Applications of Chiral Forces to Nuclear Matter and Neutron Stars

Christian Drischler
with K. Hebeler and A. Schwenk

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[Credit: ORNL]

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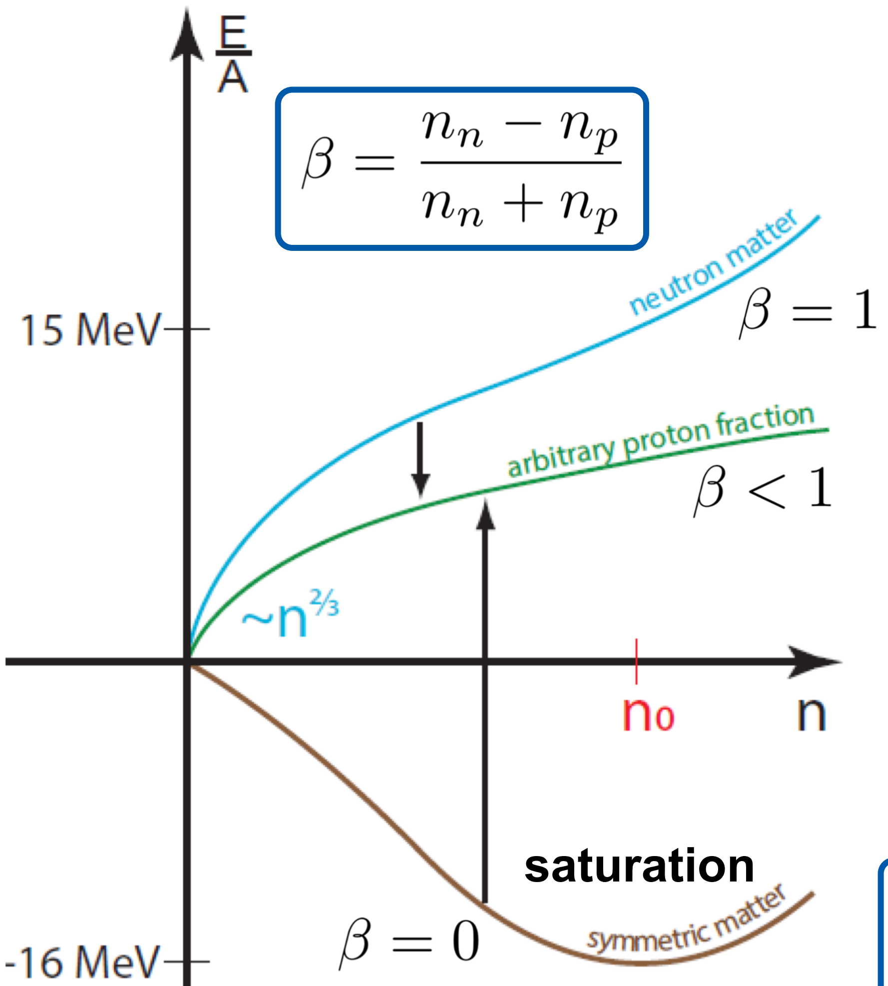
Homogeneous nuclear matter



- theoretical **testbed** for benchmarking nuclear forces
  - saturation point (n_0, a_v)
  - incompressibility (K)
  - symmetry energy (S_v) and its slope (L) at saturation density
- **many-body perturbation theory,** but also in QMC, CC, SCGF, …

for a recent review see:
Hebeler *et al.*, Annu. Rev. Nucl. Part. Sci. **65**, 457

Bethe–Weizsäcker formula

$$\frac{E}{A}(\beta, n) = \frac{E}{A}(\beta = 0, n) + \beta^2 E_{\text{sym}}(n)$$

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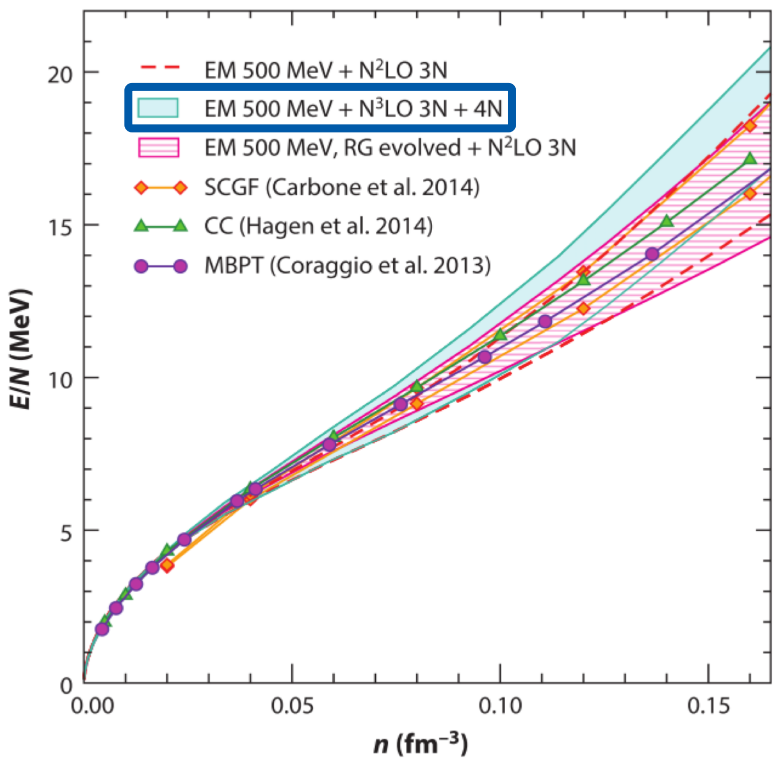
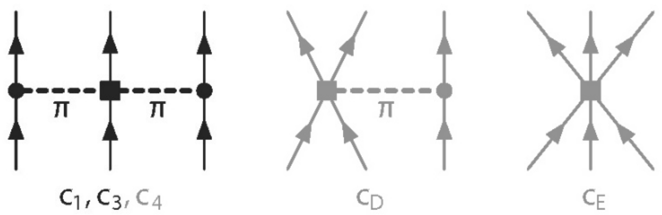
Neutron-matter EOS

