National Aeronautics and Space Administration

Shields Up! Towards Forecasting Solar Particle Threats through Simulation

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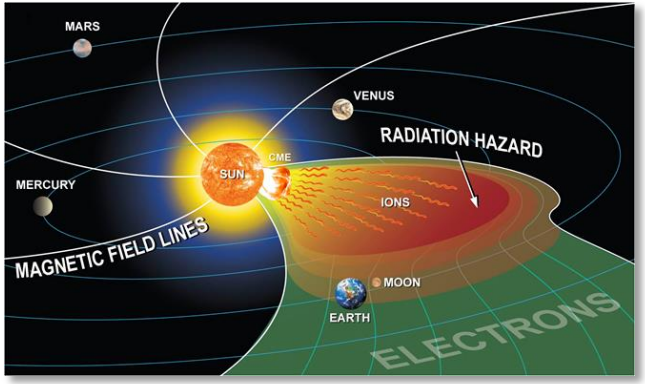
Solar Storms

- **Large explosive events on the Sun including solar flares and coronal mass ejections (CME)**
- **CMEs can eject billions of tons of magnetized million-degree plasma out into space**
- **CME impacts on Earth can cause interference and damage to electronic infrastructure including GPS satellites and the power grid**

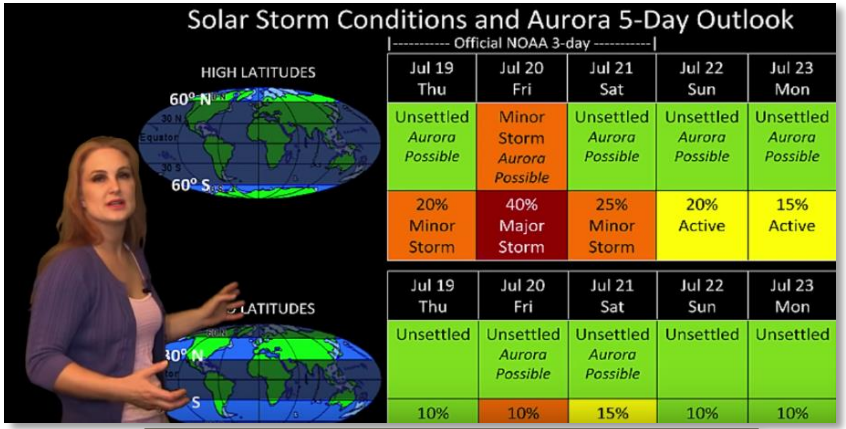
Solar Particle Events (SPE)

- **Both solar flares and CMEs can greatly accelerate solar wind particles causing a Solar Particle Event (SPE)**
- **SPEs pose many dangers including:**
  - Damaging solar cells in satellites
  - Harming aircraft avionics, communication, and navigation systems
  - Posing radiation risks to aviation flight crews and passengers in high-altitude/polar flights, as well as potentially leathal radiation exposure to astronauts, both in low-Earth orbit and future lunar/interplanetary missions



SPE Forecasting

- **Due to hazard of SPEs, forecasting is a major goal**
- **Very difficult to do!**
  - SPEs arrive at Earth in just hours
  - Mechanisms for solar energetic particle (SEP) acceleration are not fully understood – but CMEs are known drivers

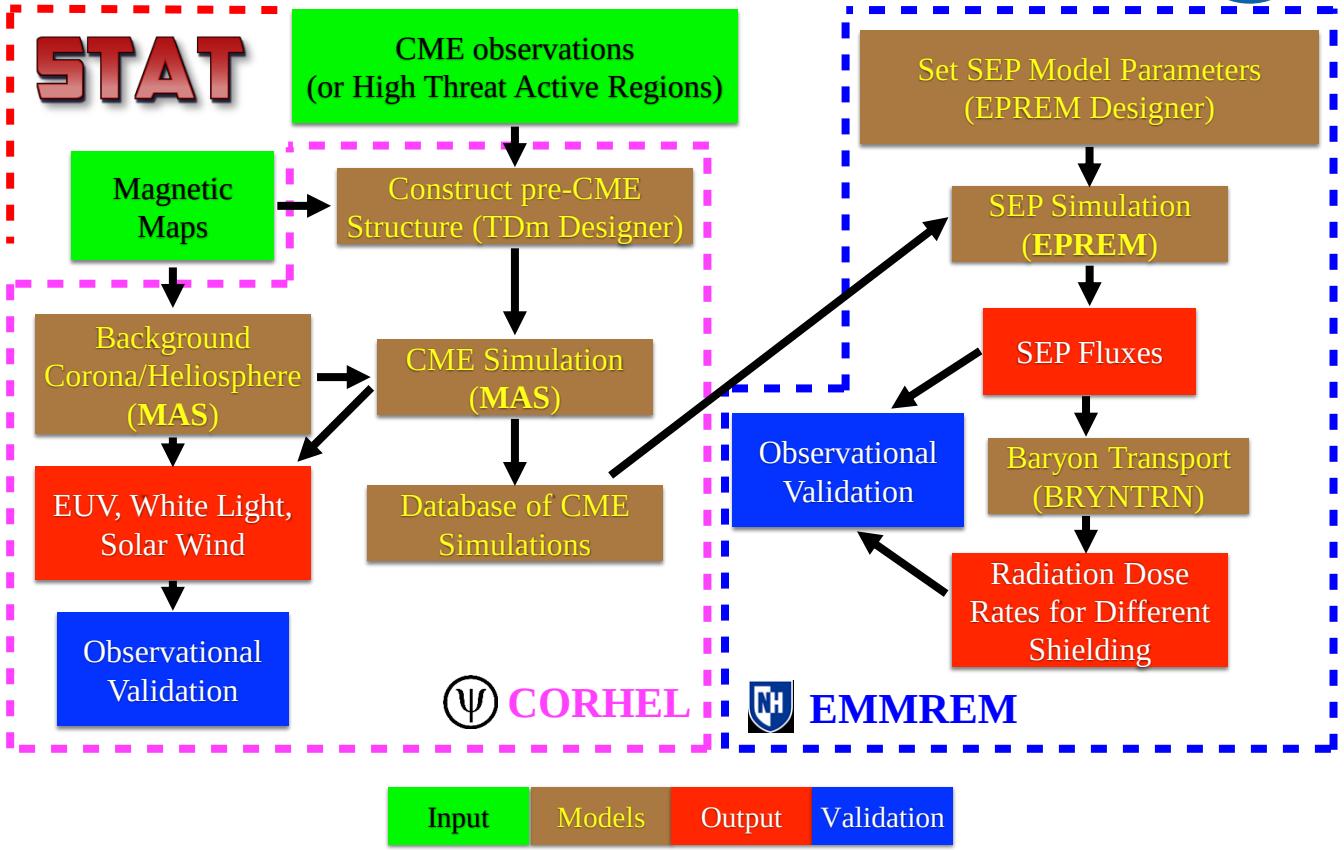


Tamitha Skov https://www.youtube.com/user/SpWxfx/

- **Observational-based forecasting (statistical methods, AI, phenomenological ensemble modeling)**
- **Model-based forecasting (physical simulations) – very challenging to include the required level of physics and resolution**
- **Combinations (use previous simulation results to help predict future events)**

