounded in theory of interacting Fermi systems
  - Adjustable number of parameters depending on application

    (optimal for bulk nuclear properties and neutron stars: 3+4 EoS coefficients)
  - In medium effective mass is decoupled from the EoS coefficients
  - No forced, unphysical correlations

Reviewed in:
PP&Hyun,
Symmetry 15 (2023) 683

Easy to use - like an extended Skyrme functional

02 Curvature parameter K_{sym} of the symmetry energy

Xu&PP, Phys. Rev. C 105,044305
Zhou,Xu,PP, Phys. Rev. C 107, 055803
Gil et al., IJMPE 31, 2250013

Selected results from:

- ❑ Bayesian analysis of isovector nuclear properties; neutron-star properties
- ❑ Combined analyses of nuclear properties and neutron-star properties

02 Curvature parameter K_{sym} of the symmetry energy

Bayesian analysis of isovector nuclear properties

Examined ^{208}Pb and ^{120}Sn

Isovector constraints: Neutron skin thickness, giant dipole resonance, dipole polarizability

	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 constraints: mass, charge radius, energy of the isoscalar monopole resonance

Results for KIDS are compared with standard Skyrme-Hartree-Fock

Xu&PP, Phys. Rev. C 105,044305

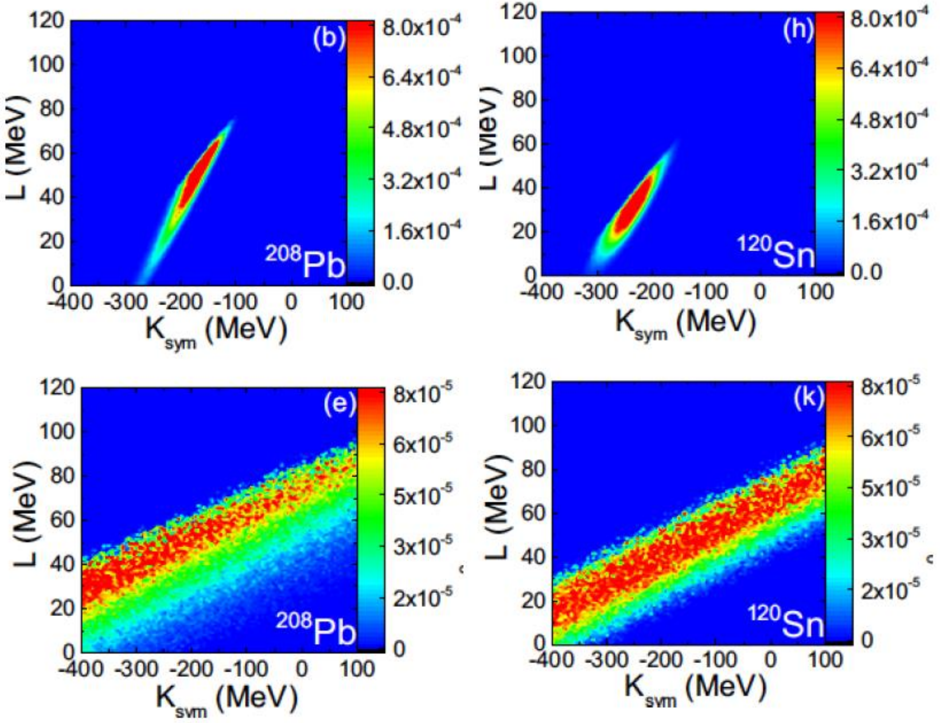
02 Curvature parameter K_{sym} of the symmetry energy

Bayesian analysis of isovector nuclear properties

Ksym vs L

Skyrme:

KIDS :
Broader PDFs
K_{sym} not constrained



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02 Curvature parameter K_{sym} of the symmetry energy

Bayesian analysis of isovector nuclear properties

Ksym vs 3J-L

Skyrme:

