High-Level Overview: High Performance Simulations of Neutron Stars in C++

Omokuyani Chibuzor Udiani

Michigan State University: FRIB
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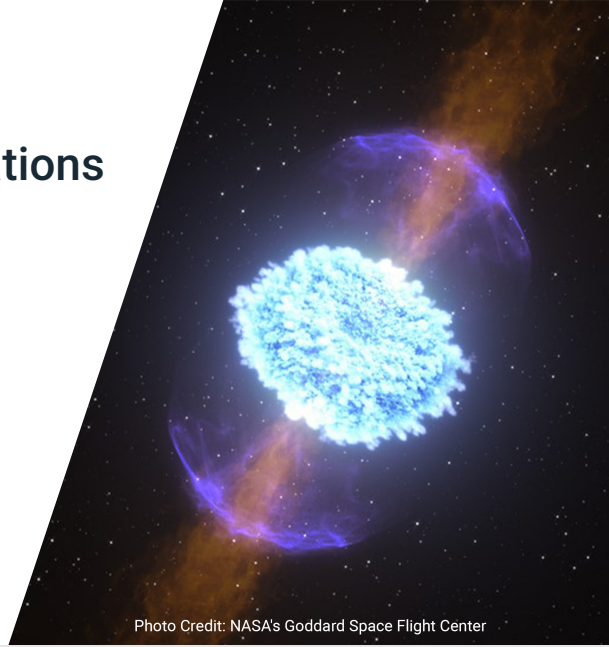
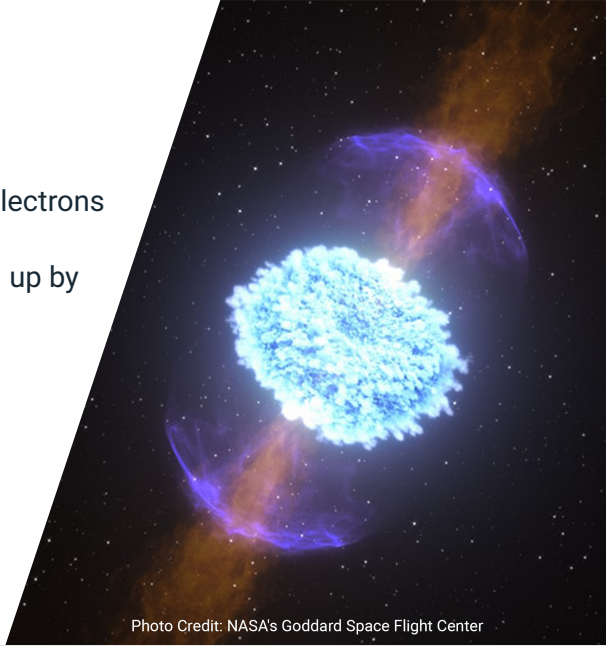


Photo Credit: NASA's Goddard Space Flight Center

Neutron Stars

- Composed of neutrons, protons, and electrons
- Gravity compresses them, but are held up by nuclear pressure
  - We need to understand this pressure
    - New states of matter
    - Origin of heavy elements
    - Probe physics beyond Standard Model



