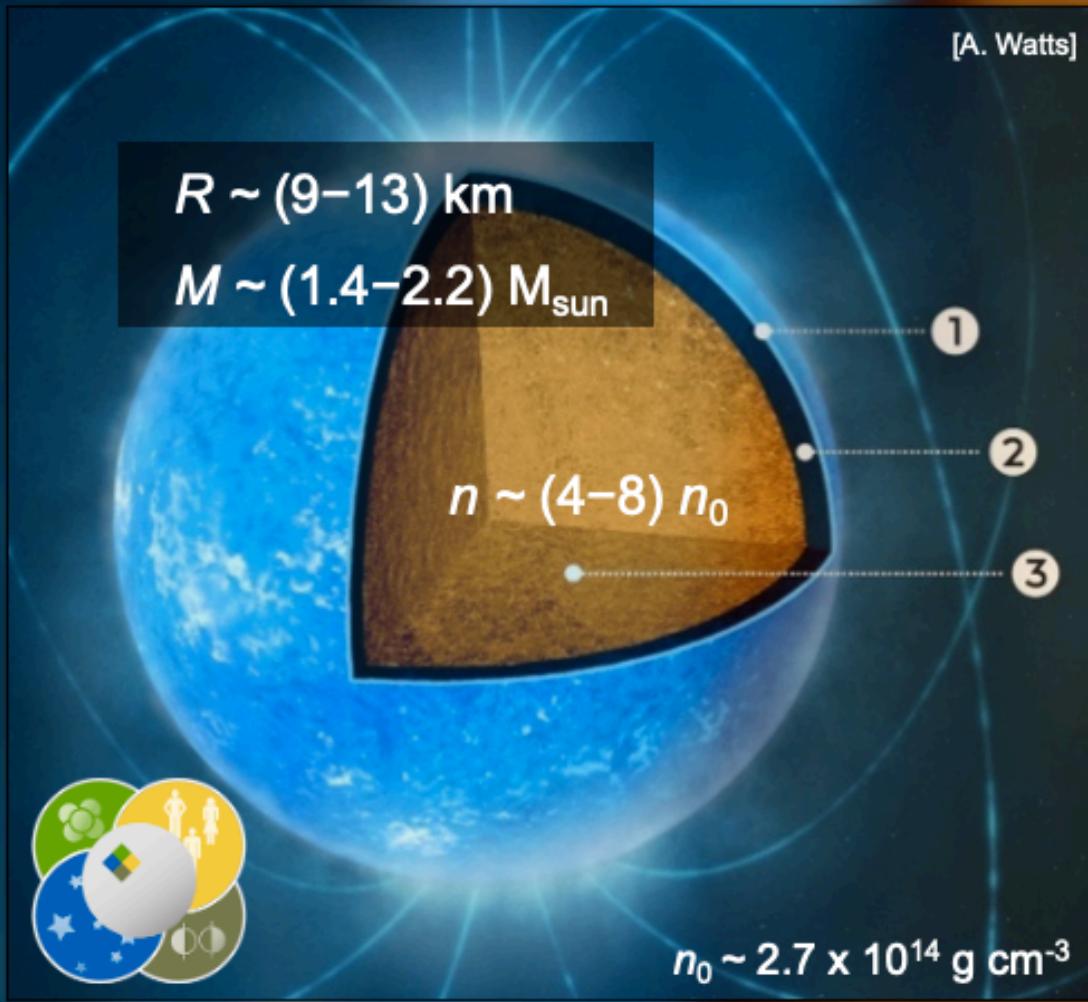


# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

MICHIGAN STATE  
UNIVERSITY

Christian Drischler

November 19, 2021 | The 10th International Workshop on Chiral Dynamics



## Keywords:

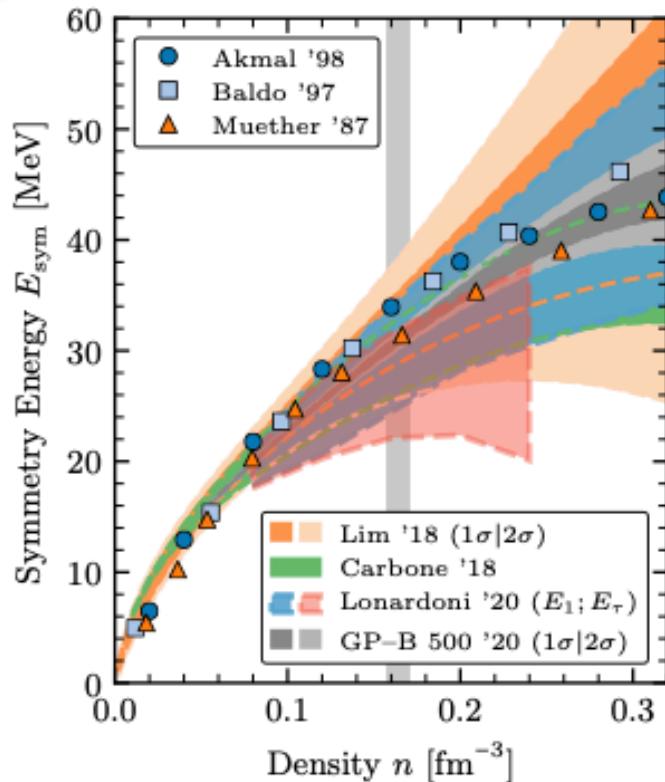
- + Chiral EFT
- + infinite nuclear matter
- + Bayesian UQ
- + symmetry energy
- + N<sup>3</sup>LO NN + 3N forces
- + nuclear saturation
- + ...

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

Recent review article

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CD, Holt, and Wellenhofer, ARNPS 71, 403



see also, e.g.:  
Tews, Front. in Phys. 8, 153



## Chiral Effective Field Theory and the High-Density Nuclear Equation of State

C. Drischler,<sup>1,2,3</sup> J. W. Holt,<sup>4</sup> and C. Wellenhofer,<sup>5,6</sup>

<sup>1</sup>Department of Physics, University of California, Berkeley, California 94720, USA

<sup>2</sup>Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

<sup>3</sup>Facility for Rare Isotope Beams, Michigan State University, Michigan 48824, USA; email: [drischler@frib.msu.edu](mailto:drischler@frib.msu.edu)

<sup>4</sup>Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA; email: [holt@physics.tamu.edu](mailto:holt@physics.tamu.edu)

<sup>5</sup>Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany; email: [wellenhofer@theorie.ikp.physik.tu-darmstadt.de](mailto:wellenhofer@theorie.ikp.physik.tu-darmstadt.de)

<sup>6</sup>ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany

invited contribution to Annu. Rev. Nucl. Part. Sci. 71, 403  
see also: Lattimer, Annu. Rev. Nucl. Part. Sci. 71, 433

Annu. Rev. Nucl. Part. Sci. 2021. 71:1–30

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[10.1146/annurev-nucl-102419-041903](https://doi.org/10.1146/annurev-nucl-102419-041903)

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Annu. Rev. Nucl. Part. Sci. in press.

### Keywords

chiral effective field theory, nuclear matter, neutron stars, many-body perturbation theory, bayesian uncertainty quantification

### Abstract

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

Multi-messenger astronomy

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[ligo.caltech.edu](http://ligo.caltech.edu)



- + Virgo
- + GEO600
- + KAGRA
- + ...

What is the secondary object  
in GW190425 and GW190814 ?

Binary neutron star merger  
GW170817

$$R_{1.4} \lesssim 13.6 \text{ km}$$

$$M_{\max} \lesssim 2.3 M_{\odot}$$

e.g., see:

Margalit, Metzger, APJ 850, 19

Rezzolla et. al., APJ 852, L25

De et al., PRL 121, 091102

Lim and Holt, EPJ A 55, 209

Capano et al., NA 4, 625

Al-Mamun et al., PRL 126, 061101

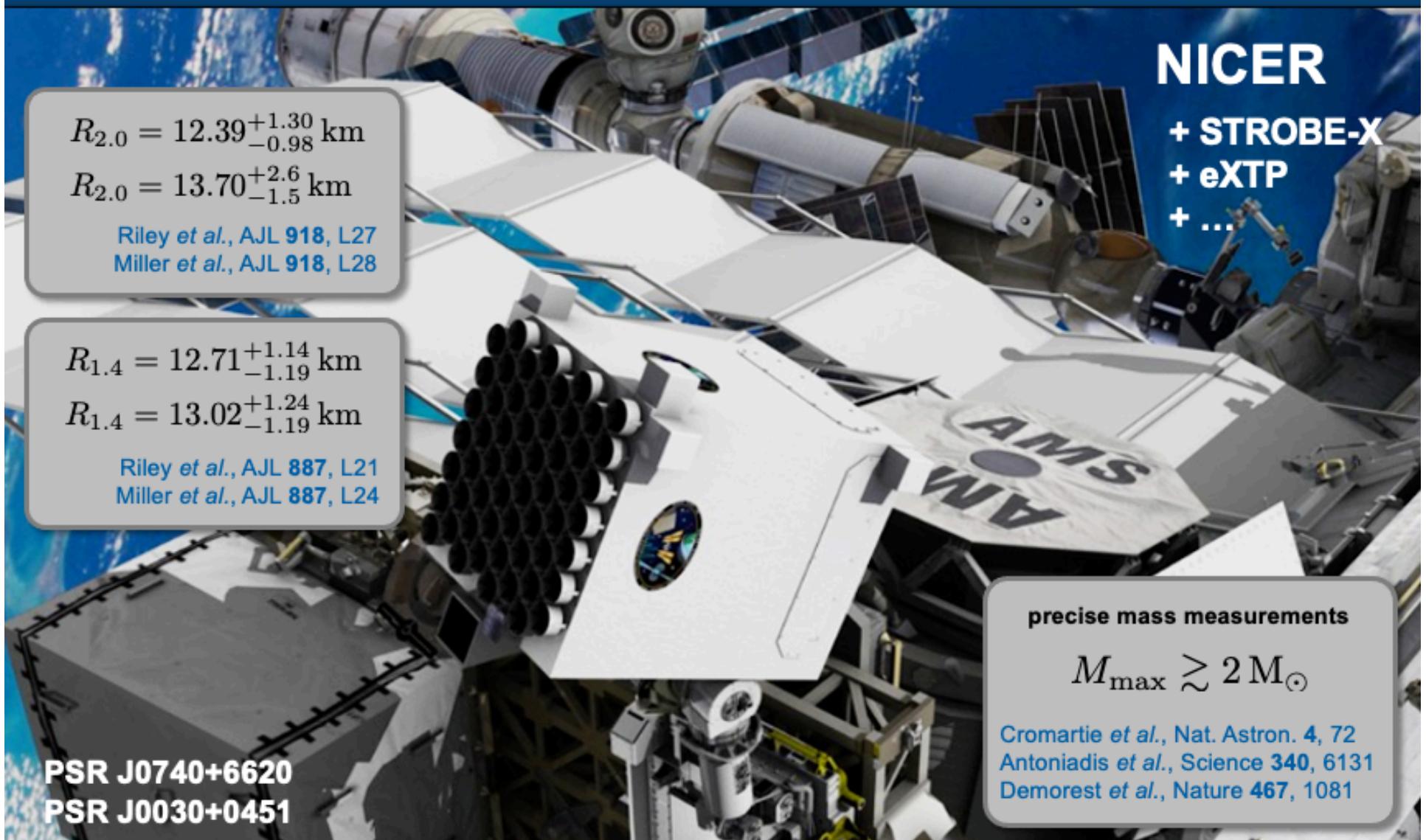
...

