iRiS 중이온가속기연구소
Institute for Rare Isotope Science

# Symmetry energy in dilute and dense matter

## and the PREX-CREX puzzle

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Daejeon, May 27, 2025

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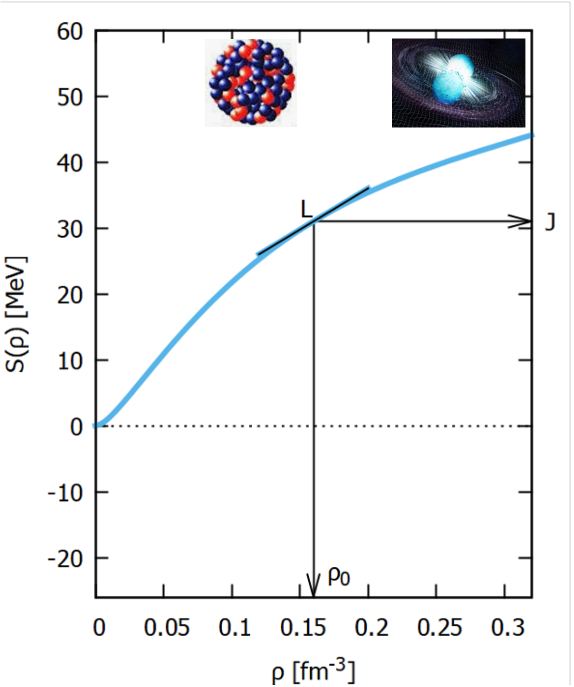
Contents

## 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:

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

- Namely its value $J$, slope $L$, curvature $K_{sym}$, skewness $Q_{sym}$, etc, at the nuclear saturation density $\rho_0$.



**Symmetry energy**

It is explored at different densities by examining various observables:

- ❑ Low density: nuclear masses, density distributions (skins), collective excitations
- ❑ High density: Heavy-ion collisions, compact stars
  - ☛ *Multi-messenger astronomy*
- ❑ Ab initio calculations are also available
  - ☛ *Variational Monte Carlo, Quantum Monte Carlo, chiral EFT, …*

Rough estimates:

- $J = 30 - 33$ 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)
Related analyses:
Li et al., Universe 7, 182 (2021)
Thi et al., Universe 7, 373 (2021)
+multiple others

# 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

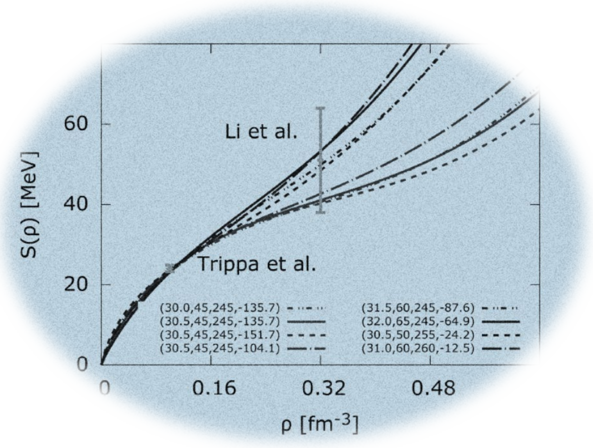
**Reviewed in:**
**PP&Hyun,**
**Symmetry 15 (2023) 683**

*Easy to use - like an extended Skyrme functional*

# 02 Curvature parameter $K_{sym}$ of the symmetry energy

## Next: Selected results from analyses of nuclear and neutron star properties

- Xu&PP, Phys. Rev. C 105, 044305
- Zhou,Xu,PP, Phys. Rev. C 107, 055803
- Gil et al., IJMPE 31, 2250013
- Gil et al, Phys. Rev. C 103, 034330



# 02 Curvature parameter $K_{sym}$ of the symmetry energy

## Bayesian analysis of isovector nuclear properties

- ❑ **Examined $^{208}$Pb and $^{120}$Sn**
- ❑ **Results for KIDS are compared with standard Skyrme-Hartree-Fock**

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

| | $\Delta r_{np}$ (fm) | $E_{-1}$ (MeV) | $\alpha_D$ (fm$^3$) |
|---|---|---|---|
| $^{208}$Pb | $0.283 \pm 0.071$ | $13.46 \pm 0.10$ | $19.6 \pm 0.6$ |
| $^{120}$Sn | $0.150 \pm 0.017$ | $15.38 \pm 0.10$ | $8.59 \pm 0.37$ |

