MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Wendelstein 7-X

Validation of a Comprehensive First-Principles-Based Framework for Predicting the Performance of Future Stellarators

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EUROfusion

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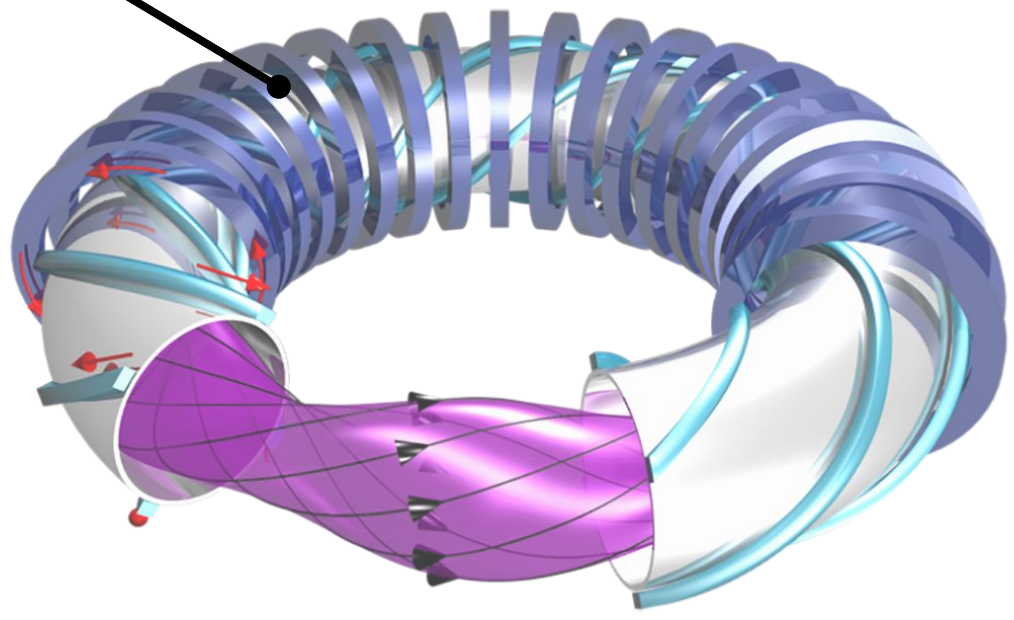
INTRODUCTION

- **Turbulence** remains a significant obstacle for magnetic confinement today.
  - Analyze turbulence across the plasma volume with **gyrokinetic codes**
  - Couple with a **transport code** to overcome timescale gap



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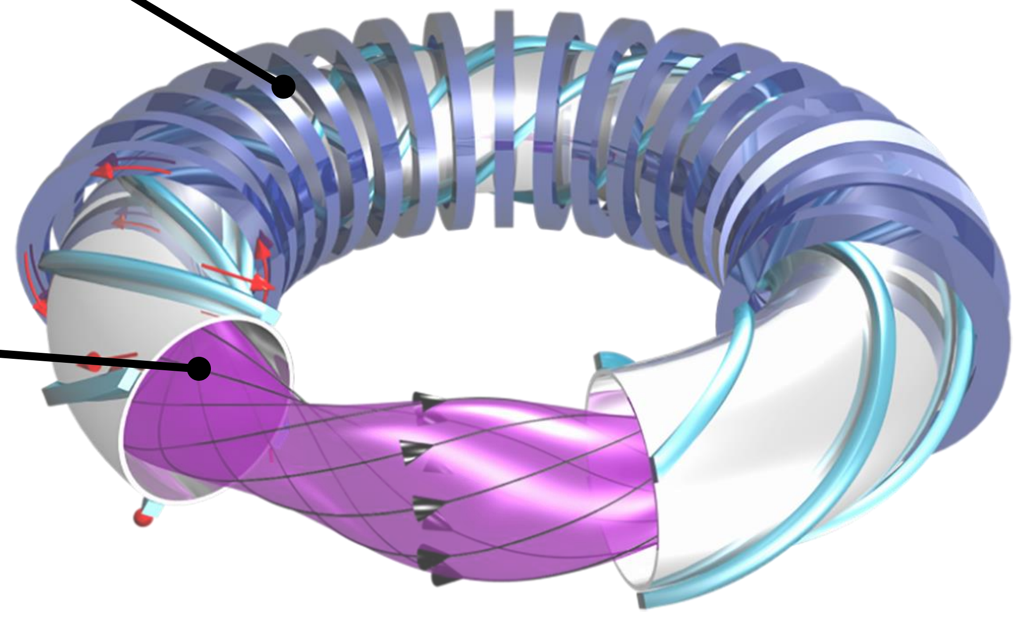

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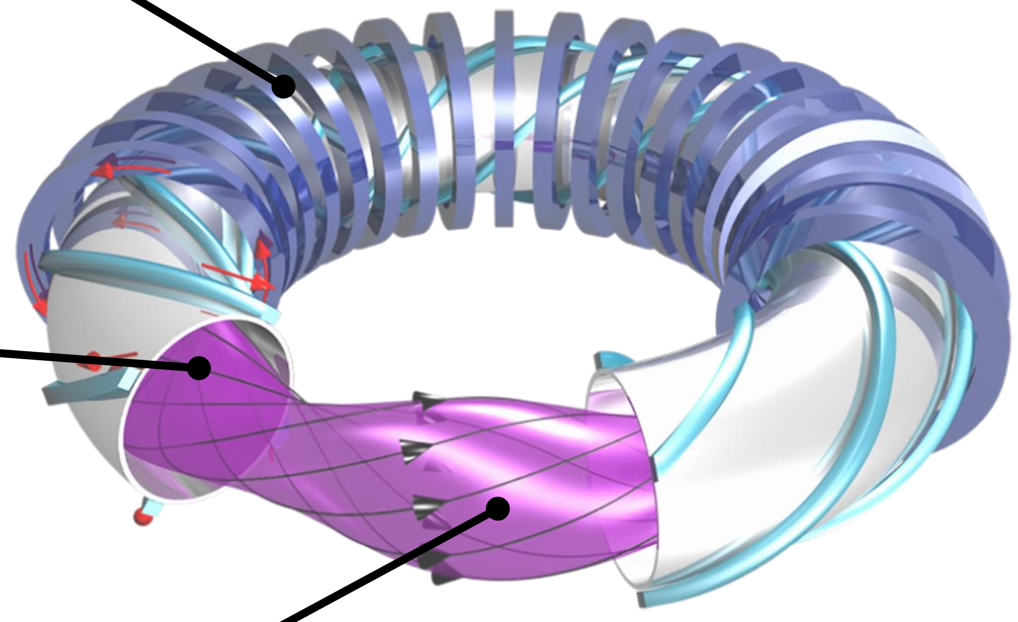
  - Couple with a **transport code** to overcome timescale gap
- **Validation studies** are necessary to ensure the accuracy of simulation results with respect to experiments.
- **Can we predict the plasma temperature and density profiles in existing experiments, given the boundary values and heating & particle sources?**
  - Necessary for profile prediction



