OAK RIDGE National Laboratory

New Science and Applications at SNS | June 11, 2026

A simulation framework for a muon-catalyzed fusion-based VNS facility

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U.S. DEPARTMENT of ENERGY

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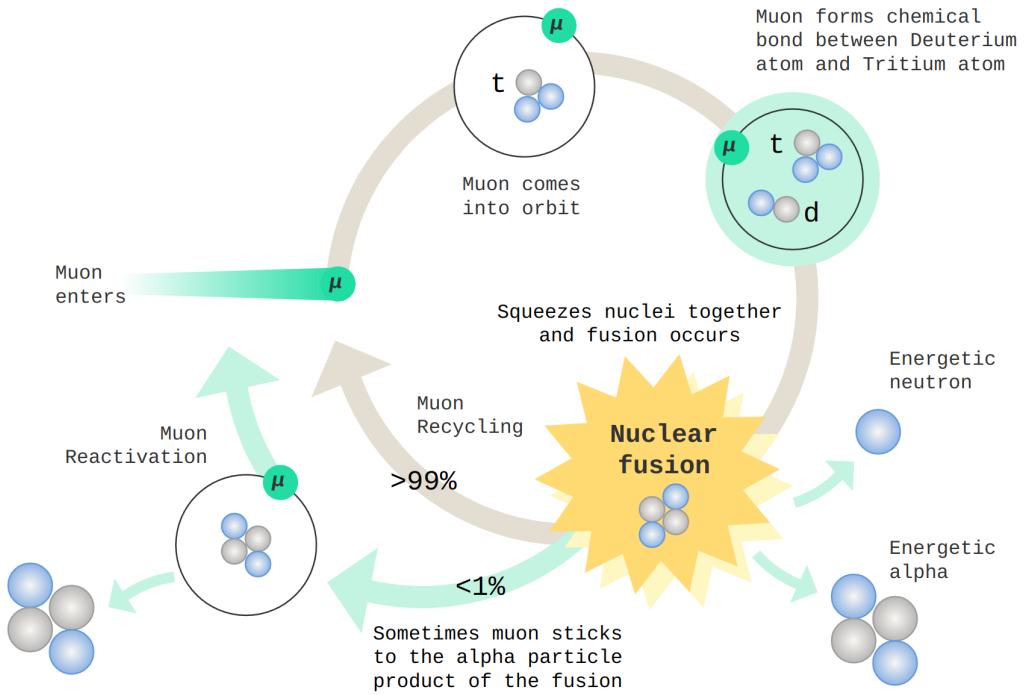
Physics & facility overview

Muon-catalyzed fusion overview



Muon-catalyzed fusion mechanism
(Image: Acceleron Fusion)

- **No inertial/magnetic confined plasma required**

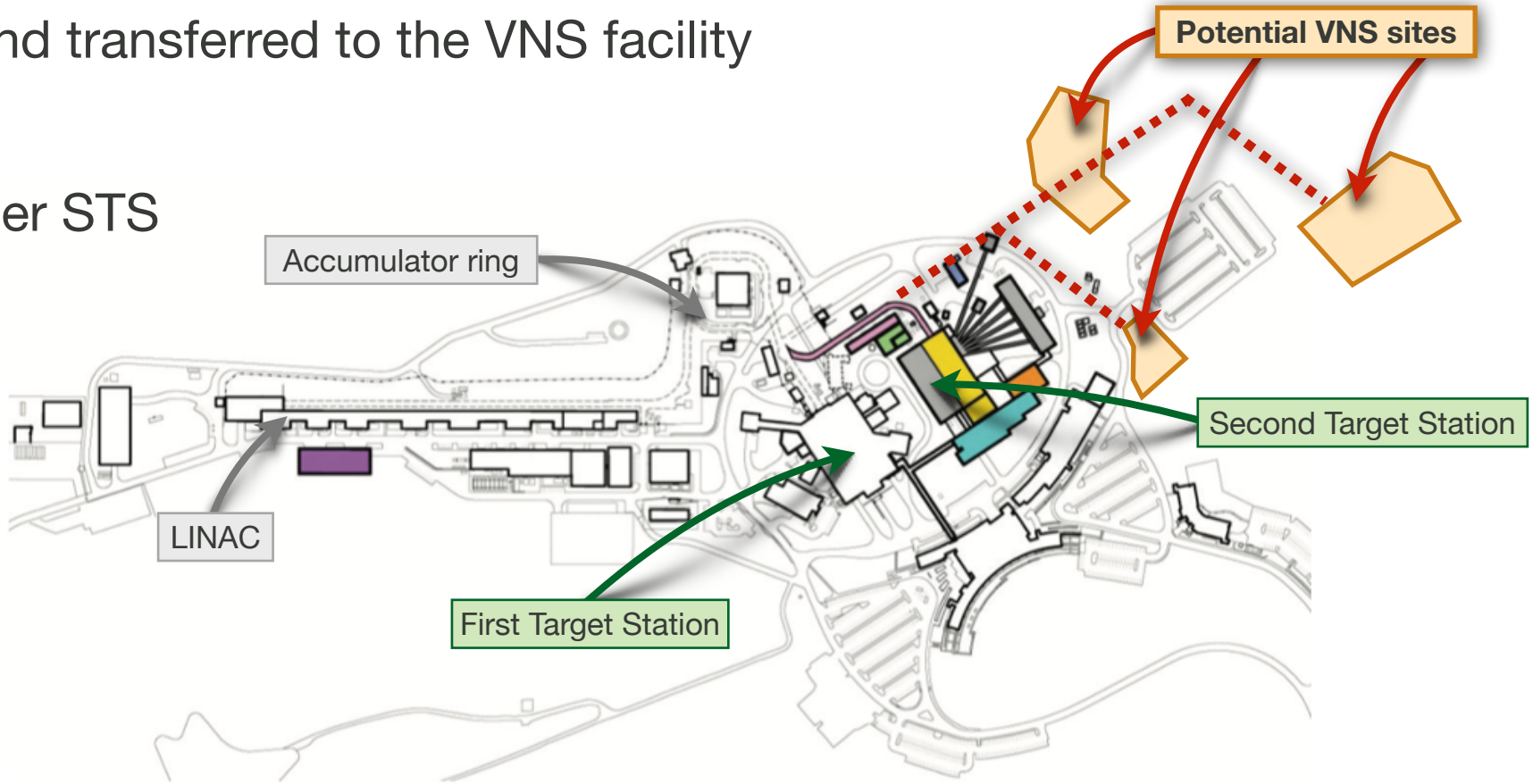
- Muonic molecules
  - Muon mass (~207×m_e) → smaller Bohr radius
- Fusion in ~10^{-12} s due to wave function overlap
  - **Catalysis**: muon is free (~99%)
  - **Sticking factor**: muon capture (e.g. α) (~1%)