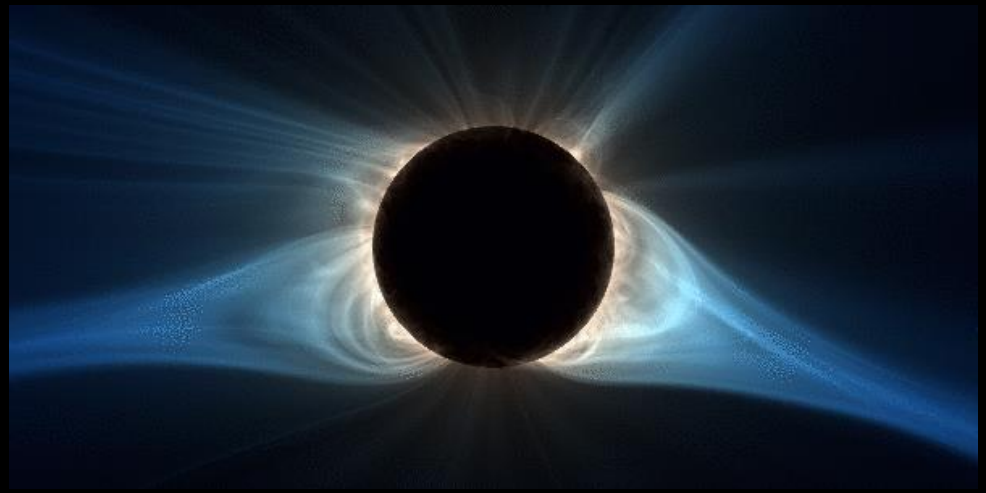
SPE THREAT ASSESSMENT TOOL

- **Simulation-based modeling suite for CME-driven SPEs**
- **Combines magnetohydrody namic model (MAS) of CME with constrained transport SEP code (EPREM)**

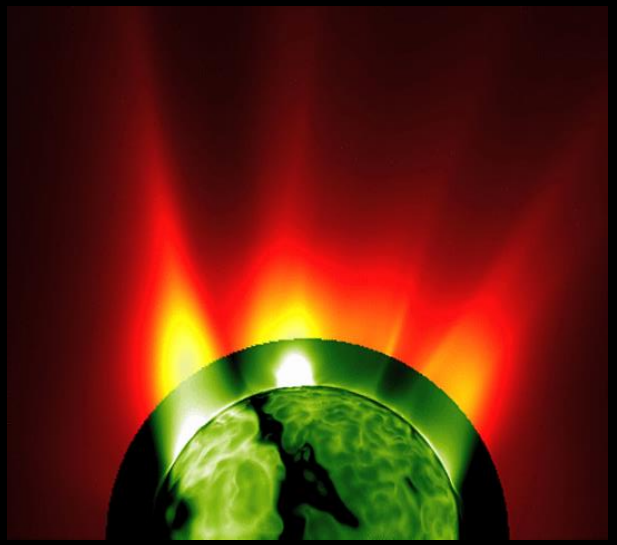


MAS
MAGNETOHYDRODYNAMIC ALGORITHM OUTSIDE A SPHERE

- Established finite-difference MHD code with over 15 years of development used extensively in solar physics research
- Written in FORTRAN 90 (~50,000 lines), parallelized with MPI
- Available for use at the **C**ommunity **C**oordinated **M**odeling **C**enter (CCMC)



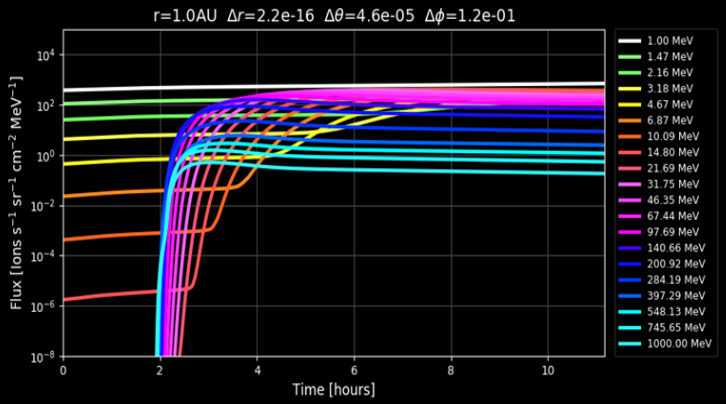
Predicted Corona of the August 21st, 2017 Total Solar Eclipse

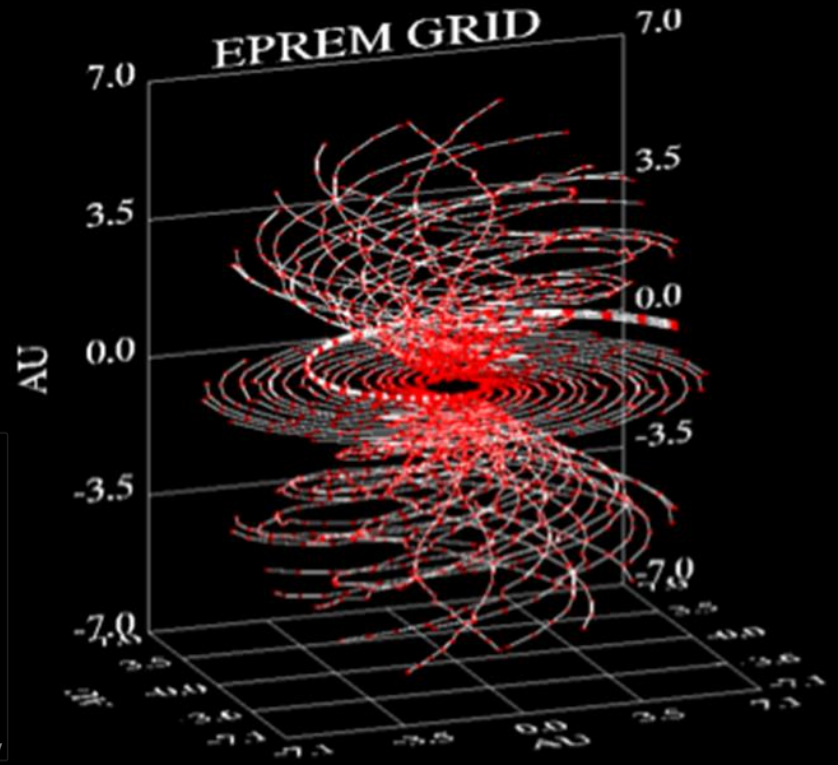


Simulation of the Feb. 13th, 2009 CME

EPREM ENERGETIC PARTICLE RADIATION ENVIRONMENT MODULE

- SEP simulations using focused transport in a Lagrangian frame
- C code (~13,000 lines) parallelized with MPI
- Available for use at the CCMC





HPC Computations

NAS's Pleiades & Electra

- SGI (MPT MPI)
- InfiniBand set in a partial hypercube topology
- Multiple processor types
- Combined, ranks 17th fastest HPC system by June 2018 Top500.org