Hebeler *et al.*, Annu. Rev. Nucl. Part. Sci. 65, 457

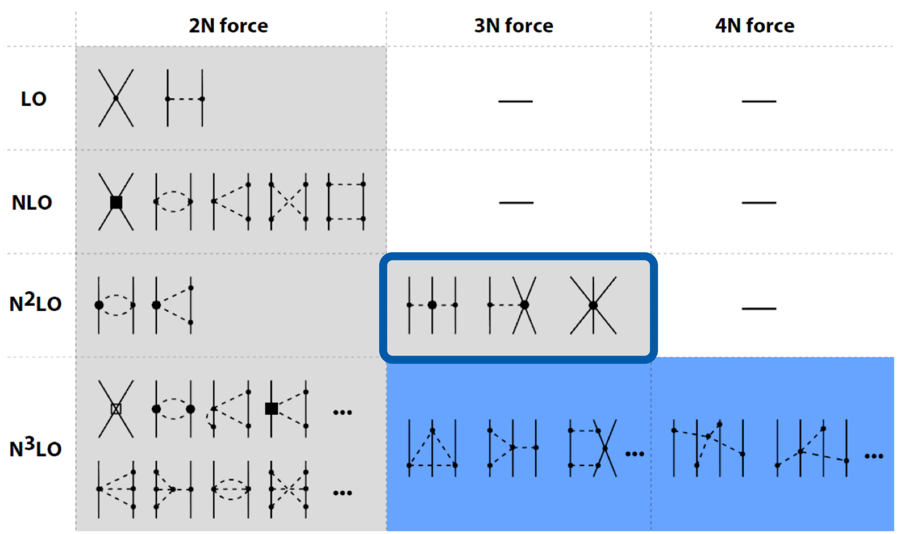


Remarkable agreement between **many-body frameworks** and **different Hamiltonians**

Leading 3N forces



Hierachy of chiral forces



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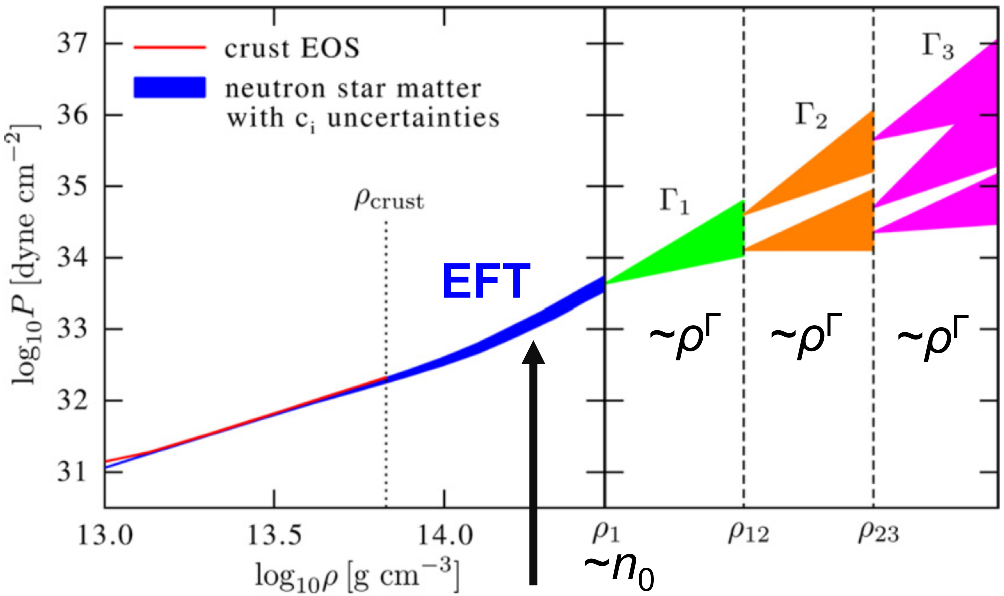
Mass–radius relation

Hebeler *et al.*, Astrophys. J. **773**, 11



Neutron matter extrapolated to β equilibrium

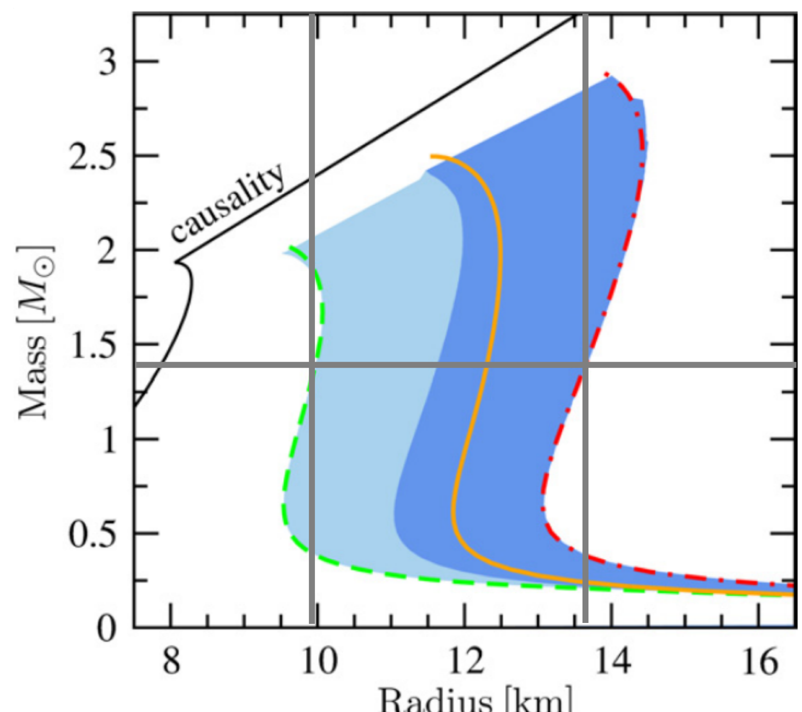
TOV eqs.