- Muon lifetime: **~10^{-6} s**
- Capture to fusion: **~10^{-8} s**

} **10^2 cycles**

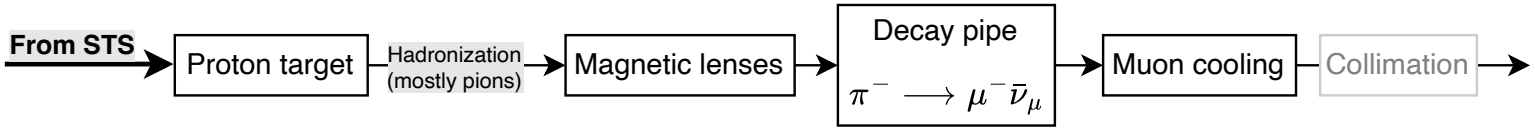
A new SNS facility

- Beam components shared with STS
- Extraction prior to STS and transferred to the VNS facility
- 100–300 kW available after STS

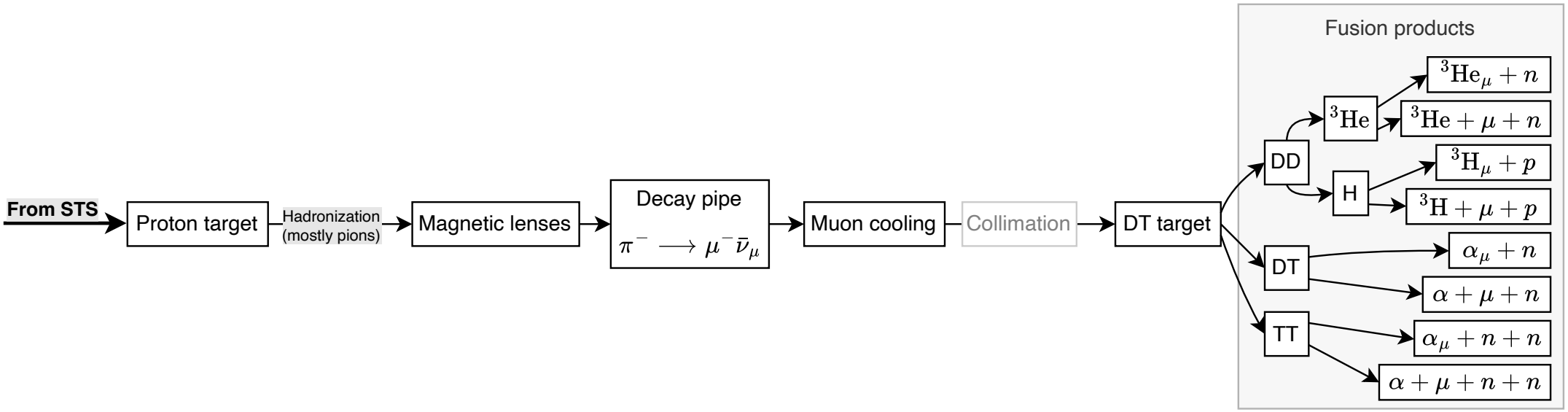


Framework overview

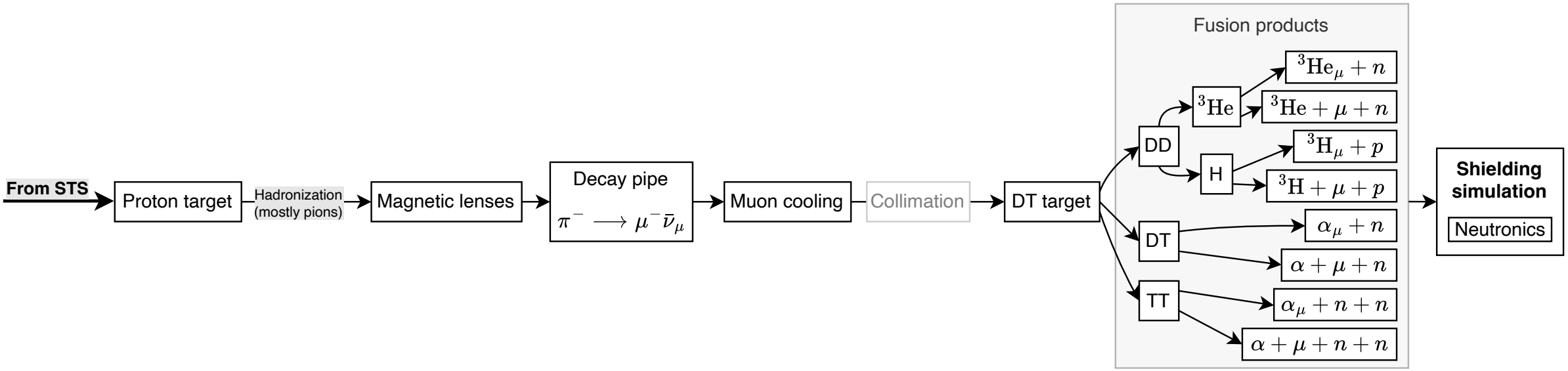
Simulation components overview



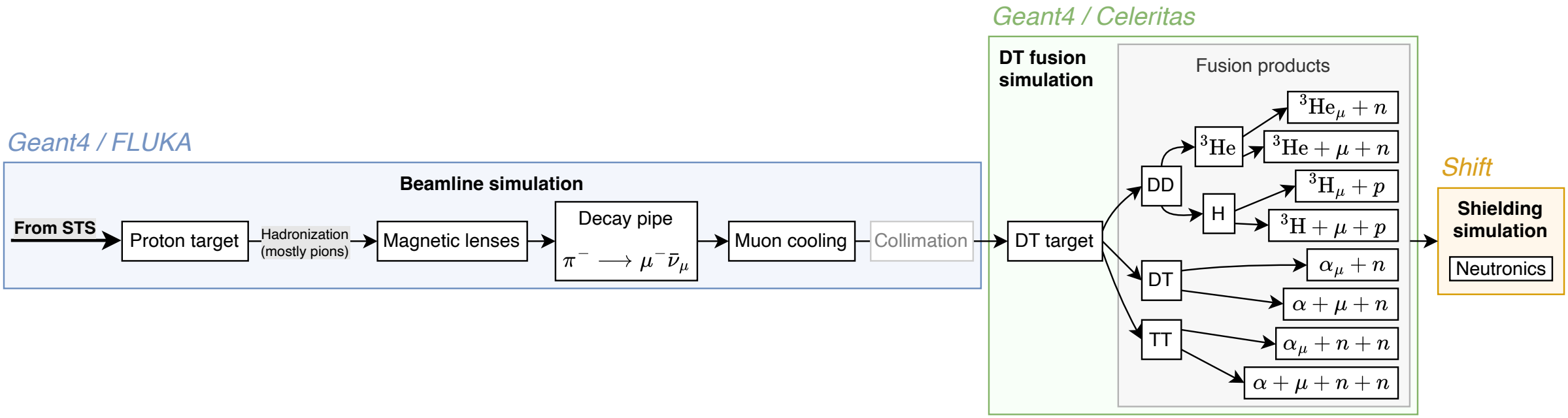
Simulation components overview



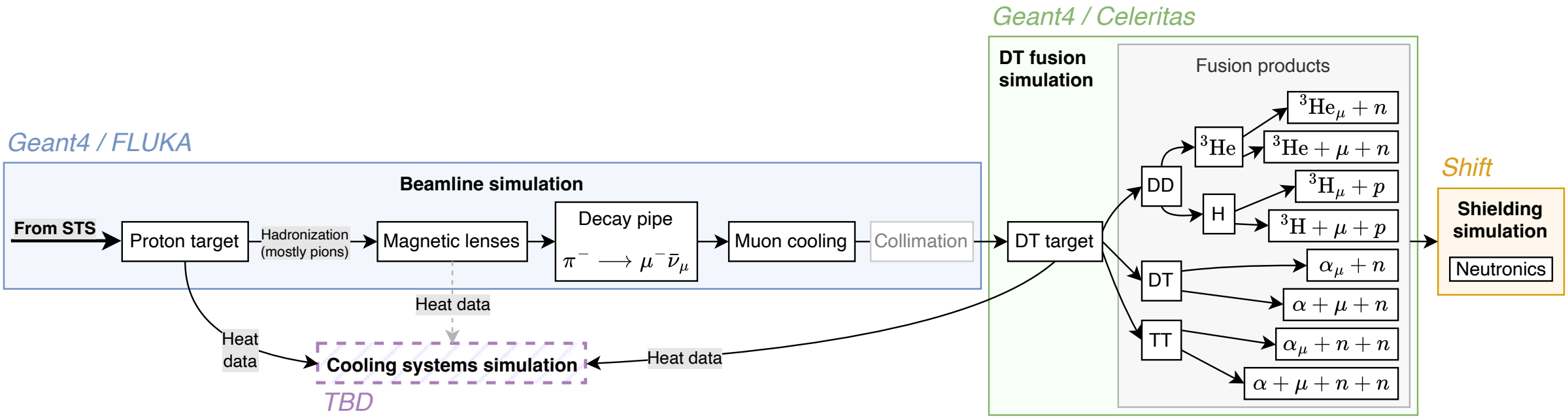
