

Summary of Track

“Nuclear Structure for Neutrinos and Astrophysics”

Conveners: Christian Drischler (Ohio University)
Anna McCoy (Argonne National Laboratory)
Ingo Tews (Los Alamos National Laboratory)

6/13/2025, CIPANP 2025, Madiscon, Wisconsin

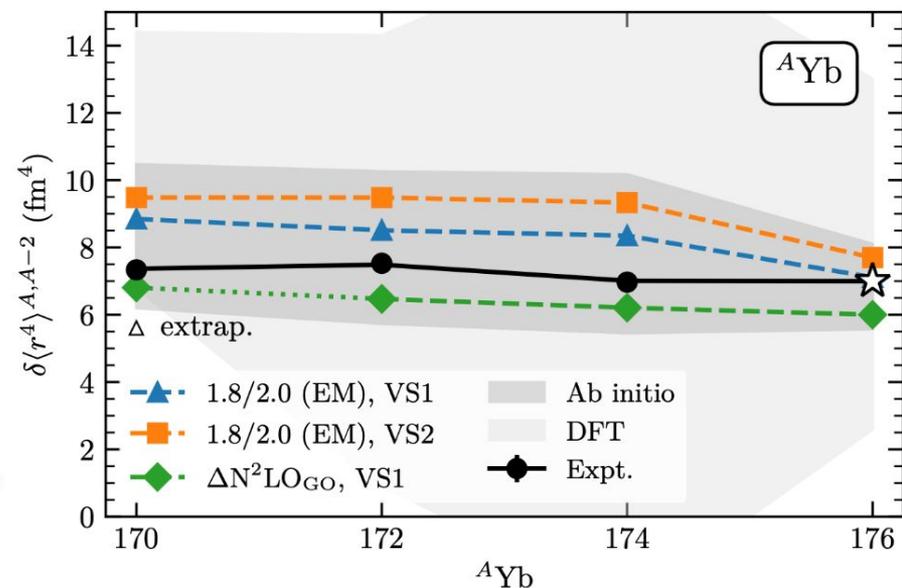
Overview:

- **3 sessions, each 90 min**
+ 1 joint session with “Neutrino Masses, Mixings, and Interactions” track
 - Tuesday (1 session)
 - Wednesday (1 session)
 - Thursday (1 session) + Joint Session
- **11 talks: 2 overview talks (30 min) and 9 contributed talks (20 min)**
- **Covered a wide range of topics:**
 - Ab initio nuclear theory for neutrinos and beta decays
 - Nuclear interactions and electroweak operators
 - Neutron-star physics
 - Uncertainty quantification using emulators
- **Positive feedback from the attendees**

Matthias Heinz (ORNL):