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

Recent neutron star observations

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NASA

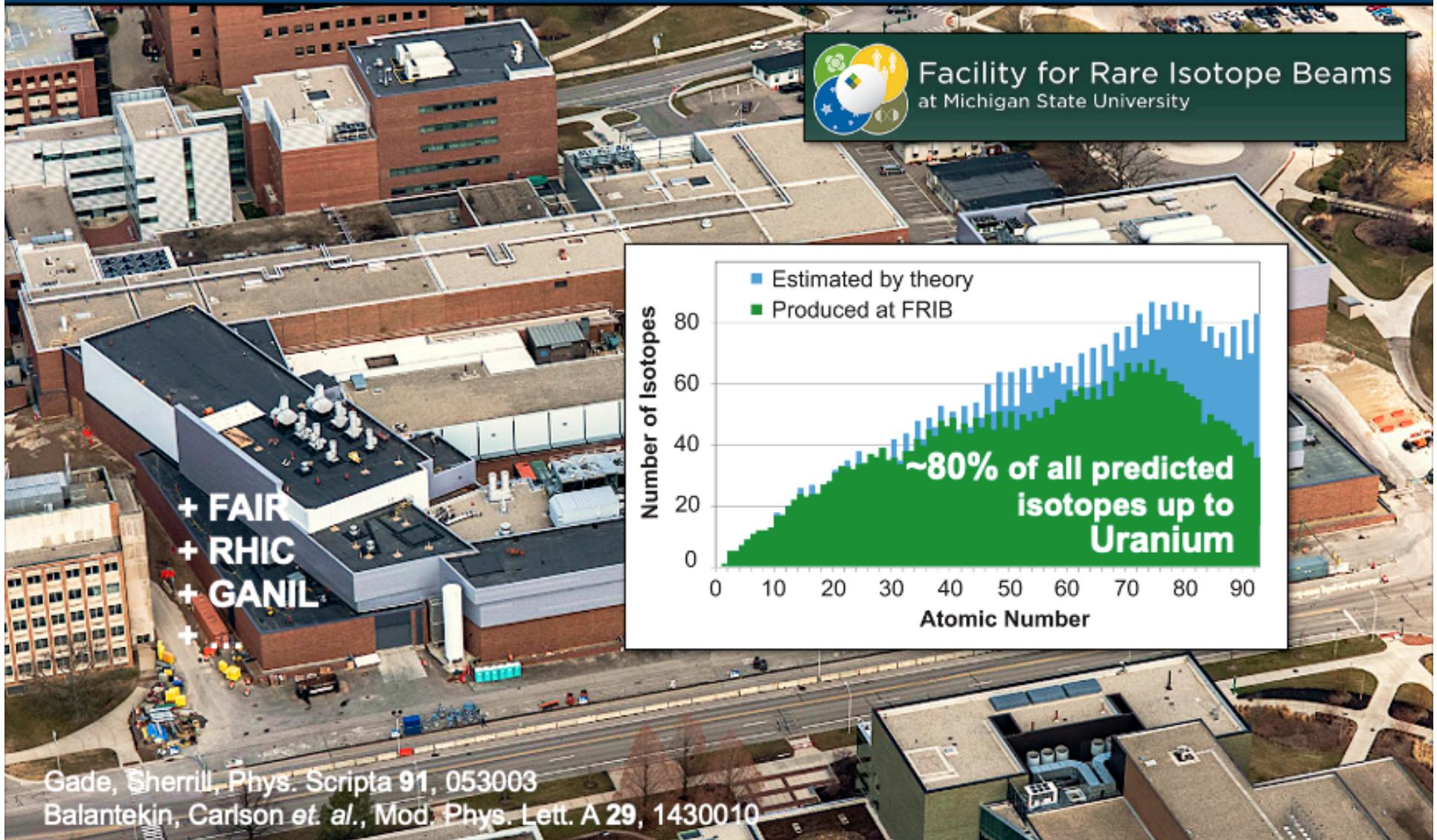


# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

Nuclear experiments: neutron-rich nuclei, collisions...

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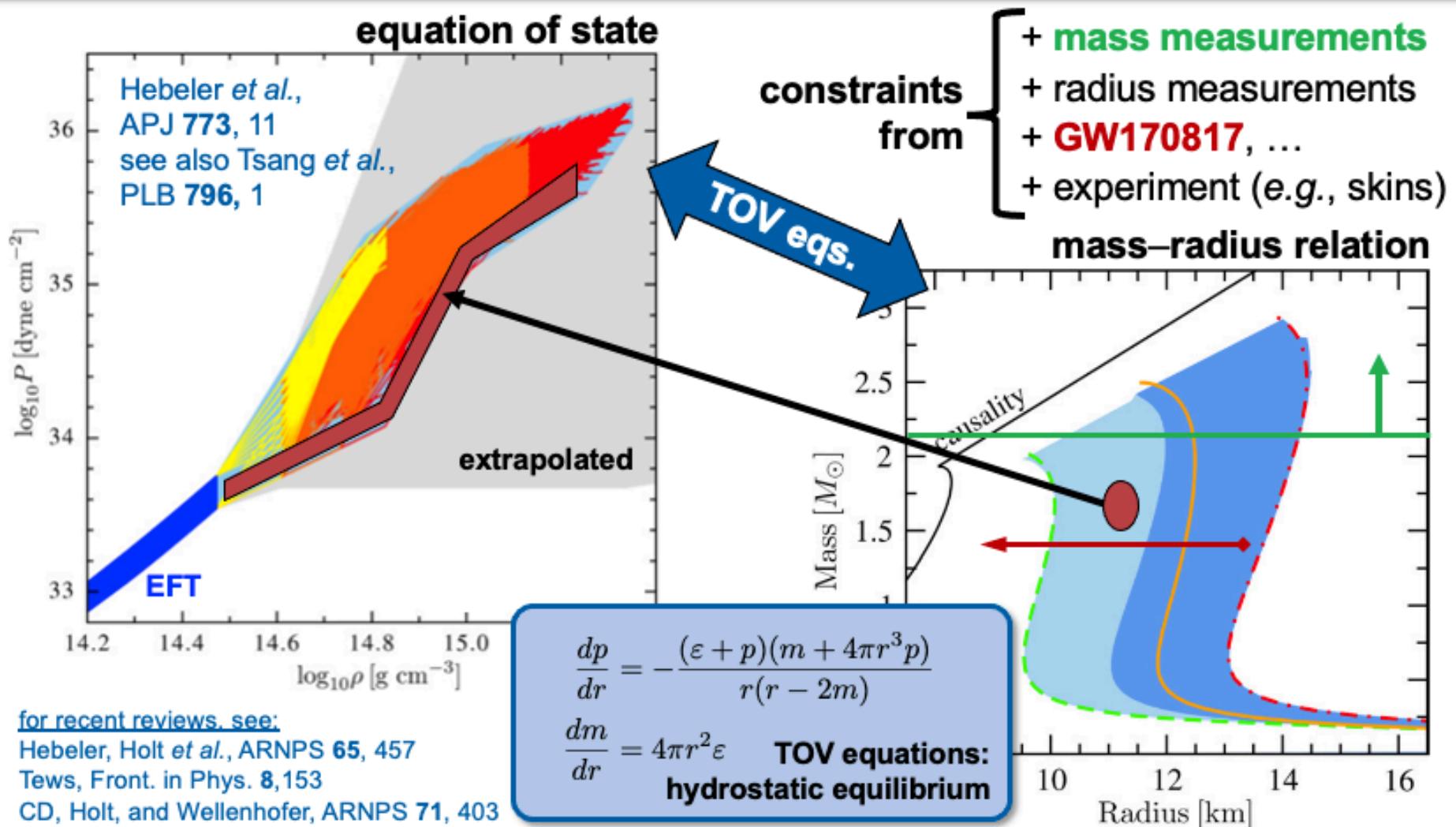
frib.msu.edu



# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

Direct correspondence:  $M$ – $R$  relation and EOS

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for recent reviews, see:

Hebeler, Holt *et al.*, ARNPS 65, 457

Tews, Front. in Phys. 8, 153

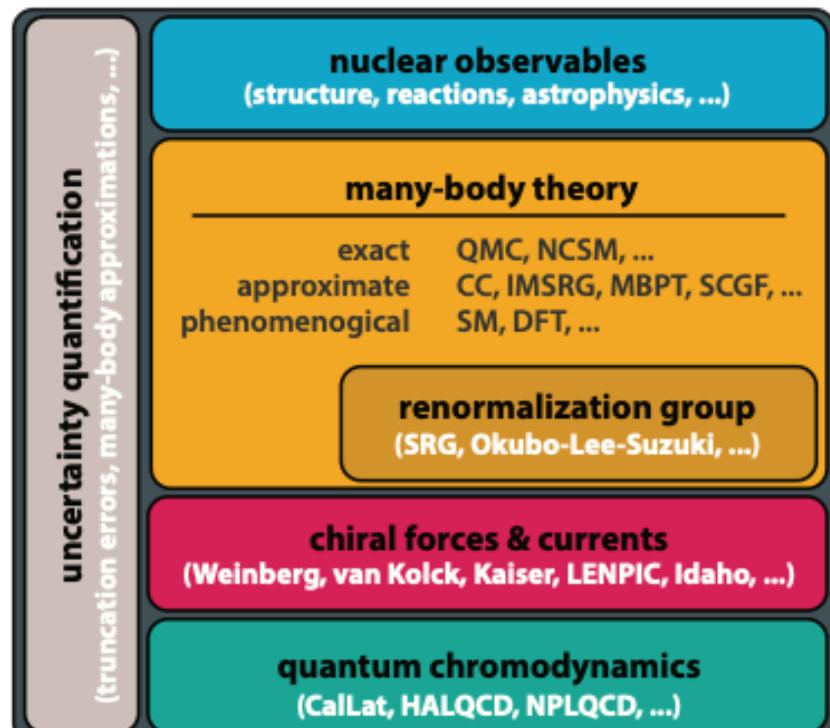
CD, Holt, and Wellenhofer, ARNPS 71, 403

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

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## Outline

### Ab initio workflow (idealized)



CD & Bogner, Few Body Syst. **62**, 109

**nuclear equation of state**  
neutron matter | symmetric matter  
nuclear symmetry energy

**many-body perturbation theory**  
computationally efficient  
asymmetric matter | finite temperatures  
many-body uncertainty estimates

**chiral effective field theory**  
systematic expansion of nuclear forces  
truncation error estimates

**see also Hermann Krebs's talk**  
*An overview of the recent and ongoing activities by the LENPIC*



# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

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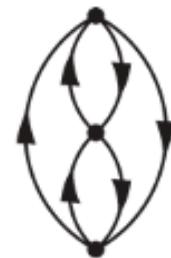
## Challenges

CD, Hebeler, Schwenk, PRL 122, 042501



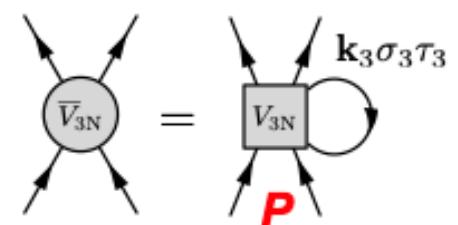
### Higher orders: particle-hole contributions

Coraggio *et al.*, PRC 89, 044321; Holt, Kaiser, PRC 95, 034326, ...



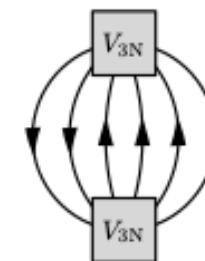
### No approximations for 3N normal ordering

CD *et al.*, PRC 93, 054314; Holt *et al.*, PRC 81, 024002, ...



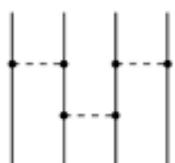
### Include residual 3N diagram(s)

Hagen *et al.*, PRC 89, 014319; Kaiser, EPJA 48, 58, ...



### Higher many-body forces

Epelbaum, PLB 639, 256, ...



see also Luca Girlanda's talk

3N interaction in pionless and pionfull EFT

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

Challenges are past!

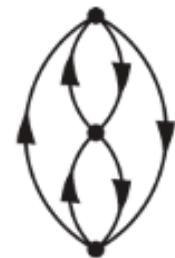
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CD, Hebeler, Schwenk, PRL 122, 042501



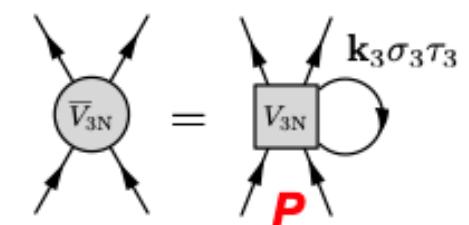
**Higher orders: particle-hole contributions**

Coraggio *et al.*, PRC 89, 044321; Holt, Kaiser, PRC 95, 034326, ...