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

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

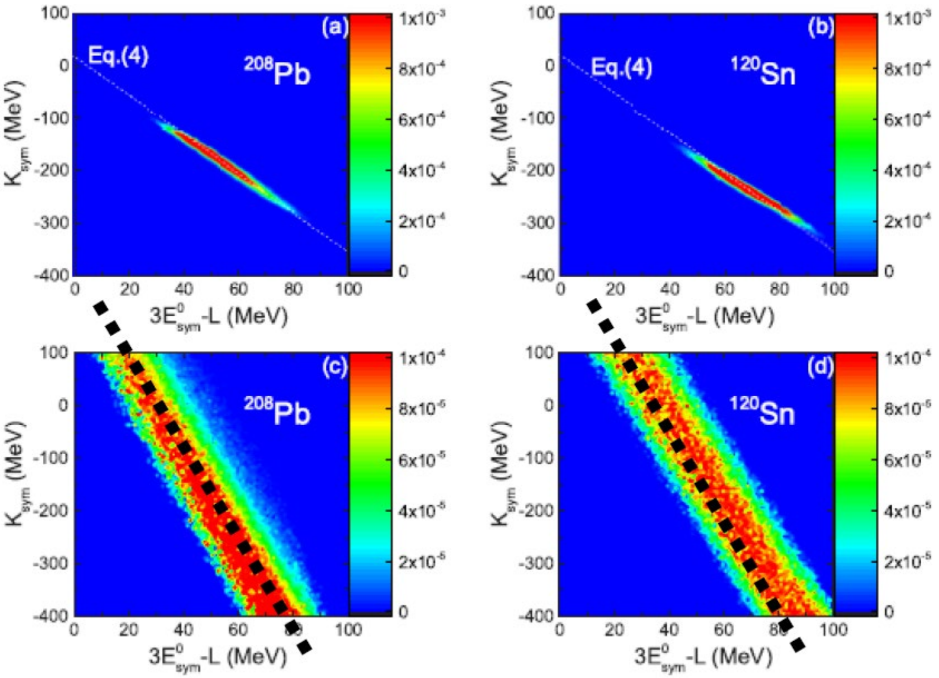
# 02 Curvature parameter $K_{sym}$ of the symmetry energy

## Bayesian analysis of isovector nuclear properties

Ksym vs 3J-L

Skyrme:

KIDS :
Broader PDFs
$K_{sym}$ not constrained




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

# 02 Curvature parameter $K_{sym}$ of the symmetry energy

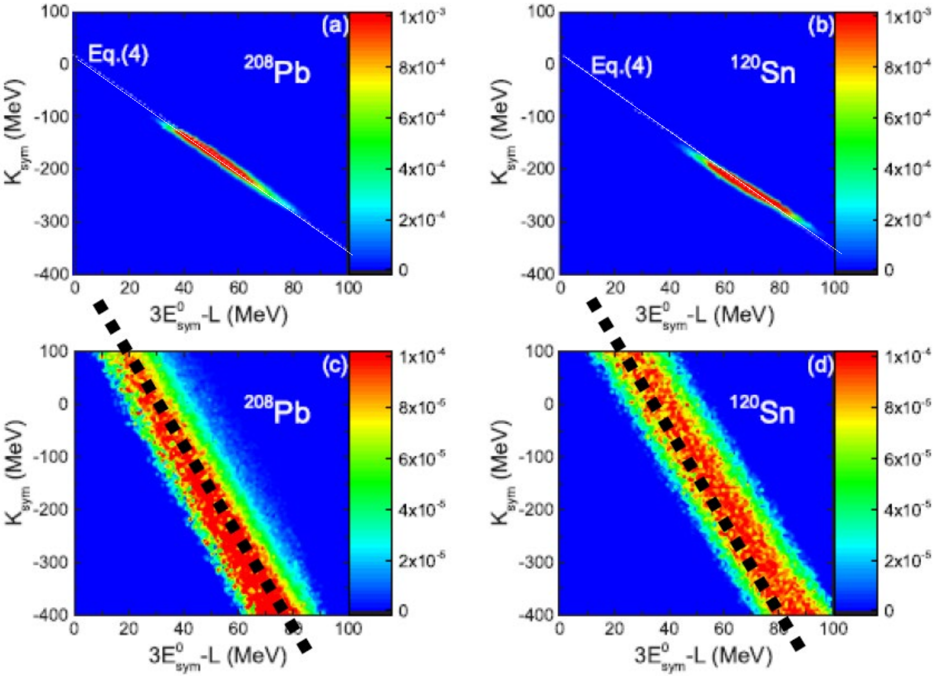
## Bayesian analysis of isovector nuclear properties

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

Skyrme:

*White line: shown equation for representative $\rho_0$, $\alpha$, $m^*$*

KIDS :
Broader PDFs
$K_{sym}$ not constrained

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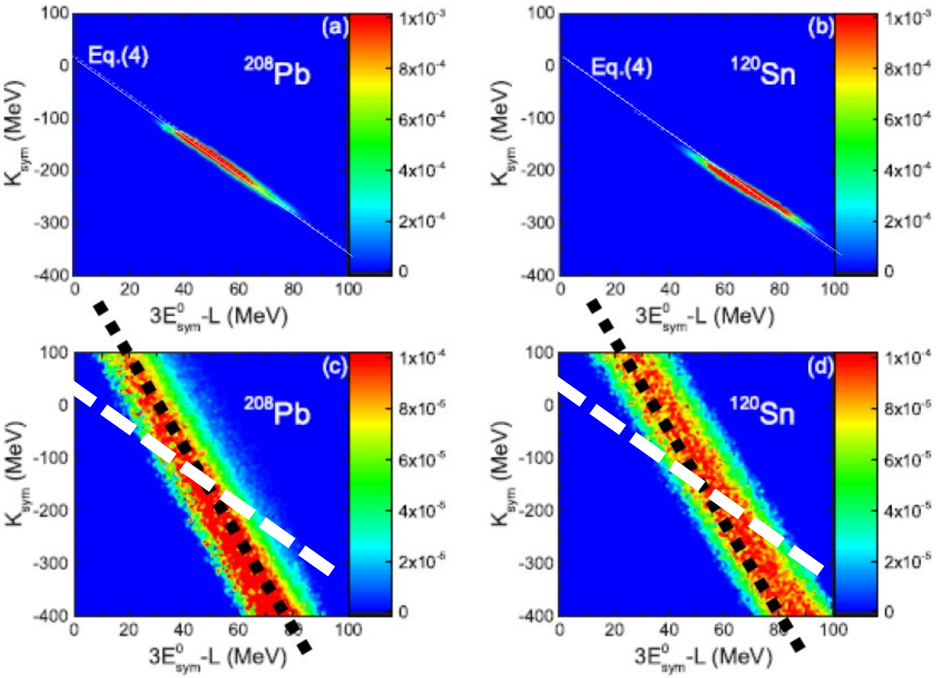
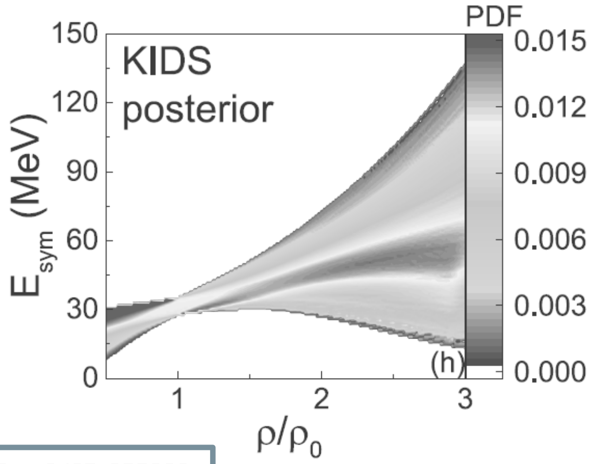



Xu&PP, Phys. Rev. C 105,044305

# 02 Curvature parameter $K_{sym}$ of the symmetry energy

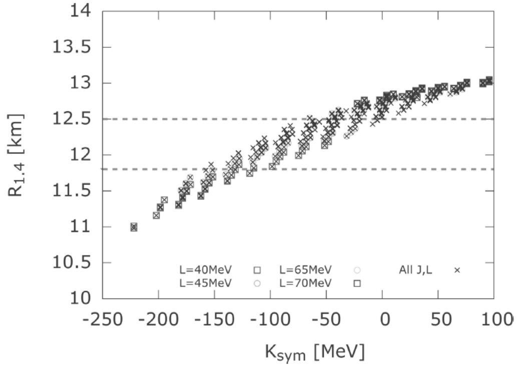
## Analyses of astronomical data

| | |
|---|---|
| $R_{1.4}$ (km) | $11.725 \pm 1.105$ [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] |
| $c_s$ | $<1$ |

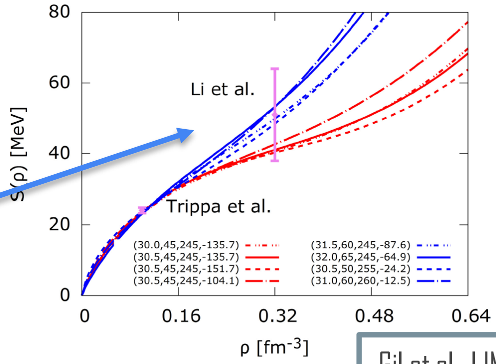



Zhou,Xu,PP, Phys. Rev. C 107, 055803

## Combined analysis with nuclear data




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




Gil et al., IJMPE 31, 2250013

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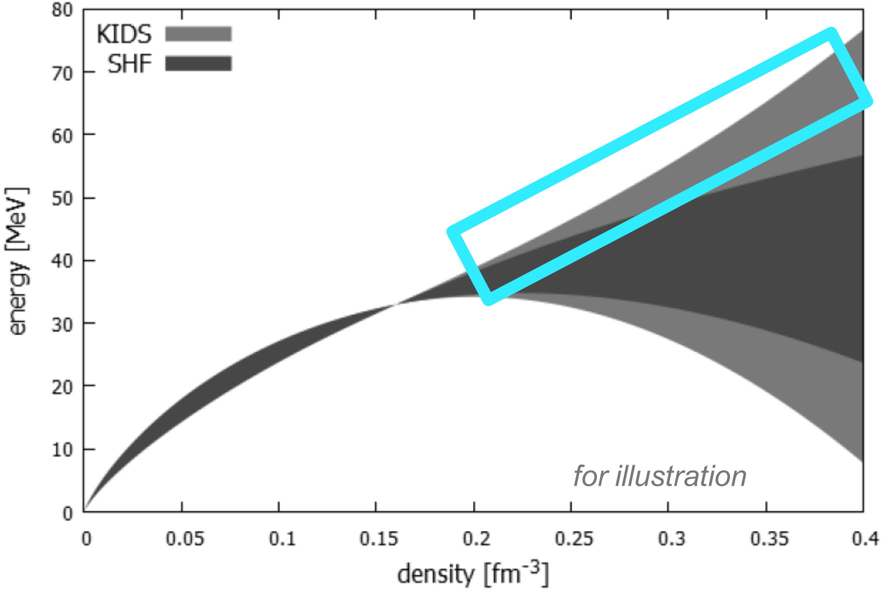
# 02 Curvature parameter $K_{sym}$ of the symmetry energy