+ $M_{max} \geq 1.97\ M_{sun}$

+ causality

+ …

mass–radius relation



<u>Improvements needed:</u>

- calculate asym. matter directly
- higher orders in the **chiral** and **perturbative expansion**

for QMC, see: Gandolfi *et al.*, Phys. Rev. C **85**, 032801

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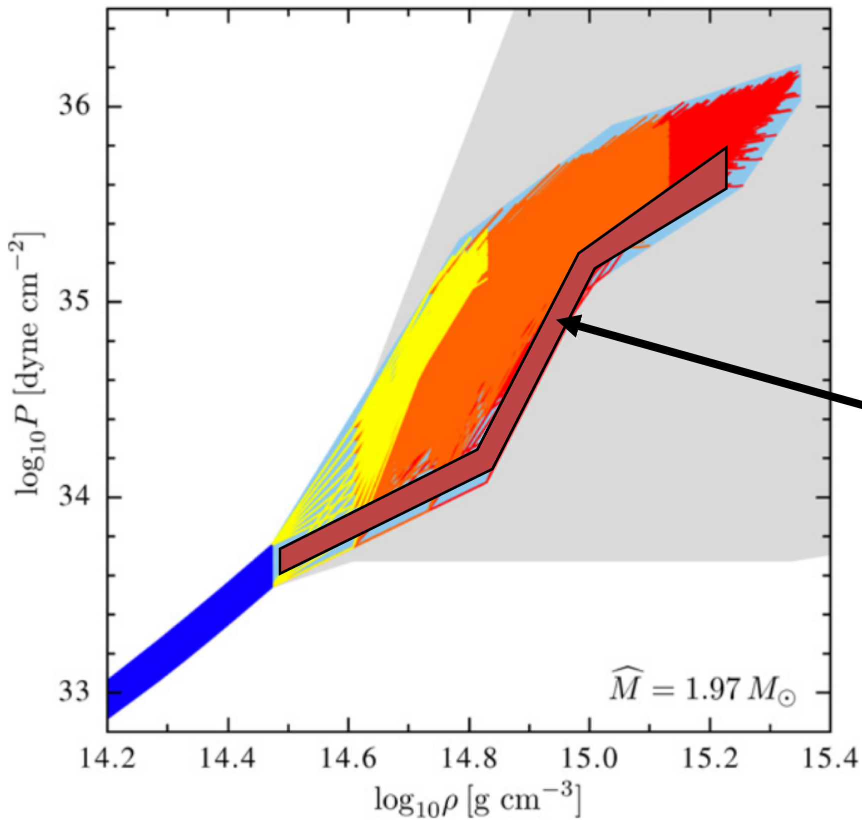
Mass–radius relation

Hebeler *et al.*, Astrophys. J. **773**, 11



TOV eqs.

+ $M_{max} \geq 1.97\ M_{sun}$

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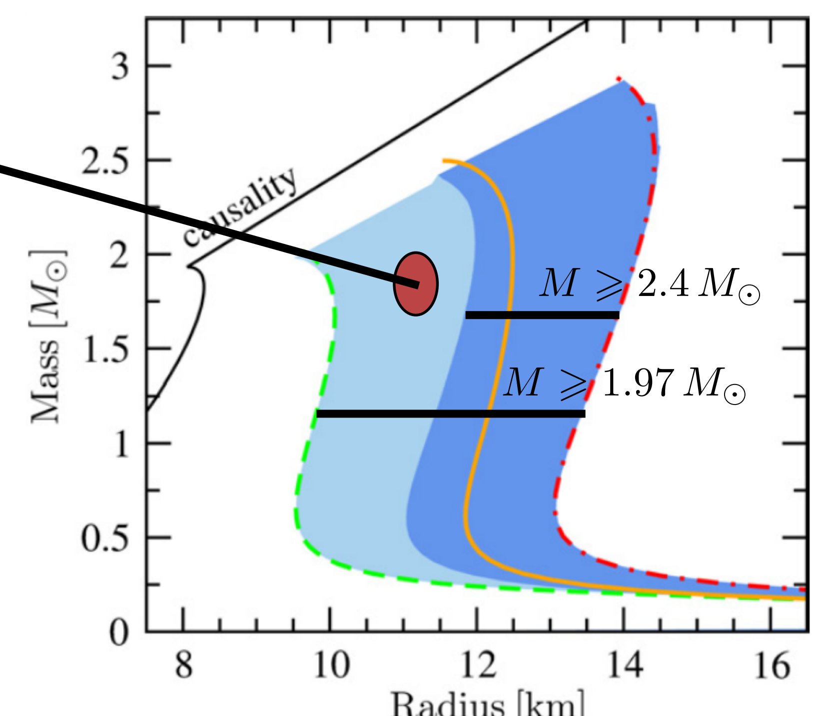