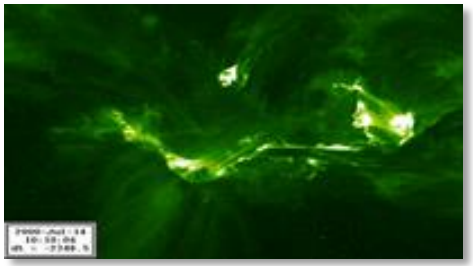
sgi

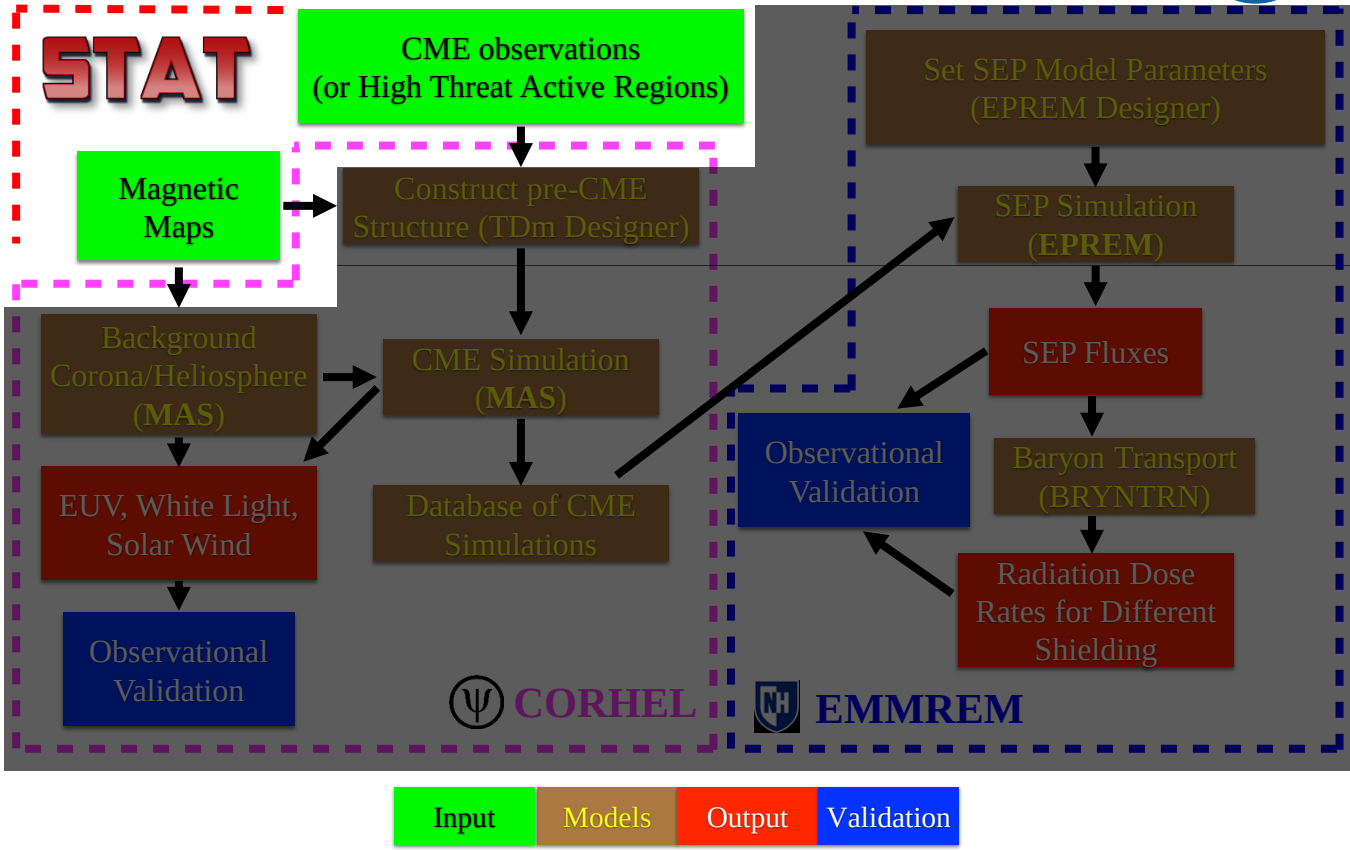
INFINIBAND™

TOP 500 The List. 17th*

Observations

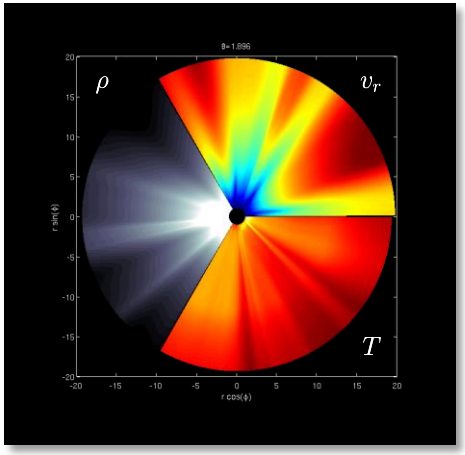
- **Surface Magnetic Field Maps**
- **Images of CME eruptions (past events) or threatening potential storm sites**