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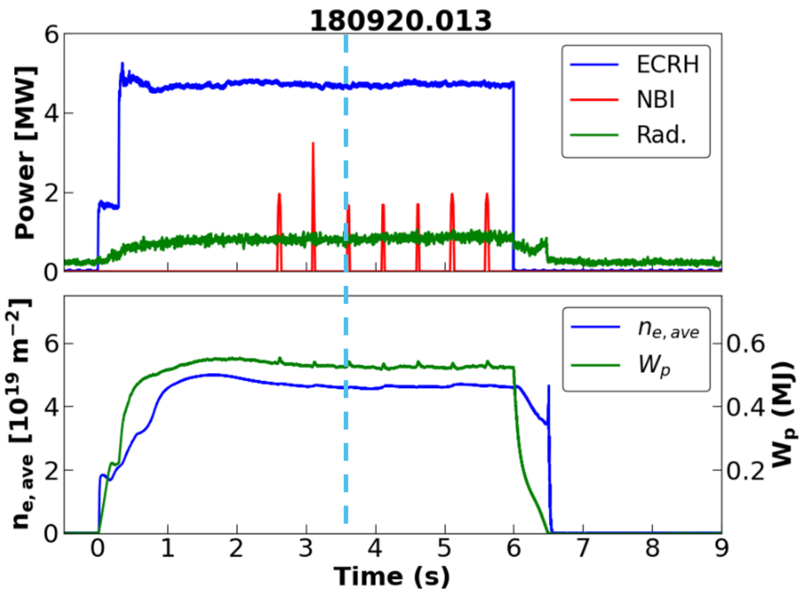
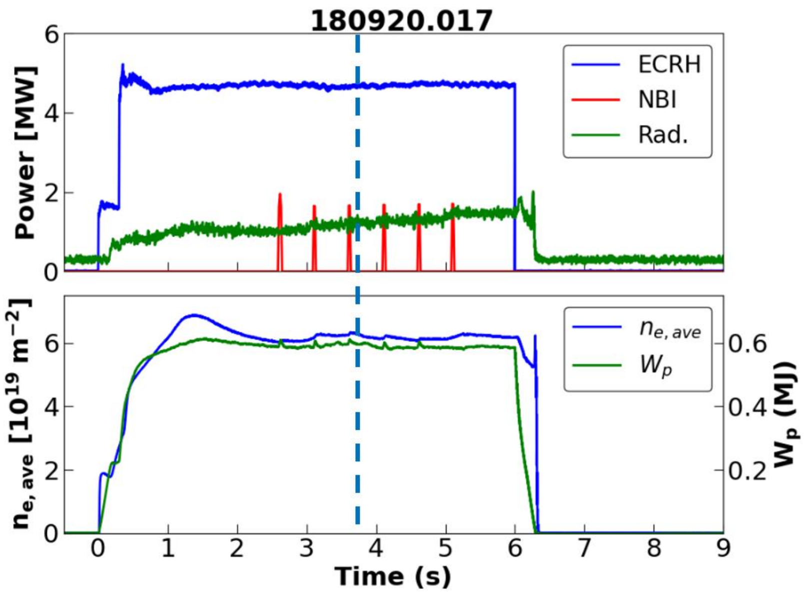