KIDS :
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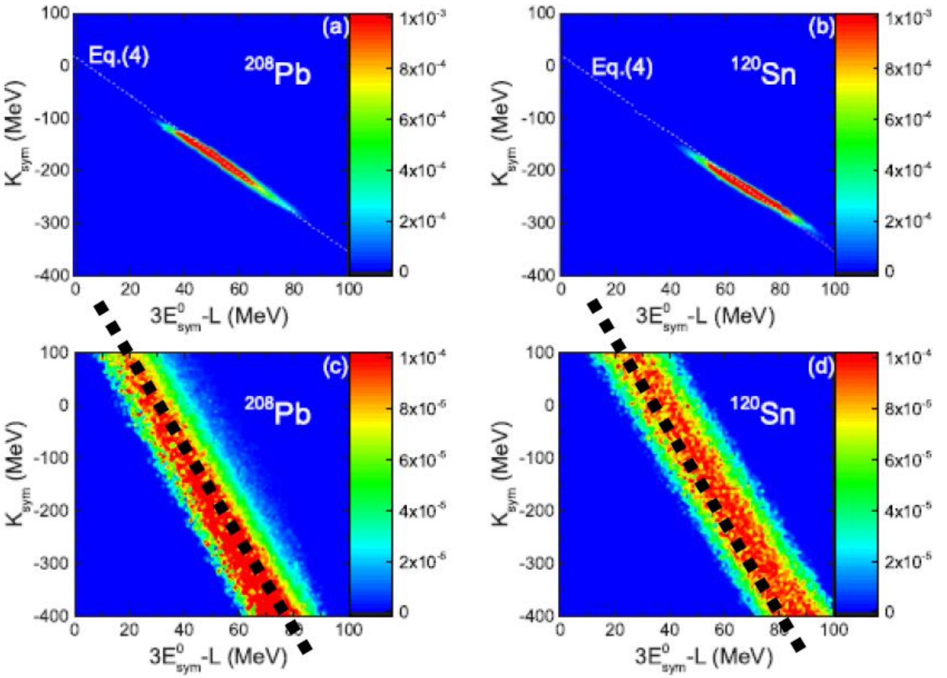


Xu&PP, Phys. Rev. C 105,044305

02 Curvature parameter K_{sym} of the symmetry energy

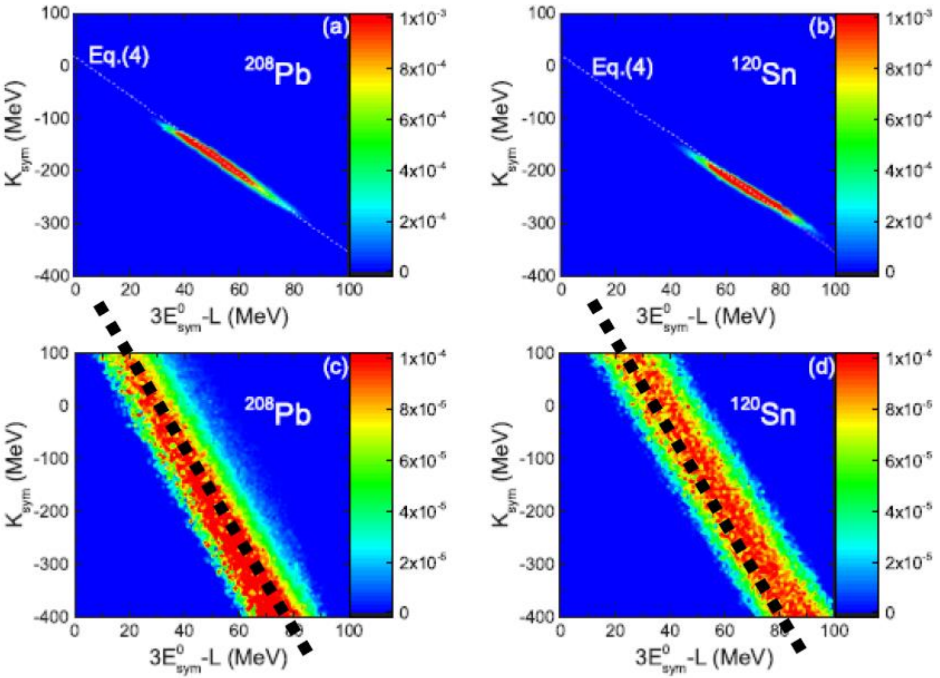
Bayesian analysis of isovector nuclear properties