$$R_{1.4\,M_\odot} = 9.7 - 13.9\,\mathrm{km}$$

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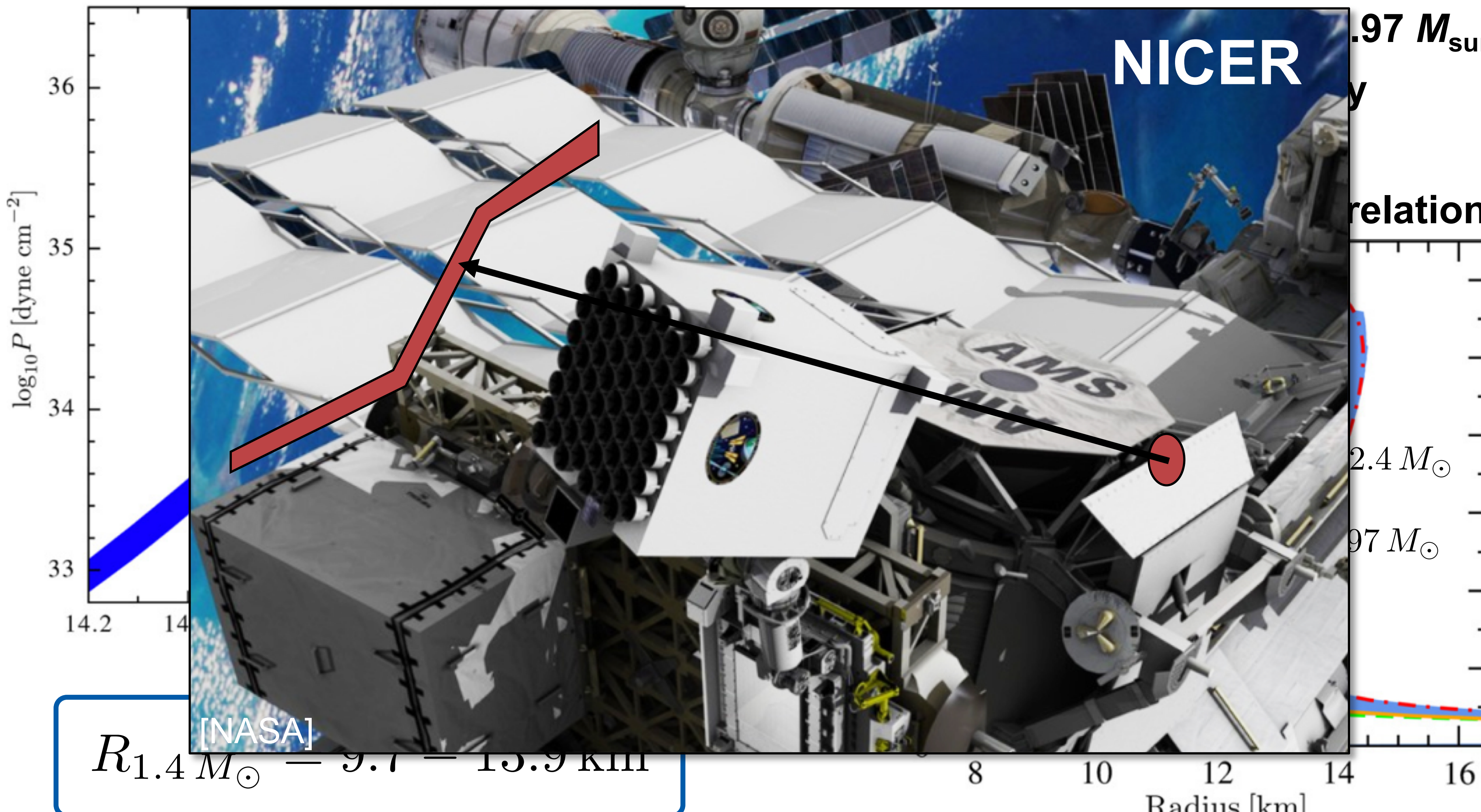
Mass–radius relation

Hebeler *et al.*, Astrophys. J. **773**, 11



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3N forces beyond Hartree-Fock?

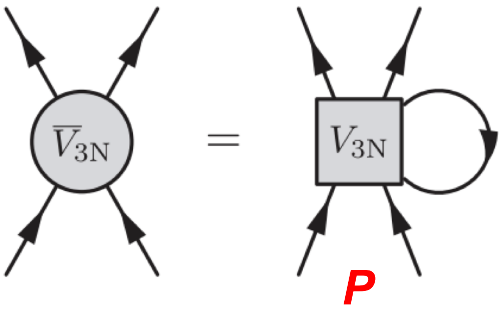
CD, Hebeler, Schwenk, Phys. Rev. C **93**, 054314

Effective NN potentials

by summing *one* particle over the occupied states of the Fermi sea

» dominant 3N contributions

Holt *et al.*, PRC **81**, 024002
Hebeler *et al.*, PRC **82**, 014314



some more applications:
Wellenhofer *et al.*, PRC **92**, 015801
Holt *et al.*, PPNP **73**, 35
Hebeler *et al.*, ARNPS **65**, 457
...

so far: only N^2LO 3N and ***P*** = 0

Improved method

- applicable to all nuclear forces
- N^3LO 3N forces due to recent partial-wave decomposition

Hebeler *et al.*, PRC **91**, 044001

towards *consistent* N^3LO calculations

Applications of Chiral Forces to Nuclear Matter and Neutron Stars

3N forces beyond Hartree-Fock?

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CD, Hebeler, Schwenk, Phys. Rev. C **93**, 054314

PHYSICAL REVIEW C **95**, 024302 (2017)

Pairing in neutron matter: New uncertainty estimates and three-body forces

C. Drischler,[1,2,*] T. Krüger,[1,2,†] K. Hebeler,[1,2,‡] and A. Schwenk[1,2,3,§]

[1]*Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany*

[2]*ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*

[3]*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*

Improved method

- applicable to all nuclear forces
- N^3LO 3N forces due to recent partial-wave decomposition