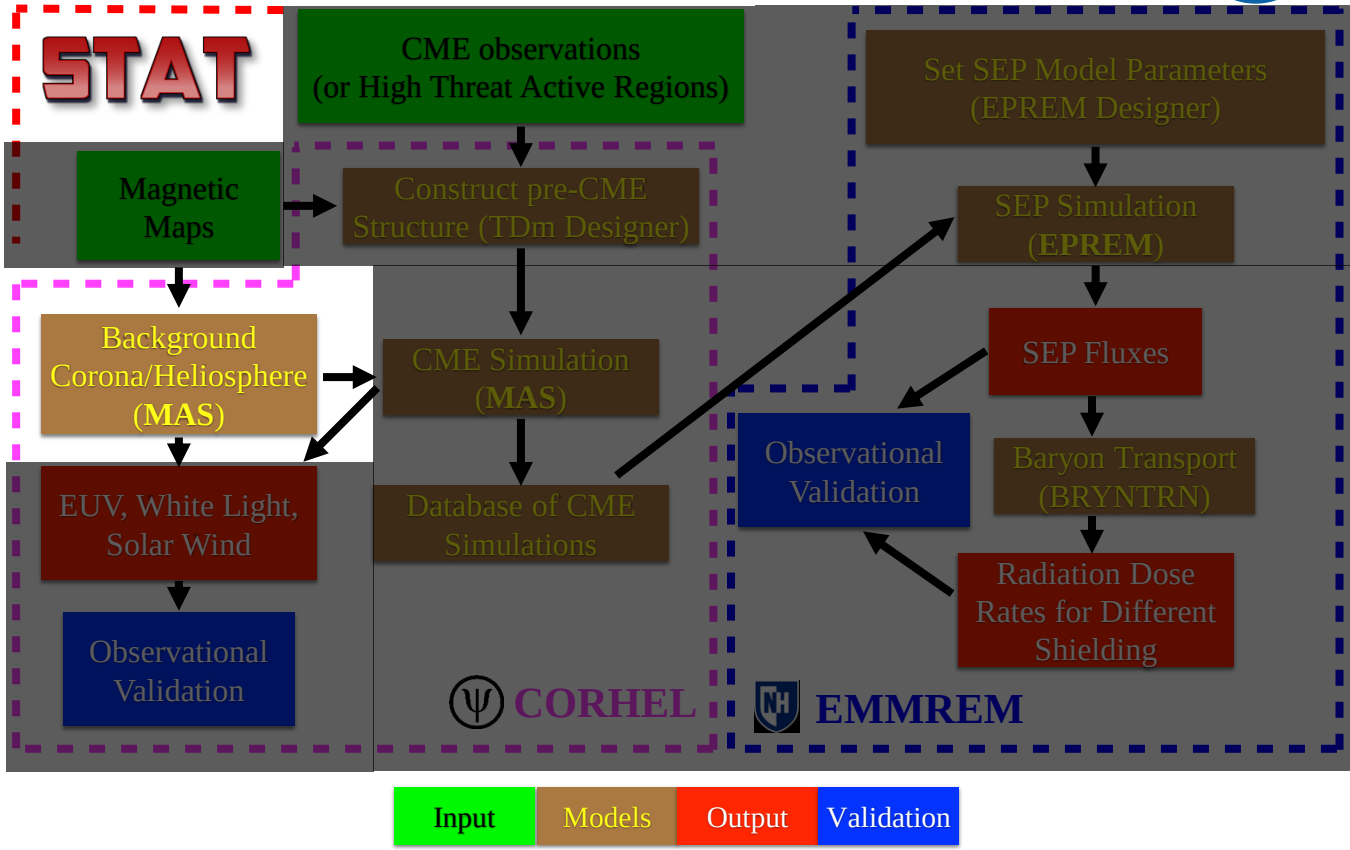




Background Heliosphere Simulation

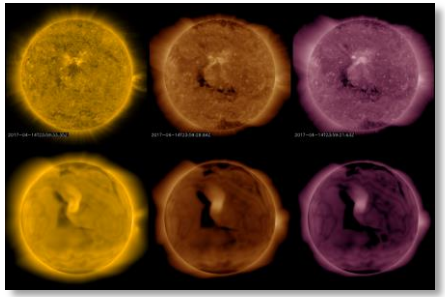
- **Use MAS to integrate heliosphere to steady-state**
- **Solution used as "back-drop" for CME simulations**

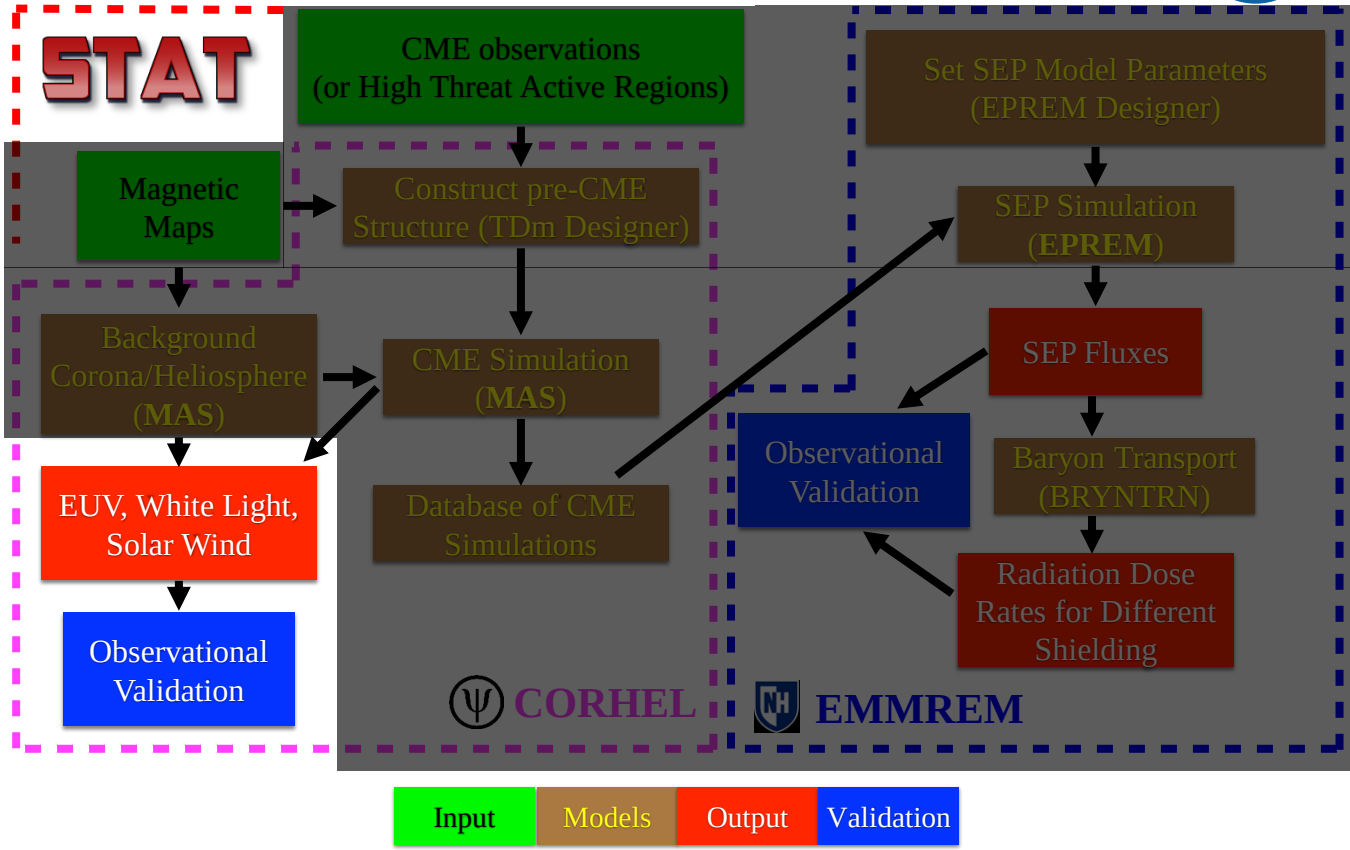




Validation with Synthetic Observables

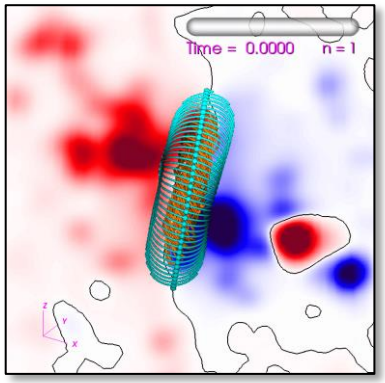
- **Synthetic observables computed from MHD solution – e.g. EUV and white light images, solar wind measurements, etc.**
- **Comparisons to observations used to validate and refine parameters**