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

Skyrme:

With line: shown equation for representative ρ_0, α, m^*

KIDS :
Broader PDFs
K_{sym} unconstrained



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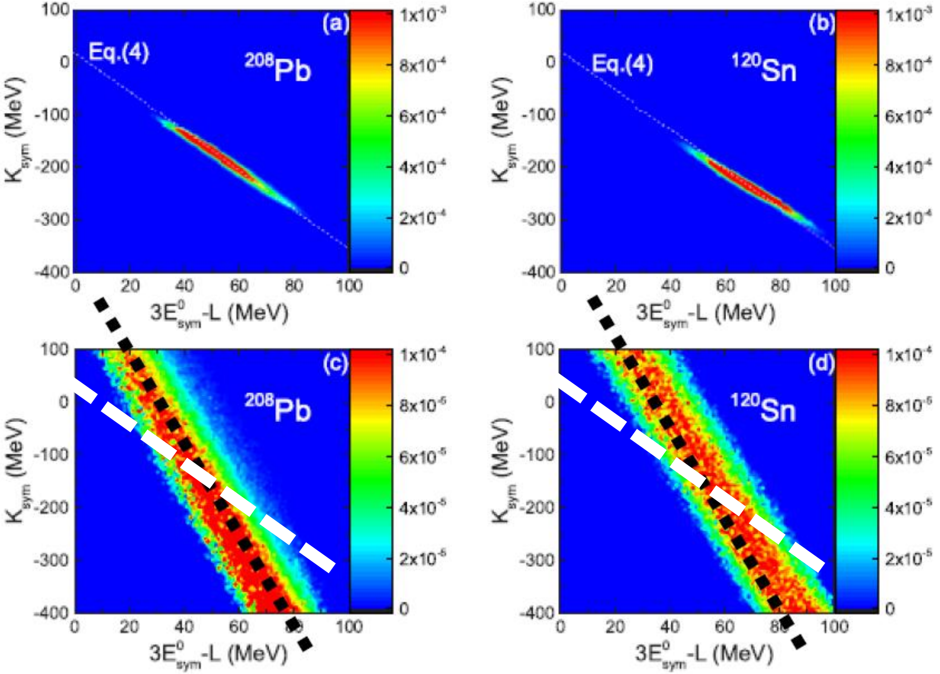


Xu&PP, Phys. Rev. C 105,044305

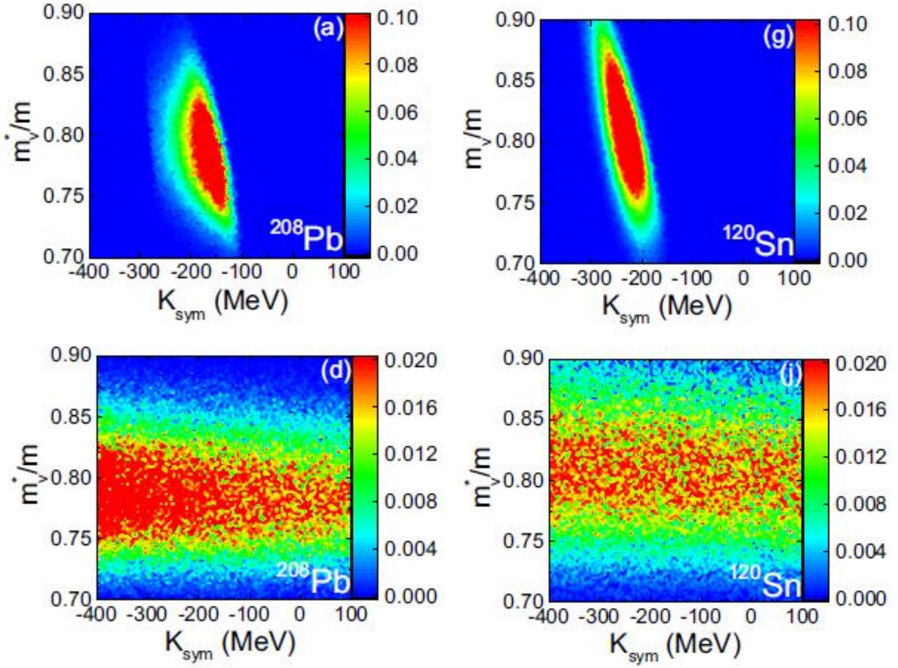
02 Curvature parameter K_{sym} of the symmetry energy