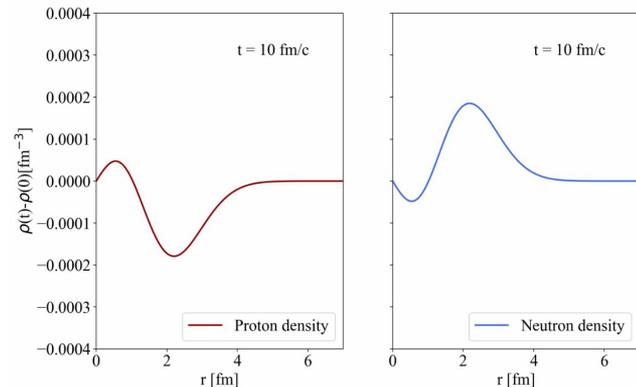
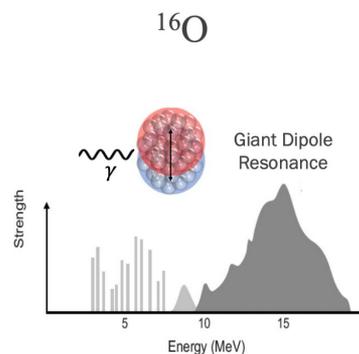
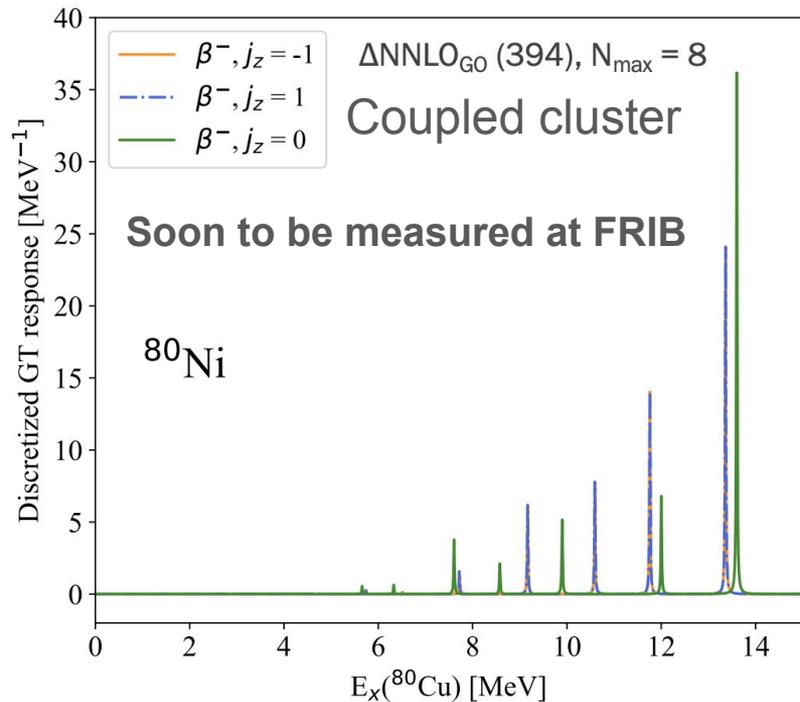
Exploring new physics and nuclear structure with Ytterbium isotope shifts.

- **Significant progress on reach, precision, and applications** of ab initio nuclear structure calculations
- Nuclear structure input with **quantified uncertainties essential** to understand Yb King plot
- Leading signal due to **nuclear structure, not new physics**
- Remarkable reach to provide input for **new physics searches** in heavy nuclei



Door, Yeh, MH, et al., PRL 134 (2025)

Francesca Bonaiti (ORNL and FRIB/MSU): Beta-decay strengths of neutron-rich nuclei relevant for astrophysics