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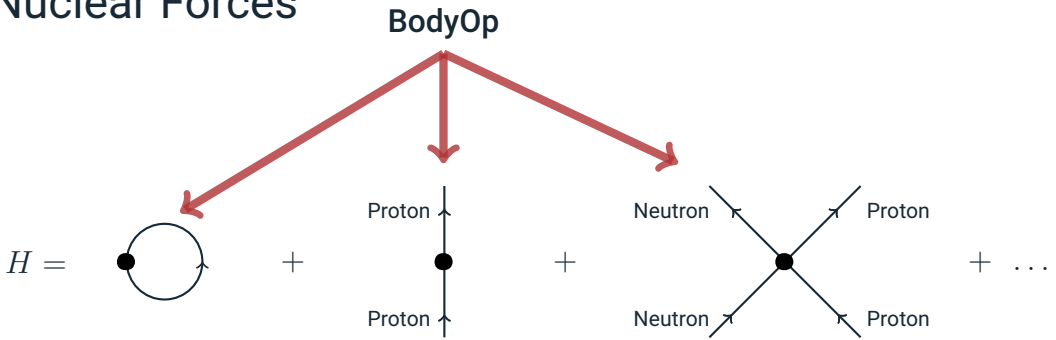
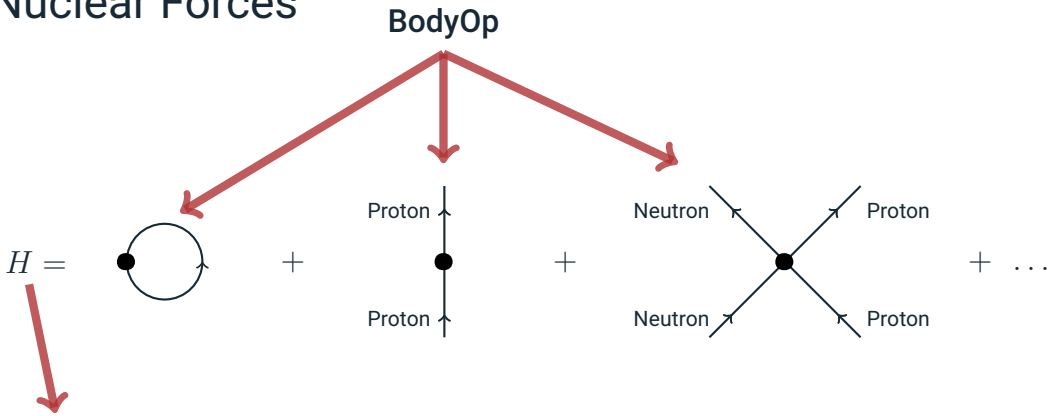
Nuclear Forces

Nuclear Forces



Nuclear Forces

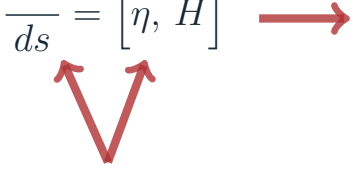


ABodyOp ∼80 GB—size of a matrix with $\sim 6e9$ std::complex double elements

(We store ∼10 of these in RAM)

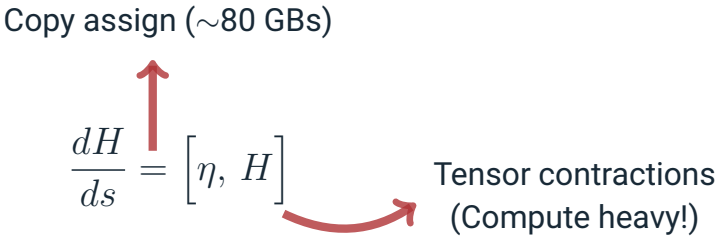
In-Medium Similarity Renormalization Group

$$\frac{dH}{ds} = \left[\eta,\ H\right]$$



Gives nuclear pressure!

Performance Critical Points



High Performance Optimizations

For compute

- ✔ Manual profile like cavemen: we need real time profiling for calculations at scale
- ✔ Use shared (CUDA and OpenMP) and distributed parallelism (MPI)
- ✔ Write/rewrite algorithms to optimize cache utilization
- ✔ Precompute data and reuse operations
- ✔ Use approximations when worthwhile
- ✔ Exploit symmetries of underlying system
- ✔ Accelerate convergence using novel physics and data-driven insights

High Performance Optimizations

Memory management

- ✔ Custom destructors, move and copy constructors, move and copy assigners
- ✔ ABodyOp resources gatekept (accessible with performant getters)
- ✔ All expensive objects are allocated once at program start, and cleaned up upon termination
- ✔ Profiled with Valgrind and Cachegrind

Why Custom Resource Management?

Default copy assignment is designed to handle:

$$A_{2\times 2} = B_{3\times 3}$$

$\sim$1K copy assignments invoked throughout our program's lifetime (worst case)

We check if shape(A) = shape(B) before dealloc+realloc: bypassing 2K kernel calls each worth $\sim$80 GB—performance killer!

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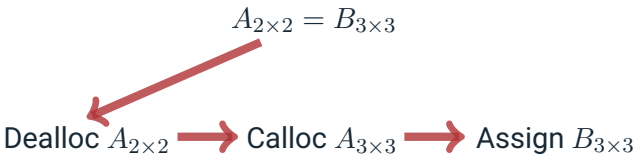

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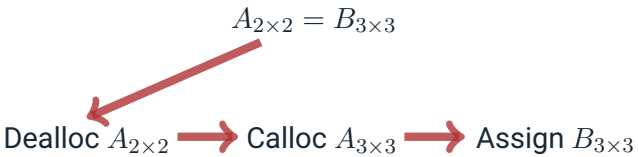

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