Reduced SOL Model for Core-Edge Coupled Modeling in TRANSP

NSTX-U Monday Physics Meeting, Oct 2021

Xin Zhang
Department of Astrophysical Sciences,
Princeton University

This work is supported by Department of Energy contract number DE-AC02-09CH11466.

Outline

NSTX-U

- Particle balance in TRANSP and source of uncertainties
- A Cartoon of the SOL Box Model
- Time-dependent Interpretative Analysis: NSTX #139396
- Time-slice comparison with SOLPS: NSTX #204202
- Details on the Box Model and analytical behavior
- Next steps:
  - Extension to 2D
  - Proposed coupling workflow
  - Coupling with DEGAS, NUBEAM, RF modules, etc..

U.S. DEPARTMENT OF ENERGY Office of Science PPPL

Particle Balance in TRANSP

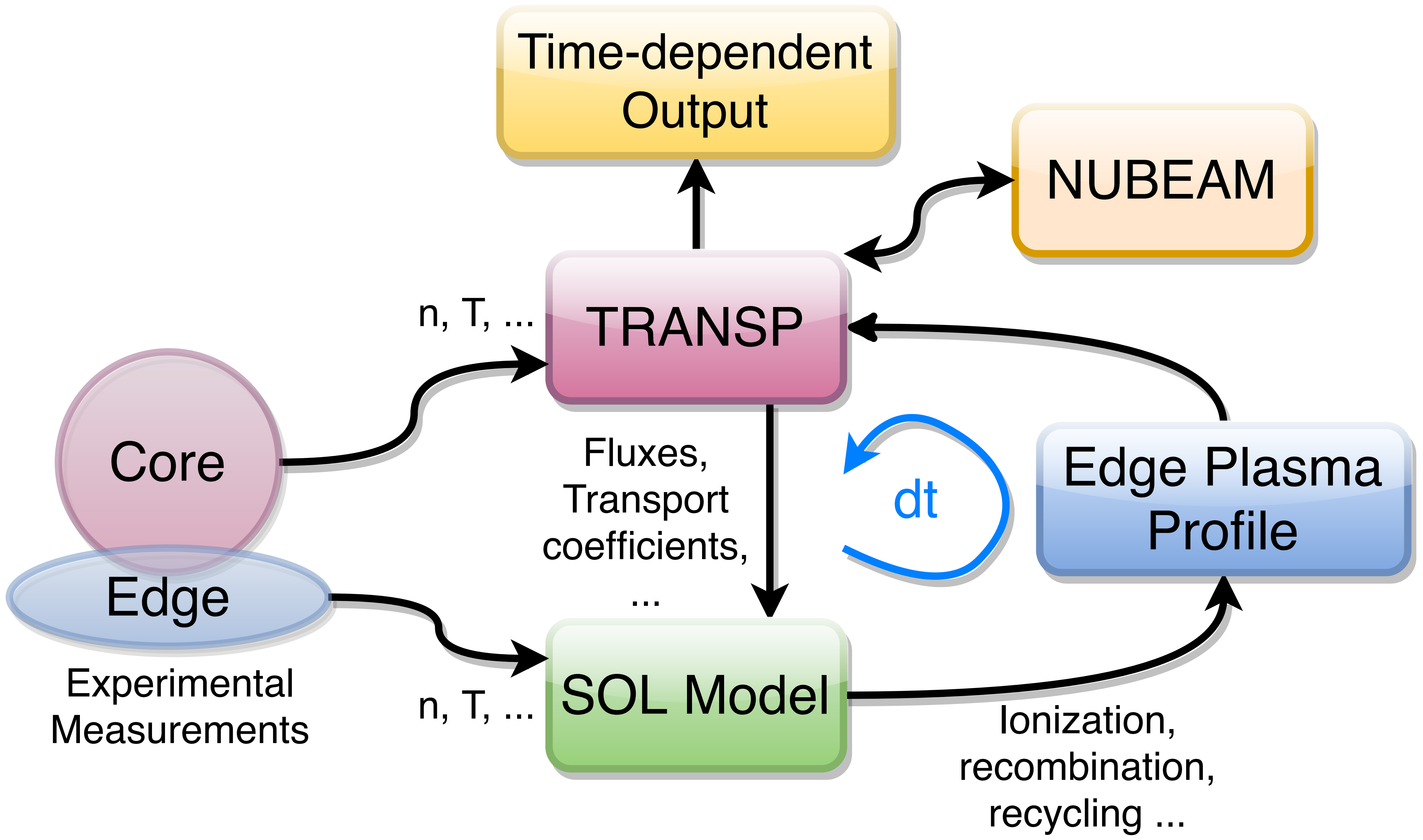
$$\frac{\partial N_s}{\partial t} = S_{bs} + G_{0s} + R_{0s} - F_s$$

- F_s: Total ion out flux for species *s*
- R_{0s}: Edge neutral recycling flux for species *s*
- G_{0s}: Edge neutral gas injection flux for species *s*
- S_{bs}: Net particle source due to neutral beam for species *s*
- $\frac{\partial N_s}{\partial t}$: Total rate of change of density for species *s*

- Each term on the RHS carries an uncertainty:
  - S_{bs}: Description of interactions between fast particles and the SOL plasma is dramatically simplified (handled by NUBEAM)
  - G_{0s} and R_{0s}: Calculated with a 0-D neutral model, too simplistic;
  - F_s: Ion out flux model is chosen by user; source of systematic errors.
- Calculated particle flux is then used by energy balance; uncertainty propagates.