Collective oscillations in real time

Gamow-Teller response in $^{76,80}\text{Ni}$

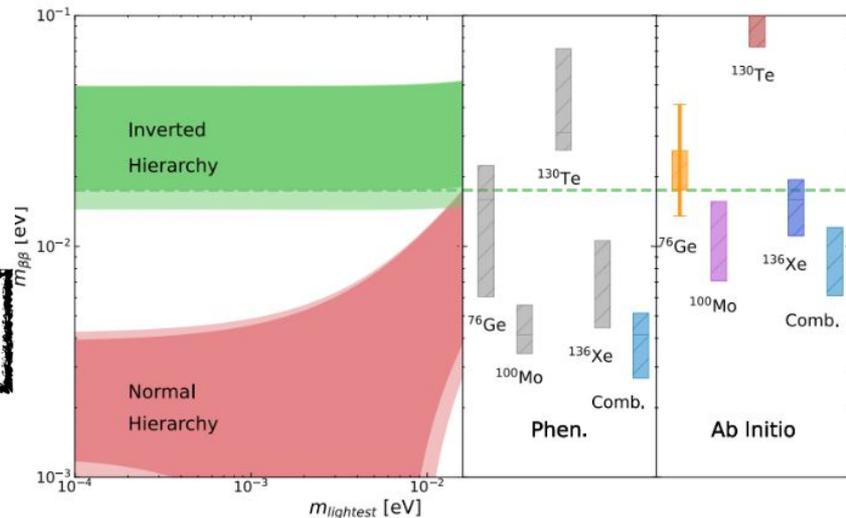
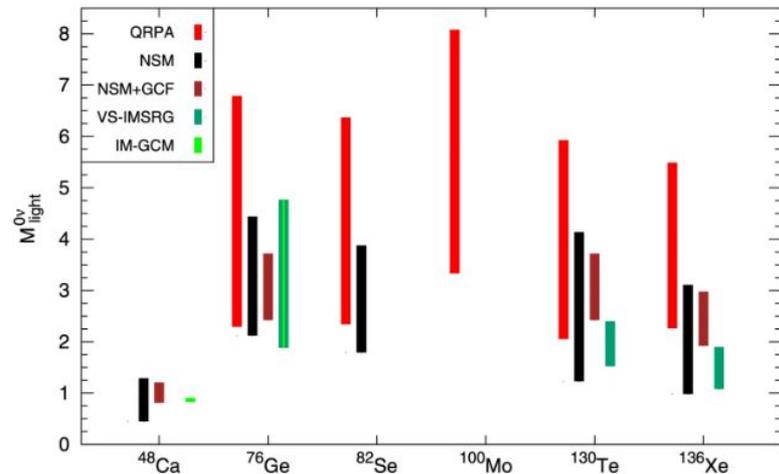
Lotta Jokiniemi (Darmstadt): Ab initio calculations of Neutrinoless Double-Beta Decay

- $0\nu\beta\beta$ decay is a robust yet challenging probe for BSM physics and neutrino properties
- *Ab initio* methods are becoming capable of computing the needed nuclear matrix elements
- χ EFT analysis of the operators allows for uncertainty quantification
- Next-generation experiments likely to fully cover the inverted-hierarchy band of neutrino masses

- Nuclear deformation
- Two-body currents
- Consistent order-by-order convergence study
- ...

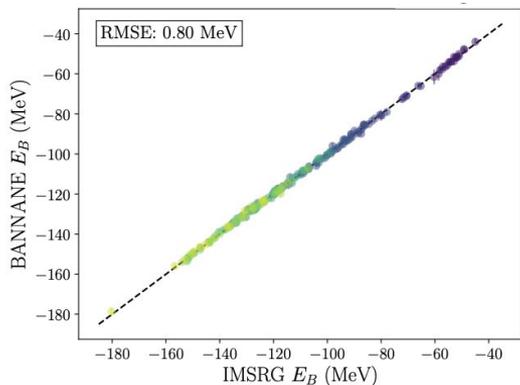
TODO

See talk by G. Chambers-Wall tomorrow at 4:46 pm

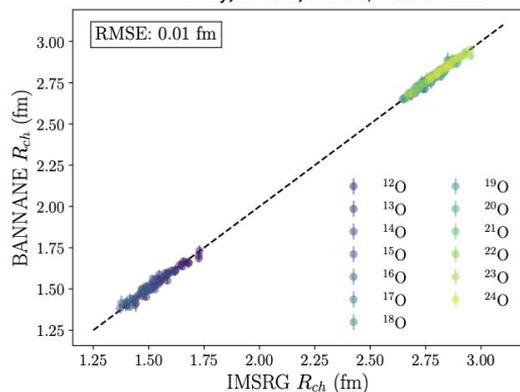


Antoine Belley (MIT):

Ab Initio Neutrinoless Double Beta Decay Matrix Elements



Belley, Muñoz, García, arxiv:2502.20363



Summary ...

- Emulators are required to obtain uncertainty quantification of nuclear theory observables required for searches of new physics.
- Emulator further allows the use of other statistical tools like global sensitivity analysis.
- Many-body uncertainty is the main source of uncertainty in current calculations.

... and Outlook

- Improving the emulator with other machine learning models.
- Reducing the many-body error using methods that probe the IMSRG(3).
- Doing a similar analysis for other nuclear processes.
- Computing other observables for BSM searches with uncertainties.