Bayesian analysis of isovector nuclear properties

Ksym vs IV effective mass

Skyrme:

KIDS :
Practically no correlation

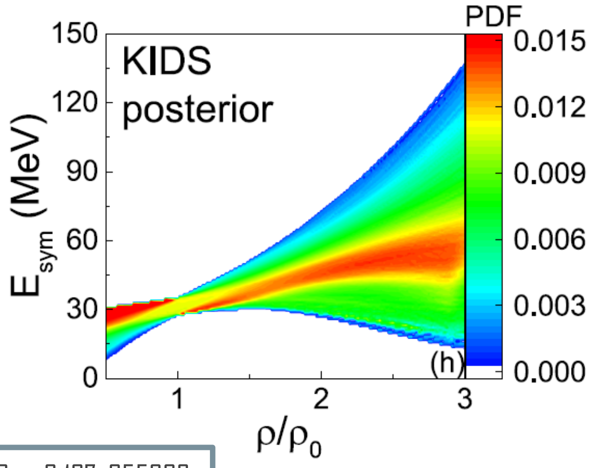


Xu&PP, Phys. Rev. C 105,044305

02 Curvature parameter K_{sym} of the symmetry energy

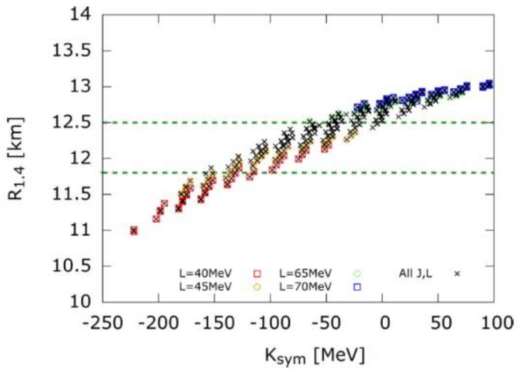
Analyses of astronomical data

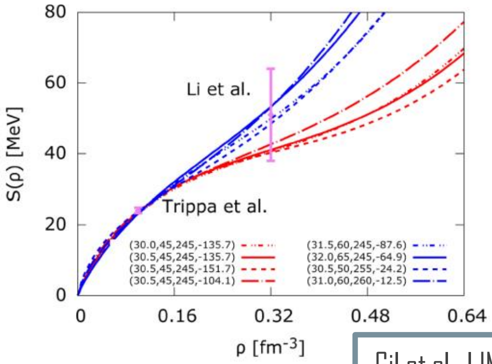
$R_{1.4}$ (km)	11.725 ± 1.105 [15]
$R_{2.08}$ (km)	$13.7^{+2.6}_{-1.5}$ [13] and $12.39^{+1.30}_{-0.98}$ [14]
$\Lambda_{1.4}$	190^{+390}_{-120} [18]
M_{max}	$>2.08 M_{\odot}$ [12]
c_s	<1