Hebeler *et al.*, PRC **91**, 044001

»

towards *consistent* N^3LO calculations

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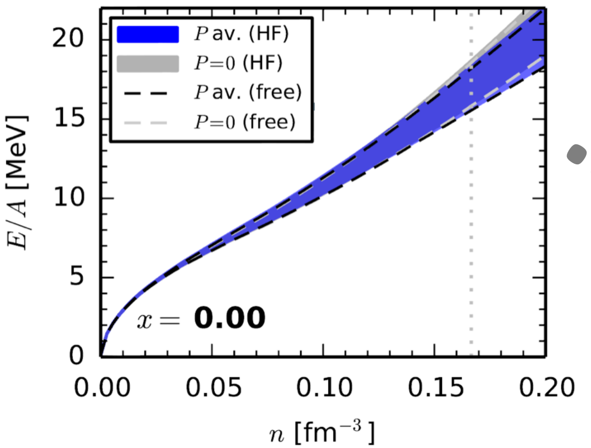
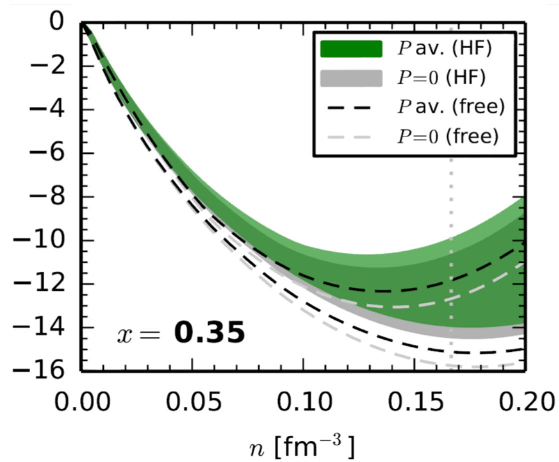
Equation of state

CD, Hebeler, Schwenk, Phys. Rev. C **93**, 054314



Neutron Matter



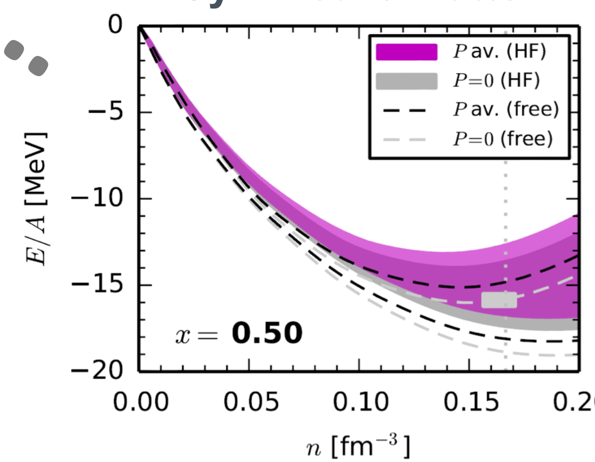
11 proton fractions

***x* = 0.0, 0.05, ..., 0.5**

up to second order

$$x = \frac{n_p}{n_n + n_p}$$

Symmetric Matter



Uncertainty bands: Hebeler *et al.*, PRC **83**, 031301

- 7 potentials: evolved N^{3}LO NN + bare N^{2}LO 3N
- different combinations of λ/Λ_{3N}
- c_D, c_E fit *only* to few-body data
- free and Hartree-Fock spectrum

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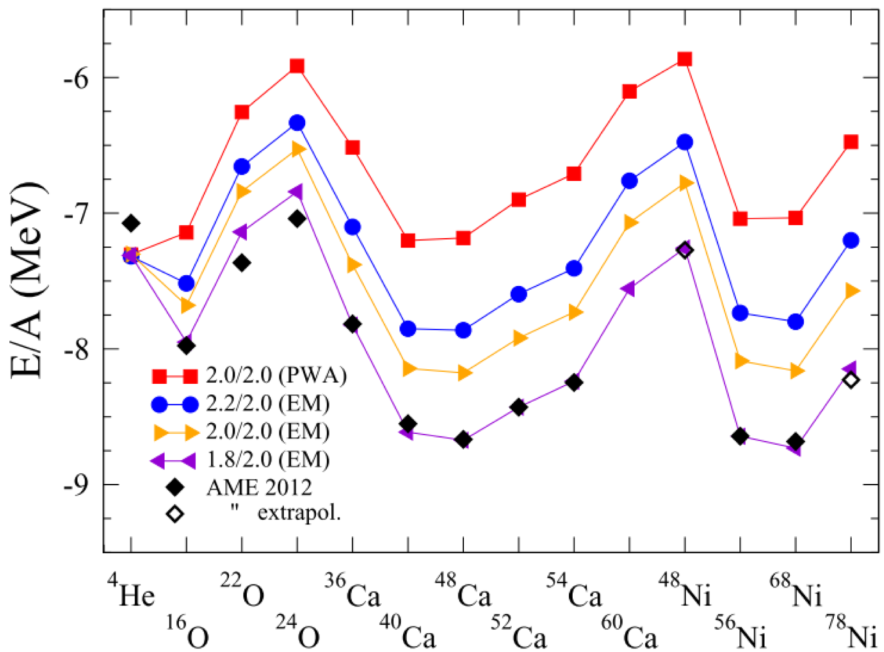
Guiding finite nuclei