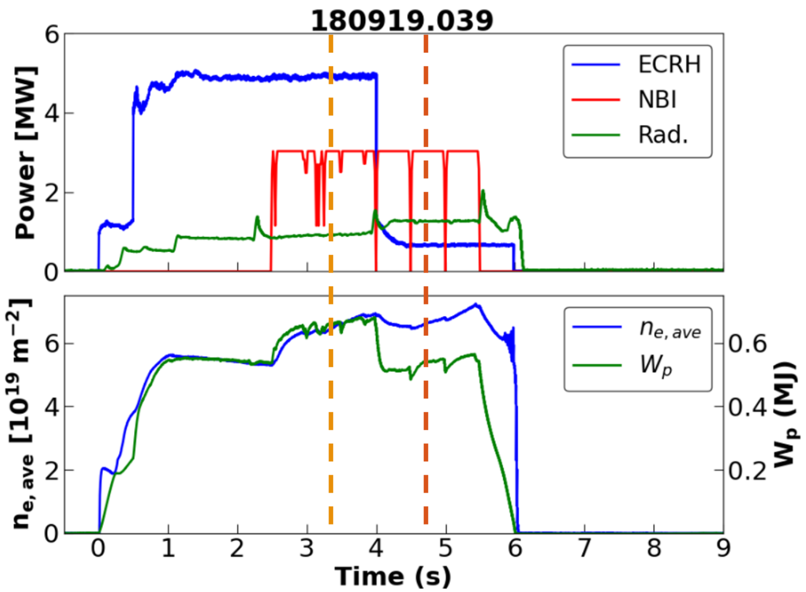
Low-density ECRH

Case 1



High-density ECRH

Case 2



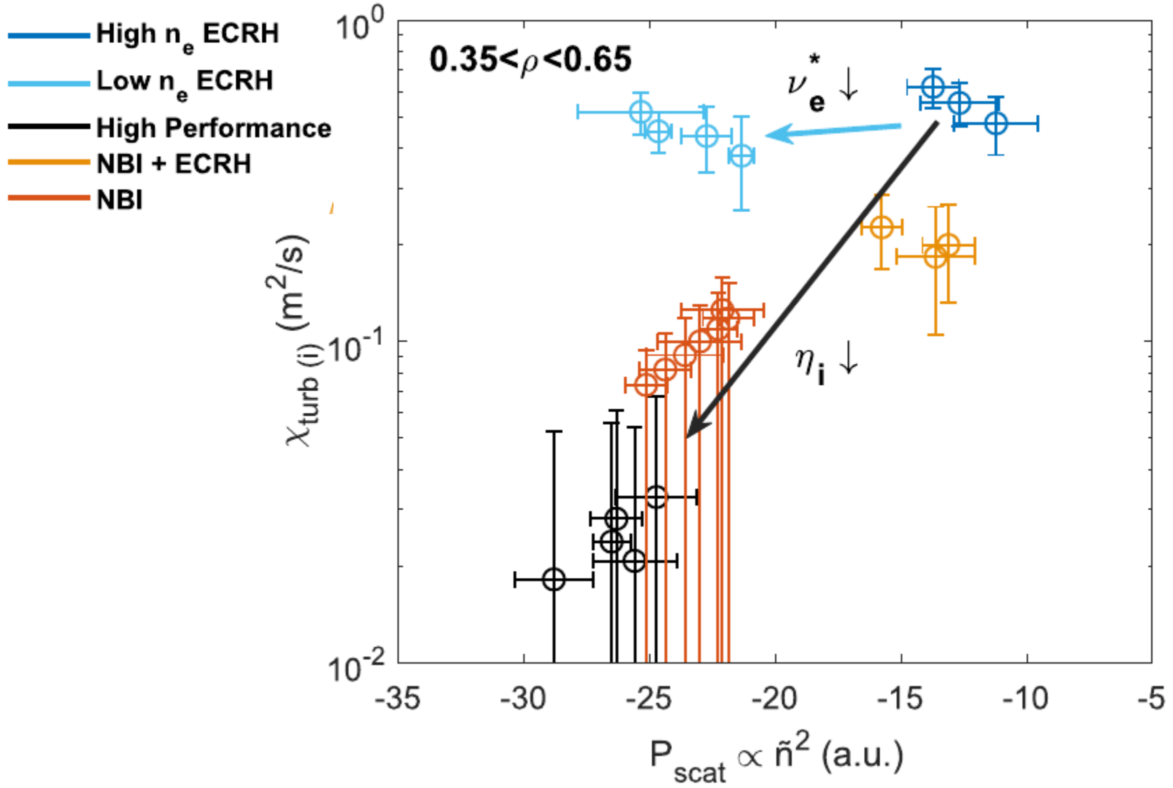
NBI (+ ECRH)

Cases 3 & 4

- 3 OP1.2b W7-X discharges, 2 of which are heated by ECRH while the other has NBI heating.
  - Shot # 180919.039 was heated with NBI & ECRH until t ≃ 3.5 s, then switched to primarily NBI until t ≃ 4.5 s.

W7-X DISCHARGES

D. Carralero, et. al., 2022, Plasma Phys. Control. Fusion



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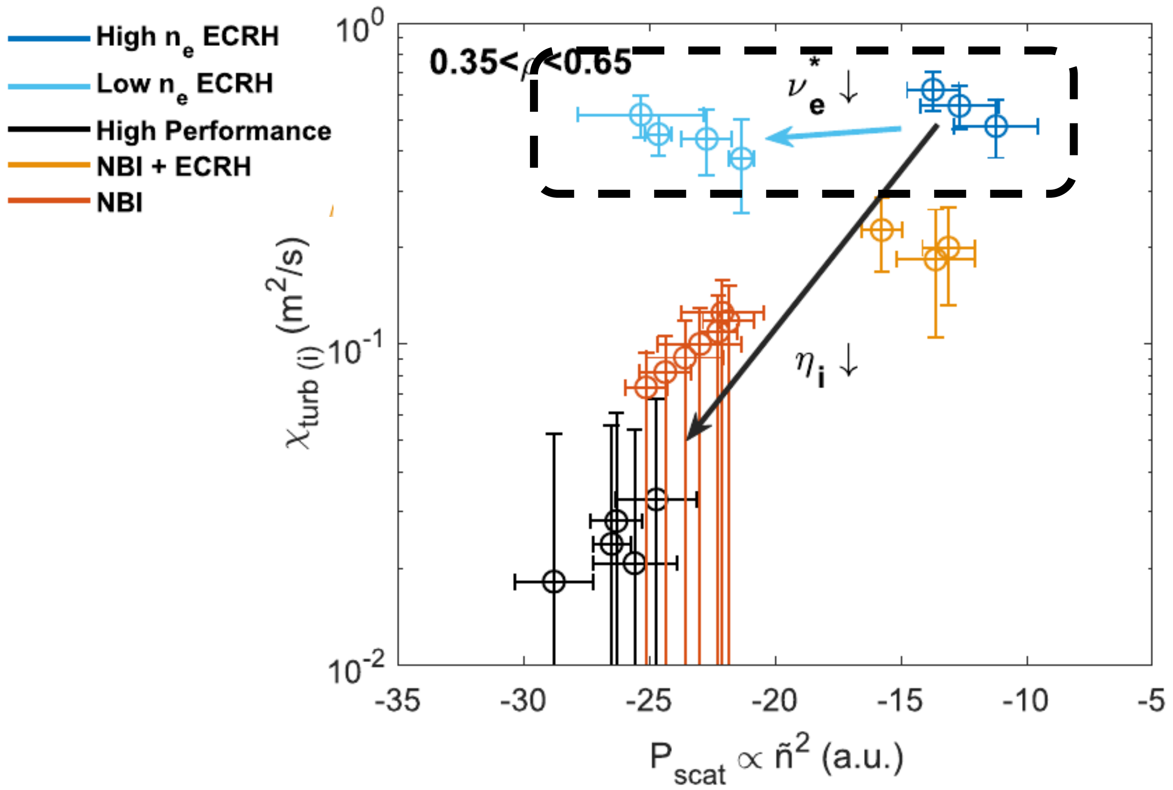