Simulation components overview



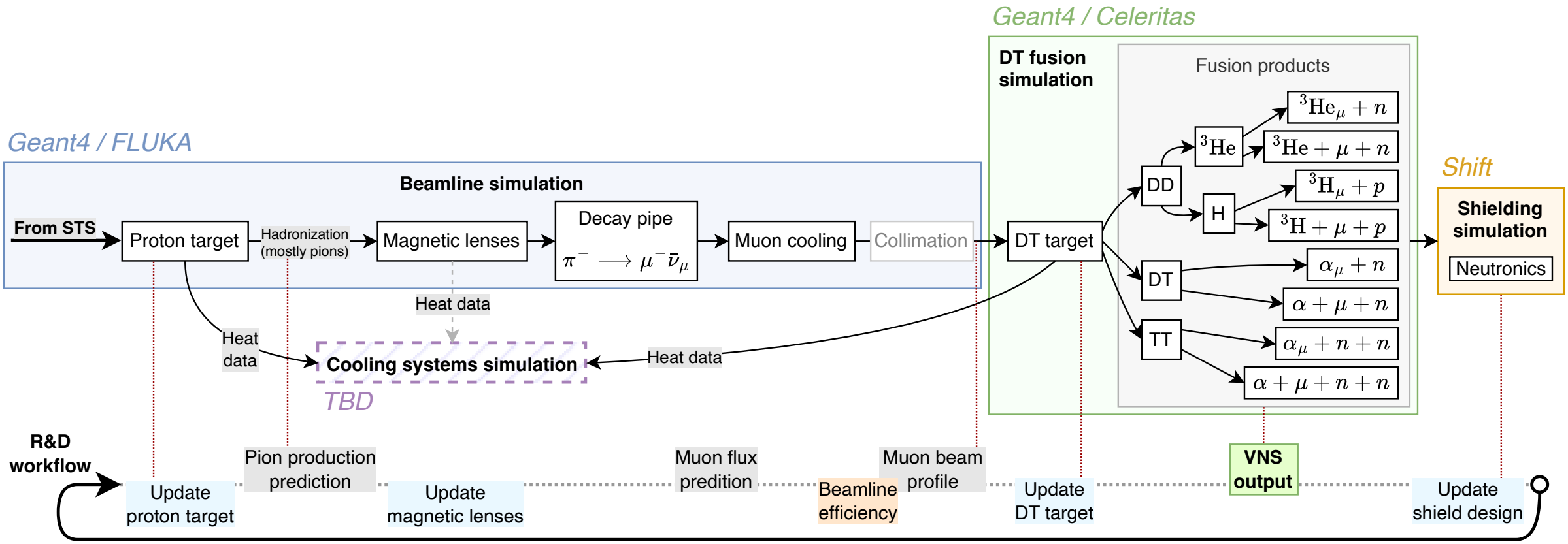
Simulation components overview



Simulation components overview

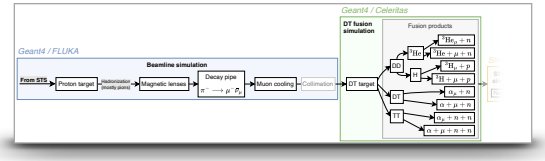


Simulation components overview



Simulation software & workflow

Geant4 overview



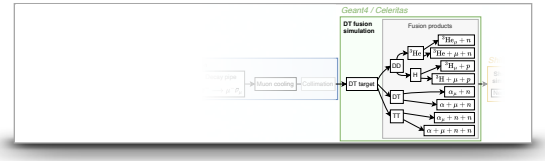
General MC particle transport code

- CPU-only, C++ library
- Used by the majority of HEP/NP experiments worldwide
- Users write their own C++ applications
- Extensible
  - Users can program new interaction models and attach them to specific particles