Simonis *et al.*, Phys. Rev. C **96**, 014303

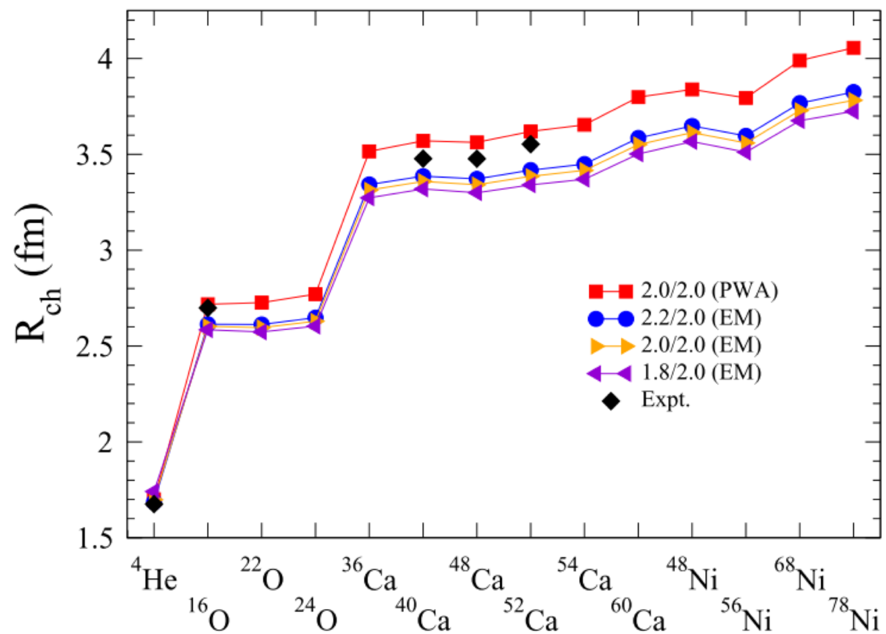
ground-state energies



"Hebeler *et al.*" interactions

- N^{3}LO NN (SRG) + N^{2}LO 3N forces
- c_D, c_E *only* fit to few-body data

charge radii



λ / Λ_{3N} = 1.8 / 2.0 (EM) exhibits good agreement with experiment

Hebeler *et al.*, PRC **83**, 031301

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Symmetry energy and slope parameter

quadratic expansion $\beta = 1 - 2x$

$$\frac{E}{A}(n,\beta) = \frac{E_{\rm SNM}(n)}{A} + S_2(n)\beta^2 + \ldots$$

$$S_2(n) = S_v + \frac{L}{3}\left(\frac{n-n_0}{n_0}\right) + \cdots$$

tight constraints

$$S_v = (30.9 \pm 1.4)\ \text{MeV}$$

$$L = (45.0 \pm 7.1)\ \text{MeV}$$

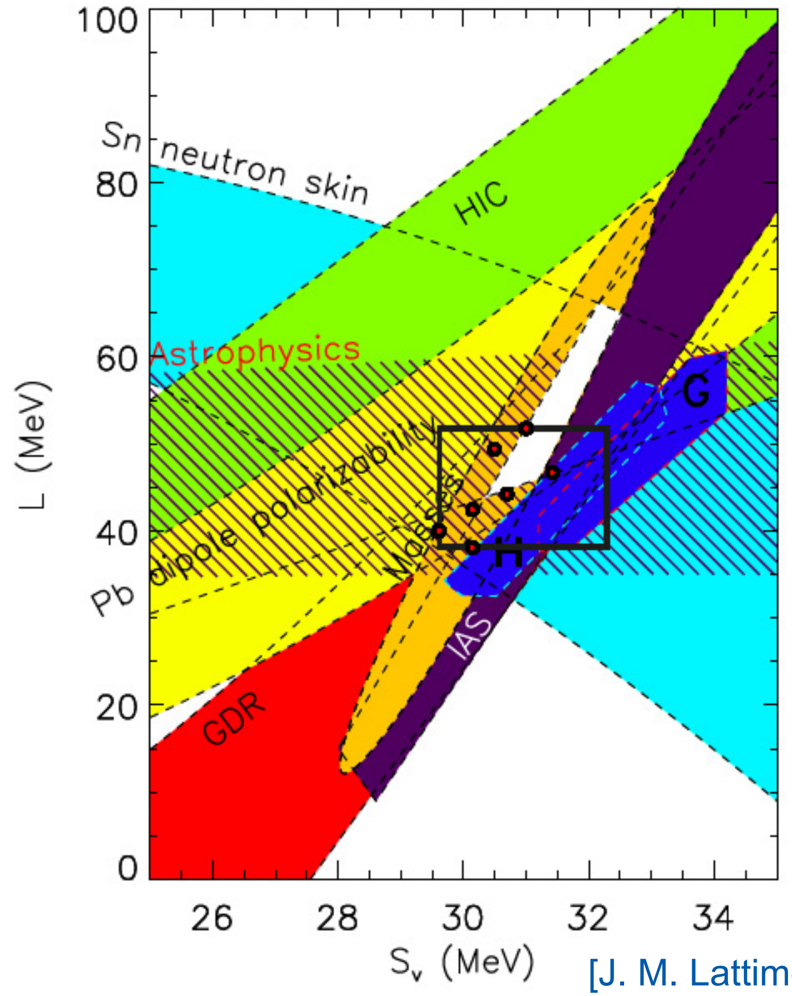
in **agreement** with quadratic expansion

Lattimer, Lim, Astrophys. J. **771**, 51

quadratic expansion is **reliable**; but nonanalytical quartic term: $\beta^4 \ln|\beta|$

Kaiser, PRC **91**, 065201

Wellenhofer *et al.*, PRC **93**, 055802



[J. M. Lattimer]

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Radius estimates for neutron stars

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Hagen *et al.*, Nat. Phys. **12**, 186

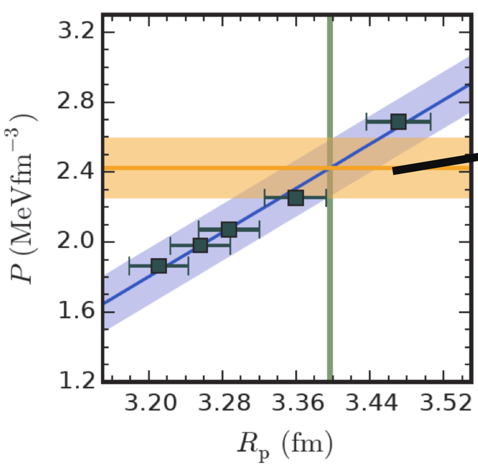
empirical relation by Lattimer & Prakash

$$P(\beta_{\mathrm{eq}},\, n_0) \simeq \frac{L}{3}\, n_0 \propto R^4_{1.4\,\mathrm{M}_\odot}$$