Thank you!

Jason Holt (TRIUMF): First-Principles Theory for New Physics Searches



(Former)
Postdoctoral
Fellows



Ragnar Stroberg



Takayuki Miyagi



Lotta Jokiniemi



Baishan Hu

Future of Ab Initio Theory

$0\nu\beta\beta$ Decay



Antoine Belley



Isabella Ginnette

Structure + Astrophysics



Kanting Motimele



Maude Larivière

Symmetry Violation



Jose Munoz



Jack Pitcher

AI/Machine Learning

CKM Unitarity



Emily Love



Matt Martin



Alex Todd



Michael Liudeng

Atomic Systems



Gaurav Tenkila



Hrishi Patel



Vijay Chand

Just the beginning:
join our revolution!
jholt@triumf.ca

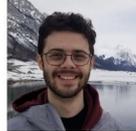
Dark Matter/ γ Scattering



Sam Leutheusser



Jose Padua

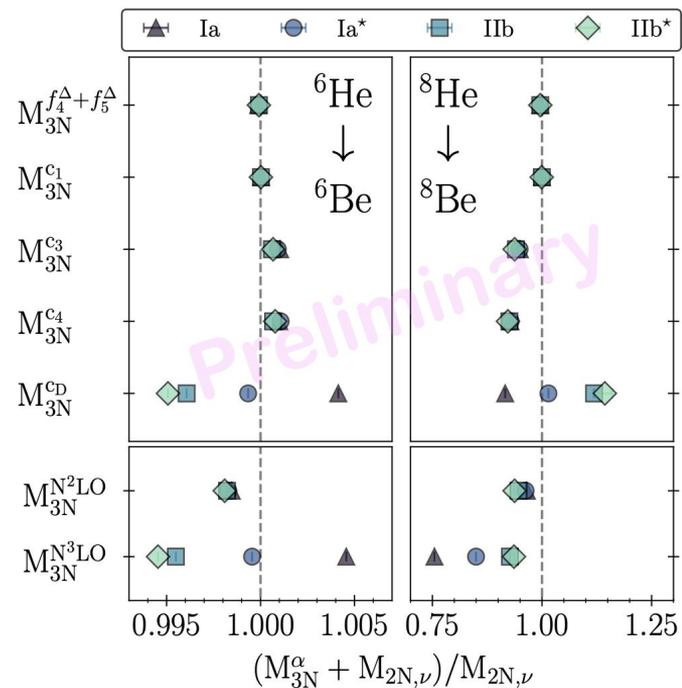
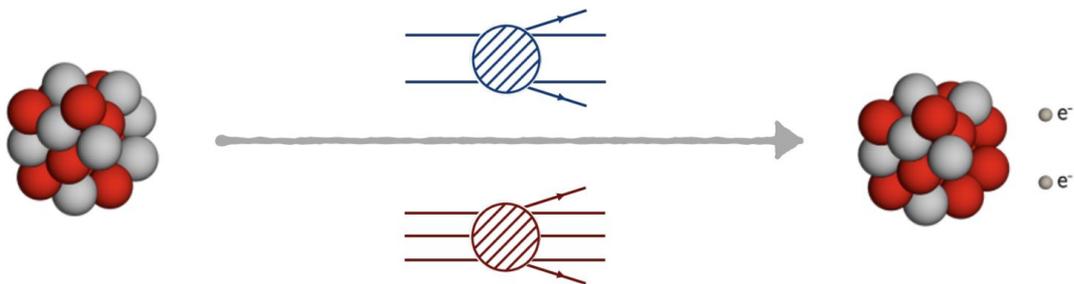


Mathieu Bruneault

Graham Chambers-Wall

Three-nucleon $0\nu\beta\beta$ potentials and their matrix elements in light nuclei