Used by Acceleron to simulate μCF

Celeritas overview

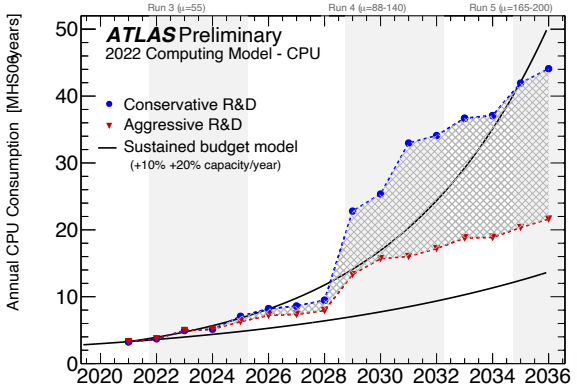
CELERITAS



GPU-optimized MC particle transport code

celeritas.ornl.gov

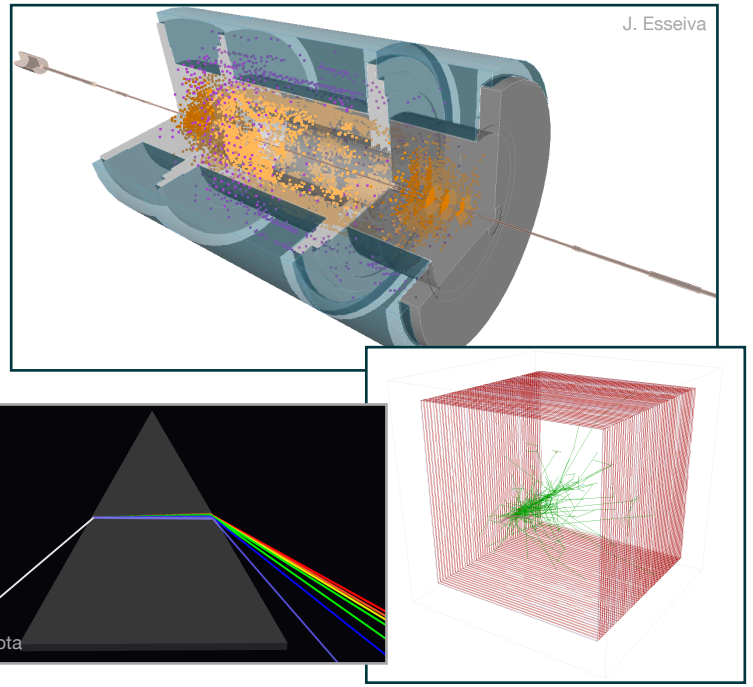
- Motivated by computational challenges on all HEP Frontiers



ATLAS Collaboration: CERN-LHCC-2022-005; LHCC-G-182

Energy	Intensity	Cosmic
• ATLAS • CMS • LHCb • ...	• DUNE • LEGEND • ...	• LZ • ...

Credit: 2014 P5 Report, Building for Discovery

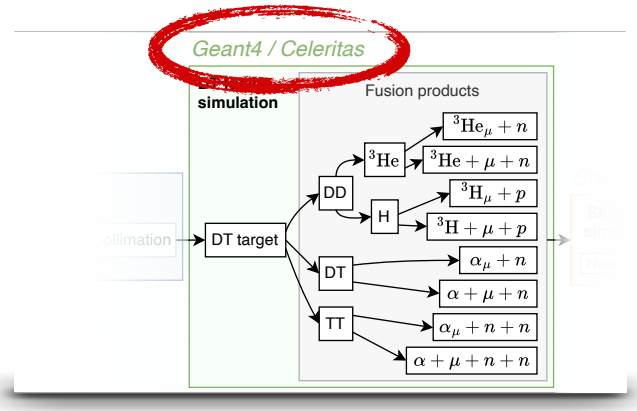


- **GOAL** Faster & more energy efficient MC simulations
- Applications go beyond HEP
  - Space, medical, **fusion**...