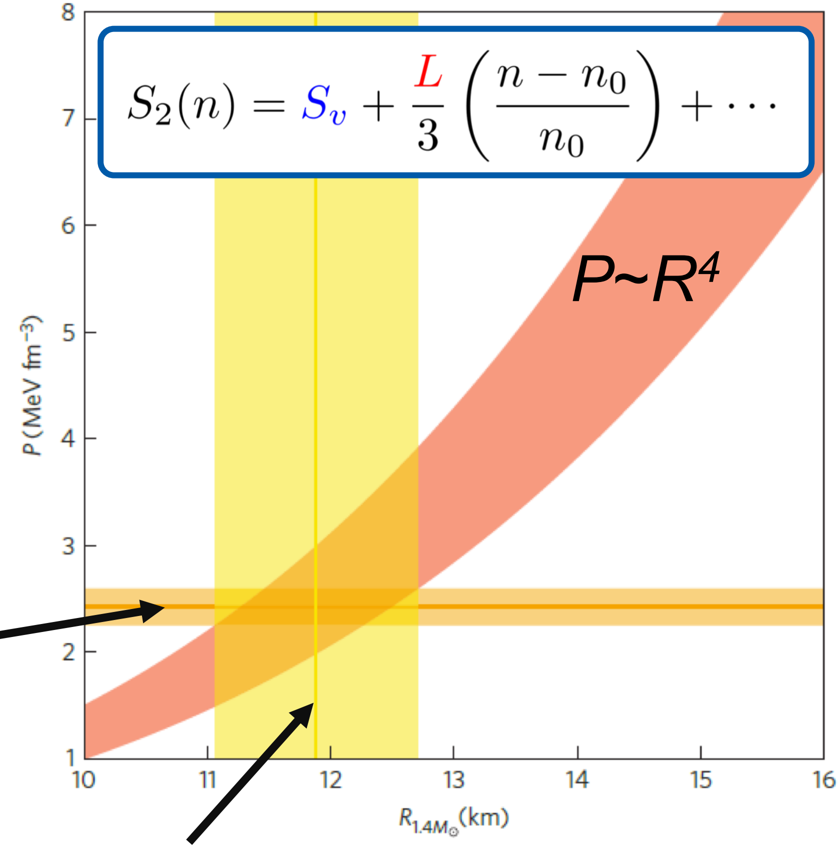
pressure of neutron-star matter

» **pin down *L* is important**

Pressure constrained by *ab initio* CC results for ^{48}Ca radii and measurement



$$S_2(n) = S_v + \frac{L}{3}\left(\frac{n - n_0}{n_0}\right) + \cdots$$



$$11.1\,\mathrm{km} \leqslant R_{1.4\,\mathrm{M}_\odot} \leqslant 12.7\,\mathrm{km}$$

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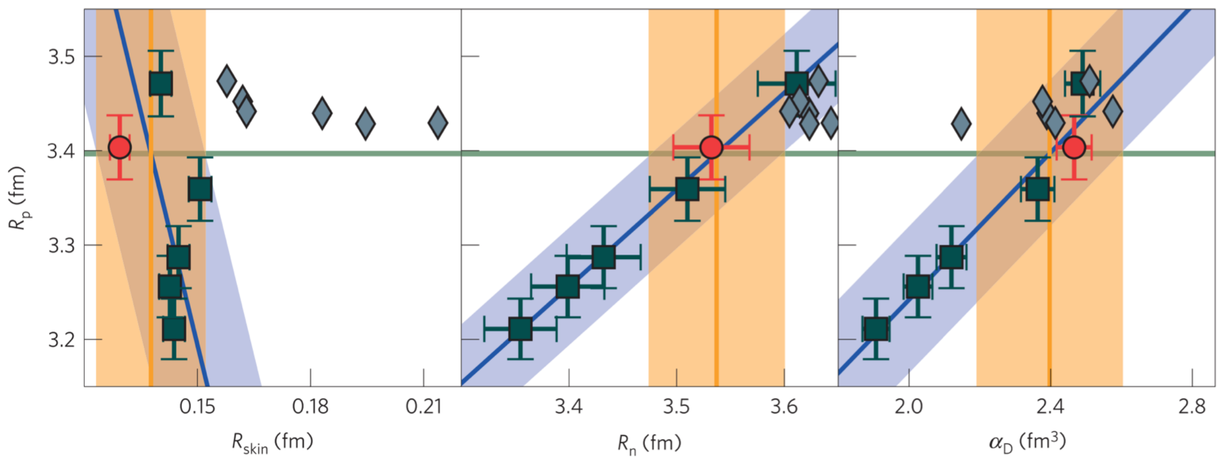
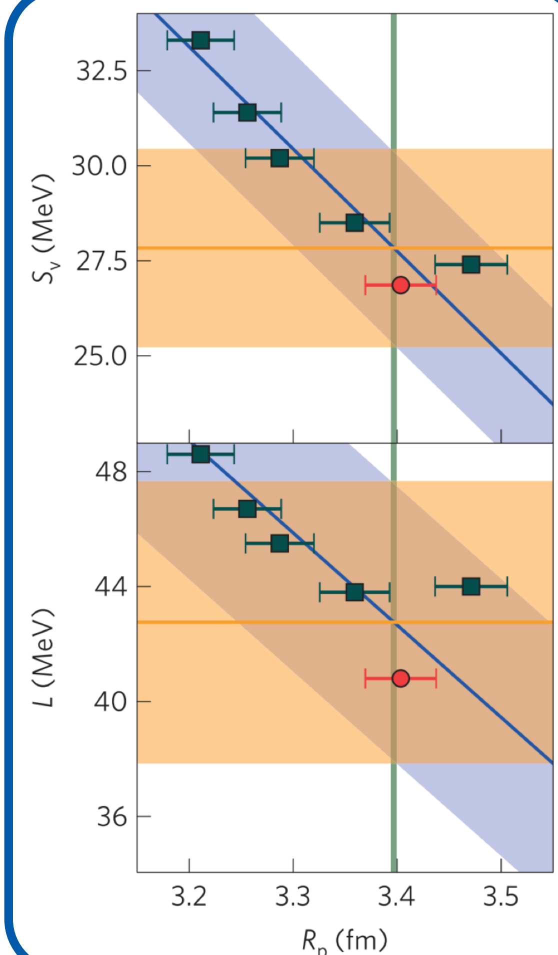
Constraints from ^{48}Ca calculations