**Density domains**

-Most EDF models correspond to a near-parabolic behavior: either stiff or soft

-KIDS framework allows for

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



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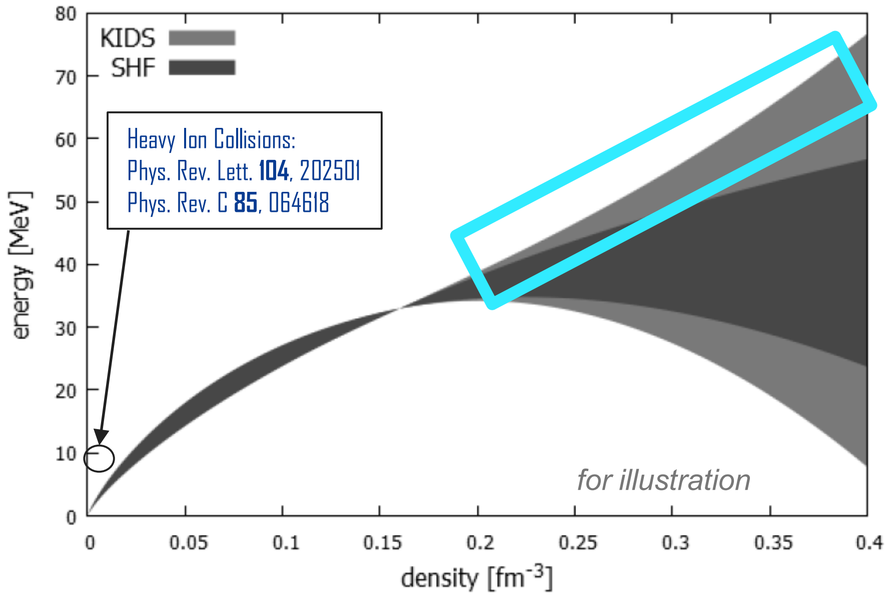
- ❑ Inflection point: soft-to-stiff transition, important for description of dense matter
- ❑ Decoupling of saturation and dense regimes
- ❑ **How about dilute matter?**



# 03 The CREX, PREXII tension

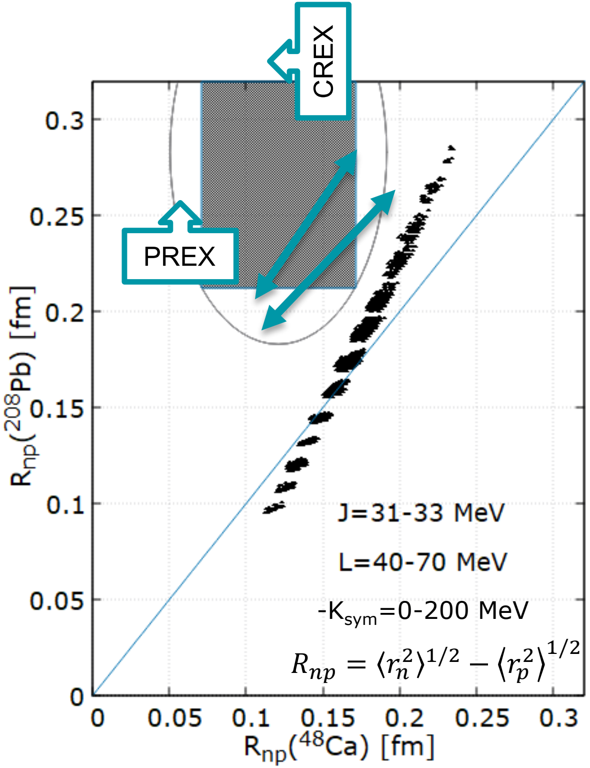
**The problem**

- Stiff EDF models which agree with the PREXII result overestimate the neutron skin thickness of $^{48}$Ca
- Soft EDF models with agree with the CREX result underpredict the neutron skin thickness of $^{208}$Pb

**Current KIDS predictions for the neutron skin**

- The tension is similar to other studies when EoS parameters are varied within realistic ranges.

see also: C.H.Hyun, arXiv:2112.00996



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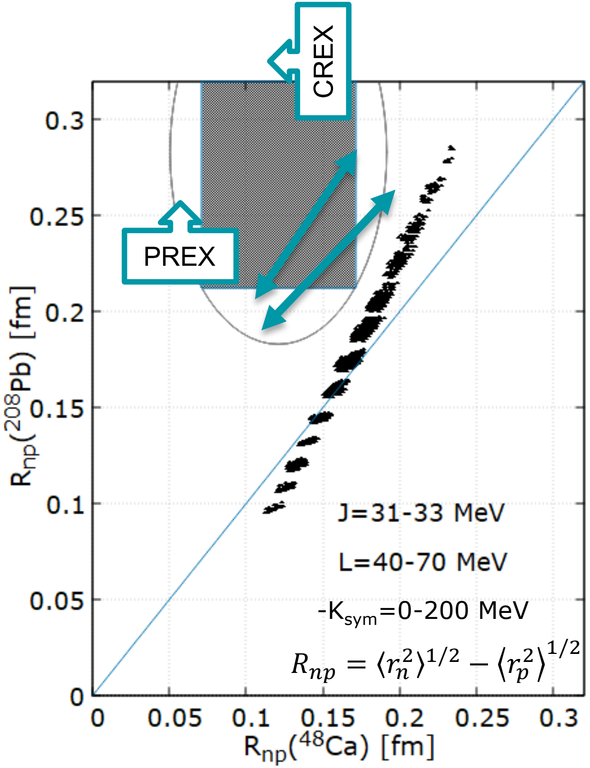
**Current KIDS predictions for the neutron skin**