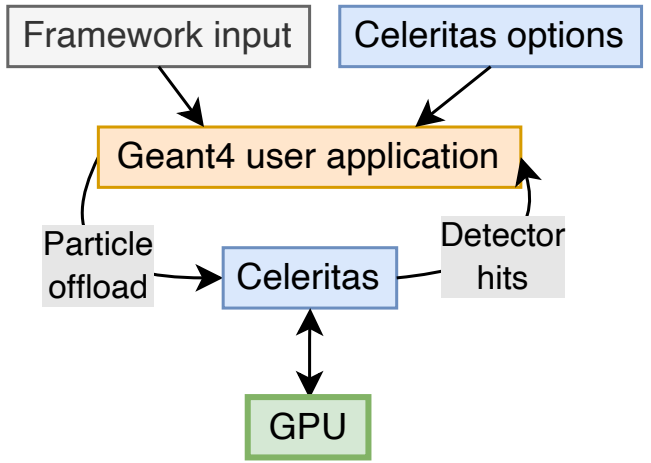
Informal core collaborators

OAK RIDGE National Laboratory

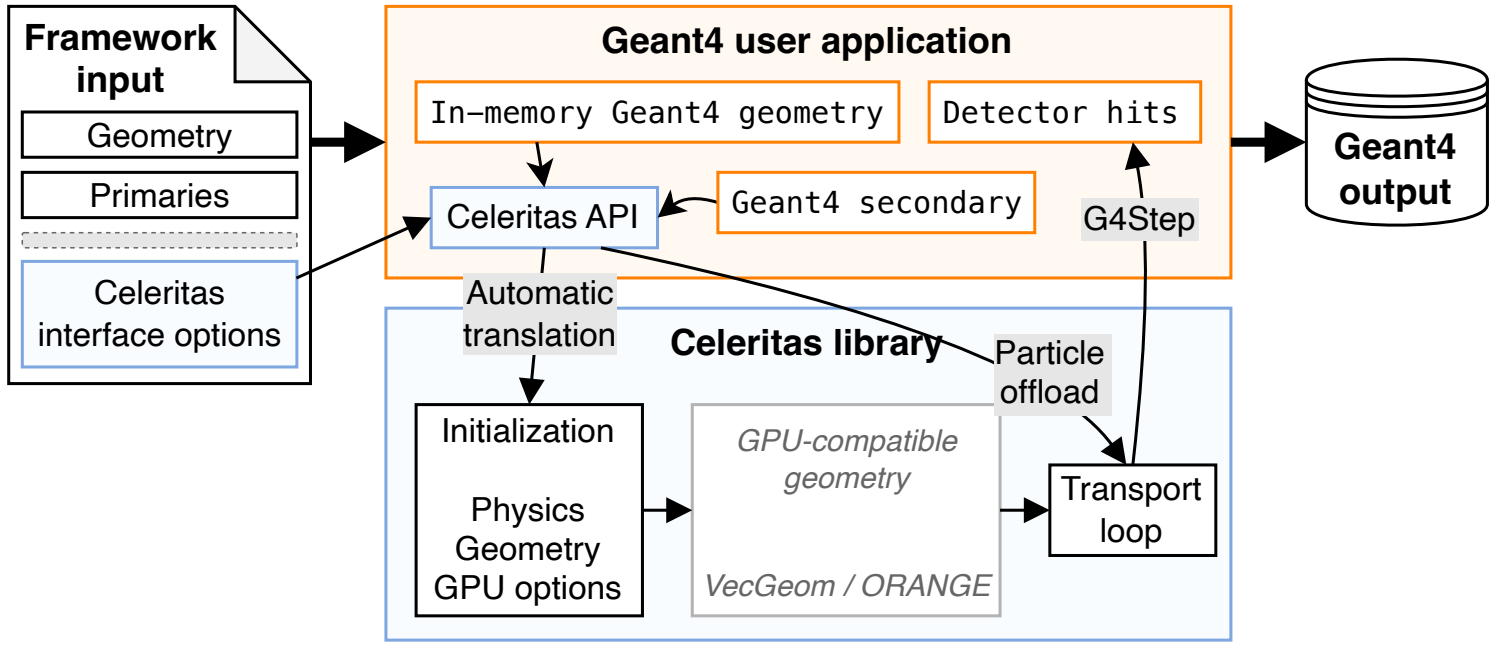
Celeritas–Geant4 API



Geant4–Celeritas interface overview

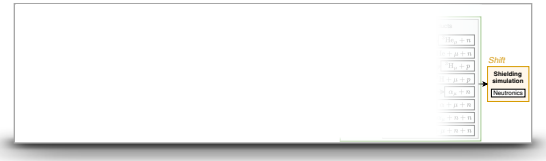


Detailed view



Integration should be transparent to existing Geant4 workflows

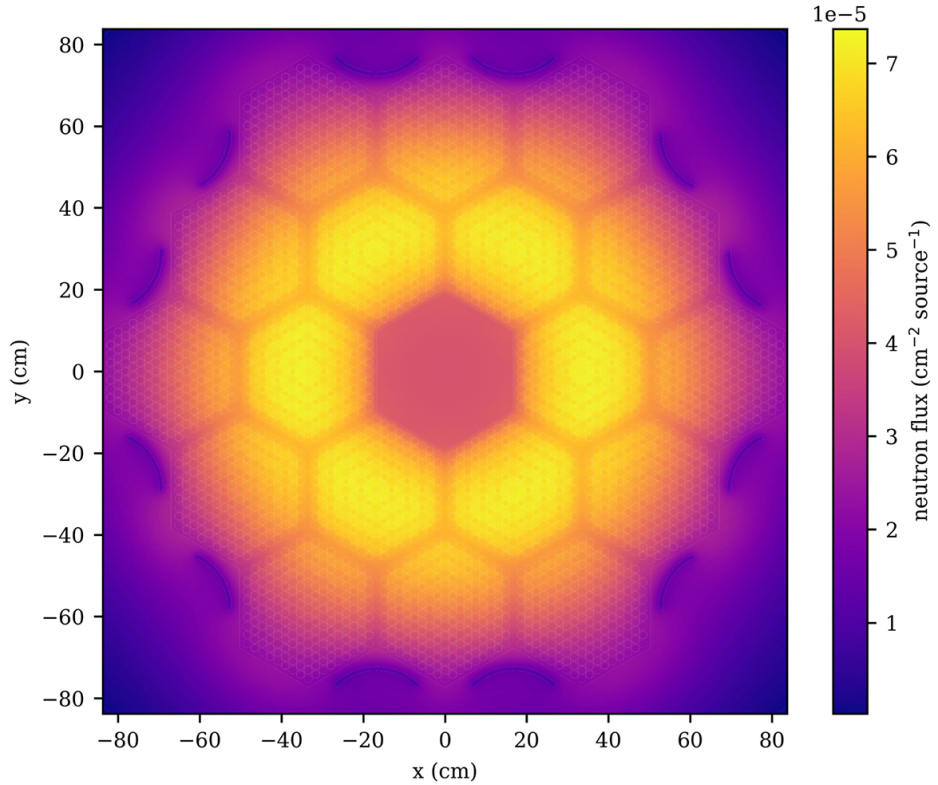
Shift overview



GPU MC code for neutron transport

- Developed at ORNL and distributed with the SCALE package
- CPU- and GPU-compatible (platform-portable)
- Provide estimates for the facility's shielding
- Coupled neutron transport and thermal hydraulics (Can help with the DT target cooling system R&D)

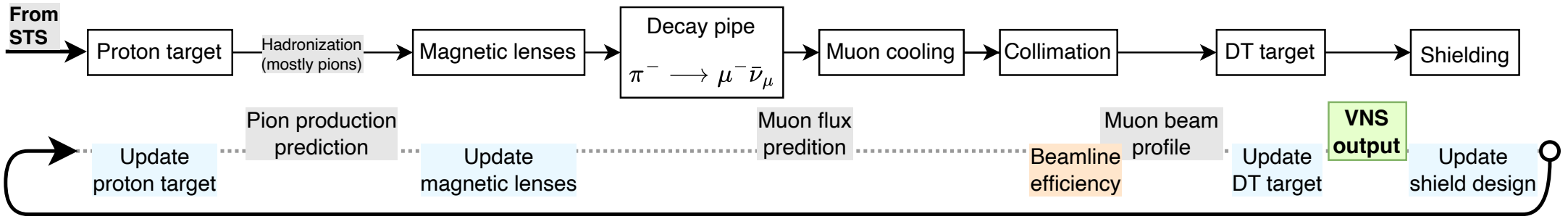
E. Biondo, *et al.* "Status of GPU capabilities within the Shift Monte Carlo radiation" transport code". EPJ Nuclear Sci. Technol. 11, 5 (2025)



Neutron flux through the EMPIRE microreactor benchmark problem

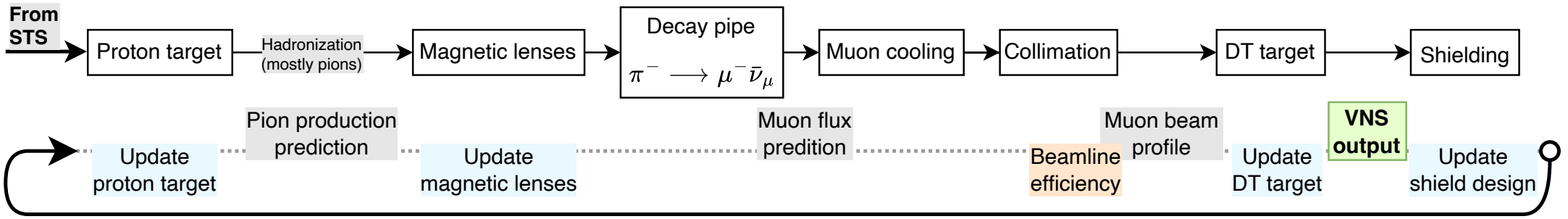
C. Lee, *et al.* Technical Report ANL/NSE-20/23 and INL/LTD-20-59263 (2020)
C. Matthews, *et al.* Nuclear Technology, 207(7):1142–1162 (2021)

Framework workflow



1. **DT target**
   - neutrons per μ × μ per bunch × bunches per second
   - Can a SNS beamline + target produce > 10^{15} n/s?
2. **Proton target**
   - POT → pions: can it generate N_μ per bunch required in **(1)**?
3. **Beamline** (from POT to muons)
   - Pion focusing + losses + muon cooling + collimation → muons per bunch needed by **(1)**
4. **Shielding**
   - Once VNS numbers are set, iterate for optimal design