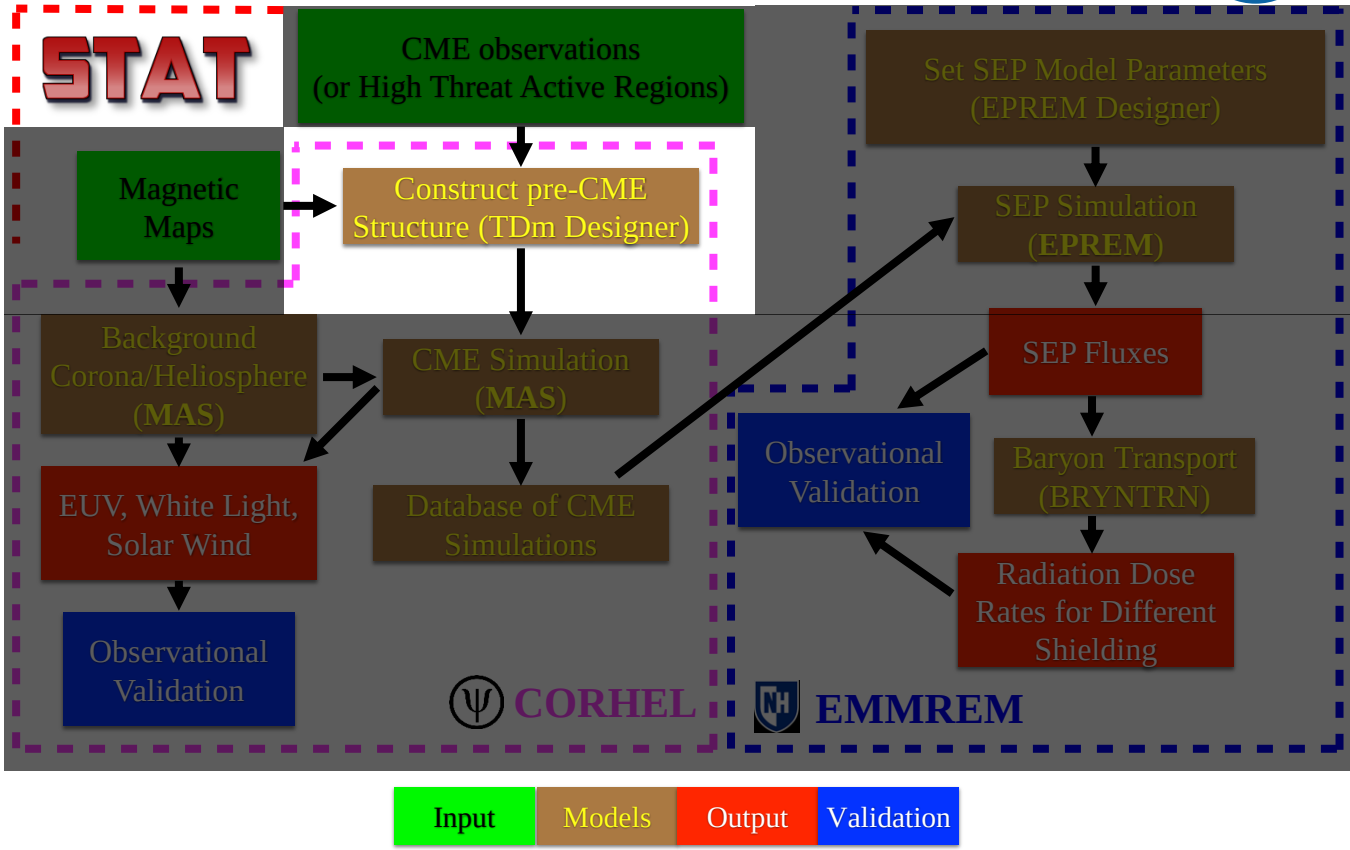




Design Pre-Eruption CME Structure

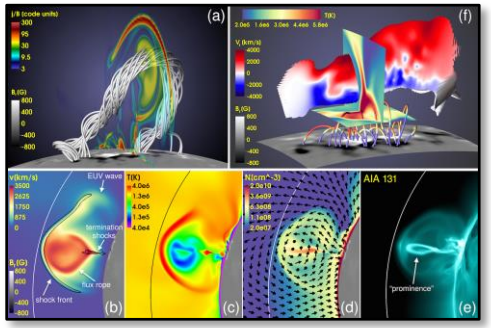
- **Web-based interface to design pre-CME structure**
- **Uses MAS simulation with reduced physics to relax solution to steady-state**

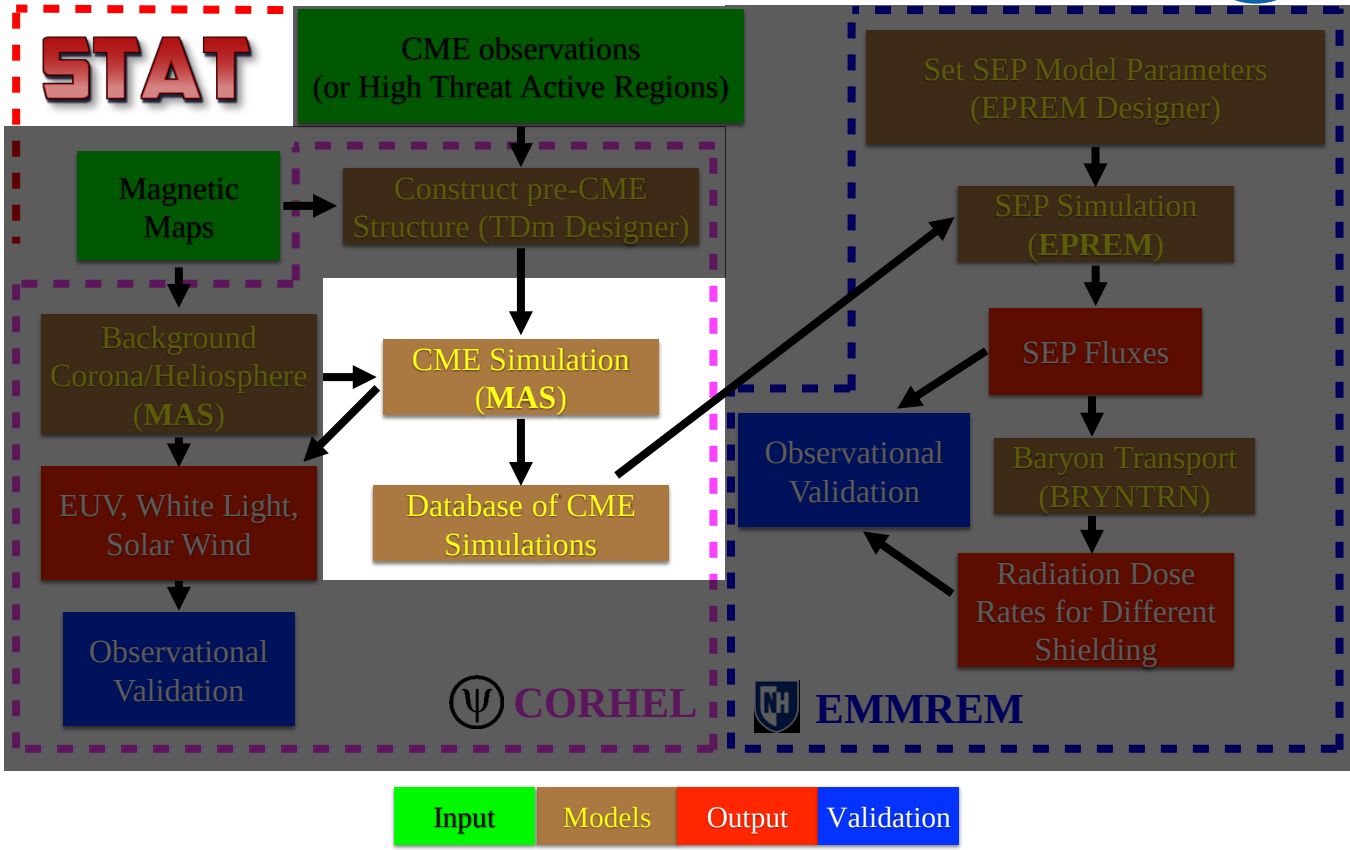




Simulation of CME Eruption

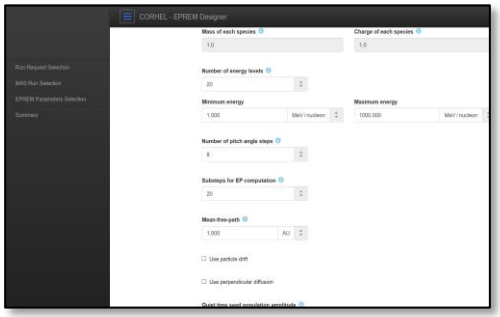
- **Large simulations using MAS**
- **Modifies surface flows/fields to erupt CME**
- **Store resulting data into CME database for use with EPREM**