- ❑ The tension is similar to other studies when EoS parameters are varied within realistic ranges.
- ❑ Too large to attribute to systematic analysis uncertainties



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**Current KIDS predictions for the neutron skin**

- The tension is similar to other studies when EoS parameters are varied within realistic ranges.
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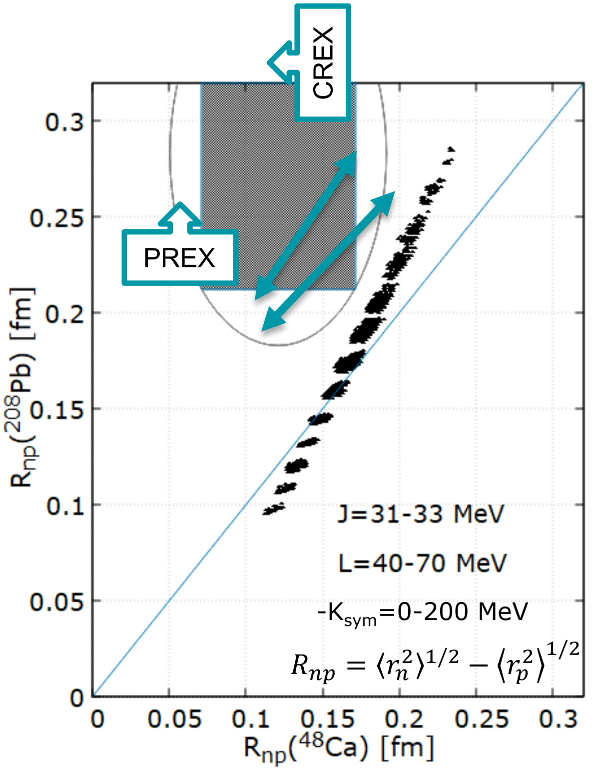
**What if we explore the very dilute regime only?**

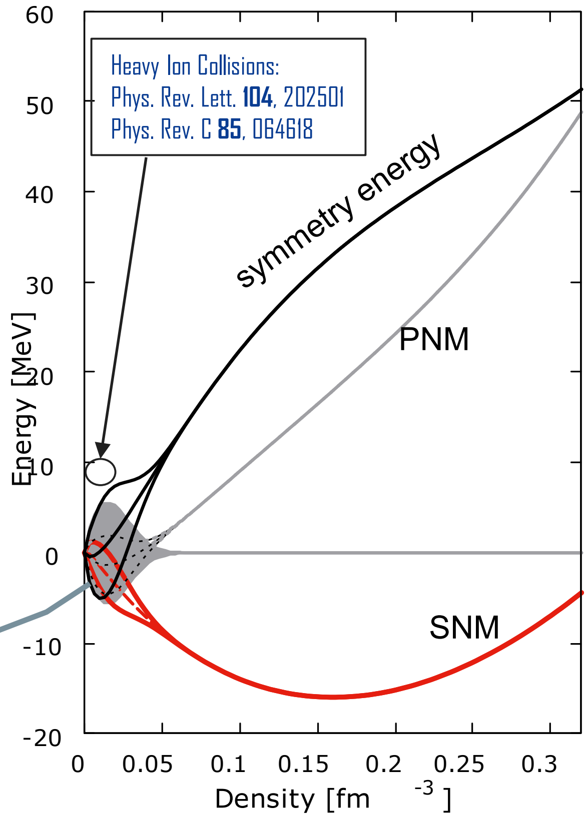
see also: PP, arXiv:2210.02696 (Proc.IWNT39)



**Modifications in the low-density regime**

- The KIDS model relies on an expansion of the energy in powers of the density
- However, dilute matter may require different expansion coefficients
- Exploring **one additional density-dependent term which decays exponentially and does not affect the saturation and supra-saturation regimes**

New term of the form $c\rho^{\alpha}\exp(-\beta\rho^{2})$



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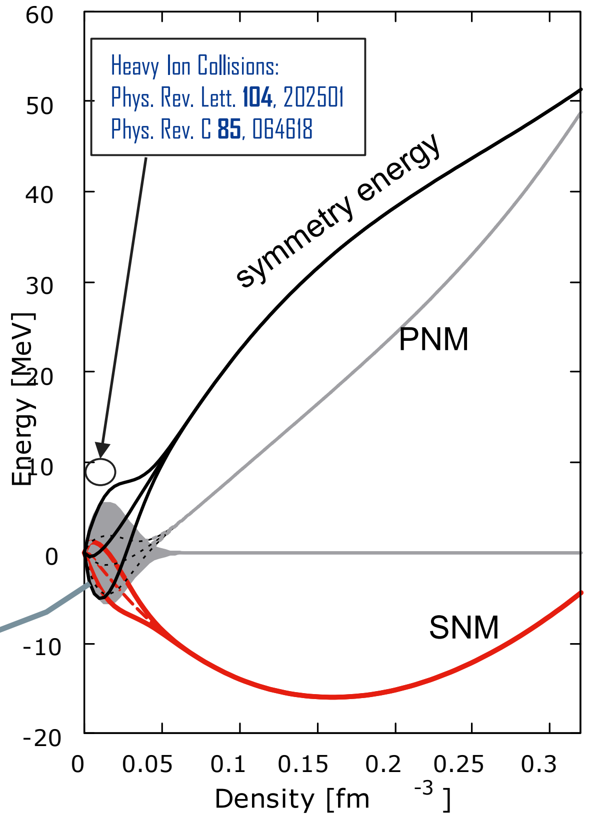
- Exploring **one additional density-dependent term which decays exponentially and does not affect the saturation and supra-saturation regimes**