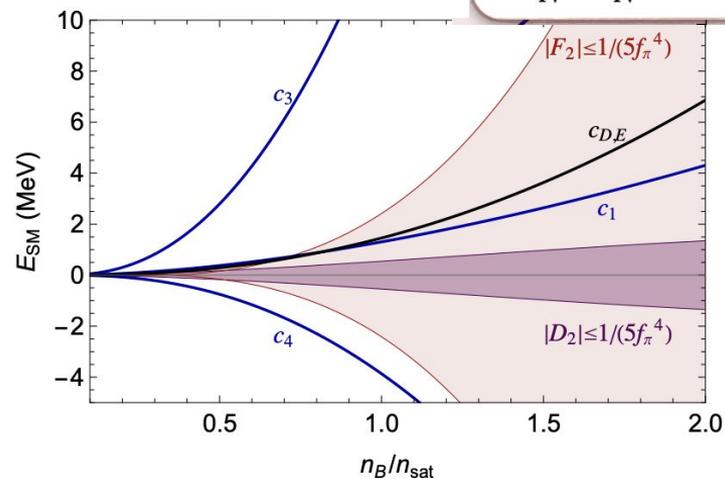
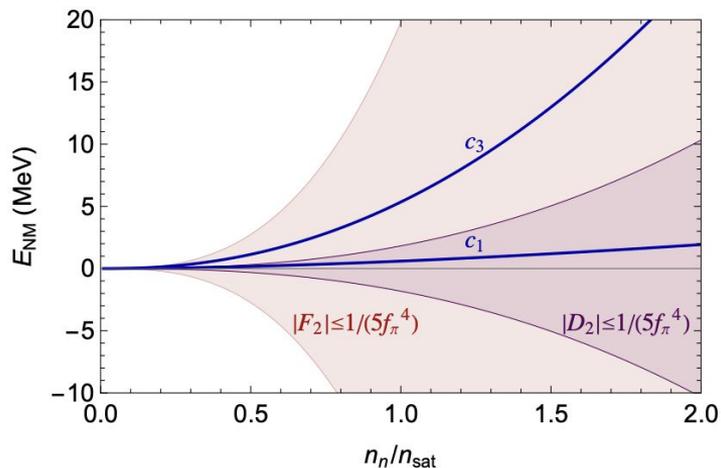
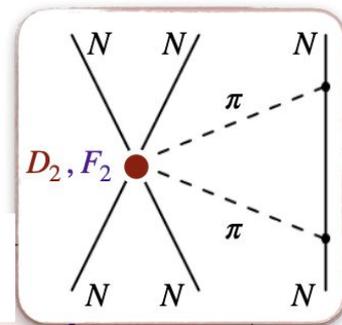
- $0\nu\beta\beta$ has a leading $2N$ component
- Derived 3N operators up to $N^3\text{LO}$ within χEFT
- Possibly large 3N matrix elements relative to $2N$
- Interesting to see 3N calculation in larger nuclei with other many-body methods



Maria Dawid (INT):

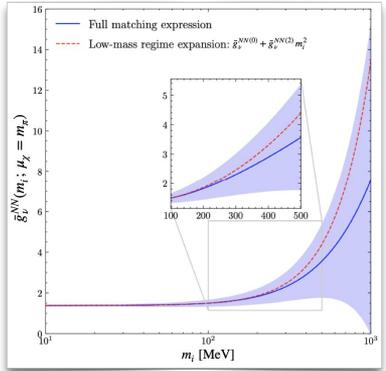
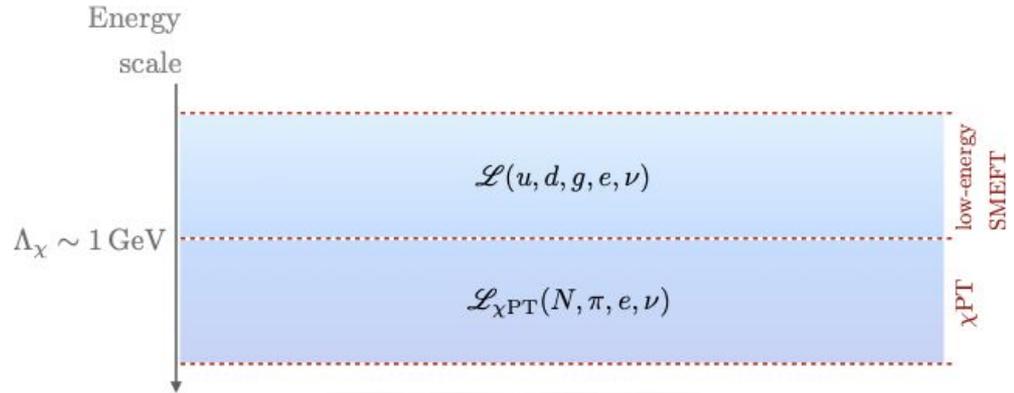
A New Class of Three Nucleon Forces and their Implications