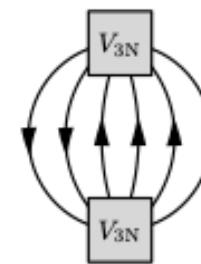
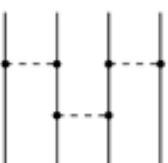
**No approximations for 3N normal ordering**

CD *et al.*, PRC 93, 054314; Holt *et al.*, PRC 81, 024002, ...



**Include residual 3N diagram(s)**

Hagen *et al.*, PRC 89, 014319; Kaiser, EPJA 48, 58, ...



**Higher many-body forces**

Epelbaum, PLB 639, 256, ...



**application of a novel  
Monte Carlo framework**

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

Efficient Monte Carlo framework

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CD, Hebeler, Schwenk, PRL 122, 042501



**efficient evaluation** of **MBPT diagrams**  
with **NN**, **3N**, and **4N forces** (single-particle basis)

- **implementing diagrams** has become **straightforward** (incl. particle-hole terms)
- multi-dimensional momentum integrals:  
(improved) VEGAS algorithm
- acceleration: openMP, MPI, and CUDA
- **controlled computation** of arbitrary interaction and many-body diagrams



**EOS up to  
high orders**



**automatic code  
generation**



**analytic form  
of diagrams/forces**

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

High-order MBPT

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Stevenson, Int. J. Mod. Phys. C 14, 1135

The number of diagrams increases rapidly!

**1, 3, 39, 840, 27 300, 1 232 280, ...**

$n =$     2            3            4            5            6            7

Integer sequence A064732:

Number of labeled Hugenholtz diagrams with  $n$  nodes.



ADG: Automated generation and evaluation of  
many-body diagrams I. Bogoliubov many-body  
perturbation theory

Pierre Arthuis, Thomas Duguet, Alexander Tichai, Raphaël-David Lasseri, Jean-Paul Ehran  
Comput. Phys. 240, 202

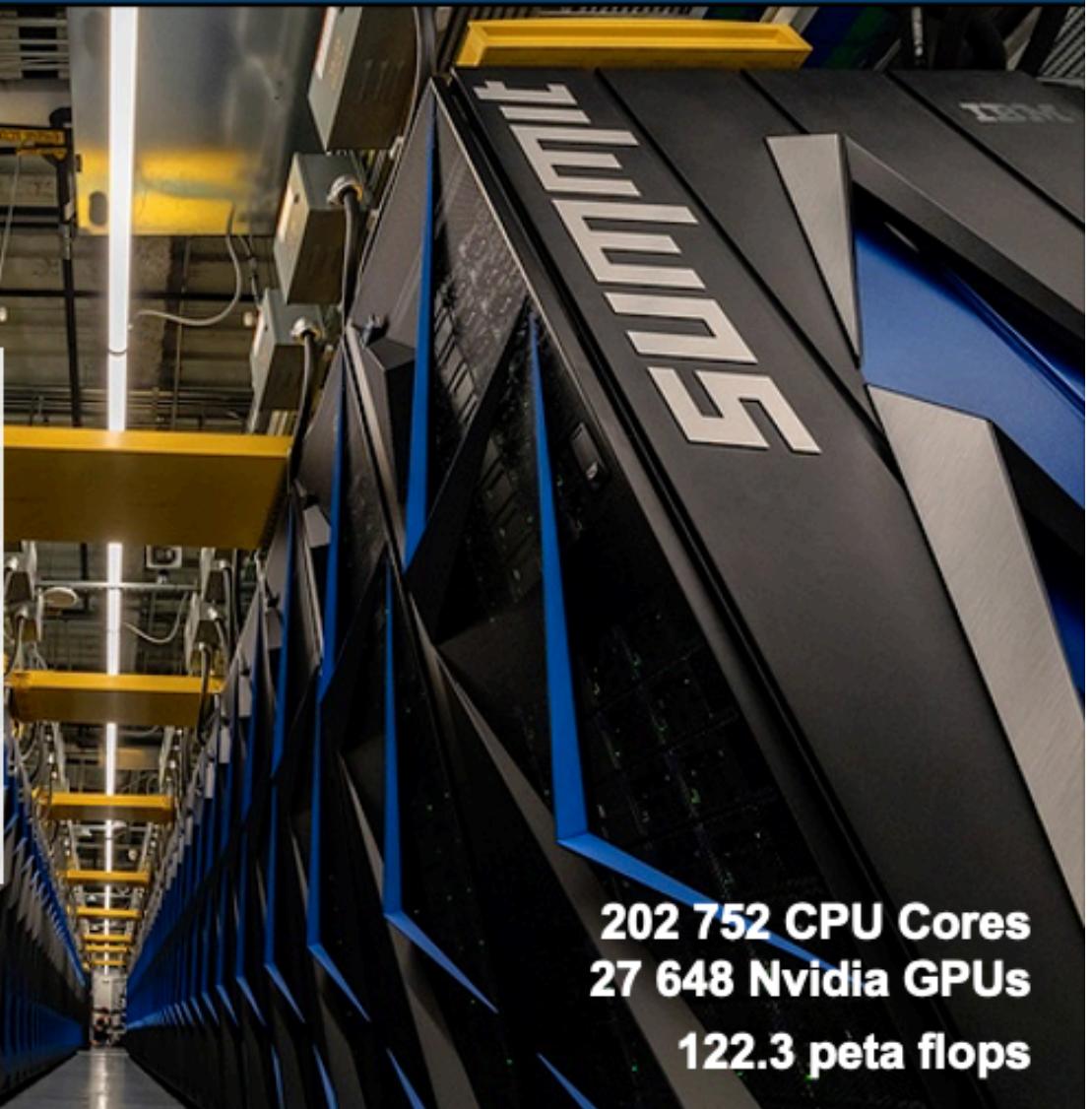
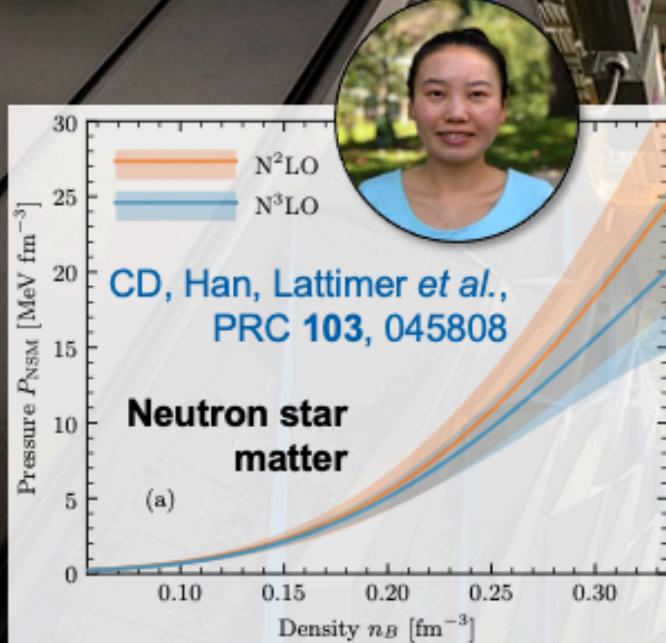
fully automated  
approach to MBPT

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

New algorithms and high-performance computing

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#1 (U.S.)



Summit @ Oak Ridge

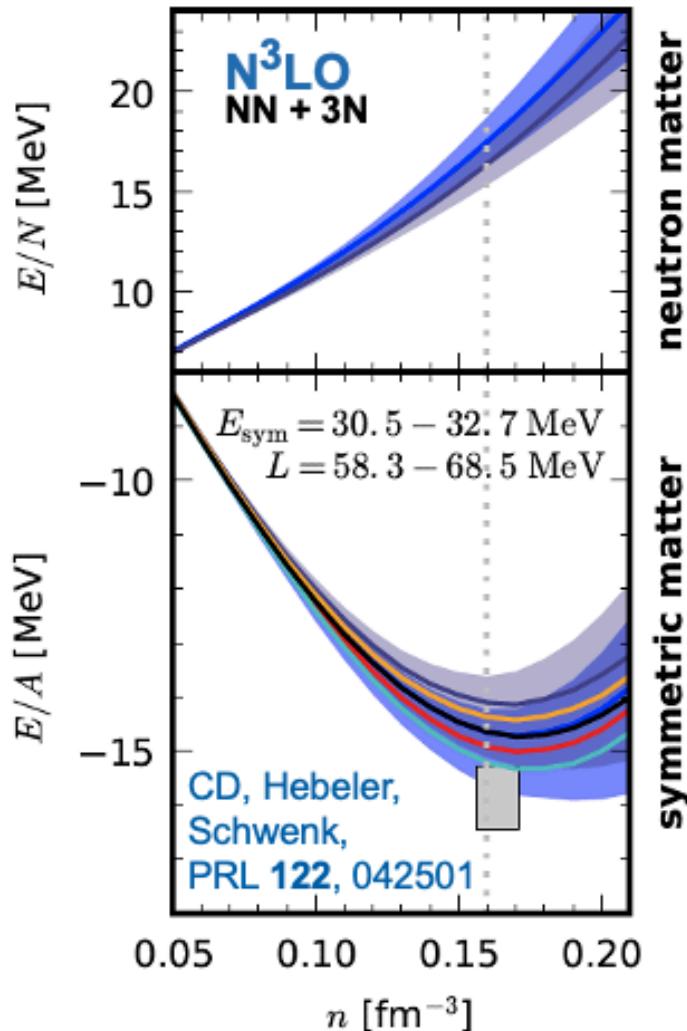
202 752 CPU Cores  
27 648 Nvidia GPUs  
122.3 peta flops

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

Nuclear matter calculations

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see also: Ekström *et al.*, PRC 91, 051301



**MBPT(4) with order-by-order chiral interactions up to N<sup>3</sup>LO**

Entem, Machleidt, Nosyk, PRC 96, 024004

**Bands: standard EFT uncertainty**

Epelbaum, Krebs, and Mei  ner, PRL 115, 122301

Epelbaum, Krebs, and Mei  ner, EPJA 51, 53

**3N forces ( $c_D$ ,  $c_E$ ) constrained by:**

- the triton binding energy
- empirical saturation properties

Hoppe, CD, Hebeler *et al.*, PRC 100, 024318

$\Lambda/c_D$ [MeV]/[1]	
450/2.25	500/-1.75
450/2.50	500/-1.50
450/2.75	500/-1.25

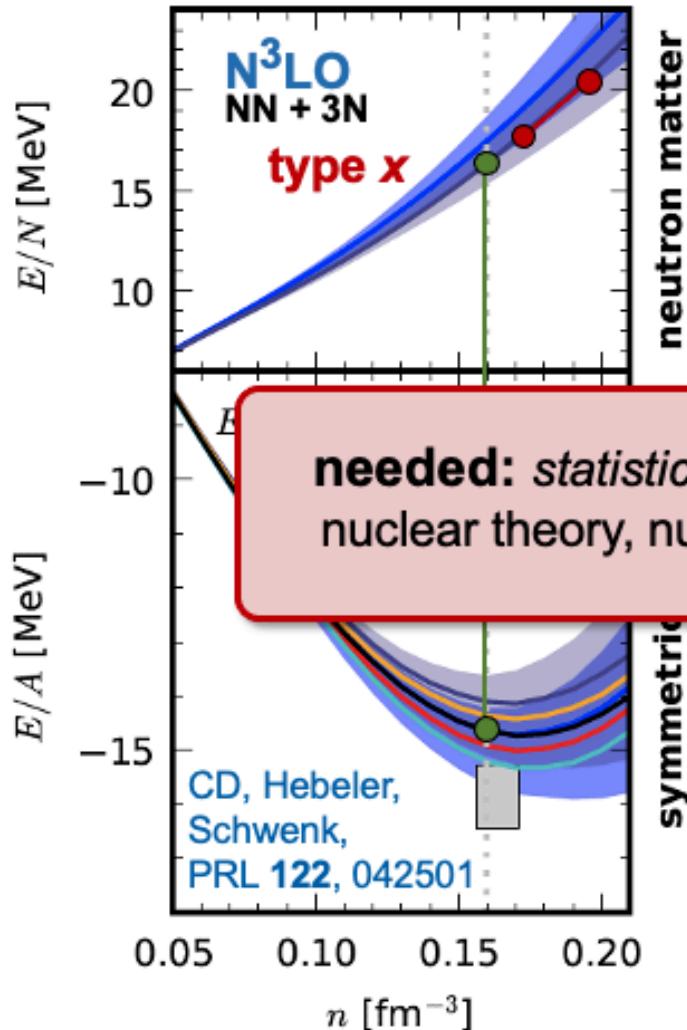
$\Lambda/c_D$ [MeV]/[1]	
450/0.00	500/-3.00
450/0.25	500/-2.75
450/0.50	500/-2.50