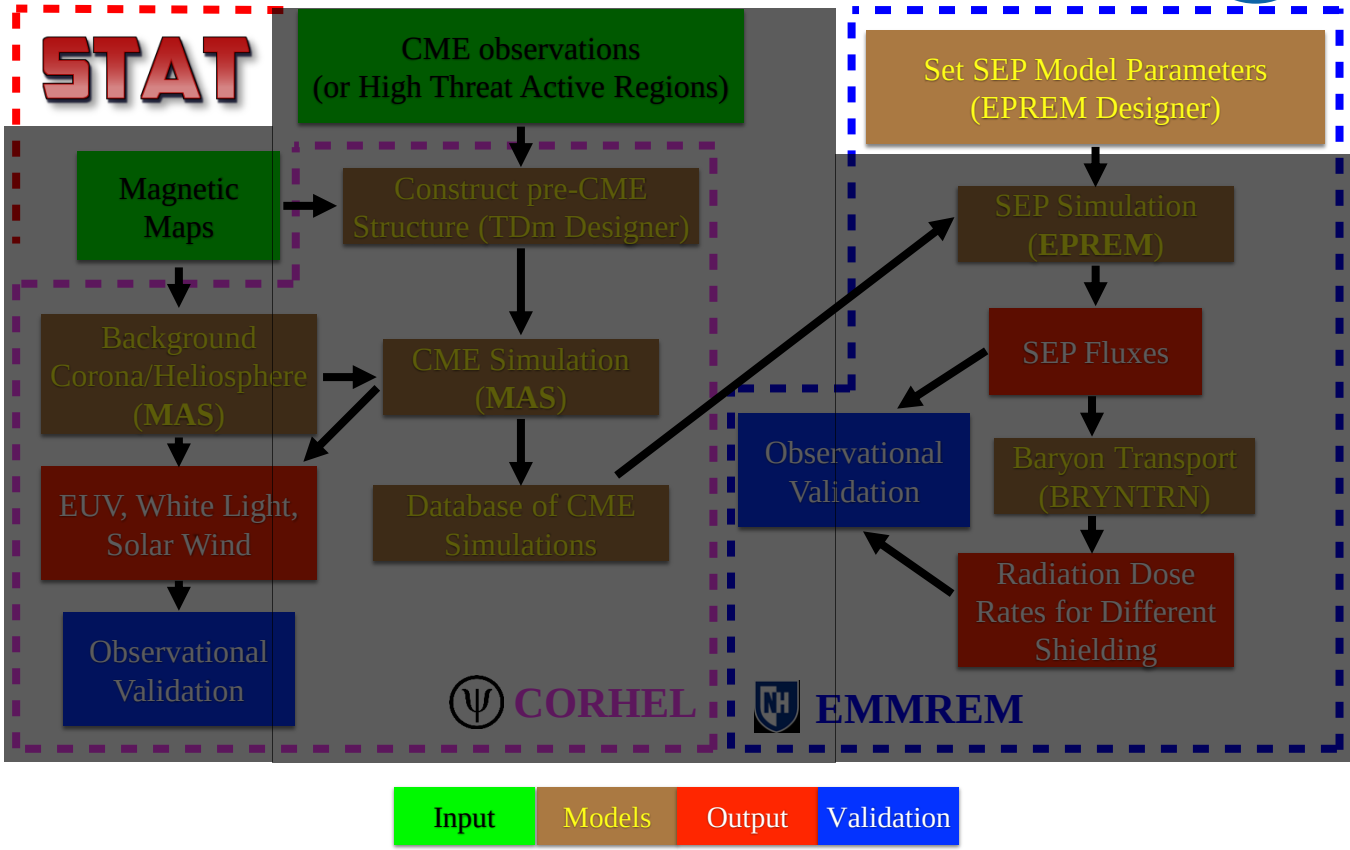




SEP Simulation Setup

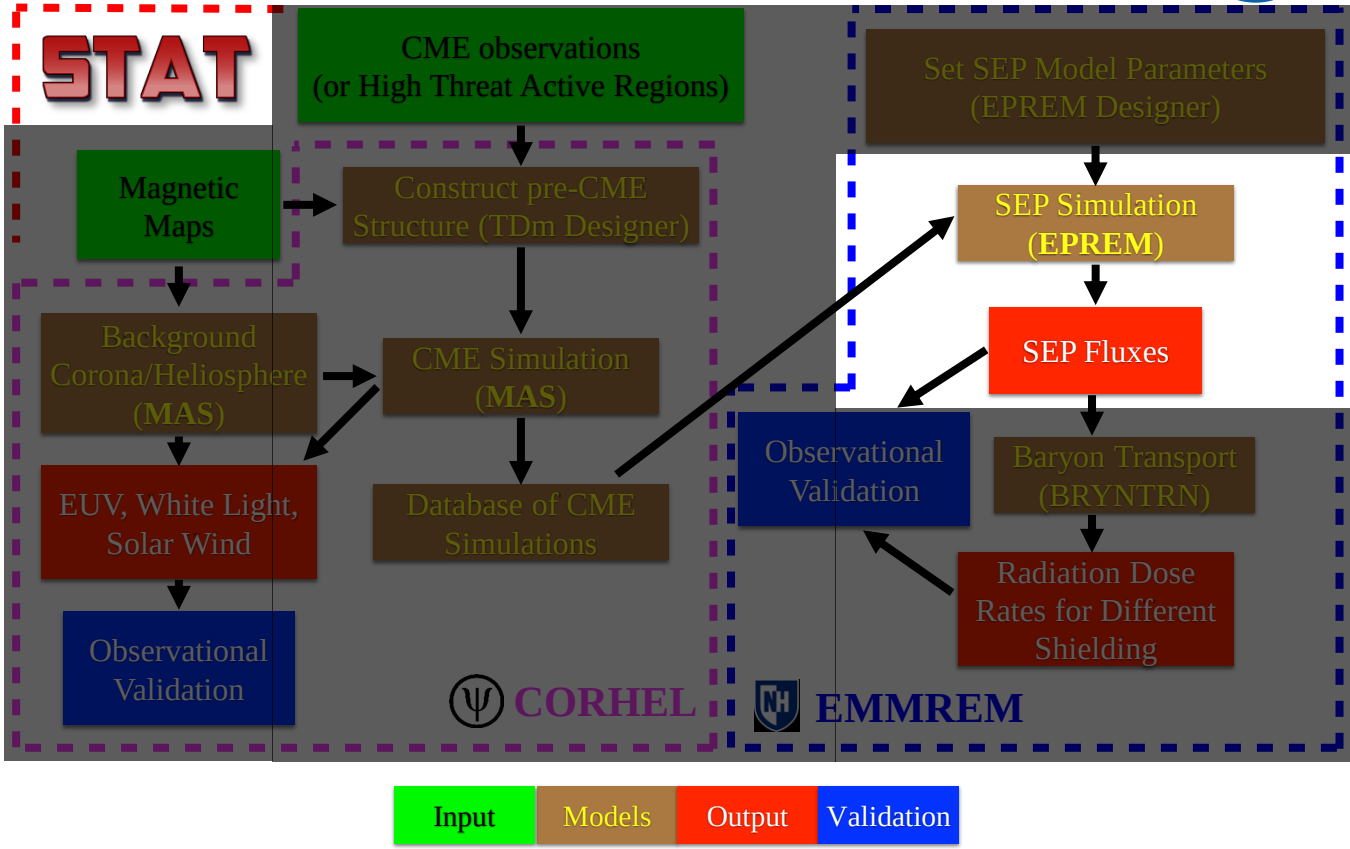
- **For a single CME simulation result, we can run multiple SEP simulations**
- **Parameter-setting web-based interface**