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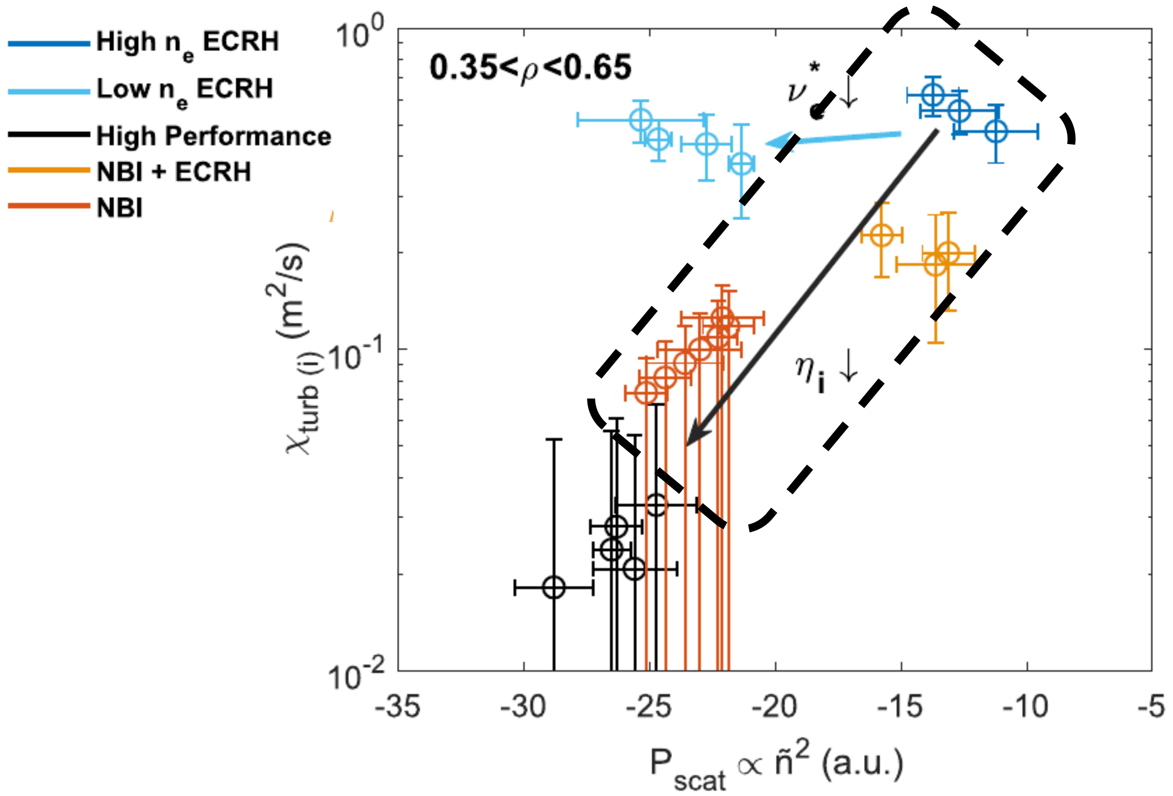

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GENE-KNOSOS-TANGO FRAMEWORK

➢ Plasma profiles are varied until target fluxes are matched.

J.L. Velasco, et. al., 2020, JCP
J.L. Velasco, et. al., 2021, Nuclear Fusion

KNOSOS: Neoclassical fluxes and the background radial electric field

F. Jenko, et. al., 2000, Physics of Plasmas

GENE: Turbulent transport of plasma species

$$\Gamma_s(i) = \Gamma_s(i)^{neo.} + \Gamma_s(i)^{turb.}$$
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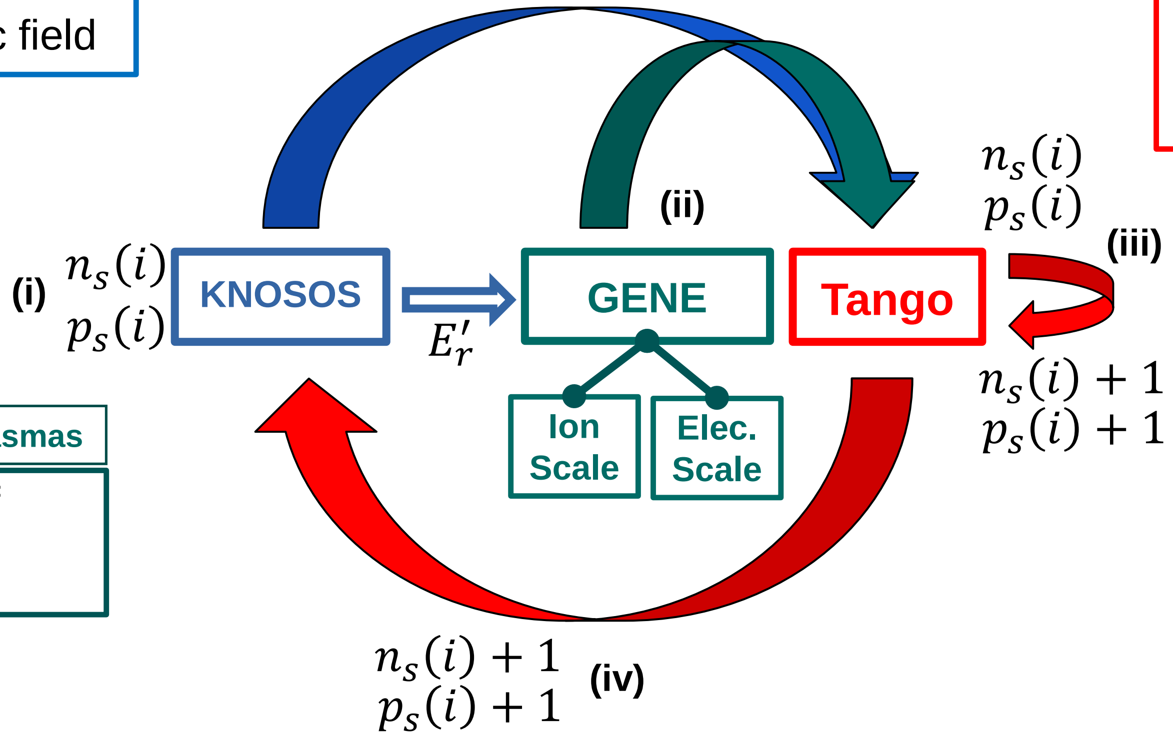

A.I. Shestakov, et. al., 2002, JCP
A. Di Siena, et. al., 2022, Nuclear Fusion

Tango: New plasma profiles accounting for both the total transport and the injected sources

$$\frac{3}{2} A \frac{\partial p}{\partial t} + \frac{\partial}{\partial x} AQ = AS_Q$$

$$\frac{3}{2} A \frac{\partial n}{\partial t} + \frac{\partial}{\partial x} A\Gamma = AS_\Gamma$$