Core-Edge Coupled Simulations with TRANSP

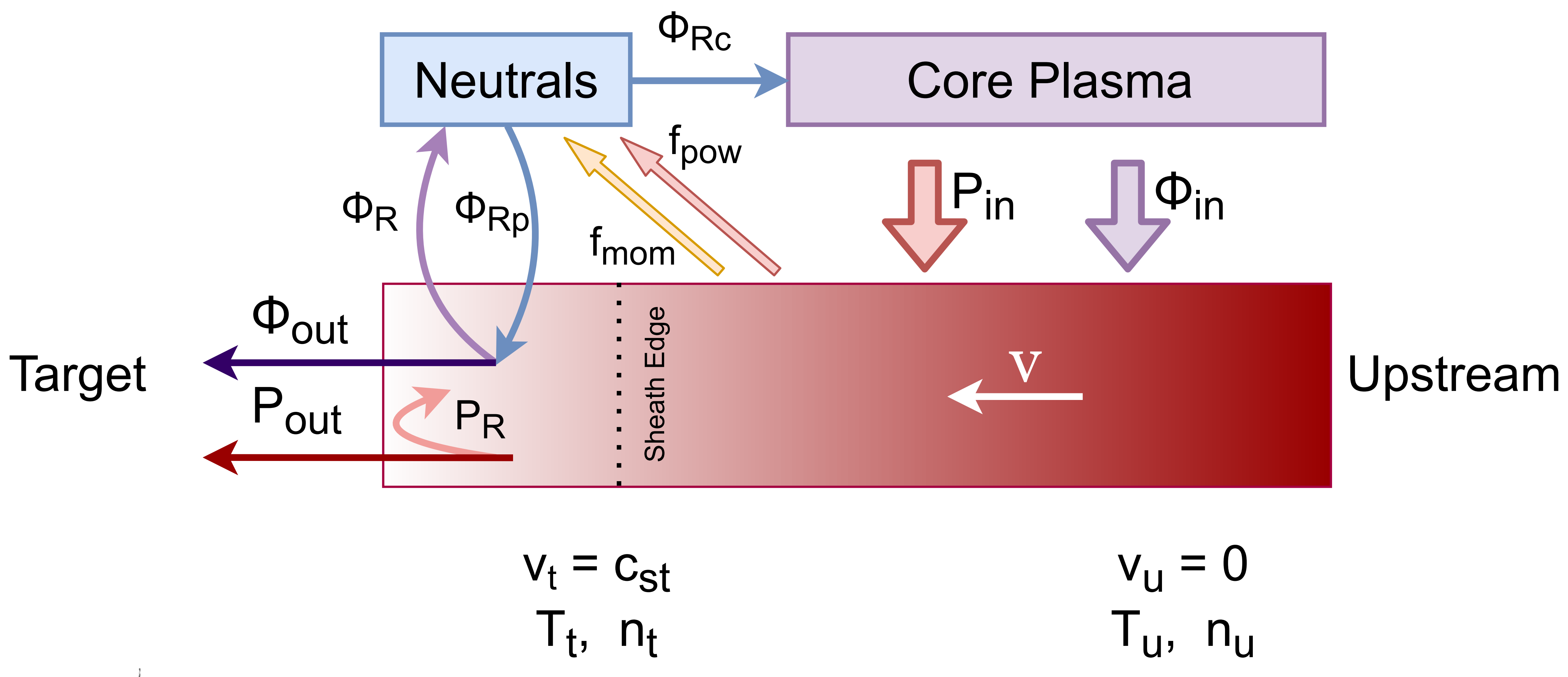
- Integrating a SOL model helps reduce the uncertainties in the particle balance.
  - SOL profiles can be solved with constraints from experimental measurements
  - Heating power and particle out fluxes from TRANSP
- A reduced model is developed for the SOL plasma, can provide plasma models for:
  - Neutral sourcing and transport in the edge
  - Fast ion losses in SOL
  - RF scattering and parasitic absorptions



A Tale of Three Boxes

NSTX-U

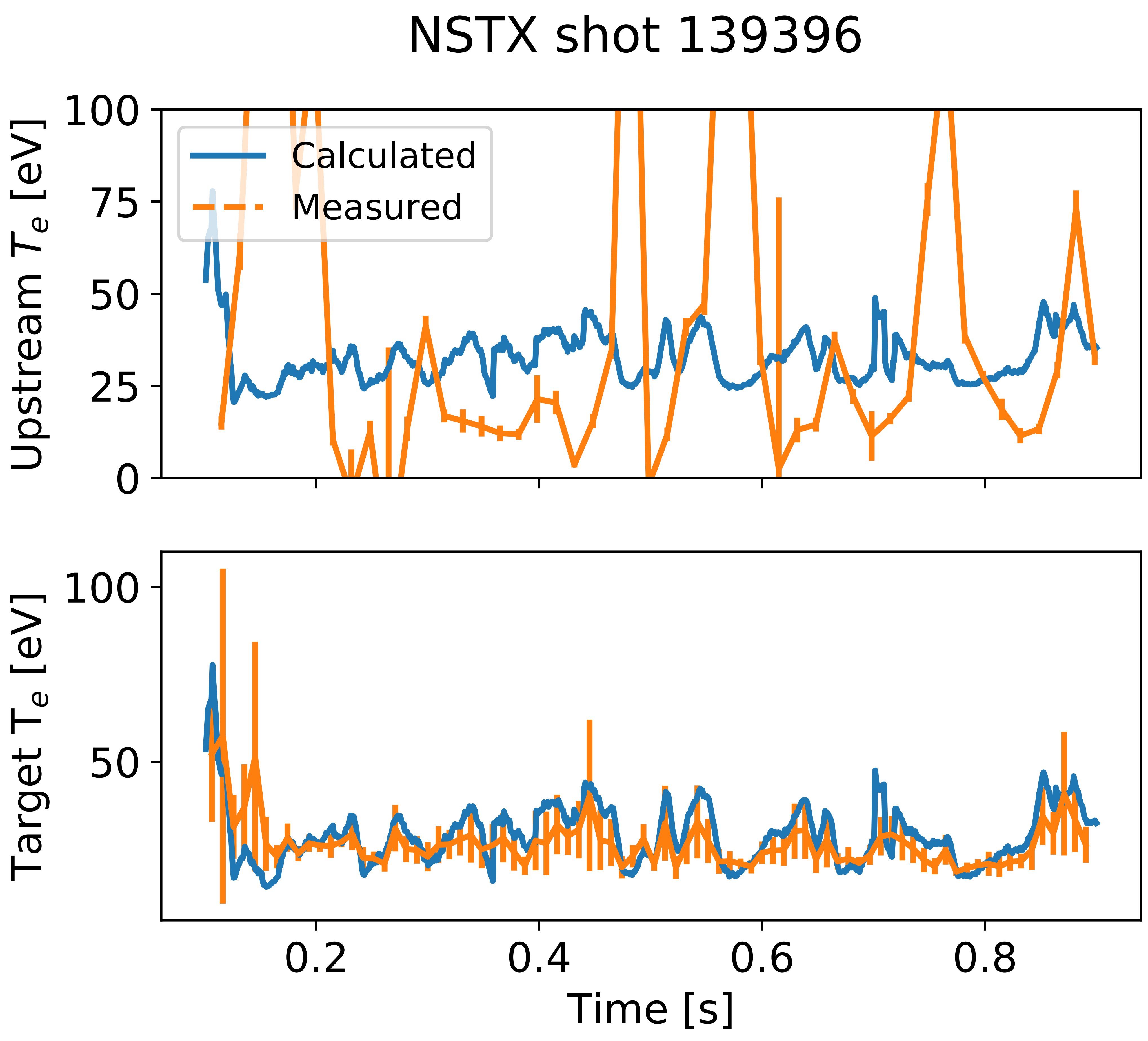
- Assume that SOL is in steady state.
- We must have balance for both power and particle flux:
  - $P_{in} = P_{out}$; $\Phi_{in} = \Phi_{out}$
- 3 “boxes” that particle and energy can go: Core, SOL, and Neutrals
- 4 equations, 4 variables
  - 2-Point Model equations for power & momentum balance, and conduction (3 equations)
  - *Particle balance that includes recycling*
- Previous efforts of reduced models: [Dnestrovskij, 1991], [Siccinio 2016]



