Nuclear Imprints on Neutron-Star Properties

A Universal-Relation Perspective

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Motivation

From nuclei to neutron stars

The nuclear EOS controls both finite nuclei and neutron-star matter.

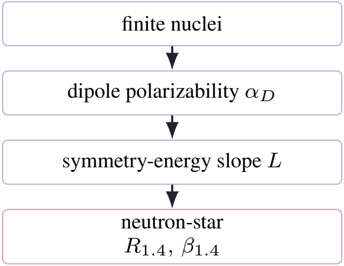
The isovector sector remains uncertain, especially the density dependence of the symmetry energy.

The electric dipole polarizability α_D probes neutron-rich dynamics in finite nuclei.

Neutron-star radii and compactness depend on the same symmetry-energy physics.

Central question

Can measured α_D values constrain neutron-star compactness and radius?



Universal relations link observables across nuclear and astrophysical scales.

Finite Nuclei – Neutron Stars

Finite nuclei

electric dipole polarizability

$$\alpha_D = \frac{8\pi e^2}{9} \int_0^\infty E^{-1} S(E1;E) dE$$

Measures the electric response of a nucleus.

Sensitive to isovector restoring force.

Experimental α_D values are available for selected nuclei.

Neutron stars

compactness

$$\beta = GM/Rc^2$$

Encodes the mass-to-radius ratio of the star.

Reflects the stiffness of the neutron-star EOS.

For $1.4\, M_\odot$, $\beta_{1.4}$ is directly linked to $R_{1.4}$.

larger $R_{1.4} \Leftrightarrow$ smaller $\beta_{1.4}$

Both quantities depend on the density dependence of the symmetry energy slope L

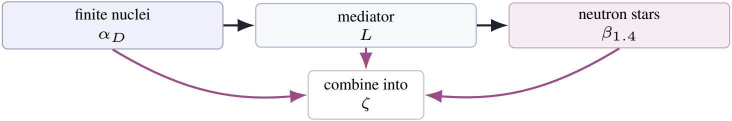
$$L = 3n_0 \left. \frac{\partial S(n)}{\partial n} \right|_{n_0}$$

α_D correlates directly with L

β reflects its influence via the neutron star radius

L acts as a natural mediator connecting nuclear and stellar properties

Universal Relation



$$\zeta(\alpha_D, A, \delta) = c_1(A) e^{-c_2(A)\alpha_D} + c_3(\delta)$$

Stellar–nuclear variable

$$\zeta = \beta_{1.4} \tilde{L}^{-1}$$

$$\beta_{1.4} = \frac{GM_{1.4}}{R_{1.4}c^2}, \qquad \tilde{L} = \frac{L}{100\ \text{MeV}}$$

$M_{1.4}$: mass at $1.4\ M_\odot$,

$R_{1.4}$: radius at $1.4\ M_\odot$,

L: slope of the symmetry energy at saturation.

Mass and isospin dependence

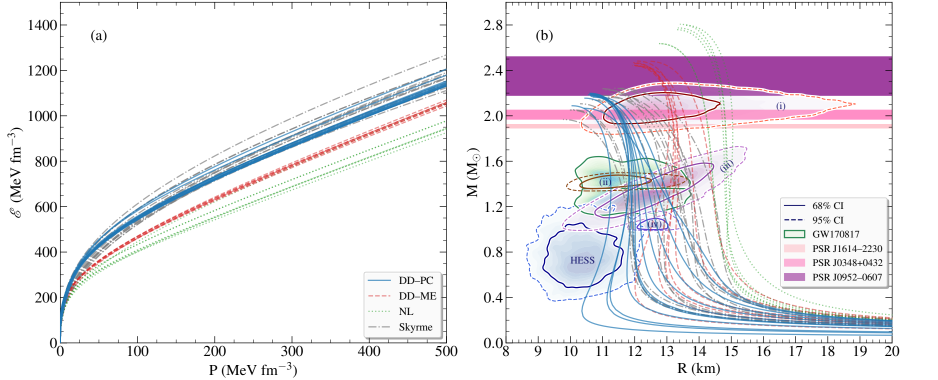
$$c_1(A) = \sum_{k=0}^{3} q_{1k} A^{-k},$$

$$c_2(A) = \sum_{k=0}^{3} q_{2k} A^{-k},$$

$$c_3(\delta) = \sum_{k=0}^{3} q_{3k} \delta^k, \qquad \delta = \frac{N - Z}{A}.$$