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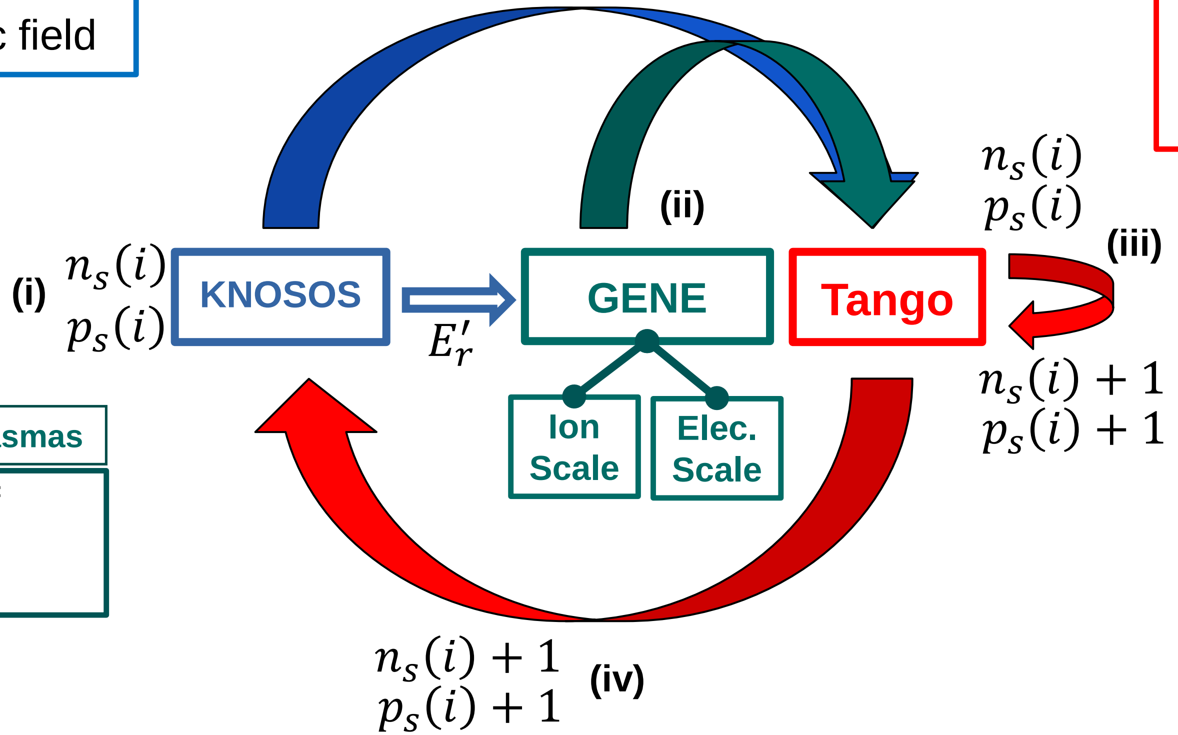

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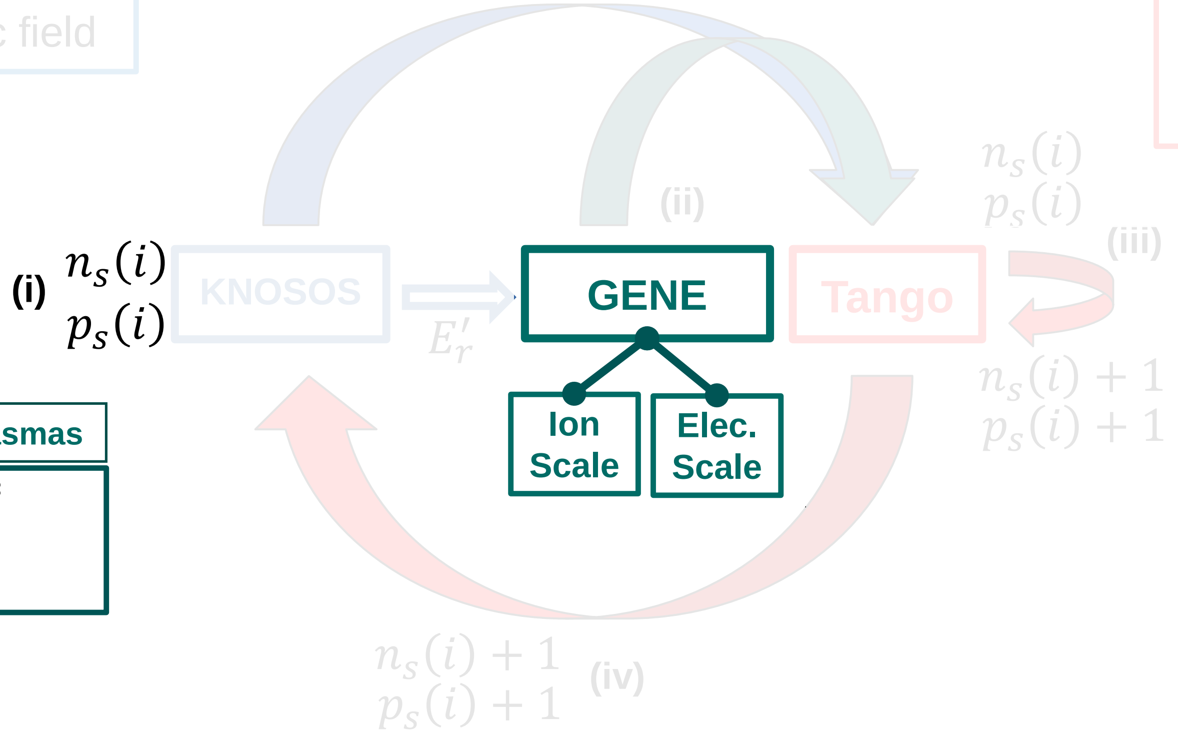