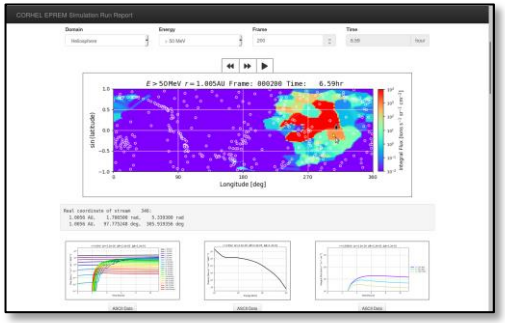
SEP Simulation and Visualization

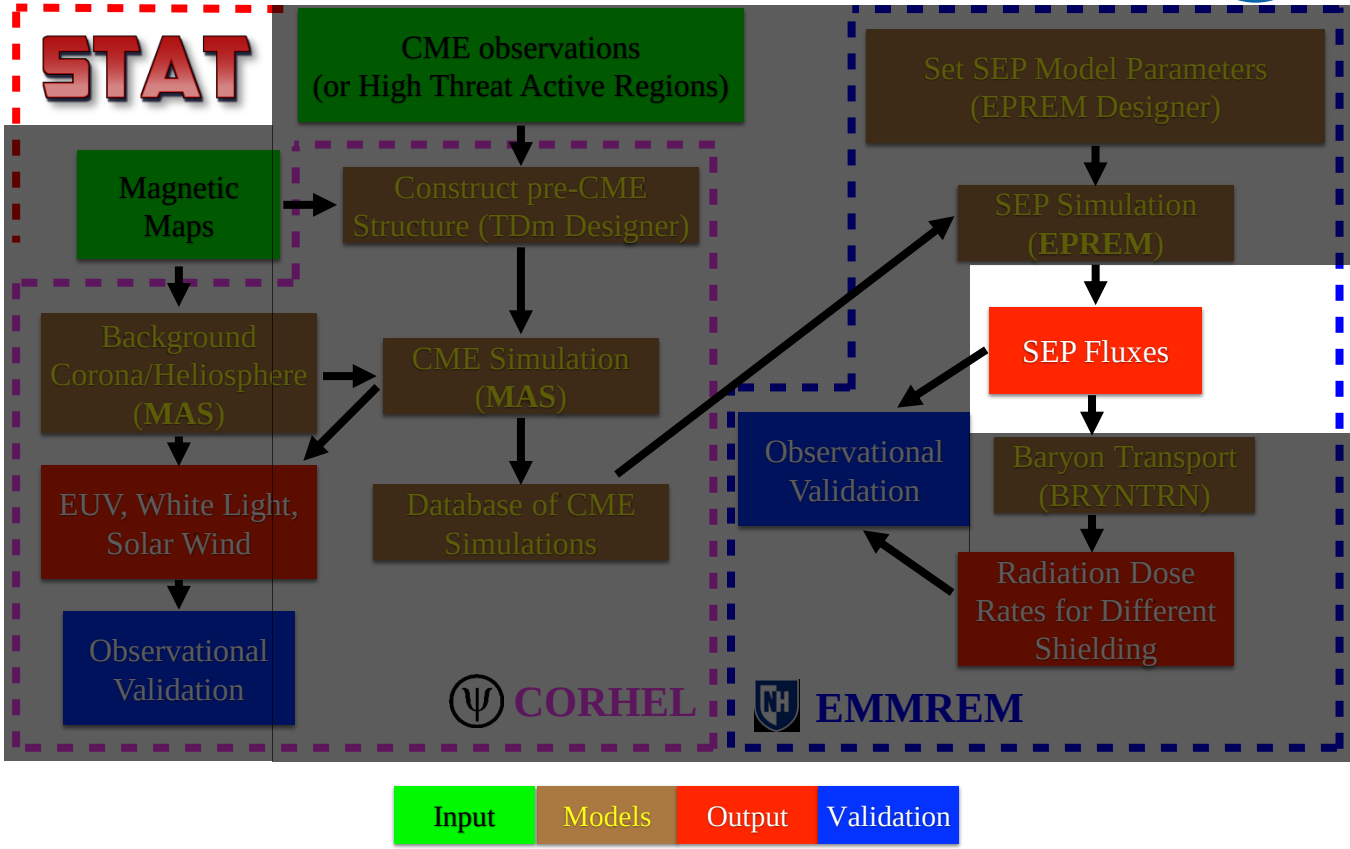
- **Large simulation using EPREM**
- **Post-process to obtain useful quantities (e.g. integrated flux)**
- **Generates LARGE amount of sparse data – challenge to analyze!**
- **3D region-growing interpolation allows visualizing results at any point in space alongside MHD output**