A^{-k} captures the smooth mass dependence of the nuclear response, while δ^k accounts for residual isospin effects; truncation at $k = 3$ balances accuracy and simplicity.

EOS Ensemble and Neutron-Star Properties

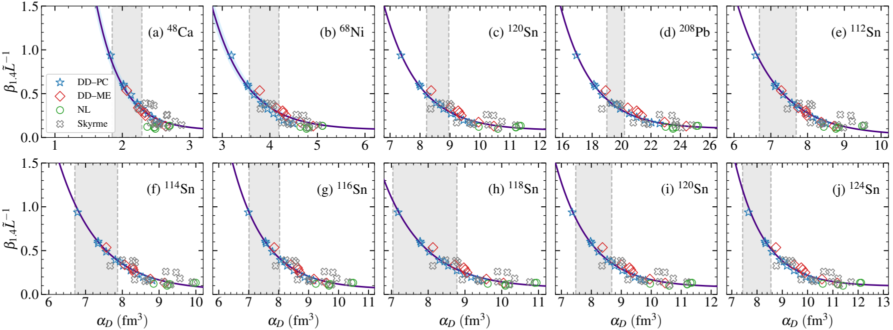


Total of 38 energy density functionals: 12 DD–PC, 7 DD–ME, 6 NL, 13 Skyrme.

EDF ensemble: $K = 211\text{–}356$ MeV, $J = 27\text{–}44$ MeV, $L = 19\text{–}140$ MeV.

Neutron-Star properties: $M_{\rm max} \geq 2\,M_\odot$, $R_{1.4} = 11\text{–}15$ km.

The broad spread in nuclear-matter parameters and radii provides a controlled test of the proposed finite-nucleus–neutron-star correlation.



Fitting properties

Training set: 14 nuclei from

Ca, Ni, Kr, Zr, Sn, Pb.

$A \simeq 48$–208 and $\delta \simeq 0.11$–0.33

Global regression quality: $R^2 \gtrsim 0.9$

Training nuclei: $^{48,54,60}\mathrm{Ca}$, $^{68,78}\mathrm{Ni}$, $^{86}\mathrm{Kr}$, $^{96}\mathrm{Zr}$, $^{112,114,116,118,120,124}\mathrm{Sn}$, $^{208}\mathrm{Pb}$.

Expansion coefficients

k	q_{1k}	q_{2k} (fm^{-3})	q_{3k}
0	5.558×10^3	-0.770	-0.257
1	-1.080×10^6	3.666×10^2	3.993
2	6.909×10^7	-2.749×10^4	-15.288
3	-1.432×10^9	8.540×10^5	20.714

Coefficients entering $c_1(A)$, $c_2(A)$, and $c_3(\delta)$.

Constraints from Experimental α_D Sets

CNSP–4

Nuclei: $^{48}\mathrm{Ca}$, $^{68}\mathrm{Ni}$, $^{120}\mathrm{Sn}$, $^{208}\mathrm{Pb}$

$$\zeta = 0.390 \pm 0.052$$

$$R_{1.4}L = 554.4 \pm 73.4 \text{ km MeV}$$

CNSP–10

Nuclei: CNSP–4 + $^{112\text{–}124}\mathrm{Sn}$

$$\zeta = 0.435 \pm 0.047$$

$$R_{1.4}L = 440.6 \pm 47.9 \text{ km MeV}$$

Including the Sn isotopic chain shifts the inferred ζ interval and tightens the constraint on $R_{1.4}L$.