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

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## Nuclear matter calculations

e.g., Hebeler, Holt et al., ARNP 65, 457



**great progress** in predicting the **EOS** of infinite matter and the structure of **neutron stars** at densities  $\lesssim 2n_0$

Hebeler, Lattimer et al., APH773, 11

Carbone, Rios et al., PRO

Hagen, Papenbrock et al. PRX

Coraggio, Holt et al. PR



Lonardoni, Tews et al., PRR

Piarulli, Bombaci et al., PRC 107, 081101

• • •

**But:** existing predictions **only** provided **rough estimates** for the with-density-growing **EFT truncation error**, and did *not* account for **correlations**

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

New framework for UQ of EFT calculations

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[buqeye.github.io](https://buqeye.github.io)



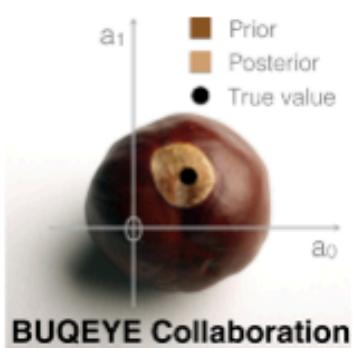
## CD, Furnstahl, Melendez, and Phillips

*How well do we know the neutron-matter equation of state at the densities inside neutron stars? A Bayesian approach with correlated uncertainties, PRL 125, 202702*

## CD, Melendez, Furnstahl, and Phillips

*Effective Field Theory Convergence Pattern of Infinite Nuclear Matter, PRC 102, 054315*

See also: Melendez et al., PRC 100, 044001  
Wesolowski et al., JPG 43, 074001



Bayesian  
Uncertainty  
Quantification:  
Errors for  
Your  
EFT

UQ framework available at  
<https://buqeye.github.io>

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

New framework for UQ of EFT calculations

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[buqeye.github.io](https://buqeye.github.io)



## CD, Furnstahl, Melendez, and Phillips

How well do we know the neutron matter

equa  
stars  
uncer

Correlated EFT truncation errors are important!  
statistically robust uncertainty estimates  
for key quantities of neutron stars

CD,

BUQEYE Collaboration

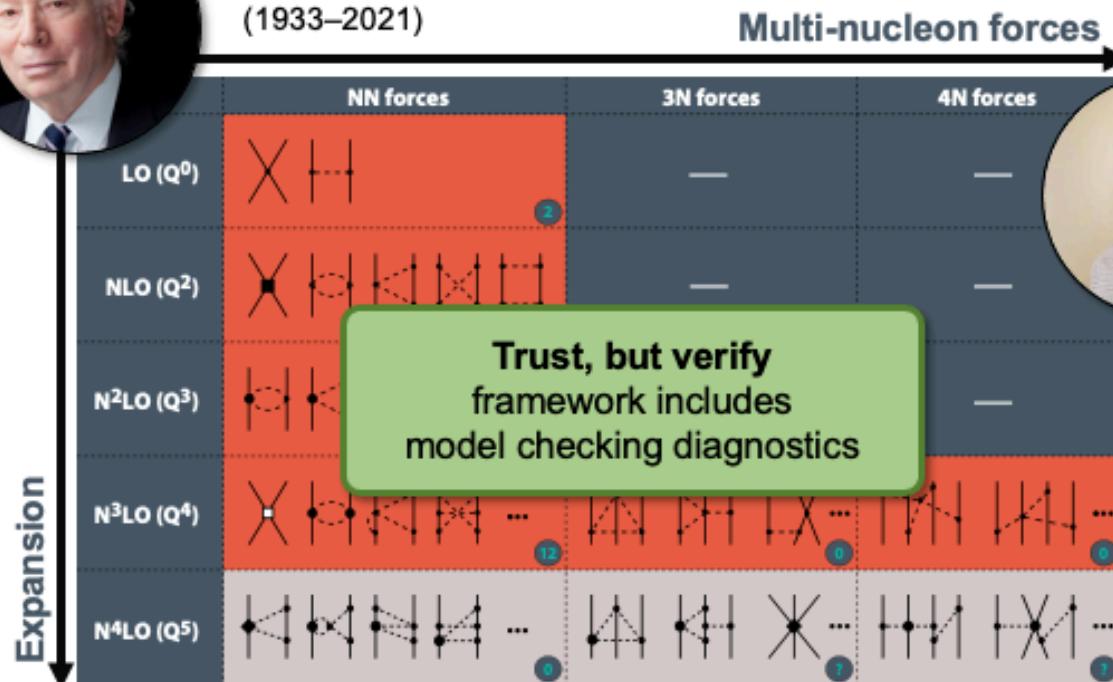
Effective Field Theory Convergence Pattern of  
Infinite Nuclear Matter, PRC **102**, 054315

See also: Melendez et al., PRC **100**, 044001  
Wesolowski et al., JPG **43**, 074001

UQ framework available at  
<https://buqeye.github.io>



S. Weinberg  
(1933–2021)



Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum,  
Kaiser, Krebs, Machleidt, Meißner, ...

For example:  $y_k = E/A$  in SNM at chiral order  $k$

**predict observable  $y_k$   
order by order in EFT**

$$y_k = y_{\text{ref}} \sum_{n=0}^k c_n Q^n$$

$c_n$  are not the EFT's LEC

**treat all  $c_n$  as  
independent draws from  
a Gaussian Process**

**learn GP's hyperparameters  
& infer EFT truncation error**

$$\delta y_k = y_{\text{ref}} \sum_{n=k+1}^{\infty} c_n Q^n$$

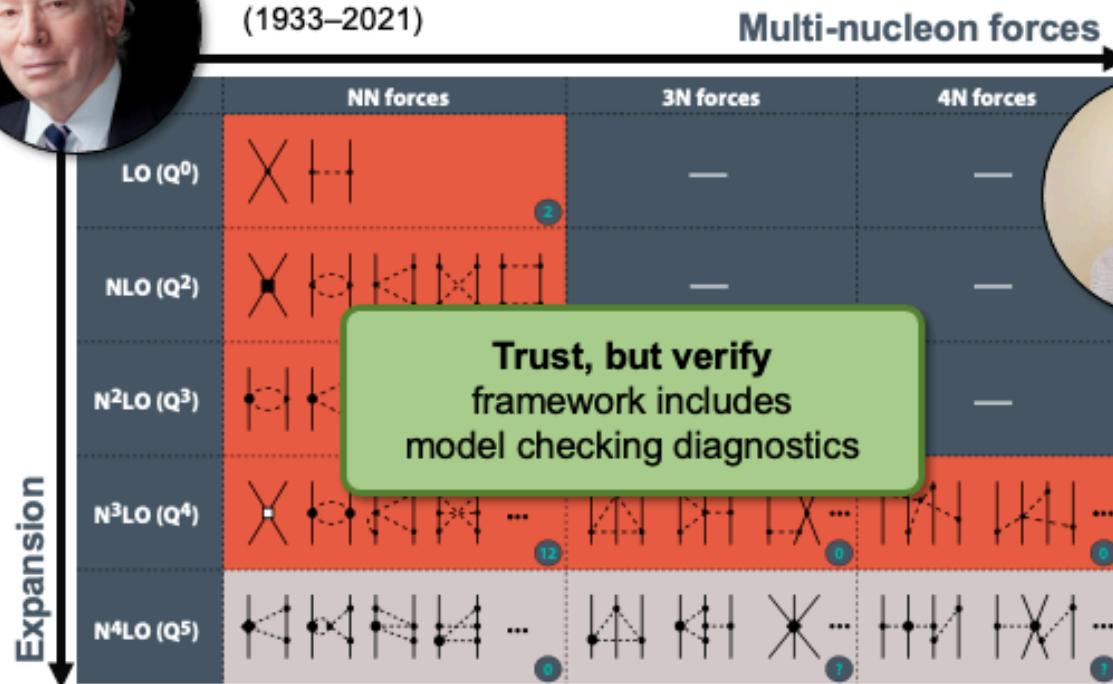
geometric sum

**see also Dick Furnstahl's talk:  
Statistically rigorous analyses of  
light nuclei with chiral interactions**





S. Weinberg  
(1933–2021)



Weinberg, van Kolck, Kaplan, Savage, Wise, Epelbaum,  
Kaiser, Krebs, Machleidt, Meißner, ...

**predict observable  $y_k$   
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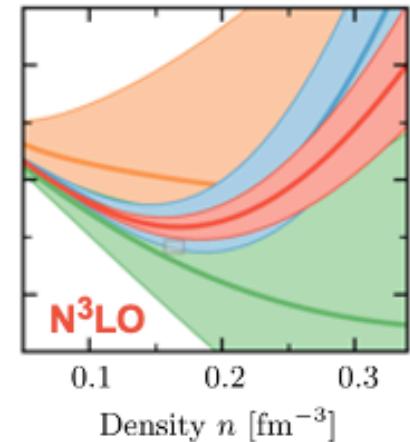
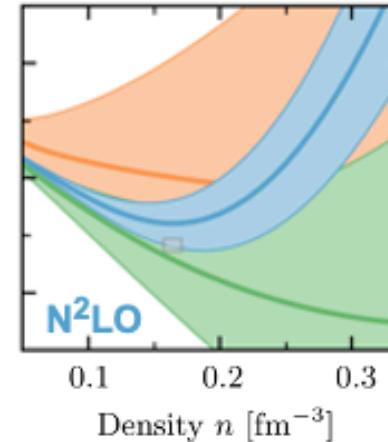
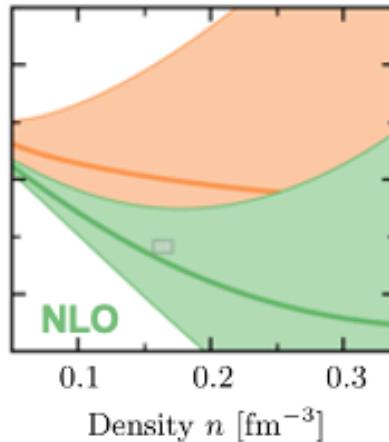
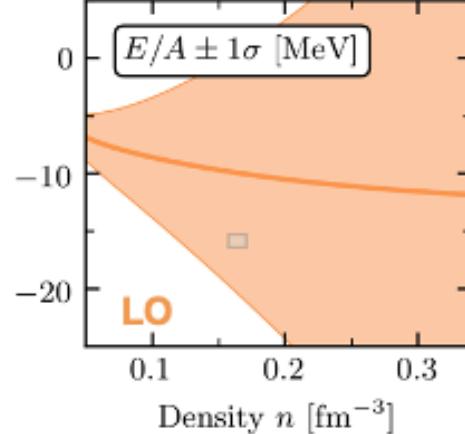
$c_n$  are not the EFT's LEC