1. We identified a new class of Three Nucleon-Forces
2. We estimate their contribution to the energy of neutron and nuclear matter
3. Future directions: constraining D_2 , F_2 , E_2

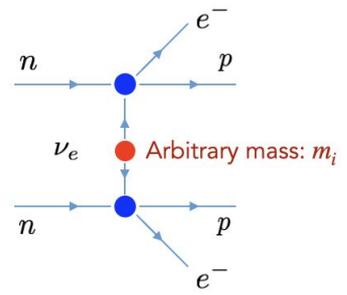


Sebastian Urrutia Quiroga (INT):

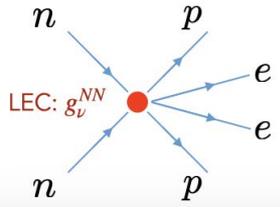
Determining the leading-order contact term induced by sterile neutrinos in neutrinoless double β decay



Leading order $0\nu\beta\beta$ operators



Tree-level exchange of Majorana neutrinos



Contact term is necessary for consistent results

Wouter Dekens (INT):

Superallowed beta decay in effective field theory

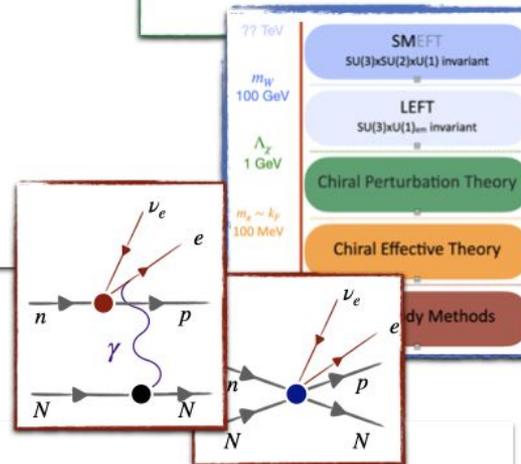
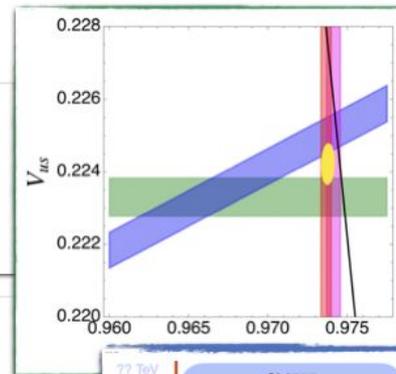
- $0^+ \rightarrow 0^+$ decays probe BSM physics to high scales ~ 10 TeV
- Requires control of SM uncertainties

+

- EFTs for superallowed decays:
 - Explicit separation of scales
 - Resums large logarithms
- Nuclear-structure dependence from two-body currents

$$\delta_{NS} = \sqrt{2} \langle f | V | i \rangle$$

+



Debora Mroczek (UIUC):

What is hiding in the core of a neutron star?