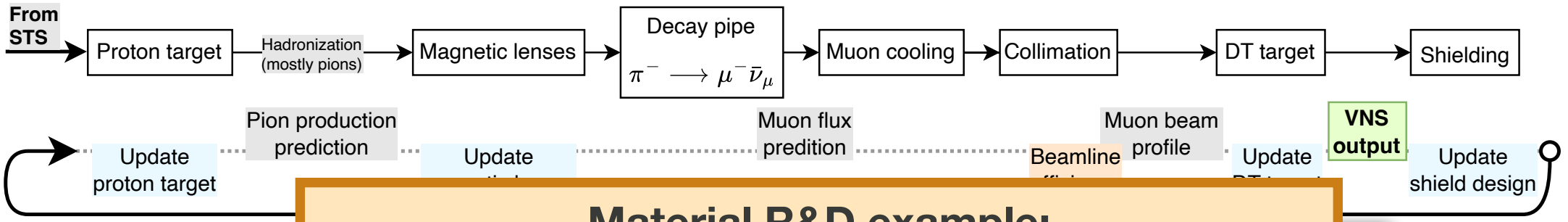
Framework workflow



Shared Acceleron/ORNL expertise, infrastructure, and software

- **Phase I**: Feasibility study
  - Consolidate main simulation components; confirm scientific viability of a VNS
- **Phase II**: Full facility R&D
  - Achieve a matured simulation workflow
  - **Used beyond commissioning/upgrades**
    - Test new physics models; provide input data for facility users

Framework workflow



Shared A …**are**

- **Phase I**: Feasibility
  - Consolidate ma… a VNS
- **Phase II**: Full facili…
  - Achieve a matu…
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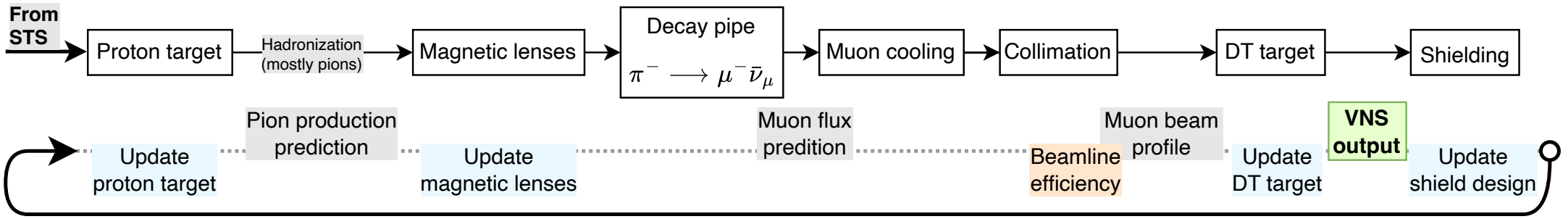
Material R&D example:

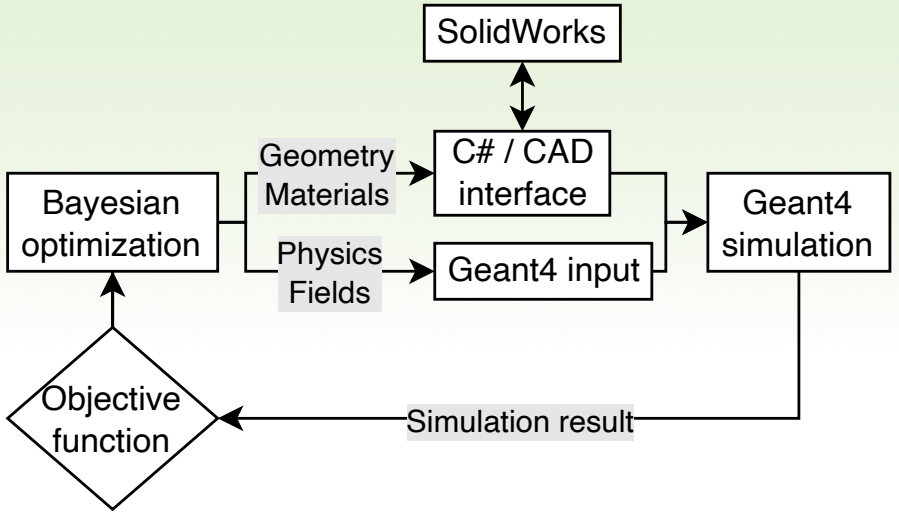
- **VNS**: provides (via this framework):
  - Neutron flux + deposited energy
- **Users**: Validate theoretical material degradation in their own workflows (via MeV/s → watt) and compare with experimental data

Framework workflow



Shared Acceleron/ORNL expertise, infrastructure, and software

- Acceleron Fusion workflow
  - Bayesian optimization loop
  - Integrates CAD with Geant4



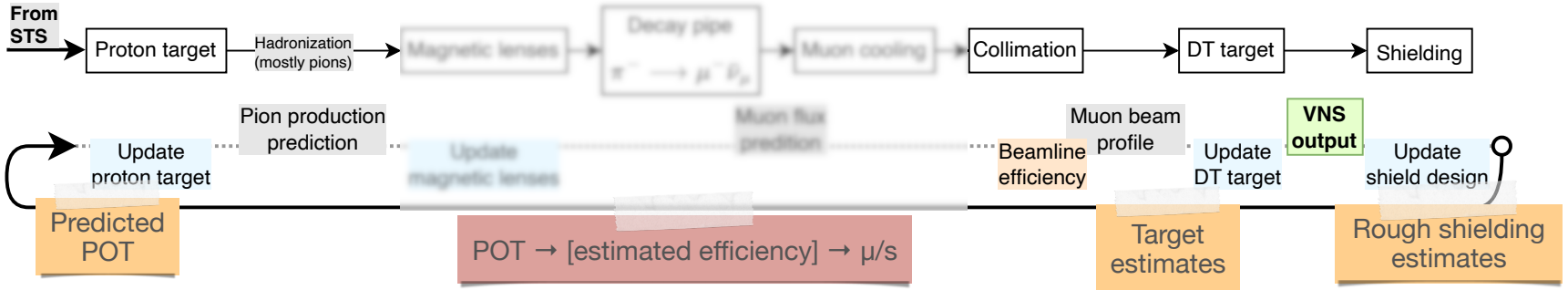
- Already in place
- Little changes required for Phase I estimates

Phase I

Feasibility study

Phase I: Feasibility study

- **Not a full workflow**



- Some components will be abstracted
  - Within SNS constraints, can we generate a reasonable muon beam profile?
  - Can this muon beam produce 10^{15}–10^{17} n/s in a reasonable DT target?