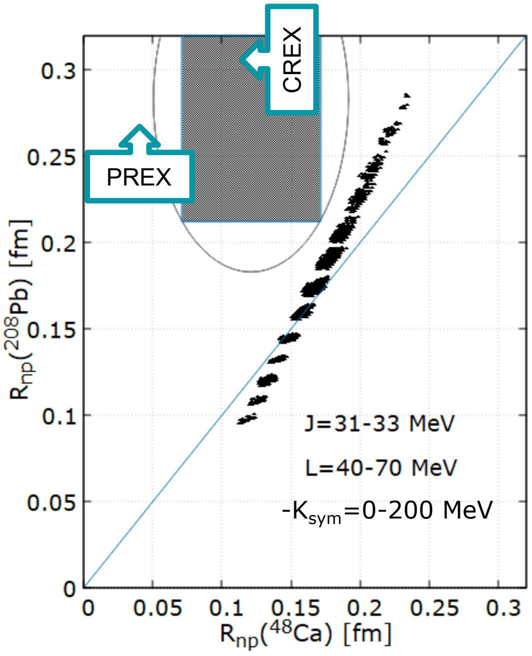
New term of the form $c\rho^{\alpha}\exp(-\beta\rho^2)$

New effective interaction term:
$\frac{1}{6}(t_{dil} + y_{dil}P_{\sigma})\rho^{\alpha-1}\exp(-\beta\rho^2)\delta(\vec{r}_1 - \vec{r}_2)$



# 03 The CREX, PREXII tension

## Preliminary results



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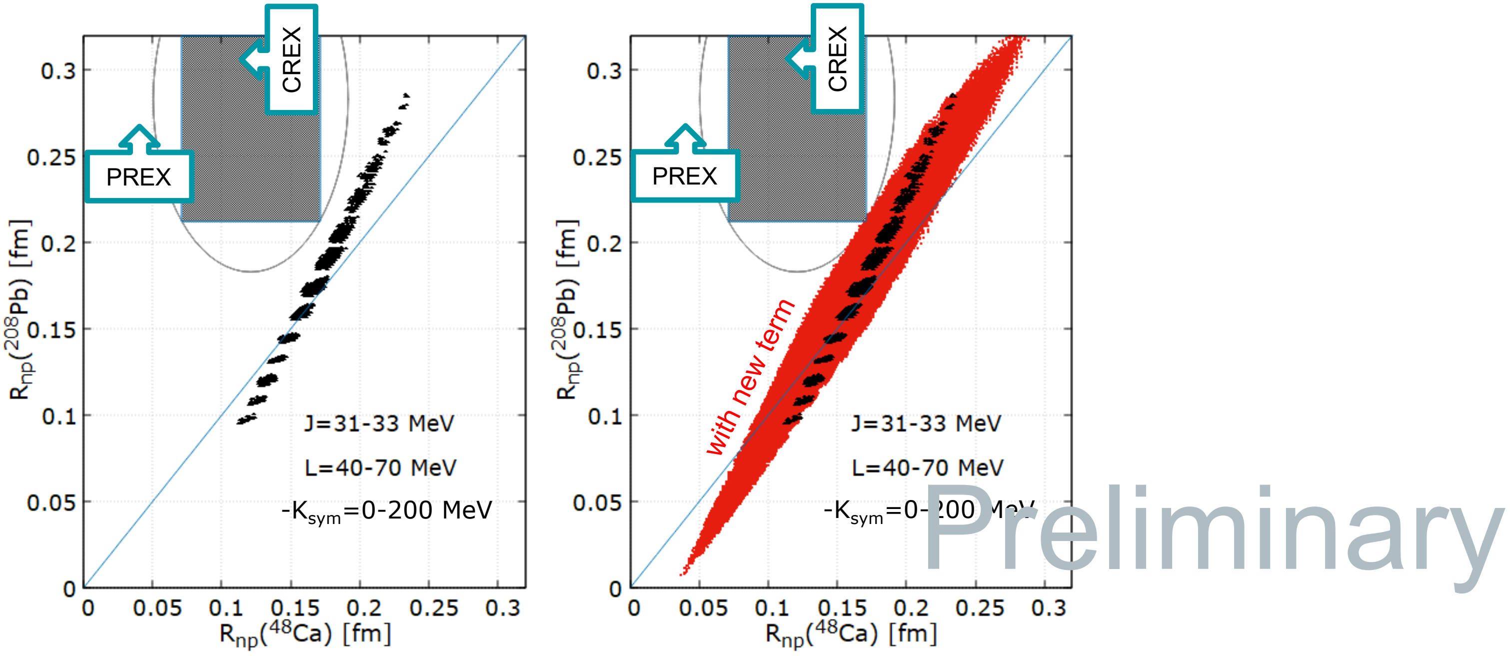
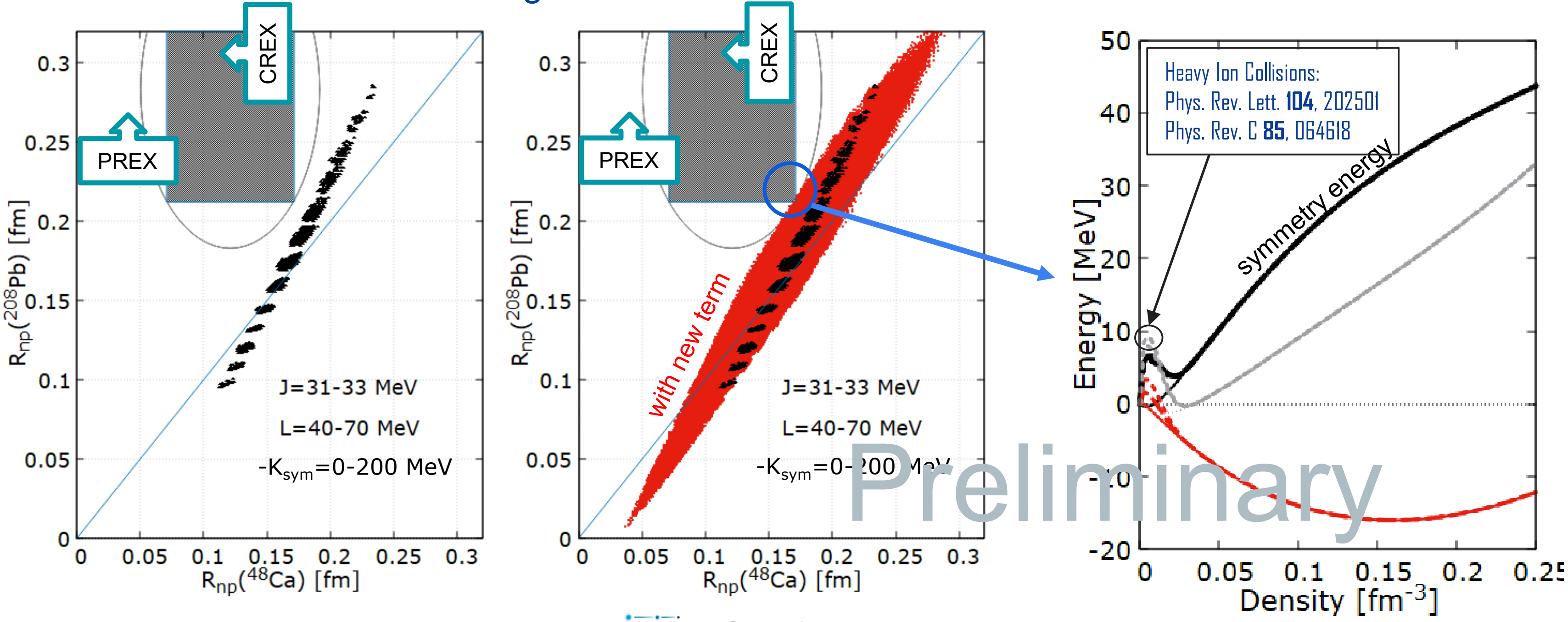