- We find a **Bayes factor of $K = 1.5$** between GP and mGP \rightarrow current constraints do not favor either model.

Physical interpretation: multi-scale correlations and nontrivial features in $c_s^2(n_B)$ which signal the onset of new phases of matter inside neutron stars are **not ruled out** by current constraints, but **neither are they required**.

- Nuclear physics models predict **nontrivial features** in c_s^2 and **multi-scale correlations** across densities when **exotic degrees of freedom are present**.
- Introduced **modified Gaussian processes** as novel approach for **modeling nontrivial features in c_s^2** .
- Performed a fully Bayesian analysis including astrophysical, low-energy, and pQCD constraints.
- **Multi-scale correlations** important for **searches for a crossover** within NS densities.

Neutron stars probe a regime of QCD that we cannot recreate in labs. The only way to extract information about QCD from neutron stars is through inference.
Quantifying theory uncertainty on the EoS is a requirement.

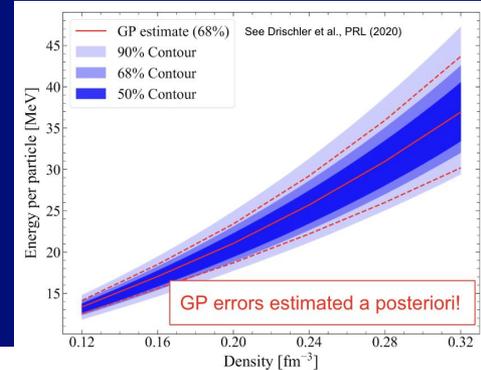
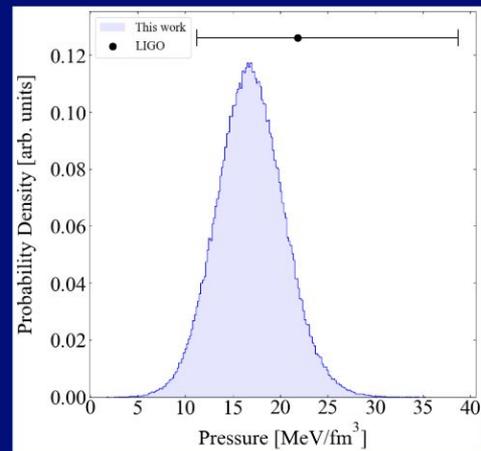


Cassandra L. Armstrong (LANL):