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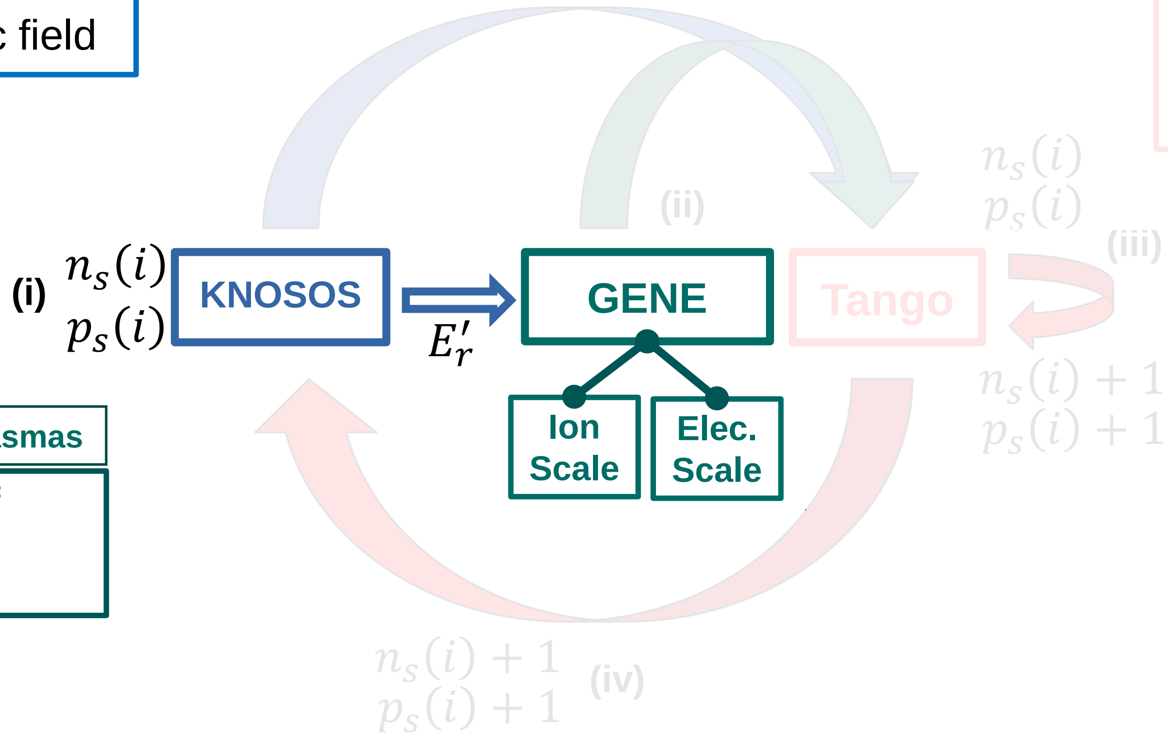

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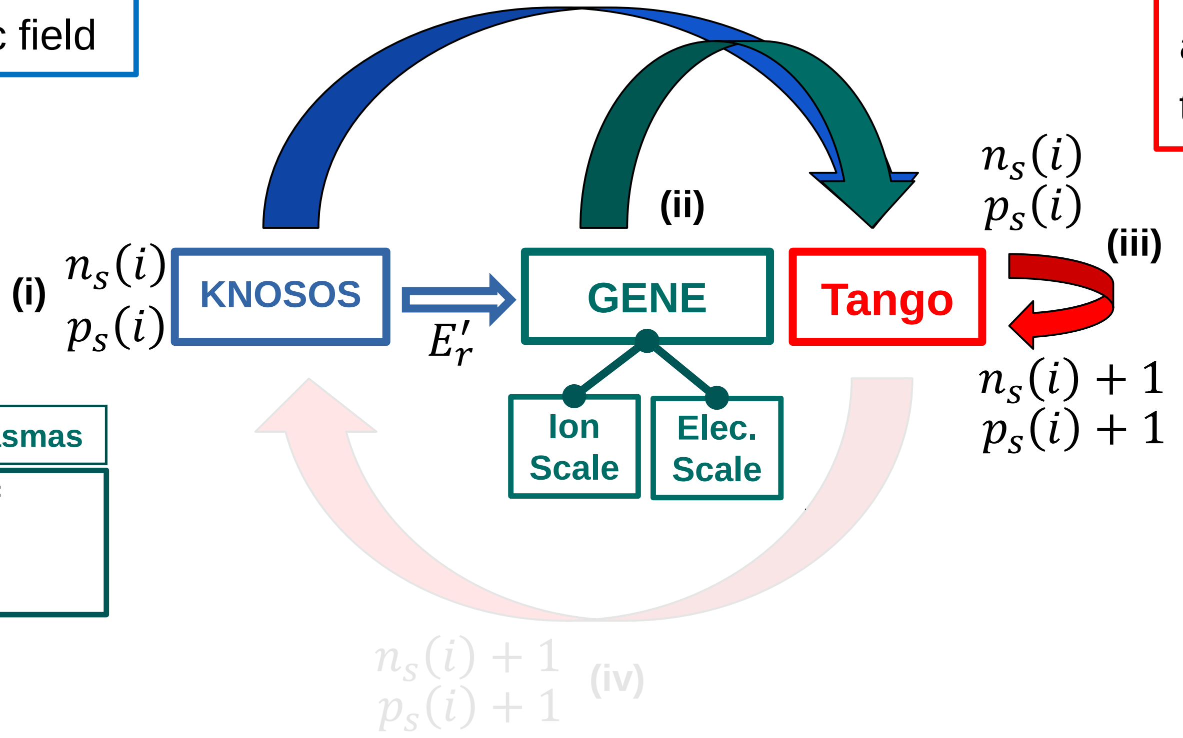

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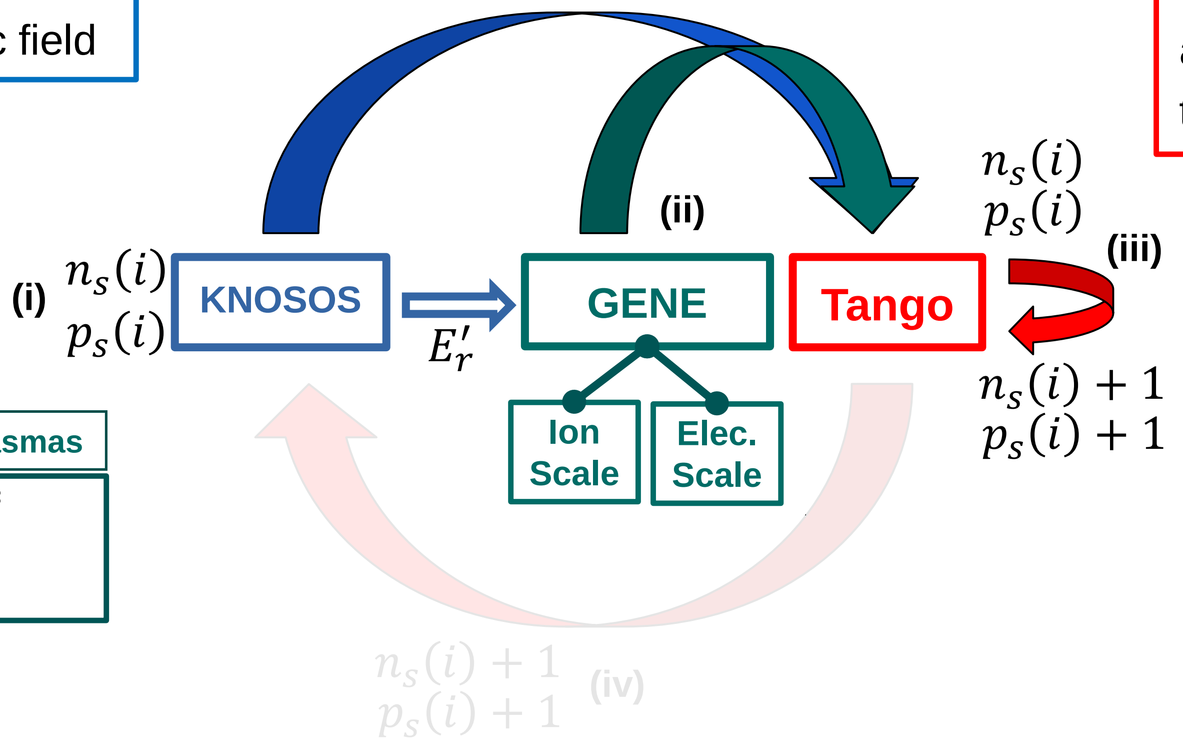