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geometric sum

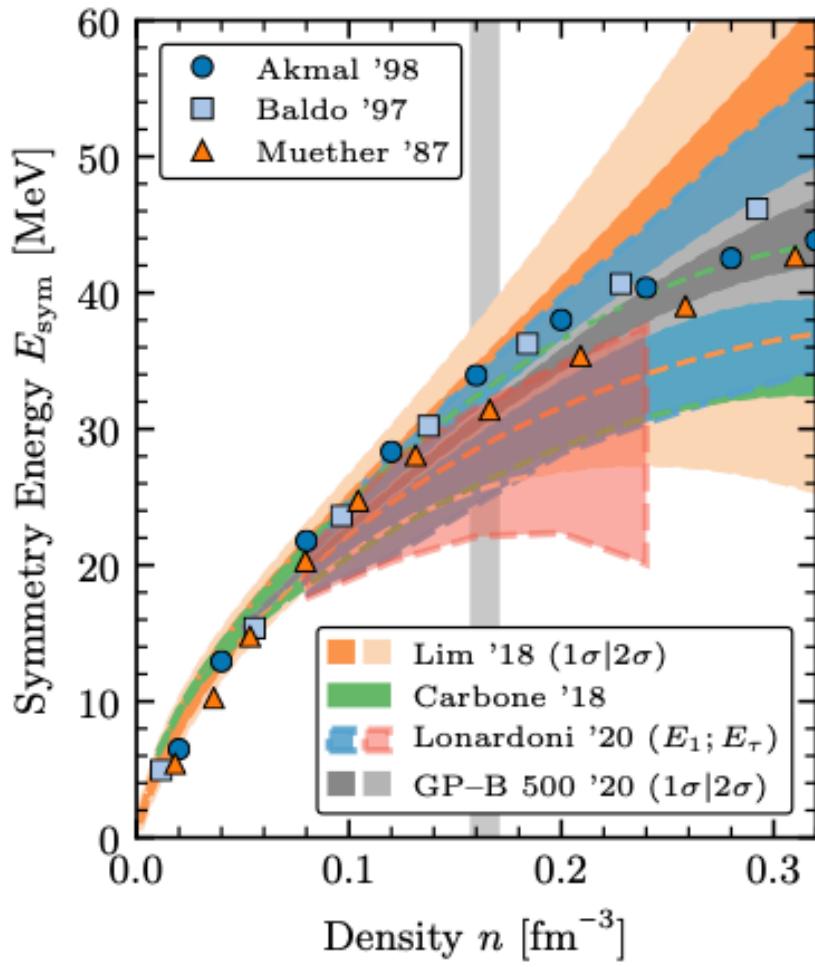


# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

Confronting chiral EFT with empirical constraints

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UNIVERSITY

CD, Furnstahl *et al.*, PRL 125, 202702



$$S_2(n) \approx \frac{E}{N}(n) - \frac{E}{A}(n)$$

! Excellent agreement with experiment  
Lattimer and Lim, APJ 771, 51

$$\text{pr}(S_v, L | \mathcal{D}) = \int d n_0 \text{pr}(S_2, L | n_0, \mathcal{D}) \text{pr}(n_0 | \mathcal{D})$$
$$\text{pr}(n_0 | \mathcal{D}) \approx 0.17 \pm 0.01 \text{ fm}^{-3}$$

$2\sigma$  ellipse (light yellow) is completely within the *conjectured* unitary gas limit

predicted range in  $S_v$  agrees with other **theoretical constraints**; but  $\sim 15$  MeV stronger density-dependence of  $S_2(n_0)$

GP-B (500): two-dimensional Gaussian

$$\begin{bmatrix} \mu_{S_v} \\ \mu_L \end{bmatrix} = \begin{bmatrix} 31.7 \\ 59.8 \end{bmatrix} \quad \Sigma = \begin{bmatrix} 1.11^2 & 3.27 \\ 3.27 & 4.12^2 \end{bmatrix}$$

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

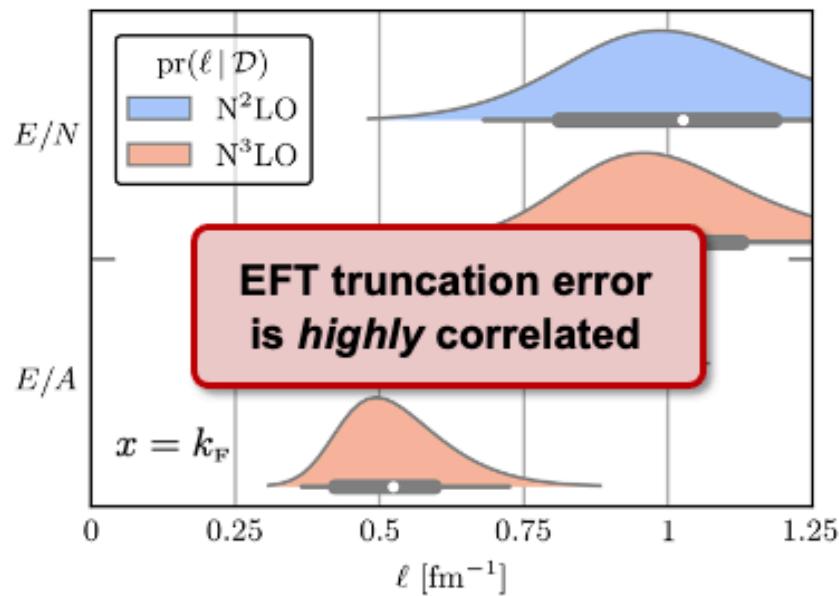
Bayesian inference

MICHIGAN STATE  
UNIVERSITY

CD, Melendez et al., PRC 102, 054315

How correlated  
is nuclear matter ?

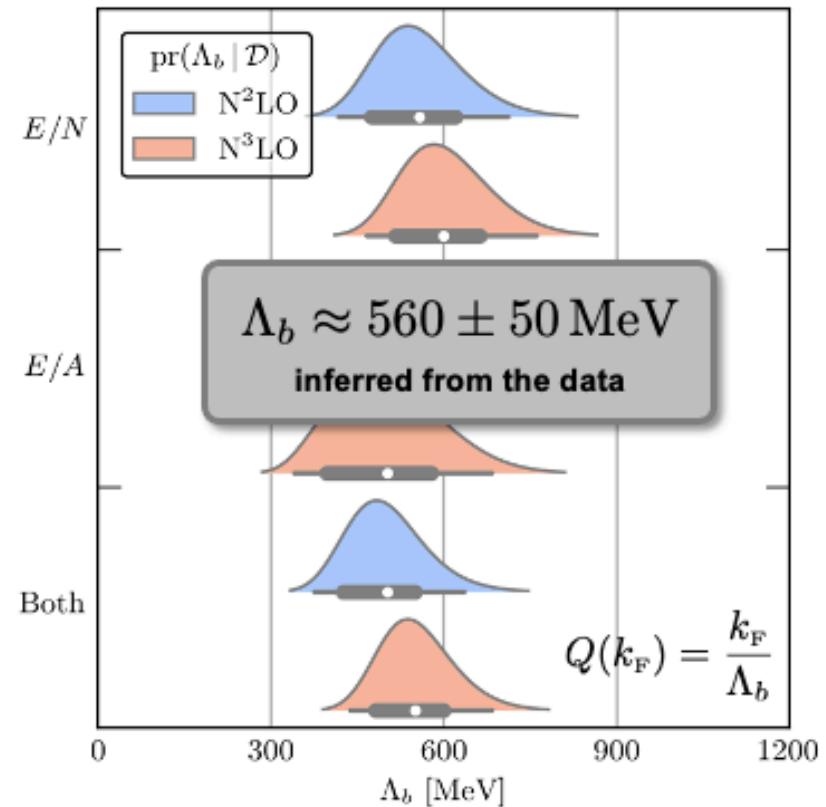
$\text{pr}(\ell | \mathcal{D})$   
correlation length



to be  
compared with  $k_F^{\max} = \begin{cases} 2.2 \text{ fm}^{-1} & \text{PNM} \\ 1.7 \text{ fm}^{-1} & \text{SNM} \end{cases}$

Where does the  
EFT break down ?

$\text{pr}(\Lambda_b | \mathcal{D})$   
breakdown scale



# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

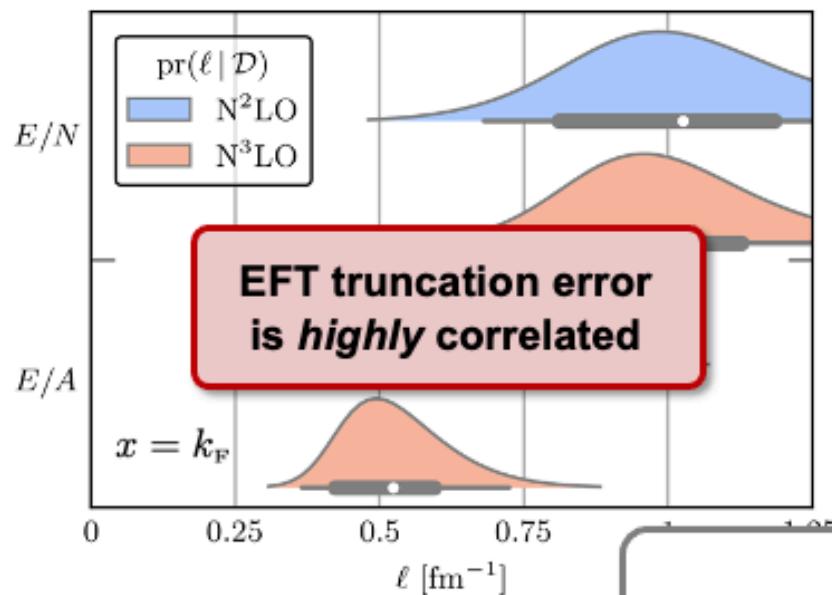
Bayesian inference

MICHIGAN STATE  
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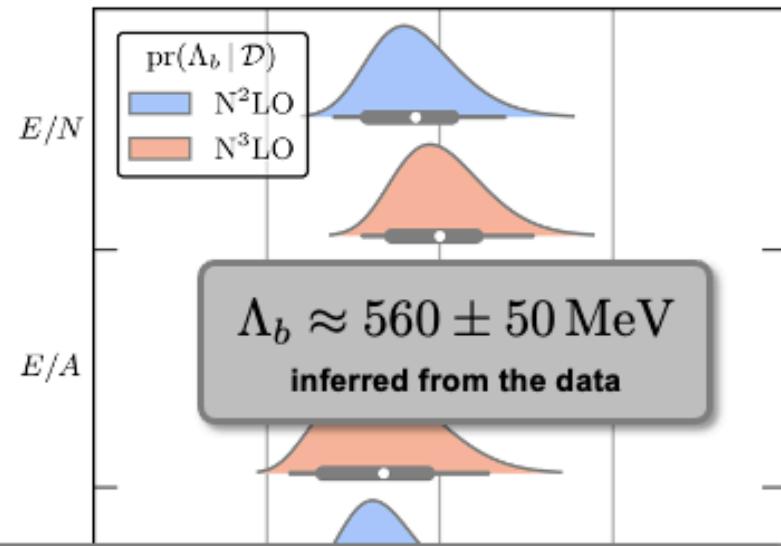


to be  
compared with

$$k_F^{\max} = \begin{cases} 2.2 \\ 1.7 \end{cases}$$

Where does the  
EFT break down ?

$\text{pr}(\Lambda_b | \mathcal{D})$   
breakdown scale



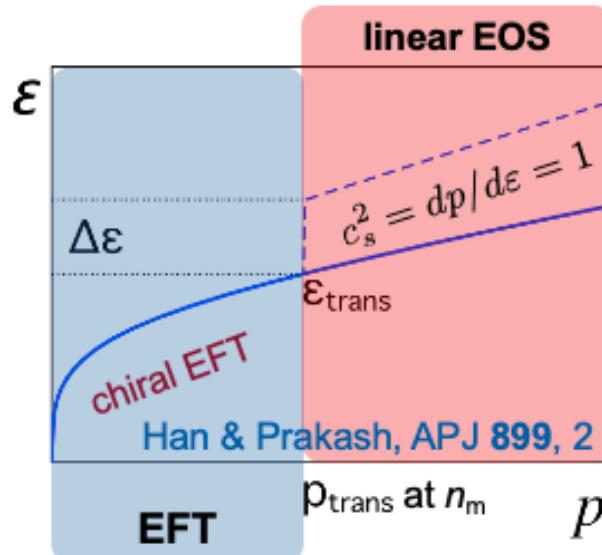
At which density scale does nuclear  
effective field theory **break down** ?