Zhou,Xu,PP, Phys. Rev. C 107, 055803

Combined analysis with nuclear data





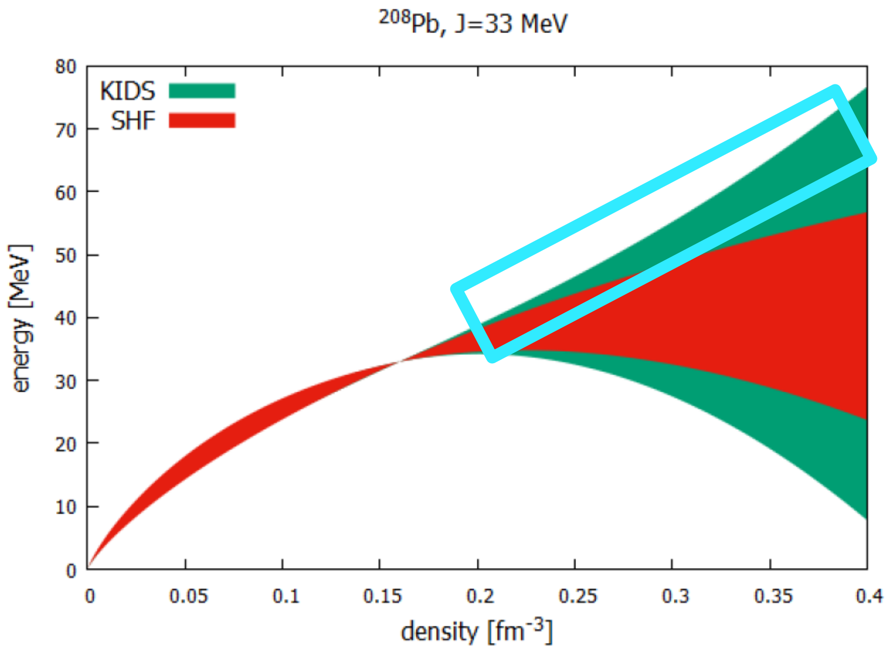
Gil et al., IJMPE 31, 2250013

02 Curvature parameter K_{sym} of the symmetry energy

Corresponding EoS domains

KIDS model allows for

- ❑ Inflection point: soft-to-stiff transition, important for description of dense matter
- ❑ Decoupling of dilute and dense regimes



Summary so far: J≈30-33 MeV, L ≈ 45-65 MeV, K_{sym} ≈ -200-0 MeV

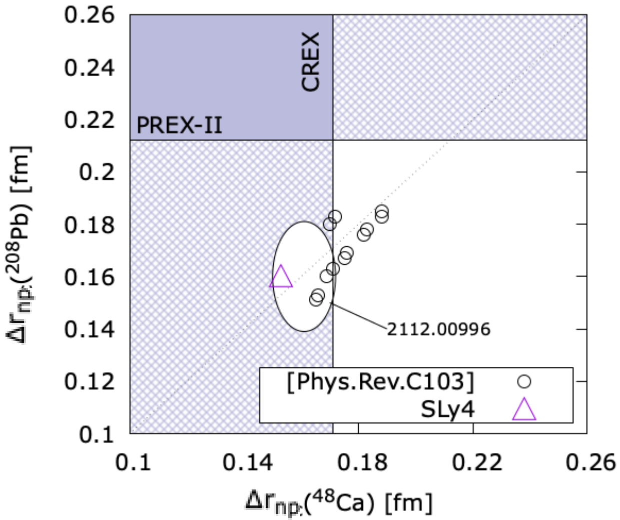
03 The CREX, PREXII, and a_D tension

- Can a KIDS EDF obeying the obtained constraints describe CREX and PREXII and the dipole polarizability simultaneously?
- (No!) What would it take?

03 The CREX, PREXII, and a_D tension

Predictions for the neutron skin

- KIDS predictions for the neutron skin when the parameters are constrained from gross nuclear properties (masses, charge radii) and neutron star properties, generally agree with CREX and underestimate PREX – see C.H.Hyun, arXiv:2112.00996 *[~300 KIDS EDFs obeying EoS]*
- The tension is similar to other studies, including RMF models (*Esra Yüksel's talk*)



03 The CREX, PREXII, and a_D tension

What will it take to reconcile CREX, PREXII, a_D?