All T & n can be solved at both upstream and target.

Time Dependent Simulation - Interpretive

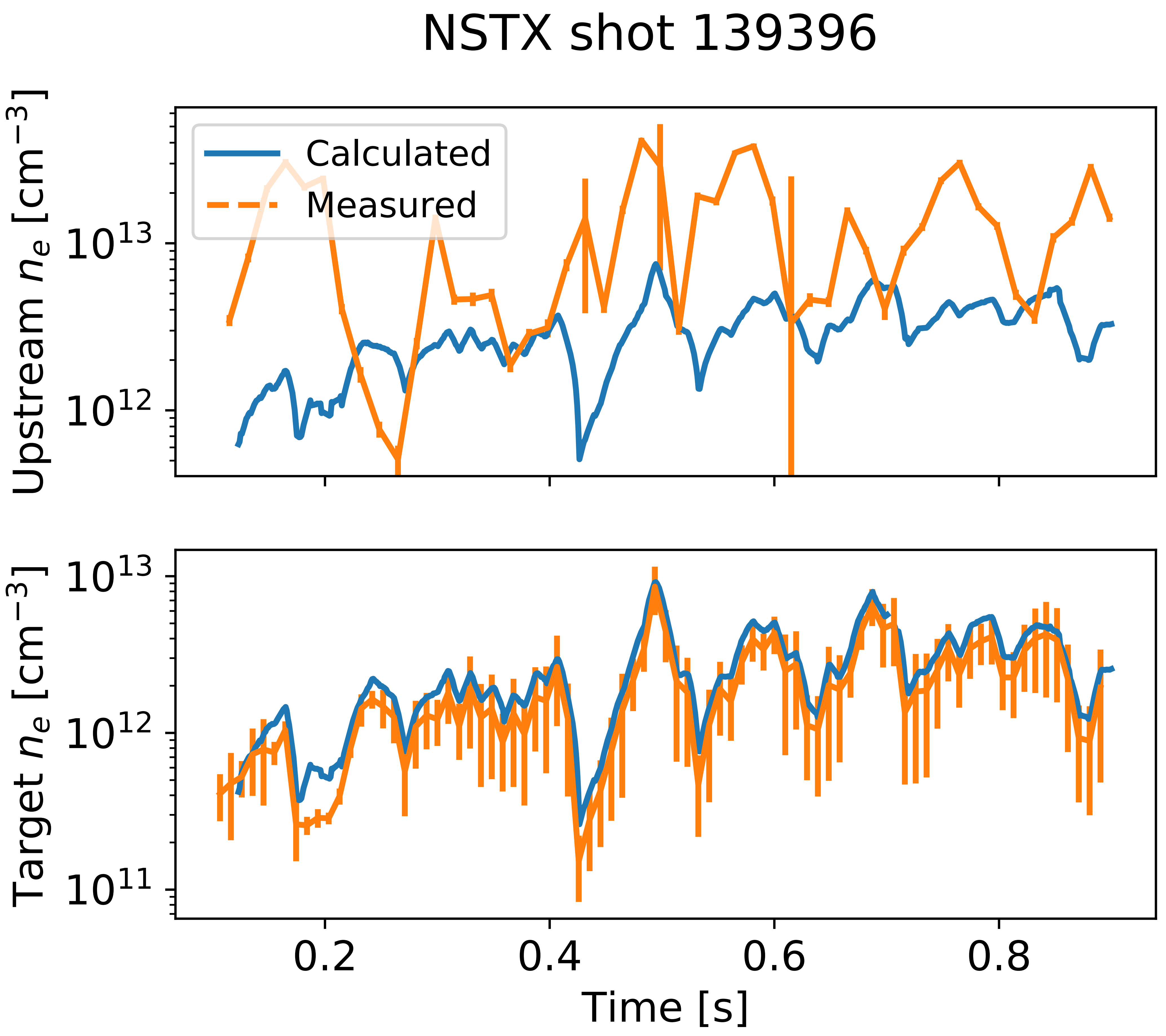
- The SOL model is constrained with Langmuir Probe (LP) target measurements
- Target temperature and density matched to data
- Electron and ion recycling coefficients calculated from target plasma conditions and core to SOL particle / power flux
- Upstream conditions calculated with box model, and compared with mid-plane measurements
- Calculated T_e agree reasonably well with Thomson measurements