Main goal: VNS output for optimistic & pessimistic scenarios

Phase II

Facility R&D

Phase II: Facility R&D

- **Fully-fledged workflow**
  - Iterative loop spanning a large phase-space for optimizing multiple components
  - Back-and-forth between simulation output and engineering/cost limitation
  - Might require more components than currently sketched out

- At least 1 FY away

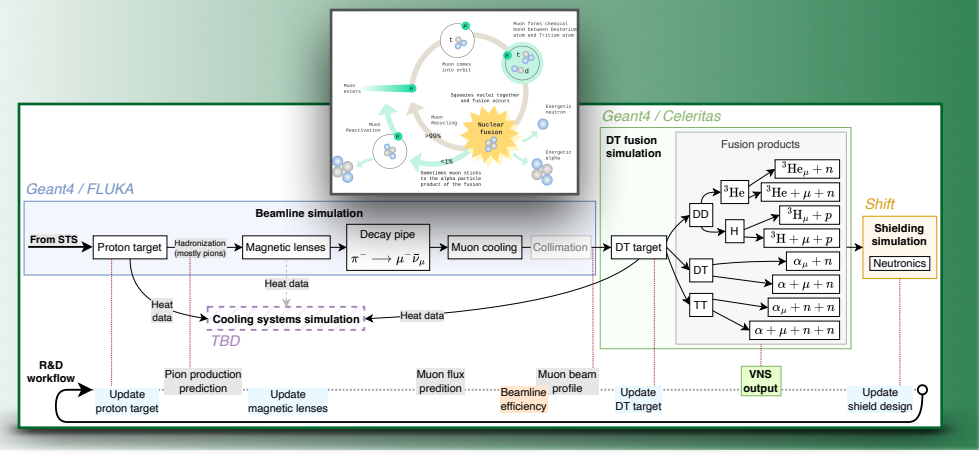
- Maximizing HPC usage will be fundamental
  - Larger phase-space for R&D → better facility

Summary

1. Preliminary computational framework design

2. HPC capability (Phase II)
   - Celeritas: μCF physics
   - Shift: Neutronics

3. Framework long-term usage
   - Upgrades/maintenance
   - Physics research
   - Provide data for users



Public-private partnerships

acceleron

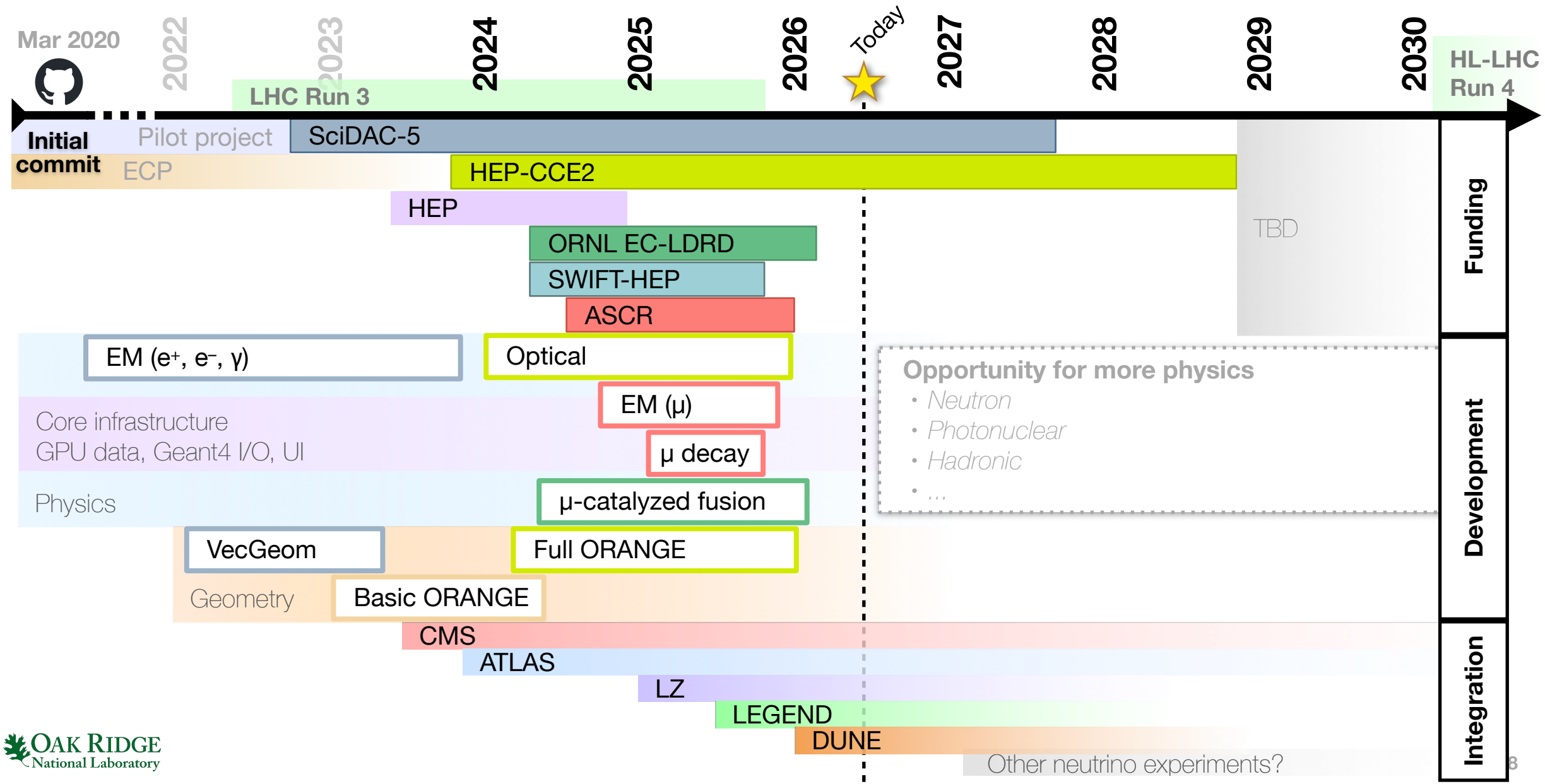
Thank you

Questions and discussion

BACKUP

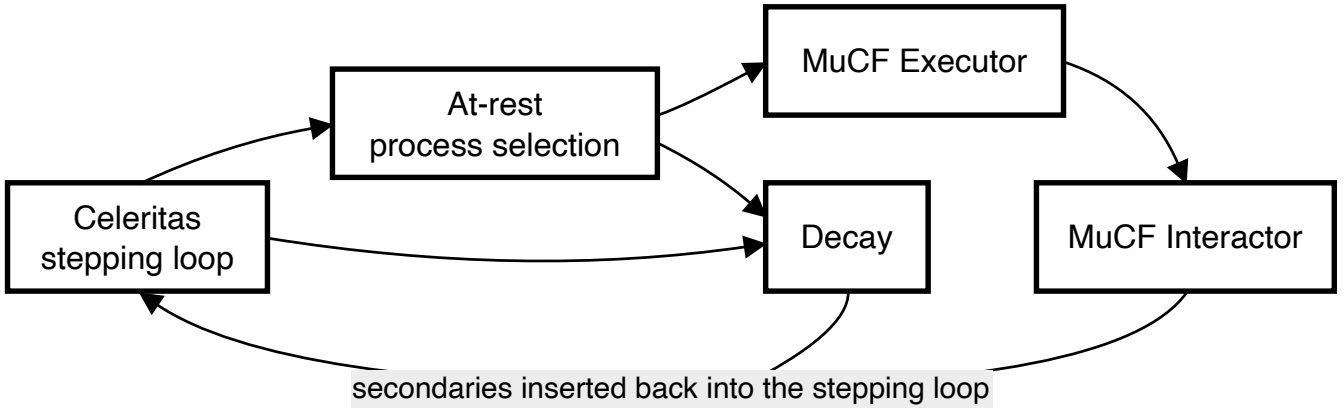
Updated timeline based on https://meetings.aps.org/Meeting/APR24/Session/D14