## Preliminary results

- The new term leads to lowering of the neutron radius in both nuclei and towards reconciliation



# 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 with the flexible KIDS framework we find:
  - $K_{sym}$ cannot be constrained from nuclear data alone
  - Correlations between $K_{sym}$ , L , effective mass in Skyrme models are artificial
- **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, but consistent with HIC data at low densities – to be continued –**

*new*

# Thank you!

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# 03 The CREX, PREXII tension

**What systematic effect of EDF theory could reconcile the two measurements?**

**A systematic reduction of neutron surface thickness for given realistic bulk EoS**

- Effect on neutron skin thickness in the Helm model, assuming **steady proton r.m.s. radius** (charge radius constraint) and **steady hard-sphere neutron radius** (bulk equation of state):



Neutron skin thickness: $R_{np} = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2}$

Helm model r.m.s.: $\langle r_q^2 \rangle^{1/2} = \left[\frac{3}{2}\left(R_q^2 + \frac{2}{5} t_q^2\right)\right]^{1/2}$ (Hard-sphere radius: $R_q$; Surface thickness: $t_q$)

Variation for steady $\langle r_p^2 \rangle^{1/2}$ : $\delta R_{np} = \delta \langle r_n^2 \rangle^{1/2} + 0$

Variation for steady $R_n^2$ : $\delta R_{np} = \frac{1}{2}\sqrt{\frac{3}{2}} \frac{0 + \frac{2}{5}\delta t_n^2}{\langle r_n^2 \rangle^{1/2}}$

$$\delta R_{np} = \frac{1}{5}\sqrt{\frac{3}{2}} \frac{\delta t_n^2}{\langle r_n^2 \rangle^{1/2}}$$

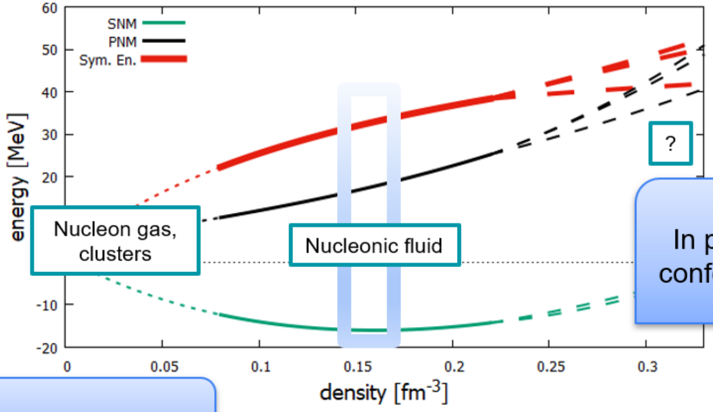
Smaller $R_{np}$ reduction for larger $\langle r_n^2 \rangle$ ($^{208}$Pb)
Larger $R_{np}$ reduction for smaller $\langle r_n^2 \rangle$ ($^{48}$Ca)

# 02 Curvature parameter $K_{sym}$ of the symmetry energy

**From INPC2022:**

## Outlook

Away from saturation regime, different phases may require different modeling




In progress: interpolations to conformal limit in dense matter

PP & Hyun, Symmetry 15 (2023) 683

What's new?