Time Dependent Simulation - Interpretive

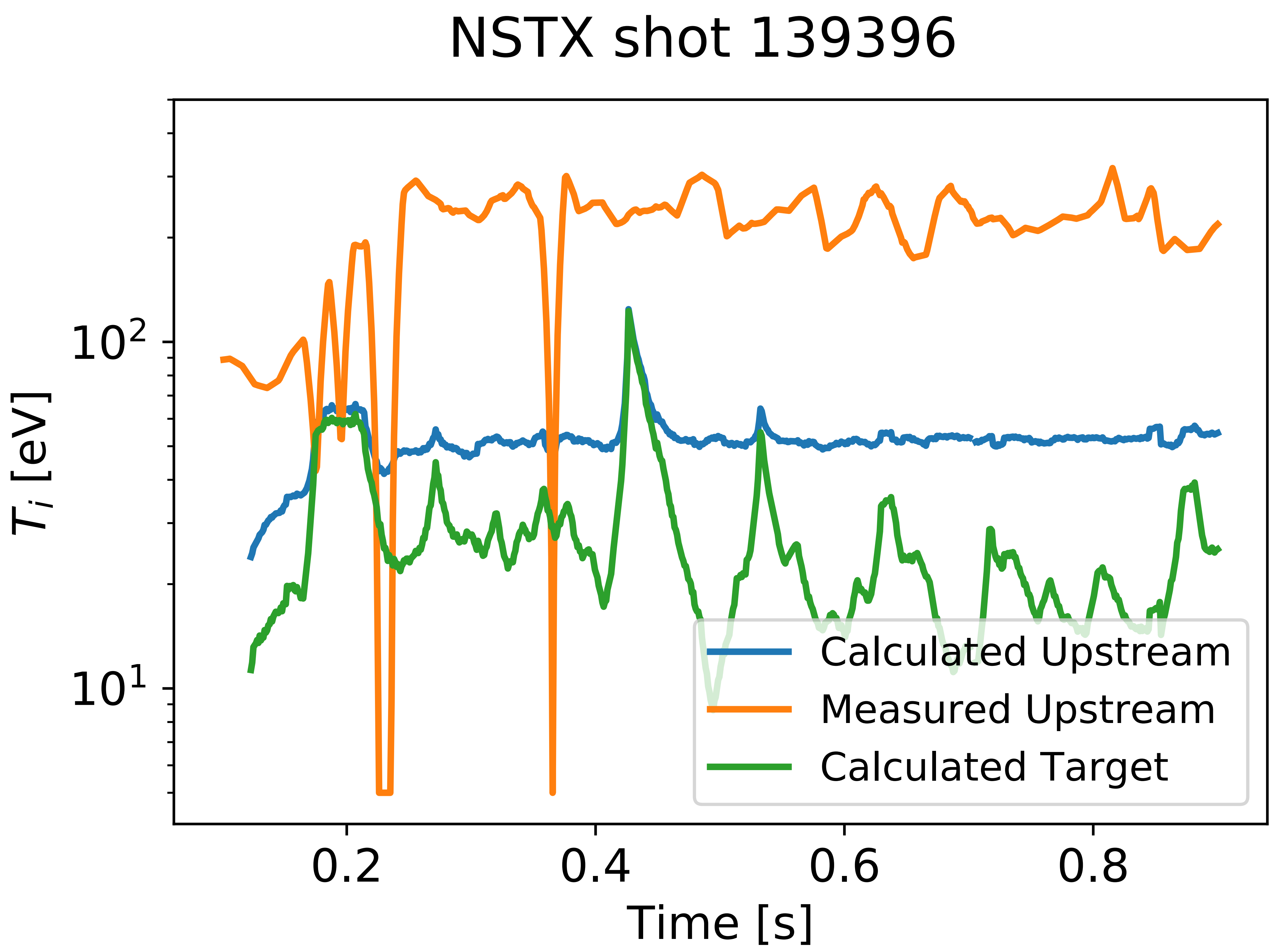
NSTX-U

- Average density across 4 probes are used to calculate ion recycling
- Calculated upstream density within order of magnitude, but systematically lower than observation.
- LP measurements of target density has large uncertainties:
  - Wide spread between different probes
  - Possible systematic under-estimate because of the probe locations (documented locations are in PFR)