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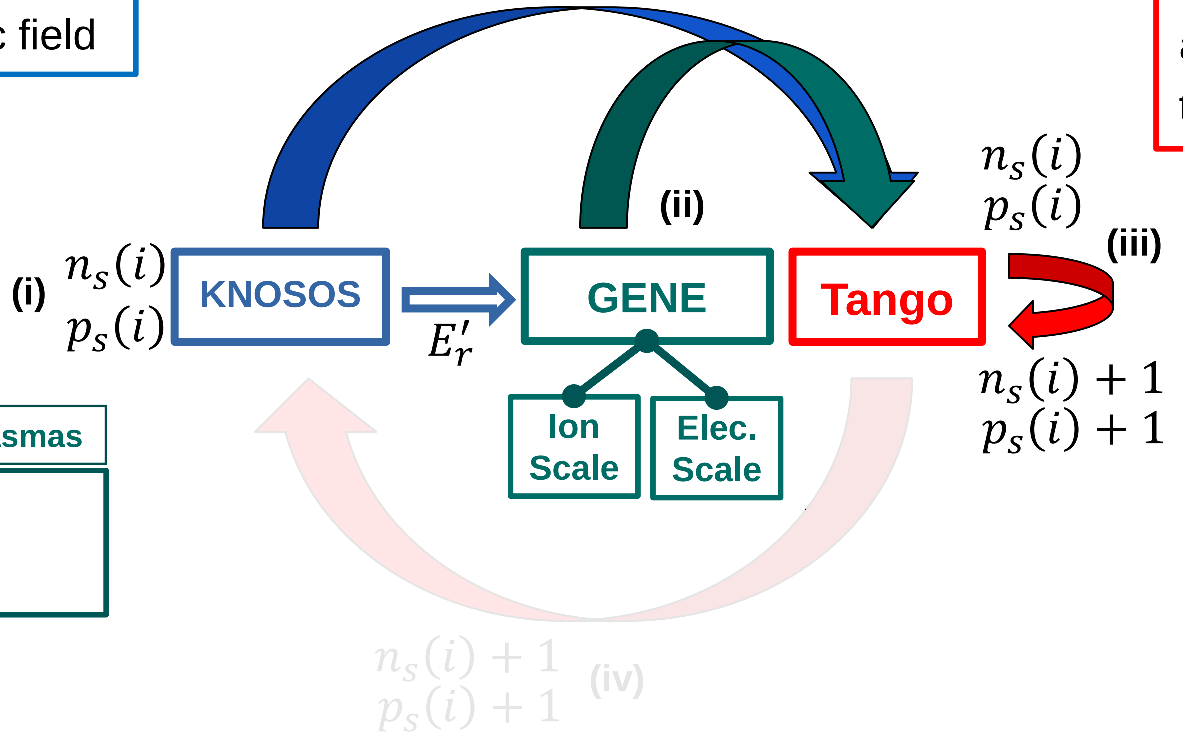

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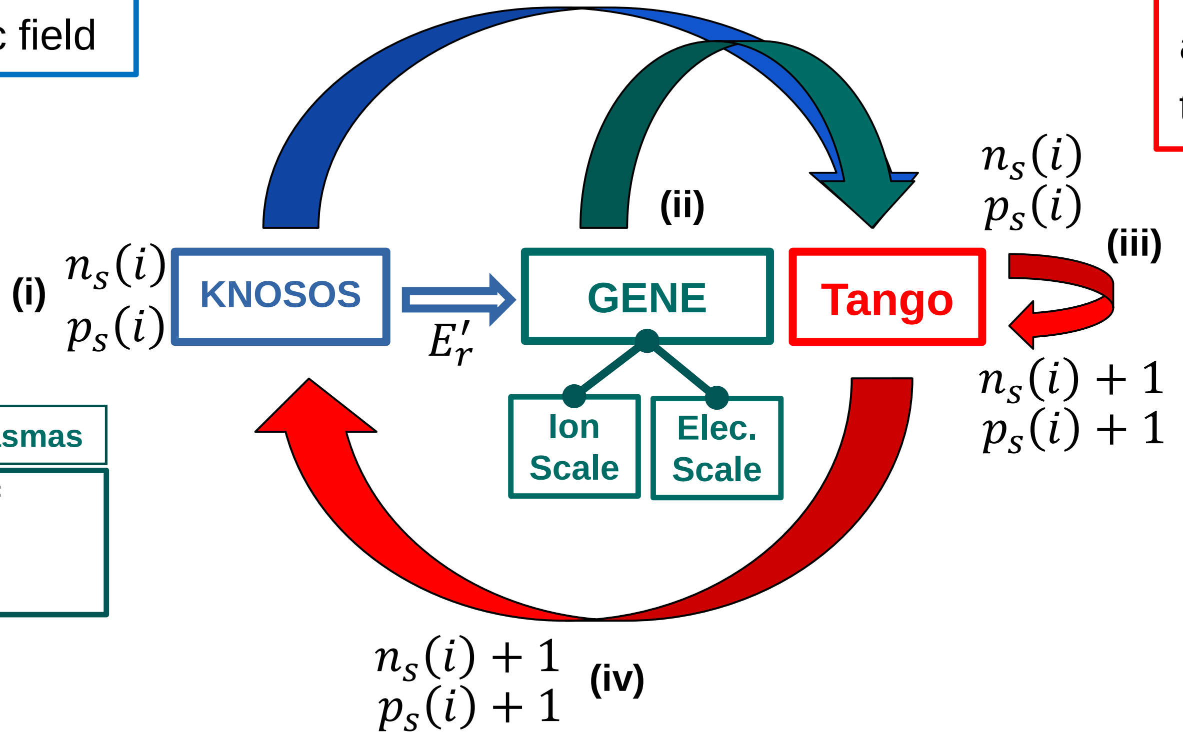

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GENE: Turbulent transport of plasma species

GENE-KNOSOS-TANGO FRAMEWORK

- Plasma profiles are varied until target fluxes are matched.
- Experimental profiles are used as the initial input; profiles are fixed beyond the chosen boundary.
- Convergence is determined based on the radial power and particle balances.