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

Limiting neutron star radii

MICHIGAN STATE  
UNIVERSITY

CD, Han, Lattimer et al., PRC 103, 045808



see also: Alford et al., JPG: NPP 46, 114001

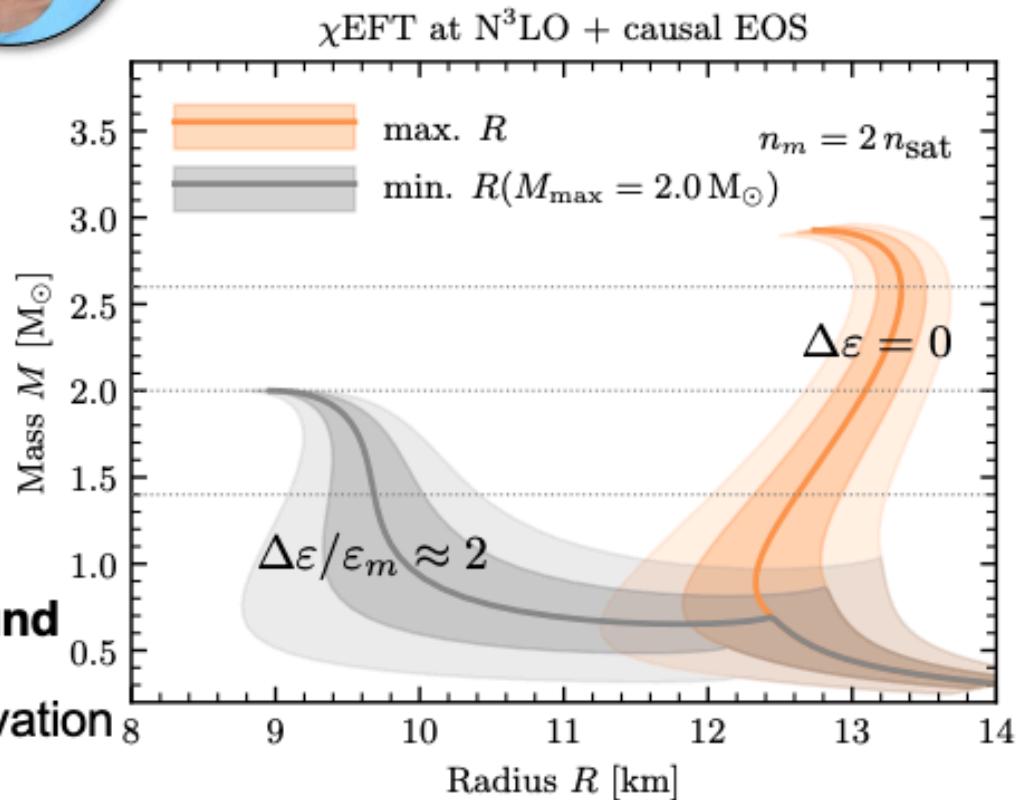
$\Delta\varepsilon$  anticorrelates with  $M_{\max}$  and  $R$

continuous match sets upper bound

use lower limit on  $M_{\max}$  from observation  
to adjust  $\Delta\varepsilon$  and constrain  $R_{\min}$



extend EFT EOS at  $n_m$  to linear EoS  
with finite discontinuity (softening)

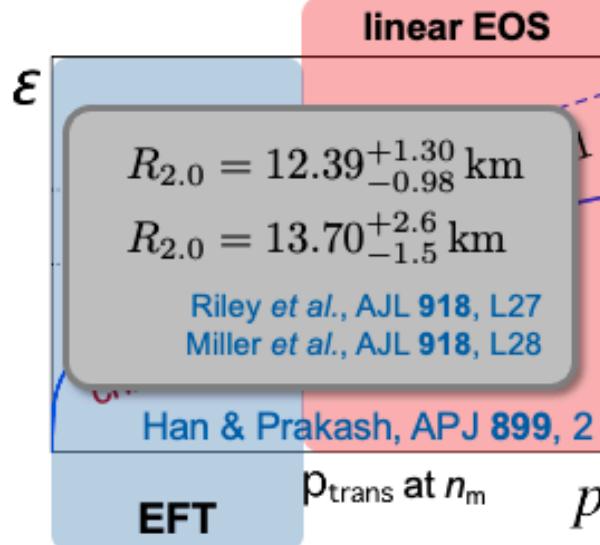


# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

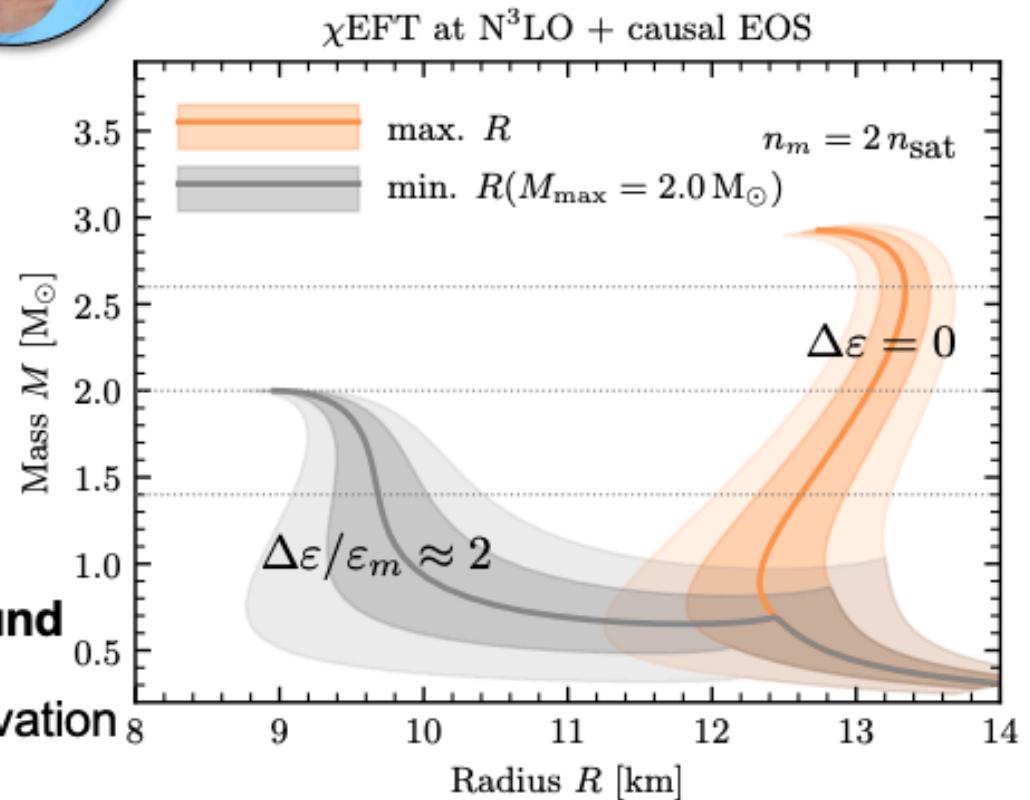
Limiting neutron star radii

MICHIGAN STATE  
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CD, Han, Lattimer et al., PRC 103, 045808



extend EFT EOS at  $n_m$  to linear EoS  
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see also: Alford et al., JPG: NPP 46, 114001

$\Delta\epsilon$  anticorrelates with  $M_{\text{max}}$  and  $R$

continuous match sets upper bound

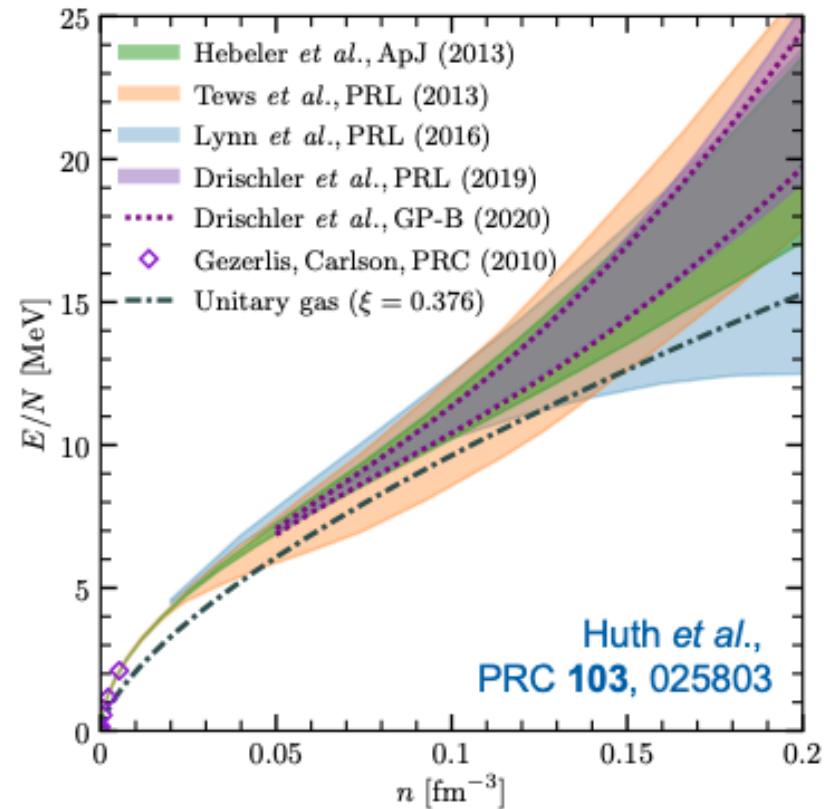
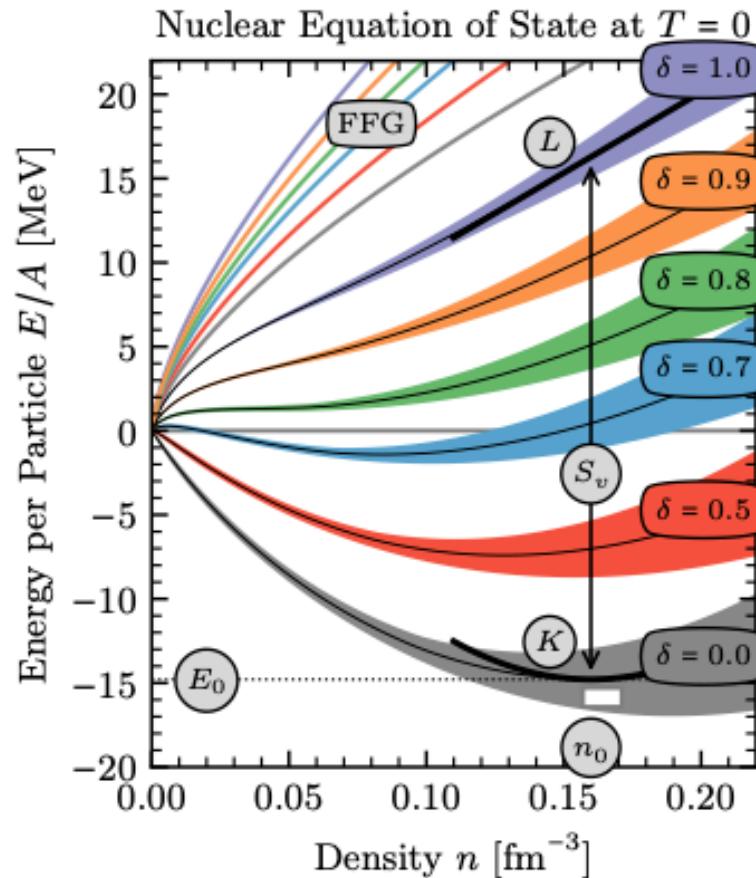
use lower limit on  $M_{\text{max}}$  from observation  
to adjust  $\Delta\epsilon$  and constrain  $R_{\text{min}}$