Machine Learning for Uncertainty Quantification in Neutron Matter

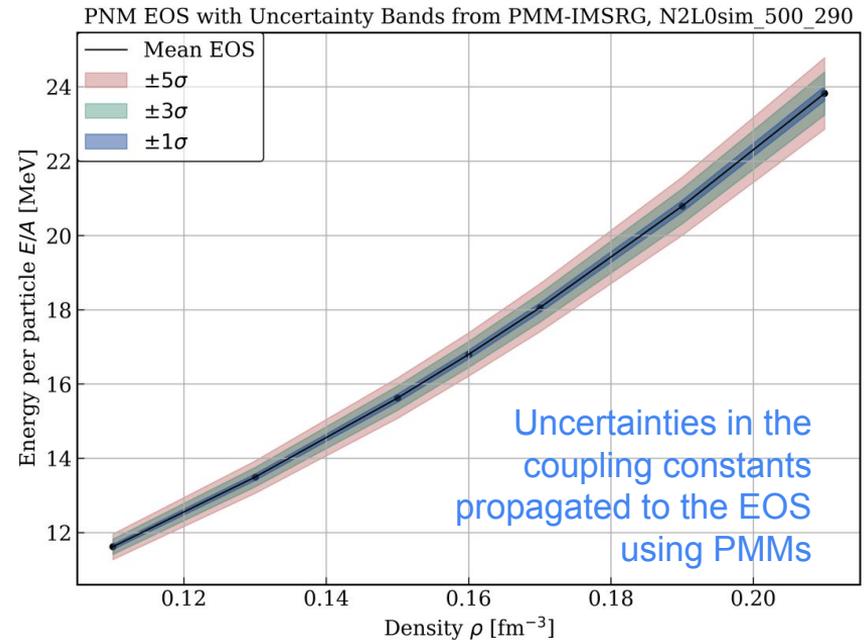
Summary and Outlook

1. We have applied the PMM to AFDMC calculations of pure neutron matter. We obtain emulator uncertainties of $\sim 1\%$ at N2LO.
2. The PMM allows us to propagate uncertainties directly from LECs to EOS: straightforward way of uncertainty estimation without the need of a posteriori assumptions.
3. We have applied emulators to the TOV equations and obtain emulator uncertainties of $\sim 0.01\%$ for all neutron star observables.
4. We will put the emulators into PyCBC and perform a Bayesian analysis of GW data to constrain the LECs.



Kang Yu (FRIB/MSU): Emulation and Uncertainty Quantification of Nuclear Matter Equation of State from *In-Medium Similarity Renormalization Group*

- Developed the nonperturbative many-body framework **IMSRG(2)** for infinite asymmetric matter calculations at zero temperature
- Constructed fast & accurate emulators for the nuclear EOS using **Parametric Matrix Models** (cf. talk by C.L. Armstrong)
- Emulators (i.e., surrogate models) enable systematic propagation of nuclear interaction uncertainties to the EOS and beyond
 - 10^6 speed-up factors, sub-percent errors



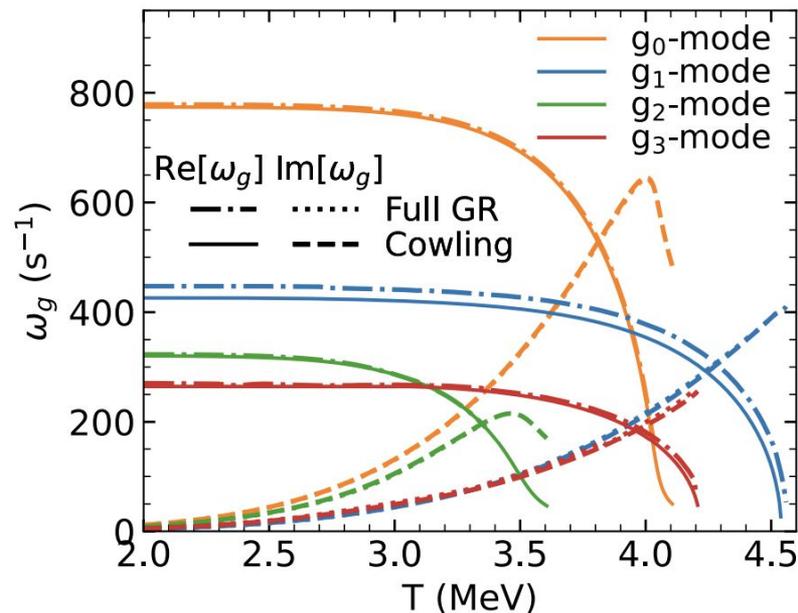
Good agreement between 3 many-body frameworks for pure neutron matter (PNM) calculations based on soft NN + 3N interactions

- IMSRG(2)
- Many-body perturbation theory (MBPT)
- Coupled Cluster (CC) theory

Tianqi Zhao (UC Berkeley/INT):

How weak interactions suppress g-modes in hot neutron stars

- **Neutron star oscillations may be detectable by next-generation GW detectors**
 - talk focused on g-modes
- They encode key properties such as composition gradients and **phase transitions**.
- During oscillations, **weak charged-current interactions serve as the dominant known dissipation mechanism**, generating bulk viscosity that can completely suppress g-modes at temperatures above approximately 5 MeV.
- However, direct detection of neutrino modulation from neutron star oscillations is **beyond the capabilities of current neutrino detectors**.



g-mode gets suppressed at larger T . Avoided crossing between g-modes