Hagen *et al.*, Nat. Phys. **12**, 186





see also Birkhan *et al.*, PRL **118**, 252501

nature physics

ARTICLES

PUBLISHED ONLINE: 2 NOVEMBER 2015 | DOI: 10.1038/NPHYS3529

Neutron and weak-charge distributions of the ^{48}Ca nucleus

G. Hagen[1,2]*, A. Ekström[1,2], C. Forssén[1,2,3], G. R. Jansen[1,2], W. Nazarewicz[1,4,5], T. Papenbrock[1,2], K. A. Wendt[1,2], S. Bacca[6,7], N. Barnea[8], B. Carlsson[3], C. Drischler[9,10], K. Hebeler[9,10], M. Hjorth-Jensen[4,11], M. Miorelli[6,12], G. Orlandini[13,14], A. Schwenk[9,10] and J. Simonis[9,10]

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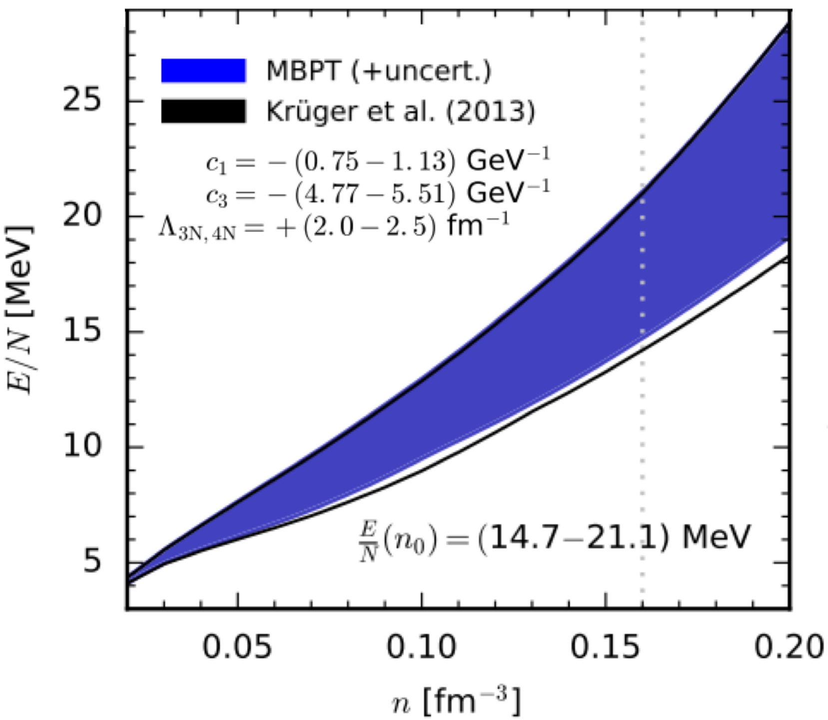
New mass–radius constraints

Most, Weih, Rezzolla, Schaffner-Bielich, arXiv:1803.00549

Neutron matter at full N³LO



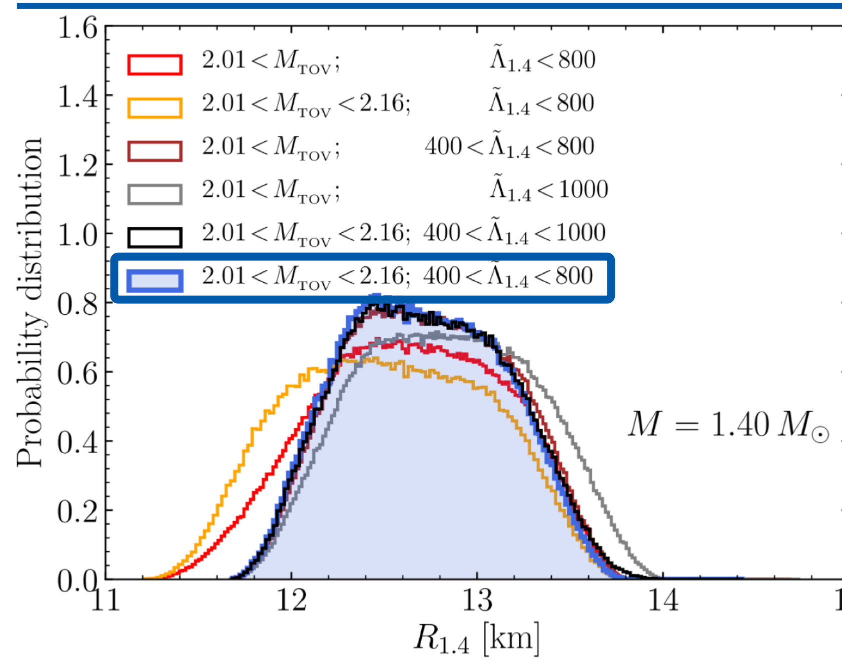
NN+3N contributions at **3rd order** and **4N Hartree-Fock energies**

CD, Carbone, Hebeler, Schwenk, PRC **94**, 054307

Agreement with our constraints

$$R_{1.4\,M_\odot} = 12.00 - 13.45\,\text{km}$$

Neutron-star radii



see also Annala *et al.*, PRL **120**, 172703

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Outlook

1. **Study asymmetric matter at full N^3LO**
   extract astrophysical quantities, mass-radius relations, …
2. **Explore finite temperatures**
   study thermal properties, single-particle energies, …
3. **Improve EFT uncertainty quantification**
   Bayesian inference, uncertainty propagation, …
4. **Tabulate the equation of state**
   make EOS accessible in astrophysical simulations, …

Collaborators:

K. Hebeler

K. McElvain

A. Schwenk

C. Wellenhofer

Thank you for your attention!

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