SEP Analysis

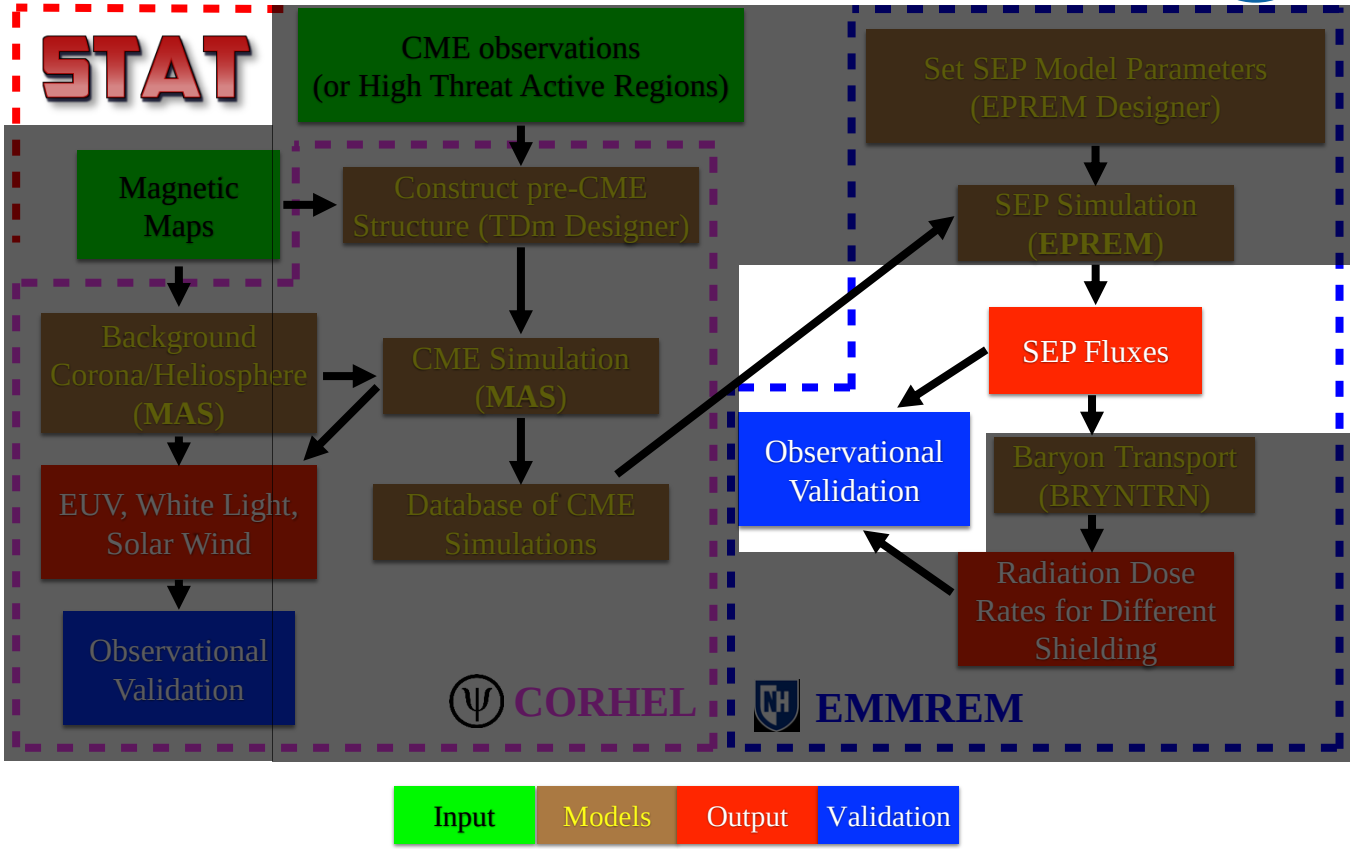
- **Web-based tool to explore results**
- **2D slices at radial cuts with EPREM stream locations indicated**
- **Using point-and-click, user can plot results at desired locations**





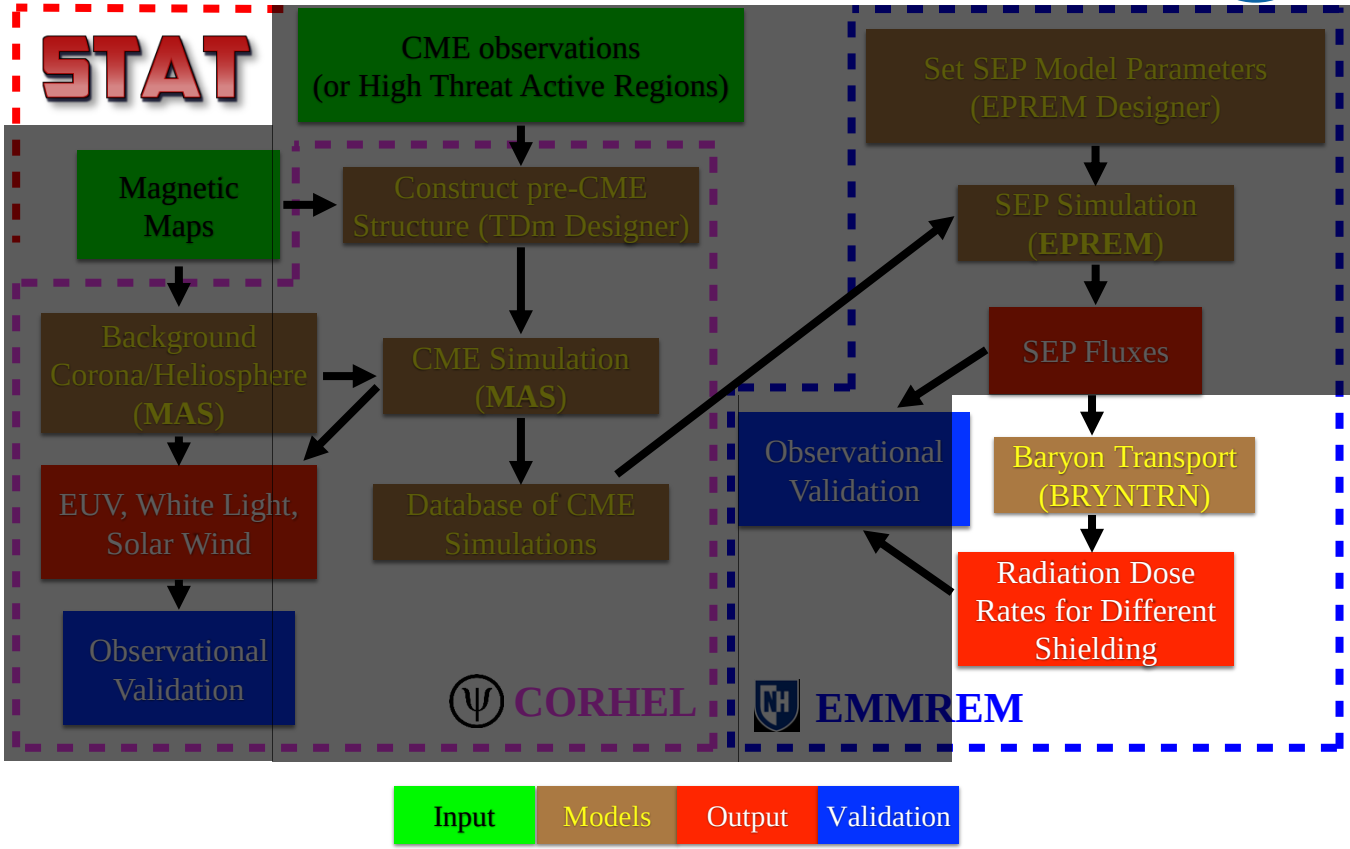
SEP Validation

- **Flux values can be directly compared to spacecraft data**
- **Near Earth, we compare with the GOES satellites**



Radiation Dose Rates

- **Baryon Transport code takes flux data and computes radiative doses for a variety of shielding materials**



SPE THREAT ASSESSMENT TOOL

Current Status

- Pre-CME generator delivered to CCMC
- Three CME eruption events simulated and stored in CME database
- Interface to run SPE simulations on CME events delivered to CCMC

COMMUNITY COORDINATED MODELING CENTER

ccmc.gsfc.nasa.gov

Next Steps

- Improve SPE simulation capabilities and conduct parameter/physics studies
- Add many more CME events to database - allowing possible forecasting of future events by analyzing past events exhibiting similar structure, energy, and location to an observed pre-CME region.

Future Goals

- Maintain a data-driven, continually-running background MHD solution, and allow users to quickly set up and run CME+SEP simulations for potential pre-CME regions and issue threat forecasts