In progress: PREX vs CREX?

Stay tuned!

## Bayesian analysis of isovector nuclear properties

Ksym vs L

Skyrme:

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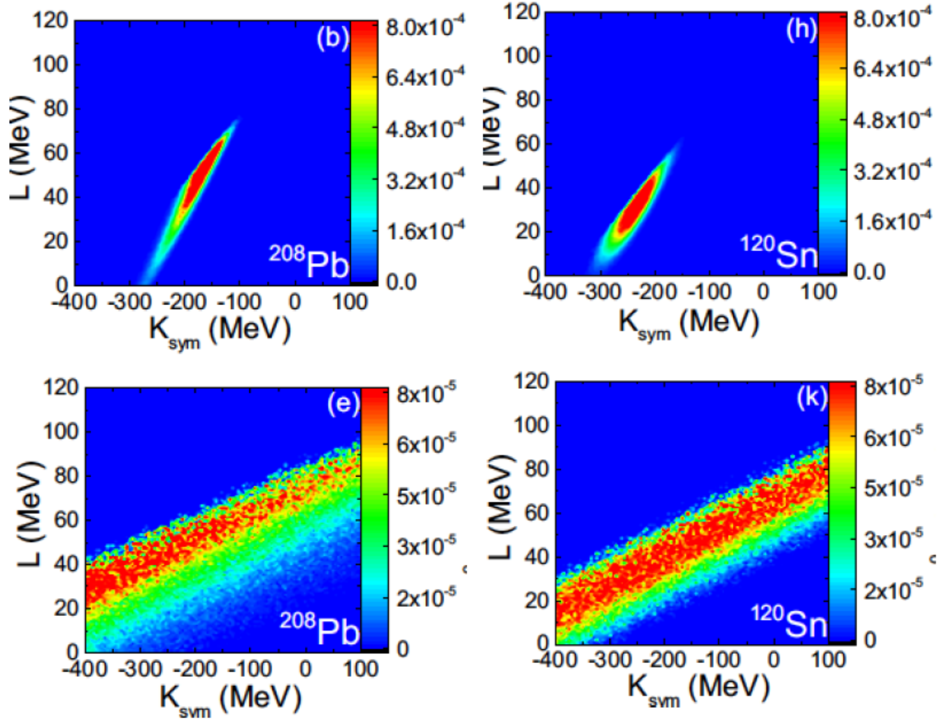


Xu&PP, Phys. Rev. C 105,044305

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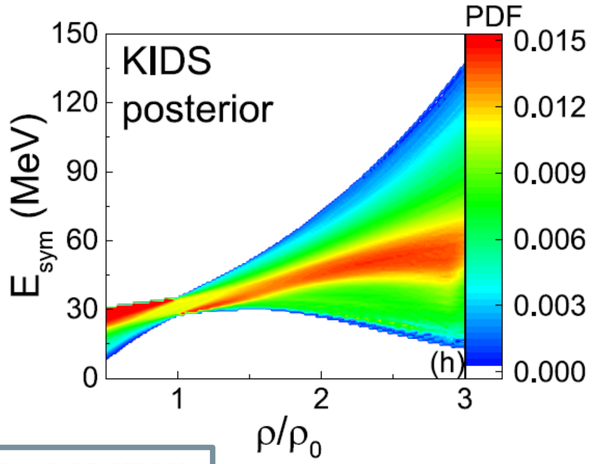


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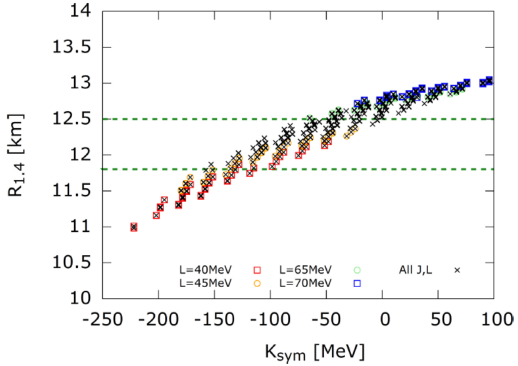


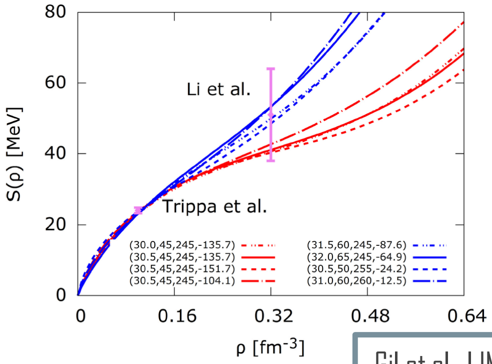


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