The $R_{1.4}L$ is a criterion that any viable EOS should satisfy.

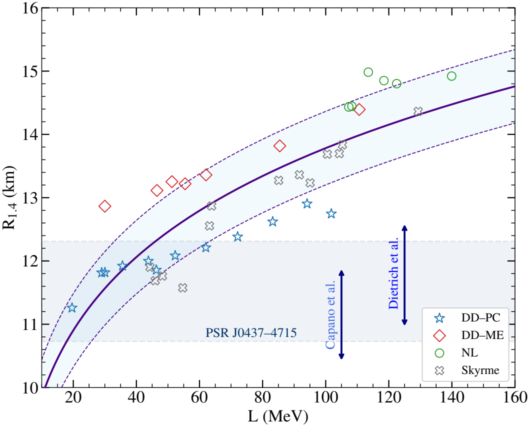
Radius–slope correlation

$$R_{1.4} = 7.049 \left(\frac{L}{\text{MeV}}\right)^{0.146} \pm 0.581\,\text{km}$$

L controls the pressure of neutron-rich matter around saturation.

Larger L generally implies larger $R_{1.4}$.

The EDF ensemble defines the baseline correlation.



Constraints in the $R_{1.4}$–L Plane

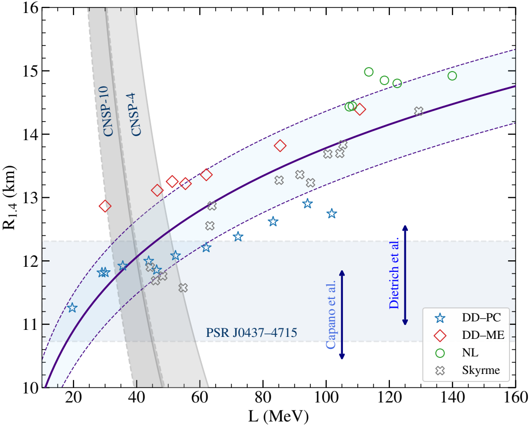
Radius–slope correlation

$$R_{1.4} = 7.049 \left(\frac{L}{\mathrm{MeV}}\right)^{0.146} \pm 0.581\ \mathrm{km}$$

L controls the pressure of neutron-rich matter around saturation.

Larger L generally implies larger $R_{1.4}$.

CNSP bands select the allowed $R_{1.4}$–L region.