Time Dependent Simulation - Interpretive

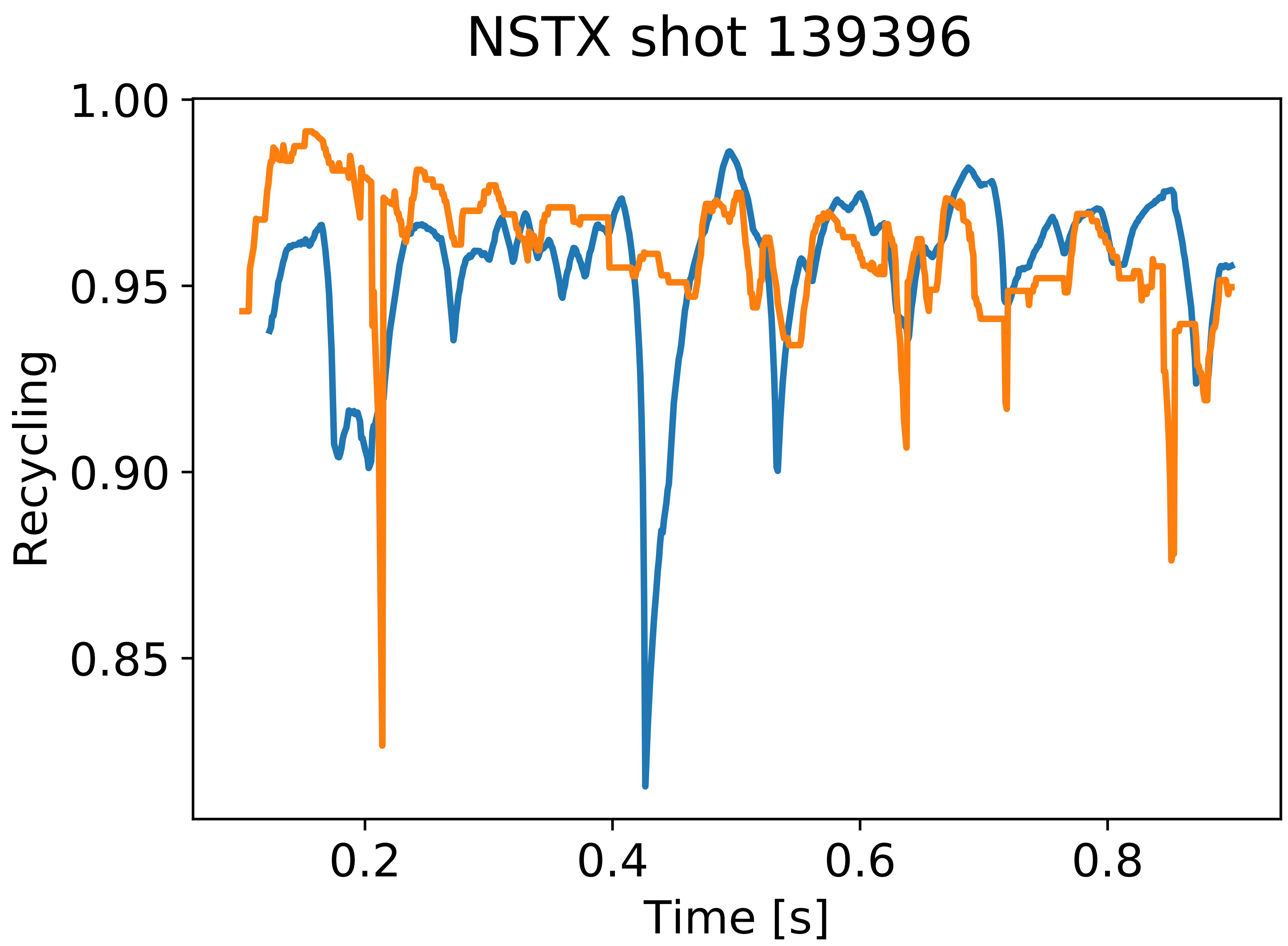
- Ion temperature comparison much more challenging:
  - Calculated upstream T_i ~ 1/6 of observed values (50 eV v.s. 300 eV) for C^{5+}, measured from passive CHERS
  - No data available from active CHERS
  - Calculated value insensitive to free parameters
- Measurements of T_i near separatrix has large uncertainties:
  - Only Carbon temperature is measured; heavy influence by core carbon with large drift orbits



Interpretive Simulations Estimate Recycling

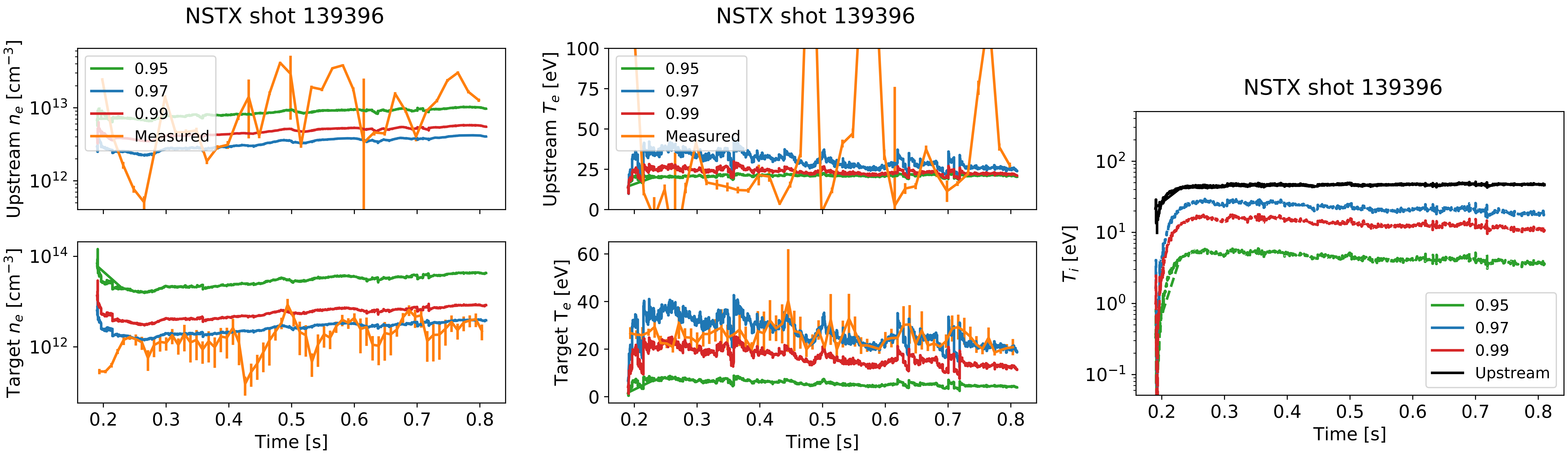
NSTX-U

- Both Ion and electron recycling coefficients are mostly within expected range (> 0.9) throughout the discharge
- Large spikes at some time points because of the large oscillations in measured target density
- Depends on input particle confinement time TAUPH in TRANSP:
  - Ratio of (particle flux) / (1 - ion recycling) is fixed by target density
  - Lower particle confinement -> higher particle flux -> lower calculated recycling
- Could be slightly under-estimated due to particles that are ionized in the core, instead of the SOL (2~3%)



Time Dependent Simulation - “Predictive”