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

Parameters of the low-density EOS

MICHIGAN STATE  
UNIVERSITY

CD, Holt, and Wellenhofer, ARNPS. 71, 403



FFG: free Fermi gas;  $\delta = (n_n - n_p)/n$ : isospin asymmetry

Annotations:  $(\Lambda / \Lambda_{3N})$  in  $\text{fm}^{-1}$  or  $(\Lambda)$  in MeV

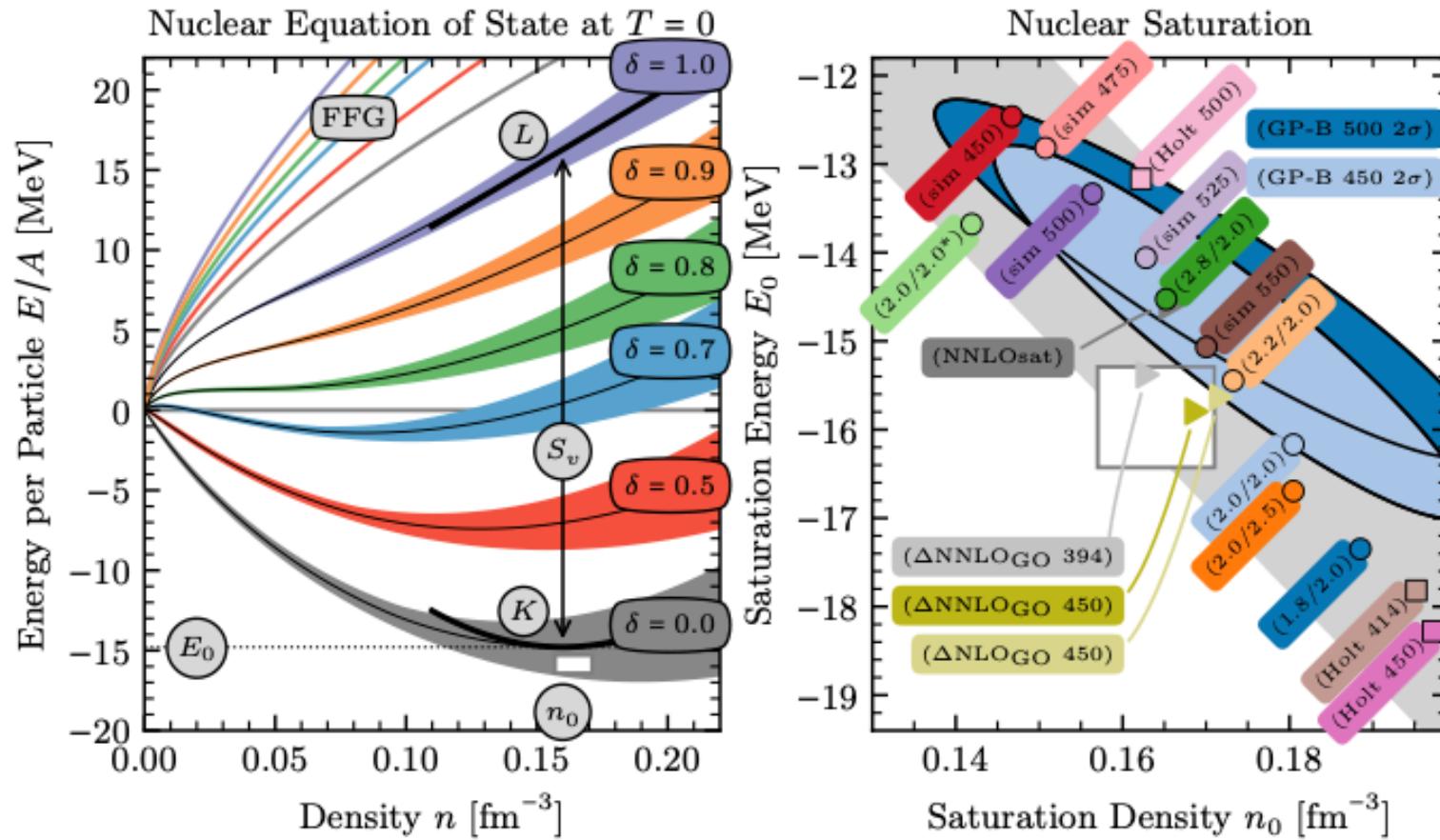
for nuclear saturation, see also Atkinson et al., PRC 102, 044333; Dewulf et al., PRL 90, 152501

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

Parameters of the low-density EOS

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CD, Holt, and Wellenhofer, ARNPS. 71, 403



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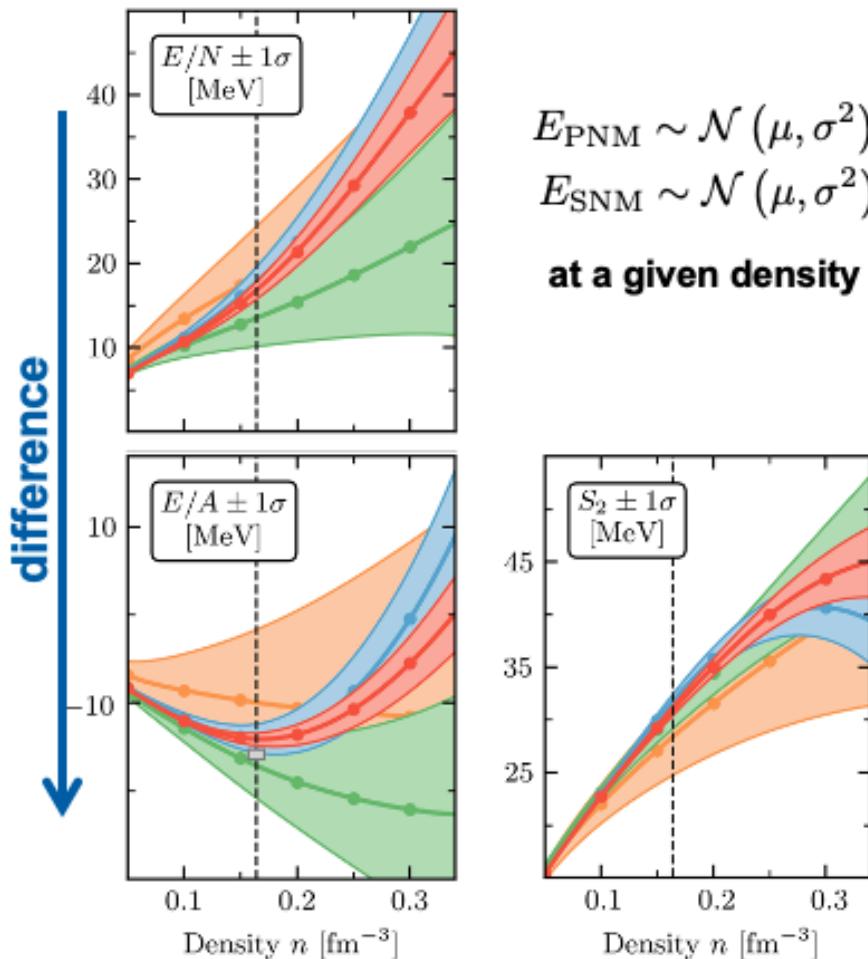
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# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

Exploit type  $\gamma$  correlations: symmetry energy

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CD, Furnstahl *et al.*, PRL 125, 202702



$$E_{\text{PNM}} \sim \mathcal{N}(\mu, \sigma^2)$$

$$E_{\text{SNM}} \sim \mathcal{N}(\mu, \sigma^2)$$

at a given density

$$S_2(n) \approx \frac{E}{N}(n) - \frac{E}{A}(n)$$

**Reminder: Statistics 101**

$$S_2 \sim \mathcal{N}(\mu_{S_2}, \sigma_{S_2}^2)$$

$$\mu_{S_2} = \mu_{\text{PNM}} - \mu_{\text{SNM}}$$

$$\sigma_{S_2}^2 = \sigma_{\text{PNM}}^2 + \sigma_{\text{SNM}}^2$$

$$- 2\sigma_{\text{PNM}}\sigma_{\text{SNM}}\rho$$

correlation coefficient  $-1 \leq \rho \leq +1$

Can result in smaller uncertainties than one might *naively* expect.

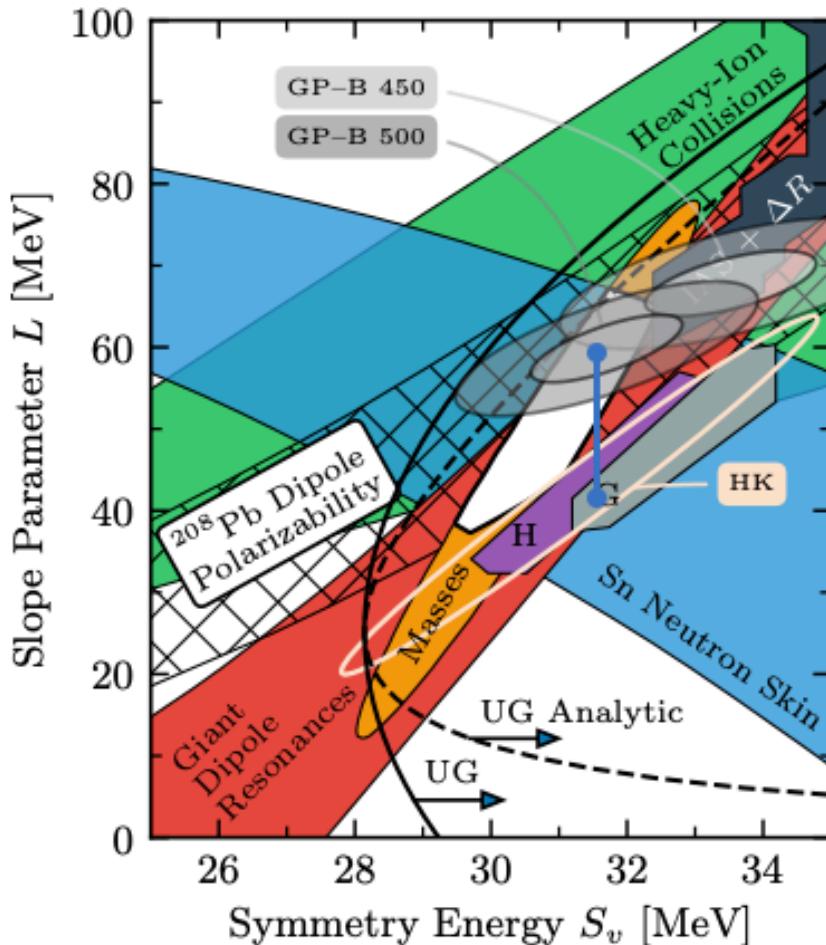
for  $S_{2k>2}(n)$ , see Wen & Holt, PRC 103, 064002 and Somasundaram, CD, Tews *et al.*, PRC 103, 045803

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

Confronting chiral EFT with empirical constraints

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CD, Furnstahl *et al.*, PRL 125, 202702



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



Excellent agreement with experiment  
Lattimer and Lim, APJ 771, 51

$$\text{pr}(S_v, L | \mathcal{D}) = \int dn_0 \text{pr}(S_2, L | n_0, \mathcal{D}) \text{pr}(n_0 | \mathcal{D})$$
$$\text{pr}(n_0 | \mathcal{D}) \approx 0.17 \pm 0.01 \text{ fm}^{-3}$$

$2\sigma$  ellipse (light yellow) is completely within the *conjectured* unitary gas limit

predicted range in  $S_v$  agrees with other **theoretical constraints**; but  $\sim 15$  MeV stronger density-dependence of  $S_2(n_0)$