- Searching for KIDS parameter sets which reproduce both CREX and PREXII within their respective errors (1σ) and at the same time basic nuclear properties (<1%)
- Extend the formalism to vary freely up to 5+5 EoS parameters: including skewness and kyrtosis of both symmetric matter (Q_0, R_0) and symmetry energy (Q_{sym}, R_{sym}) , as follows:

  ρ_0 = 0.15-0.16 fm^{-3}, E_0 = -16 MeV, K_0 = 200-240 MeV J = 30-36 MeV L = 40-70MeV

  K_{sym} varied widely in steps of 50 MeV

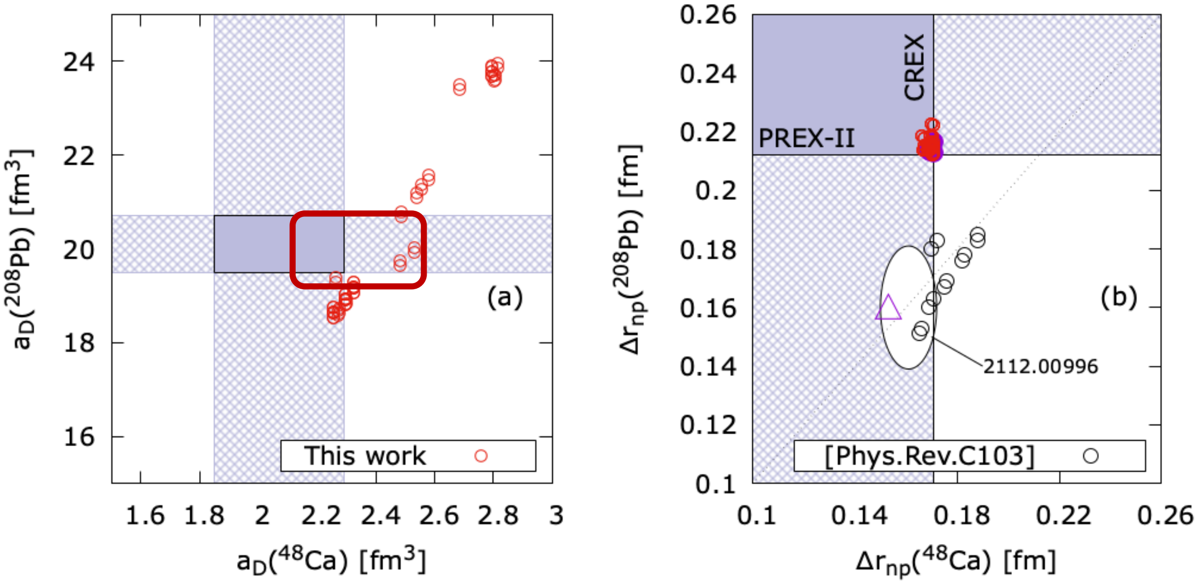
  Q_0, Q_{sym} varied widely in steps of 500MeV

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

  and in addition: 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

For a first study of CREX-PREX only, see arXiv:2210.02696 (Rila 2022 proceedings)