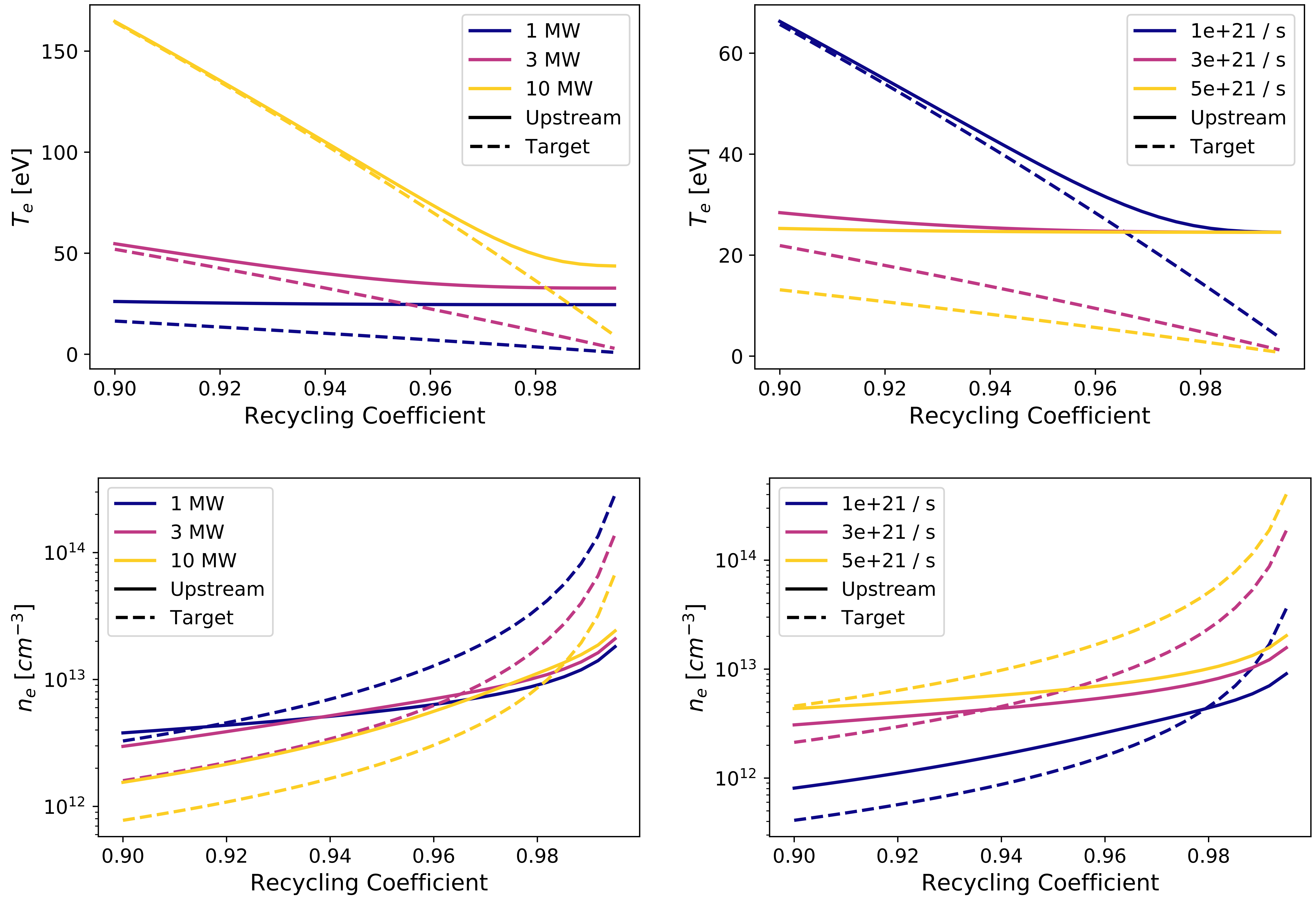
NSTX-U



- User can specify recycling coefficients instead of containing with data, and calculate both upstream and target quantities.
- Assume ion and electron share recycling coefficients, scan 3 different values.
- Density is most sensitive (both upstream and target); upstream temperature most robust.

Dependence with Recycling

- Assume electrons and ions share recycling coefficients in these plots
- As the recycling coefficient decreases, the SOL transitions smoothly from conduction limited to sheath limited regimes:
  - Temperature gradient decreases
  - Target density become lower than upstream
- SOL becomes hotter and less dense with lower recycling
  - SOL collisionality decreases with lower recycling



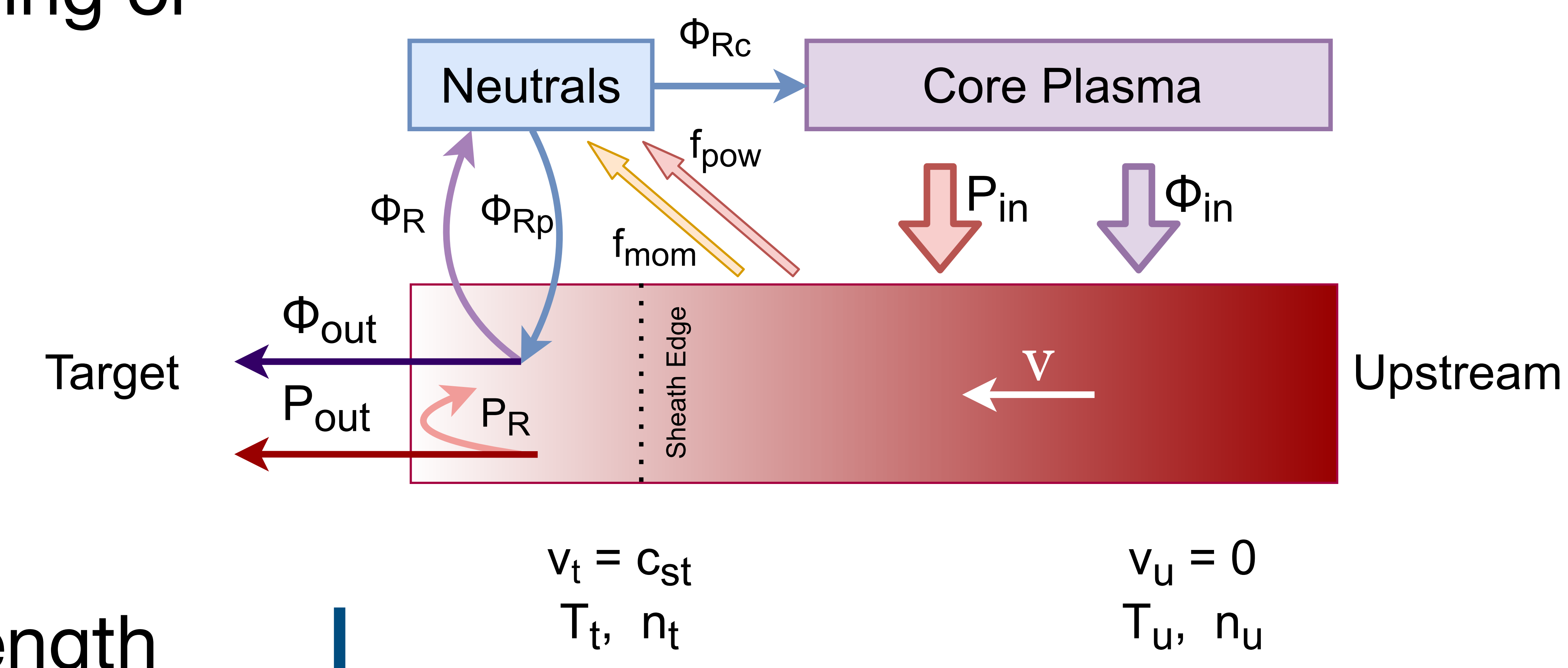
U.S. DEPARTMENT OF ENERGY | Office of Science