GP-B (500): two-dimensional Gaussian

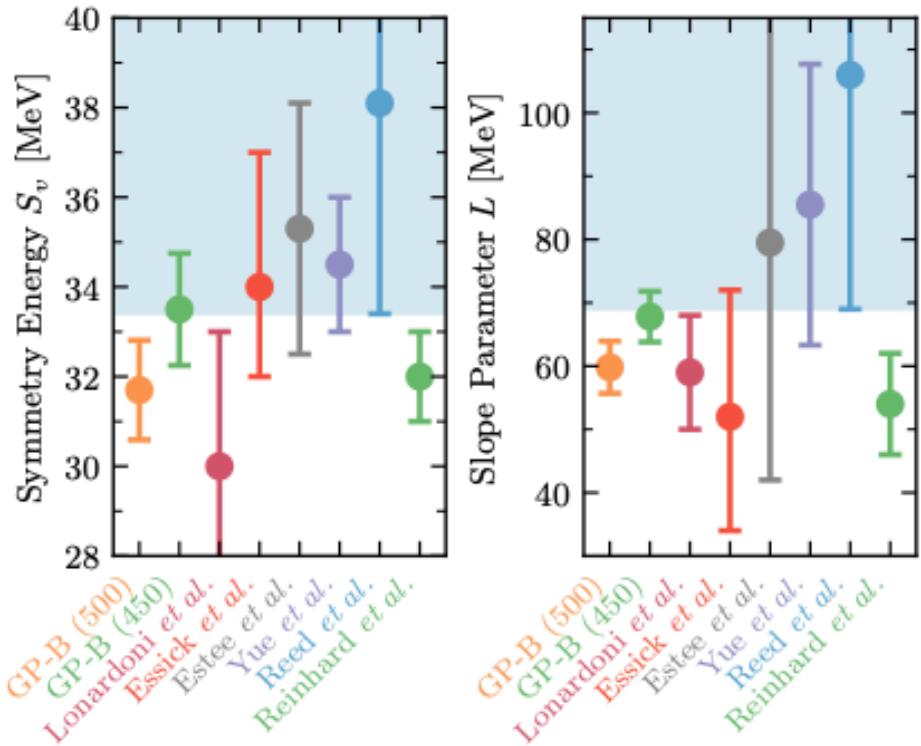
$$\begin{bmatrix} \mu_{S_v} \\ \mu_L \end{bmatrix} = \begin{bmatrix} 31.7 \\ 59.8 \end{bmatrix} \quad \Sigma = \begin{bmatrix} 1.11^2 & 3.27 \\ 3.27 & 4.12^2 \end{bmatrix}$$

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

PREX-II vs theory and observation

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see also Yue et al., arXiv:2102.05267



## Parity violating elastic e scattering

$$R_{\text{skin}}(^{208}\text{Pb}) = 0.283 \pm 0.071 \text{ fm}$$

PREX collaboration, PRL 126, 172502

## Exploiting strong correlations (EDFs)

$$S_v = 38.1 \pm 4.7 \text{ MeV}$$
$$L = 105.9 \pm 36.9 \text{ MeV}$$

Reed et al., PRL 126, 172503

## Astron. data + chiral EFT only (incl. GP-B)

$$R(^{208}\text{Pb}) = 0.18^{+0.04}_{-0.04} \text{ fm}$$
$$S_v = 34^{+3}_{-2} \text{ MeV} \quad L = 52^{+20}_{-18} \text{ MeV}$$

Essick et al., PRL 127, 192701

## Different EDFs (closest to RCNP & PREX)

$$R(^{208}\text{Pb}) = 0.19 \pm 0.02 \text{ fm}$$
$$S_v = 32 \pm 1 \text{ MeV} \quad L = 54 \pm 8 \text{ MeV}$$

Reinhard, Roca-Maza et al., arXiv:2105.15050

## Take away from PREX-II-informed results:

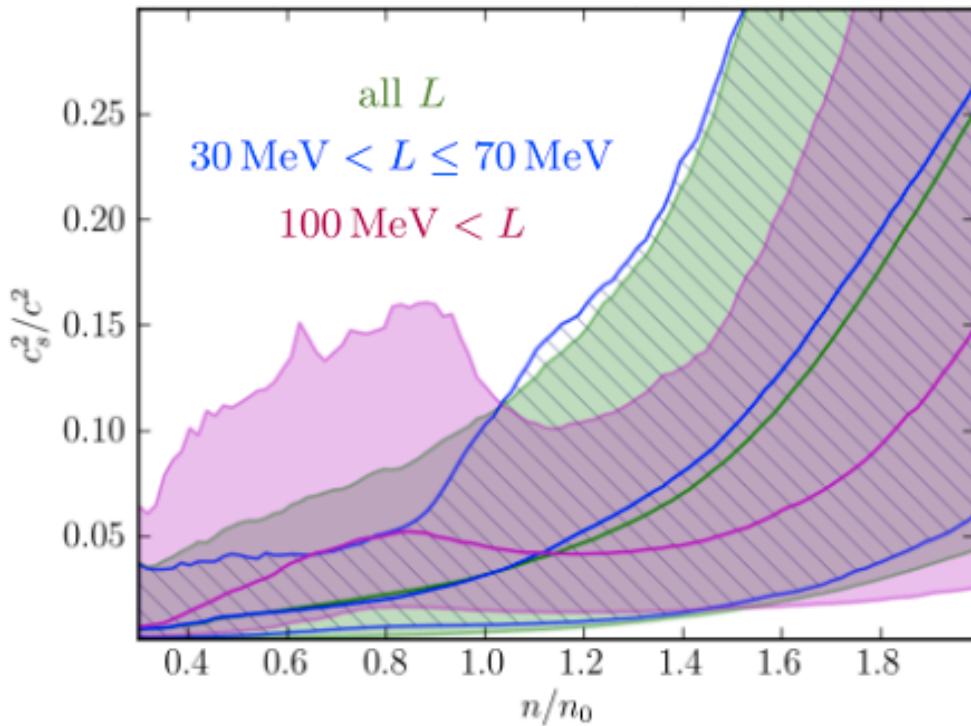
- **uncertainties are still large**
- allows for stiffer EOS at  $n \sim n_0$ , but within the large uncertainties consistent with chiral EFT
- **tension between  $A_{\text{PV}}$  and  $\alpha_D$**

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

PREX-II vs theory and observation

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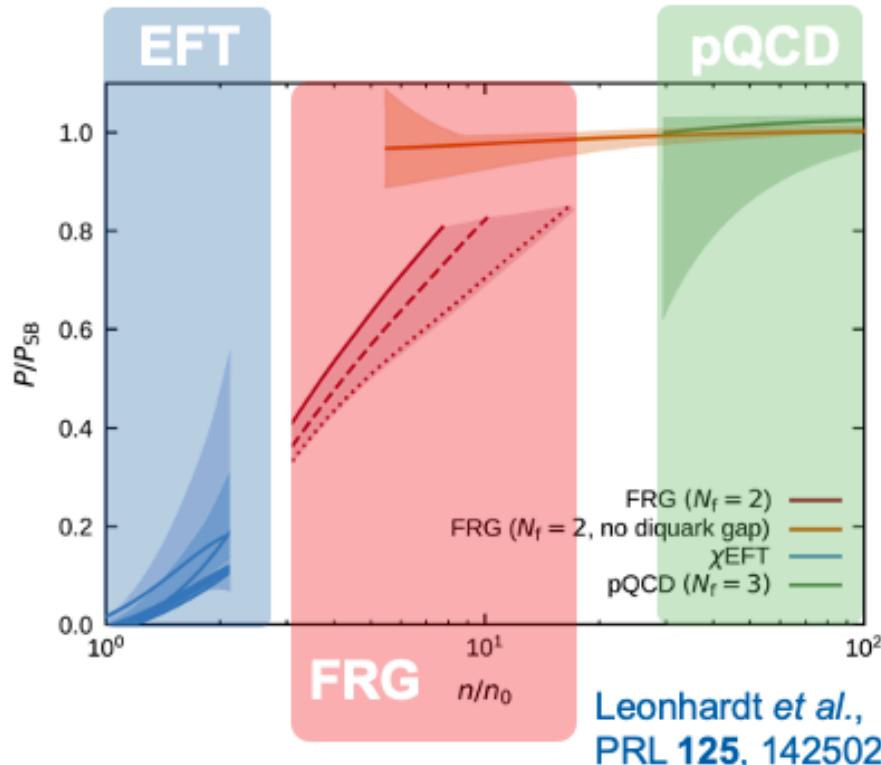
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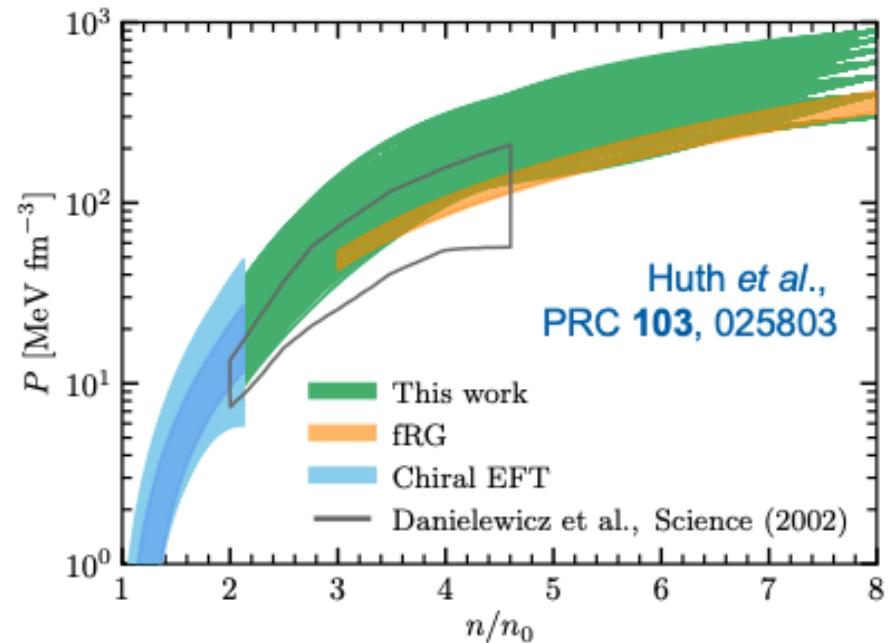
# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

New developments: symmetric nuclear matter

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**Functional Renormalization Group:**  
complementary constraints at  $> 3n_0$   
directly from the QCD action  
see also: Drews & Weise, PPNP 93, 69



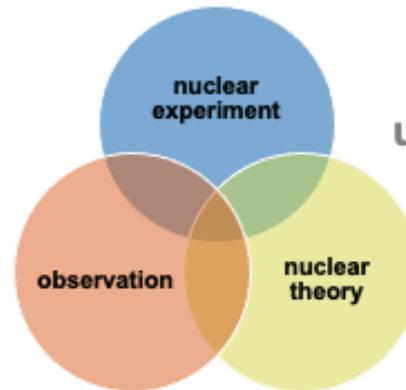
**New insights into the high-density EOS:**  
**remarkable consistency** between the  
constraints, which suggests that they can  
be combined via **simple extrapolations**

# Nuclear Equation of State with EFT Uncertainties Rigorously Quantified

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## Conclusion

multi-messenger  
nuclear precision  
FRIB



unique opportunity to constrain  
the nuclear EOS, with great  
potential for discoveries

1

### Microscopic EOS constraints *statistically robust* uncertainties

- excellent agreement of predicted  $S_v-L$  correlation with experiment
- PNM and SNM show a regular EFT convergence pattern with increasing order
- extracted  $\Lambda_b$  is consistent with NN scattering •  $N^2LO$  coefficient may be an outlier
- in future: study modified power counting at finite density; e.g., Yang *et al.*, arXiv:2109.13303

2

### full Bayesian UQ: sample over LECs & hyperparameters

- in future: consistently include uncertainties in the LECs of chiral interactions
- promising: new potentials up to  $N^2LO$  by Wesolowski *et al.*, arXiv:2104.04441



thanks to my collaborators:

R. Furnstahl J. Melendez K. McElvain D. Phillips  
S. Han J. Lattimer M. Prakash S. Reddy T. Zhao