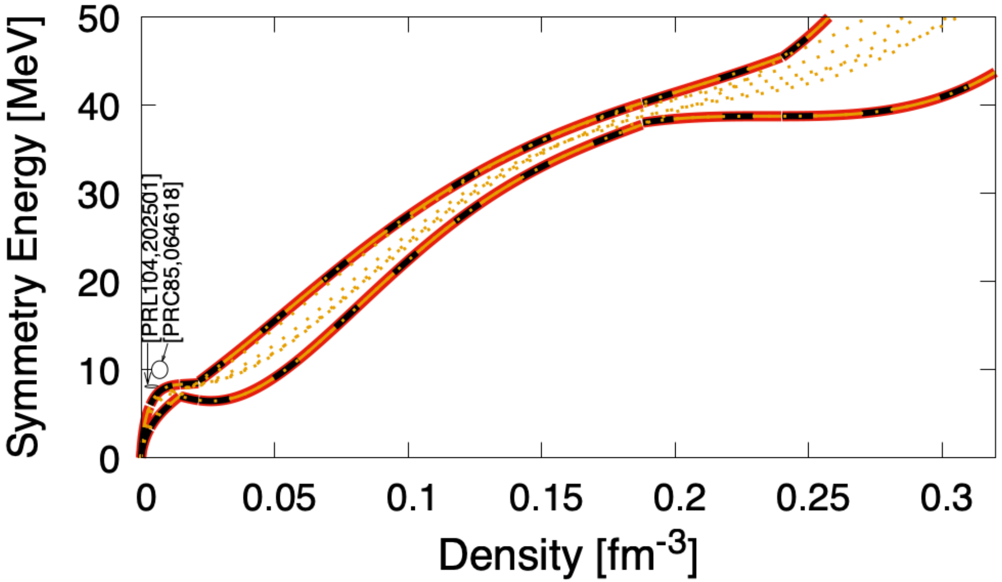
Results for a_D as well as neutron skin



03 The CREX, PREXII, and a_D tension

Domain with best a_D

- ❑ Unorthodox but not necessarily unphysical behavior at low density
- ❑ Consistent with analyses of heavy-ion collisions



03 The CREX, PREXII, and a_D tension

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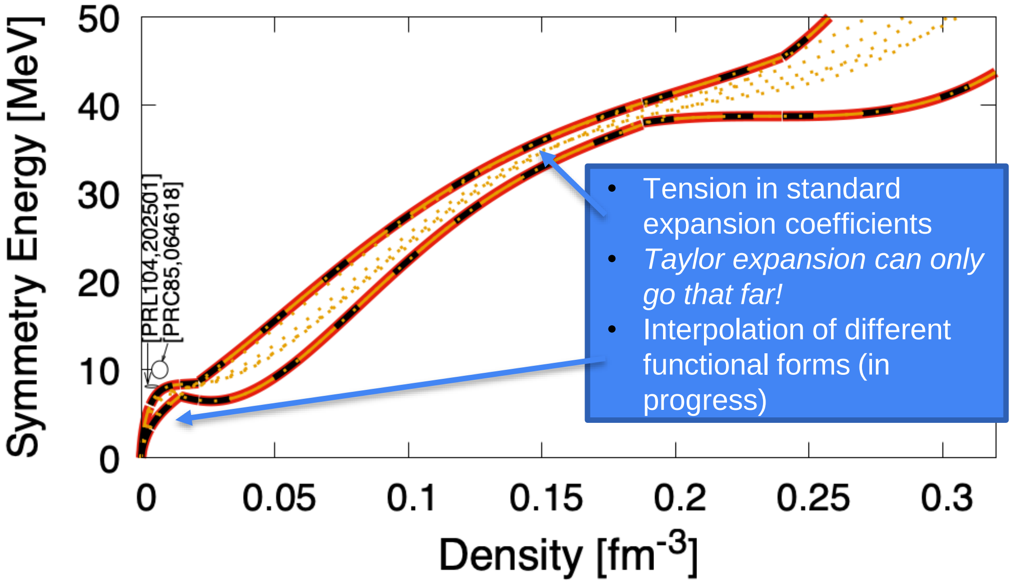

04 Conclusion

- Most traditional EDF models correspond to a symmetry energy with a near-parabolic dependence on the density, either stiff or soft
- Exploring the full density dependence of the EoS requires extended models beyond traditional functionals, as shown here with the more flexible KIDS.
  - K_{sym} cannot be constrained from nuclear data alone
  - Correlations between K_{sym} and L & effective mass in Skyrme models are a model artifact
- Combined analyses of nuclear isovector properties and astronomical observations suggest a soft-to-stiff transition somewhere above saturation density
- A reconciliation of CREX, PREXII and dipole polarizability data suggests an even more complex behavior, consistent with clusterization at low densities according to HIC data
  - Interpolations in progress

Thank you!

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