PPPL

Details of the Box Model - Assumptions

NSTX-U

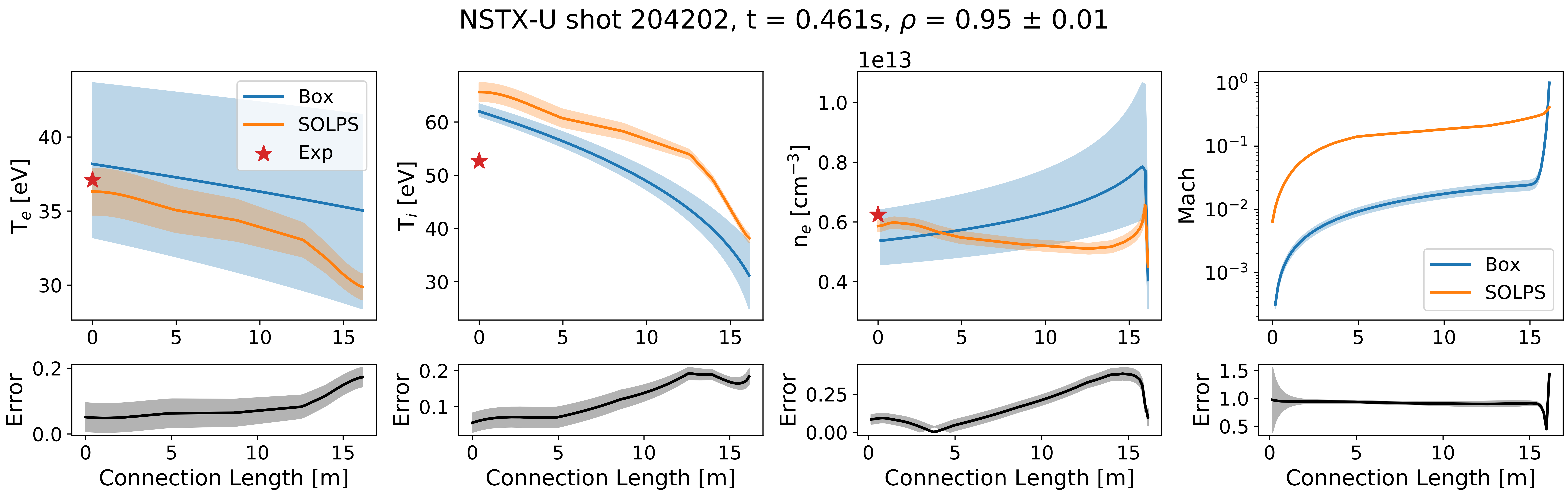
- SOL transport reaches steady at each time step
- The only particle sources in the SOL are from recycling or core to edge transport (convective & conductive)
- Gas puff not included
- Scrape-off-width follows Goldston's HD model
  - Other scrape off width can be user specified
- Linear sources and sinks (for parallel profiles):
  - Core sources enter uniformly along connection length
  - Power and momentum loss to neutrals are uniform along connection length
  - Flux expansion is linear
  - Plasma flow is sonic at the target
  - Flow stagnation point ('upstream') at outer midplane
- Recycling sources drop off exponentially from target



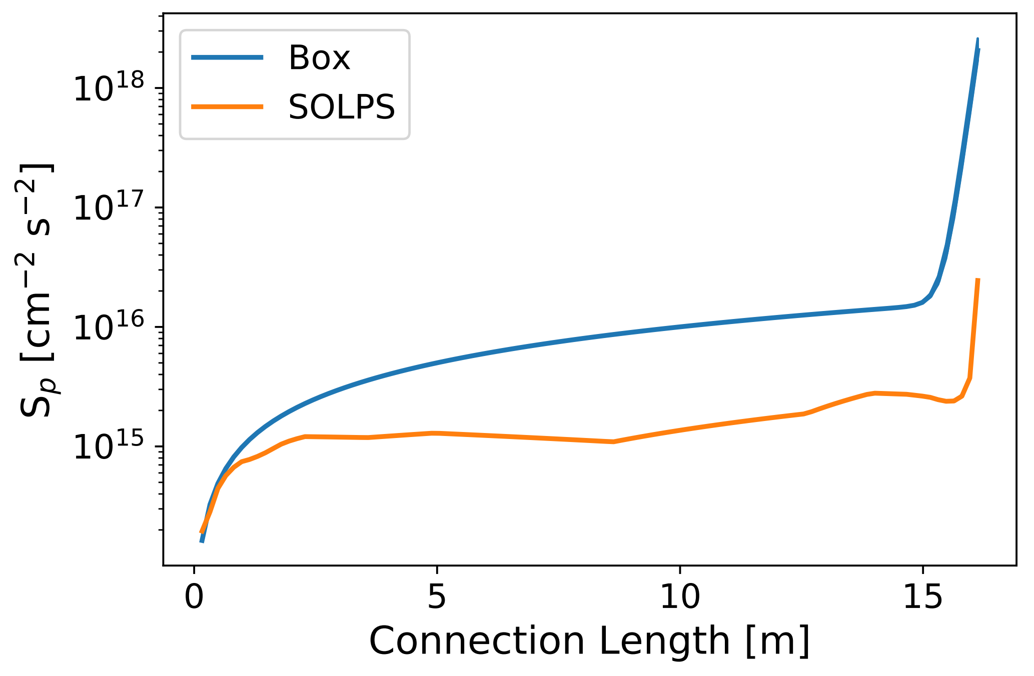
For 1D calculations

(Coming up!)