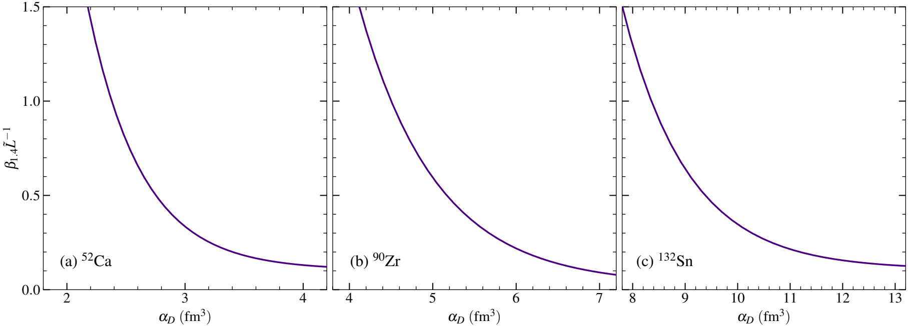


CNSP–4
$R_{1.4} = 12.06$–12.47 km, $L = 39.90$–50.34 MeV

CNSP–10
$R_{1.4} = 11.75$–12.08 km, $L = 33.42$–40.44 MeV

Predicting Dipole Polarizabilities

constrained ζ → invert universal relation → predict α_D



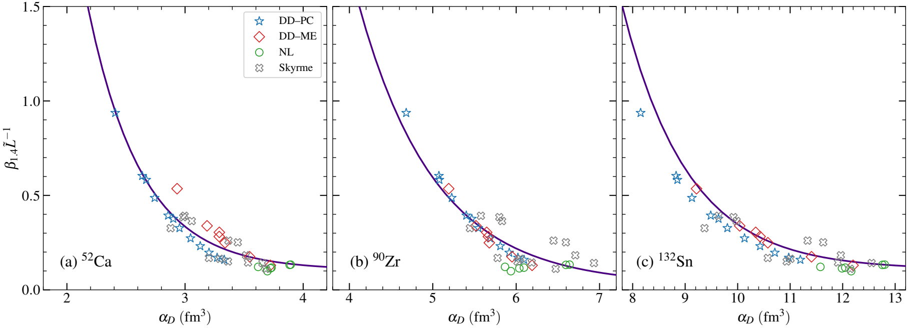
Why these nuclei?

They were not included in the fit and span different mass regions, shell structure, and isospin asymmetry.

Prediction targets

$^{52}\mathrm{Ca}$: neutron-rich, $N = 32$ subshell
$^{90}\mathrm{Zr}$: intermediate-mass benchmark
$^{132}\mathrm{Sn}$: neutron-rich, doubly magic

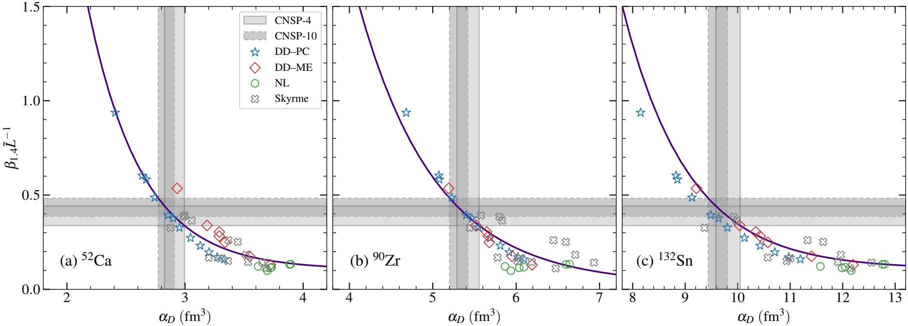
Predicting Dipole Polarizabilities



Microscopic EDF calculations are overlaid as a consistency check: the inverse prediction remains compatible with the model spread.

Predicting Dipole Polarizabilities

constrained ζ → invert universal relation → predict α_D



CNSP–4 predictions

Nucleus	α_D (fm^3)
^{52}Ca	2.91 ± 0.08
^{90}Zr	5.42 ± 0.13
^{132}Sn	9.82 ± 0.23

CNSP–10 predictions

Nucleus	α_D (fm^3)
^{52}Ca	2.84 ± 0.07
^{90}Zr	5.31 ± 0.11
^{132}Sn	9.62 ± 0.18

Predictions obtained by intersecting the CNSP ζ bands with the universal curves.

Conclusions

Finite nuclei

α_D probes the isovector response, neutron skin, and symmetry-energy dynamics.

Universal bridge

$$\alpha_D \Longleftrightarrow \zeta = \beta_{1.4} \tilde{L}^{-1}$$

The combined variable ζ reduces model dependence across EDFs.

Neutron stars

Measured α_D values constrain $R_{1.4}$, L, and $\beta_{1.4}$.

predict α_D for unexplored nuclei ⟷ translate nuclear data into neutron-star constraints

Future α_D measurements and improved astrophysical observations can further tighten constraints on the density dependence of the symmetry energy.

Thank you for your attention!

Questions?

Further information

P.S. Koliogiannis, T. Ghosh, E. Yüksel, and N. Paar, *Phys. Rev. C* **113**, 055809 (2026).

arXiv:2601.16894

Collaborators

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