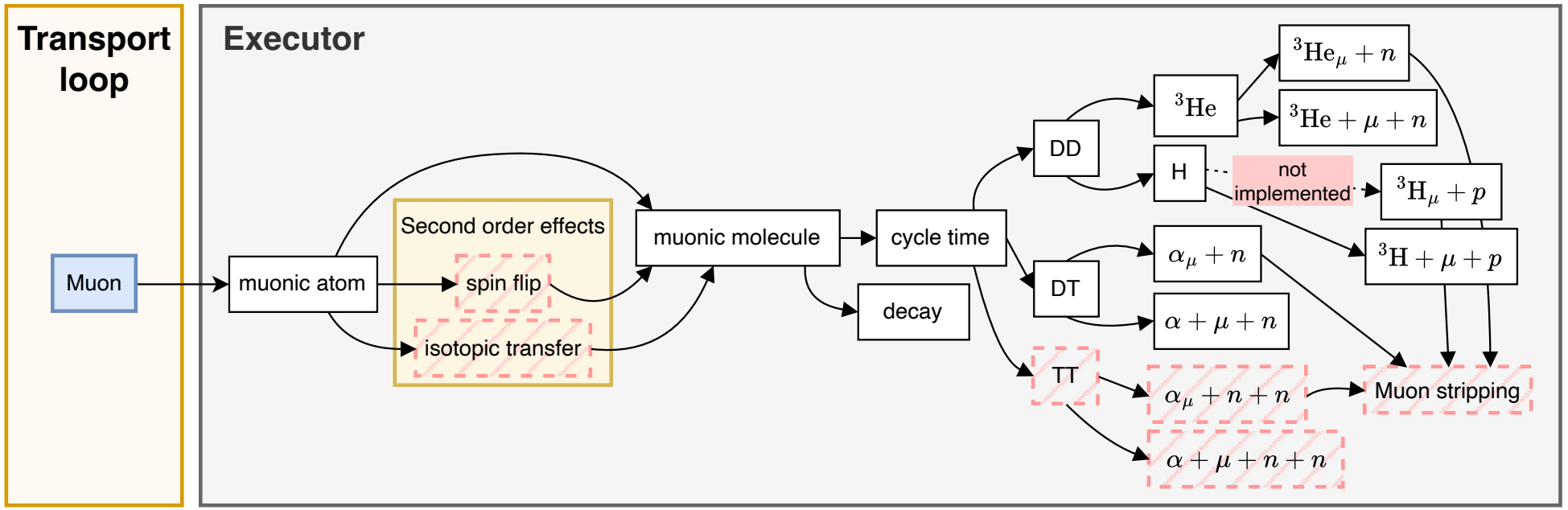
Celeritas overview



Celeritas: muon-catalyzed fusion

- Physics mostly implemented
- Missing addition to the stepping loop
- Ongoing validation



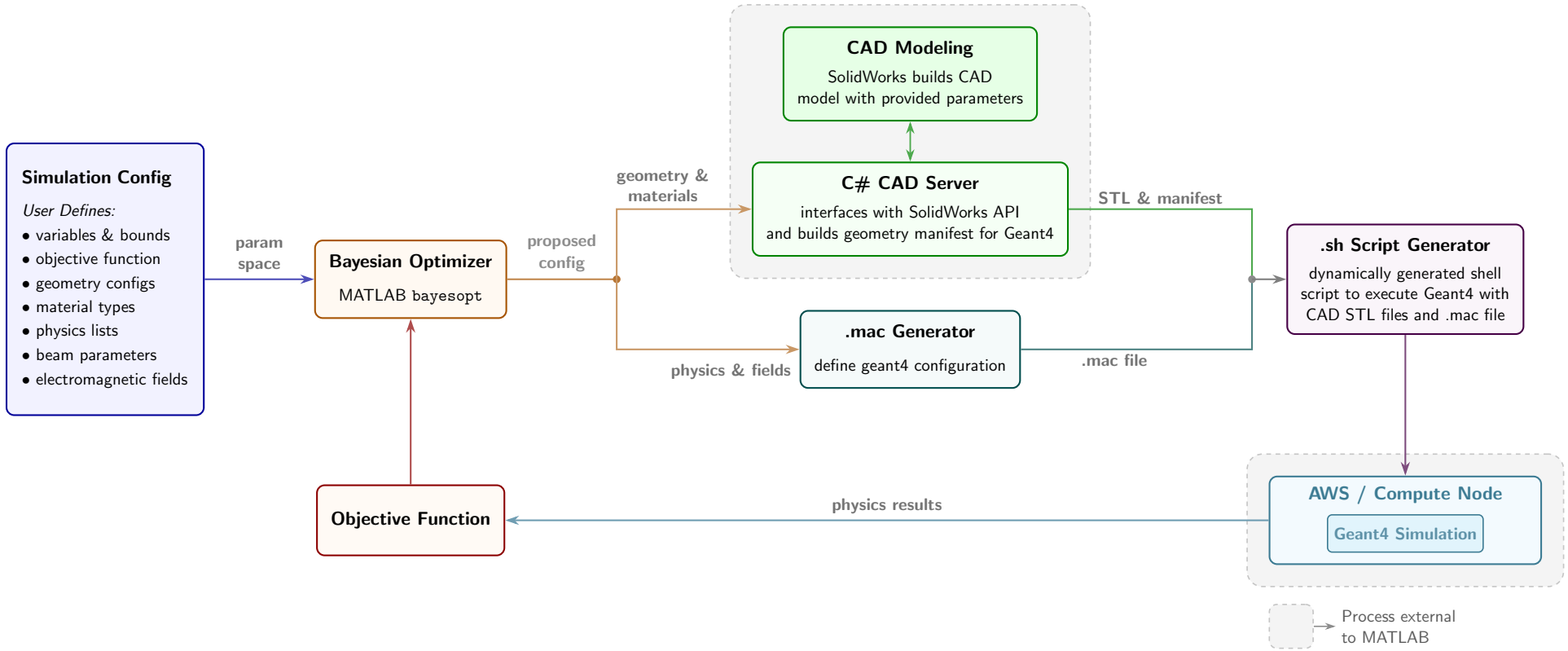


Acceleron simulation framework

Slide from Sam Novario, Acceleron

Acceleron simulation framework

acceleron



Acceleron simulation framework

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Muon-Catalysed Fusion Cycle in a DT Cell