1D Variation Comparison with SOLPS

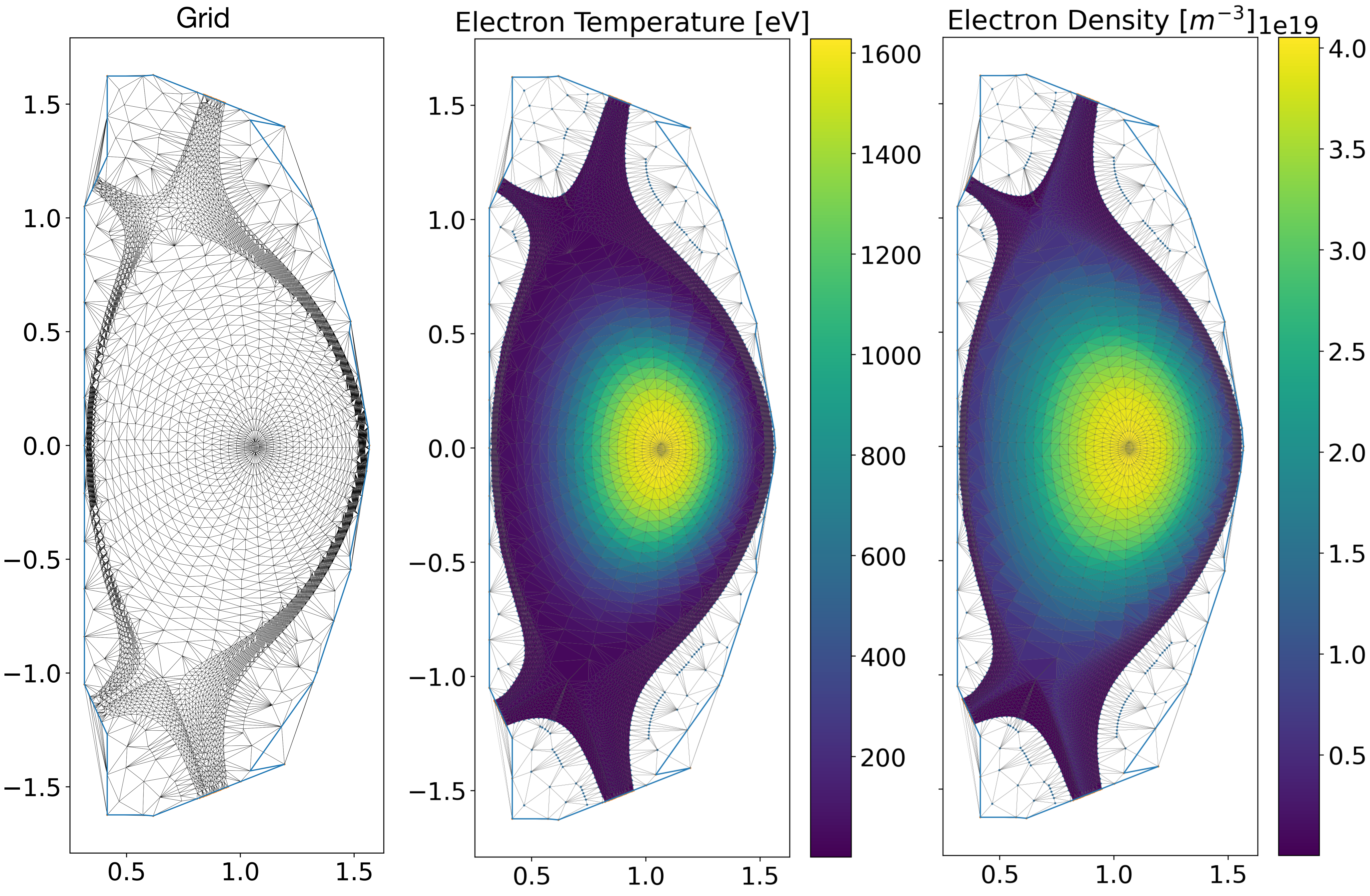


- 1D parallel plasma profile is solved analytically with assumptions on sources (next slide).
- Compared with SOLPS interpretive simulation - shown as SOL averages and spread.
- Temperature profiles show reasonable agreement; density profiles agree qualitatively.
- Majority of disagreement is attributed to the model of particle source (right →).



Extension to 2D (in progress)

- Fast and simple grid generator, called at every time step during TRANSP simulations:
  - Field-aligned for core and SOL;
  - Unstructured between SOL and limiters.
- Plasma profile calculated via box model and interpolated onto triangulated grid.
- Coupling with DEGAS2 in progress (George Wilkie):
  - Better neutral sourcing calculations for TRANSP



Extending NUBEAM to the SOL: the SOLFI code

- The Scrape-Off-Layer Fast Ion (SOLFI) tracer code resolves the dynamics of fast ions in the edge and SOL plasma.
  - A 3-D full orbit particle tracer that includes thermal collisions.
  - Finite Larmor radius effects important in NSTX / NSTX-U, especially near the plasma edge.
- Efficient algorithms for search & interpolation in the unstructured grid ready.
- New algorithm for stochastically simulating Coulomb collisions in full orbit simulations
  - Exact conservation of energy during pitch angle scattering