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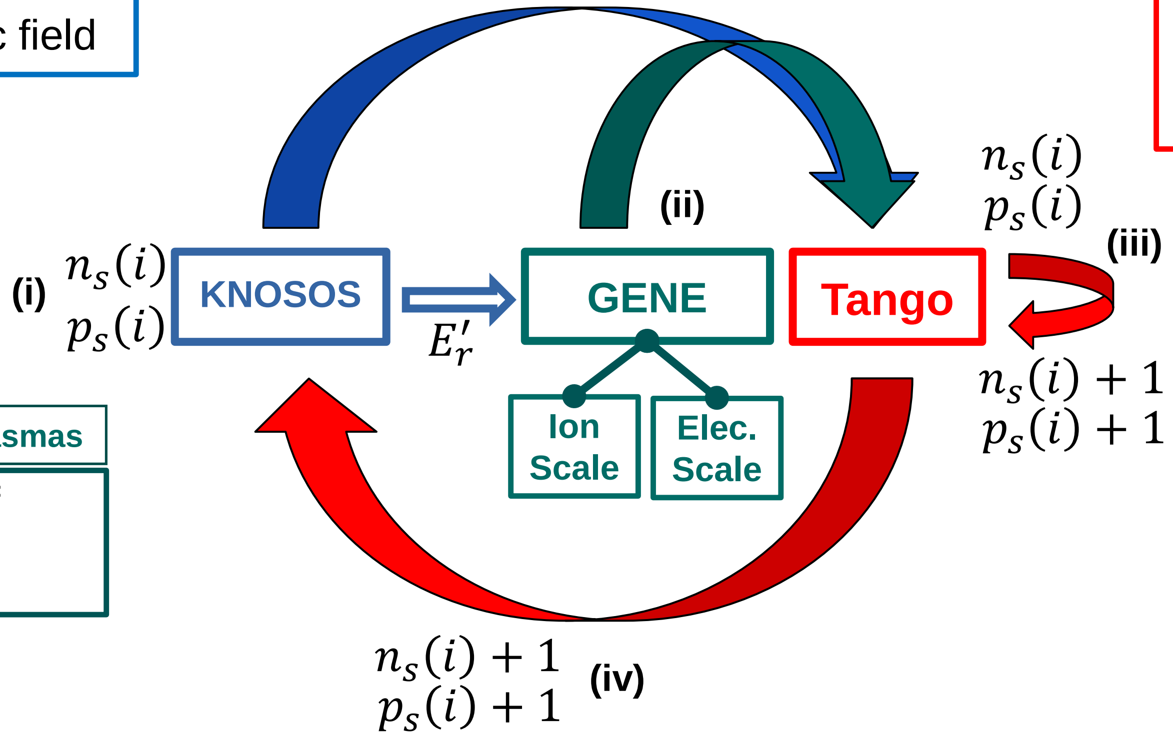

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MODEL HIERARCHY
PHASE 1

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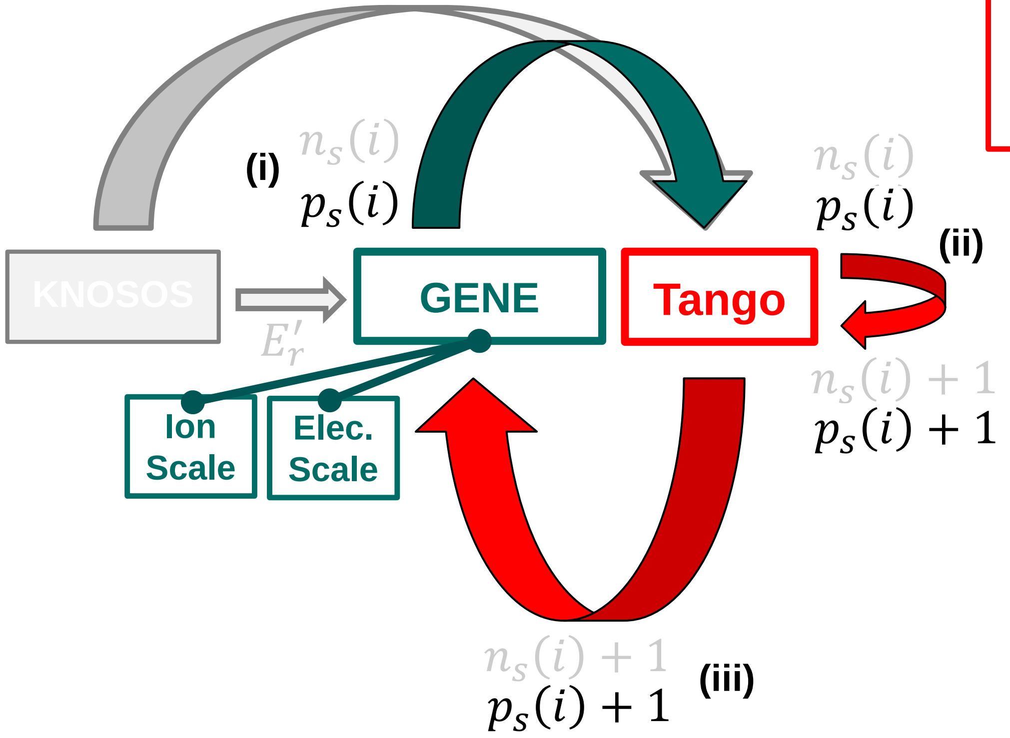

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KNOSOS: Neoclassical fluxes and the background radial electric field

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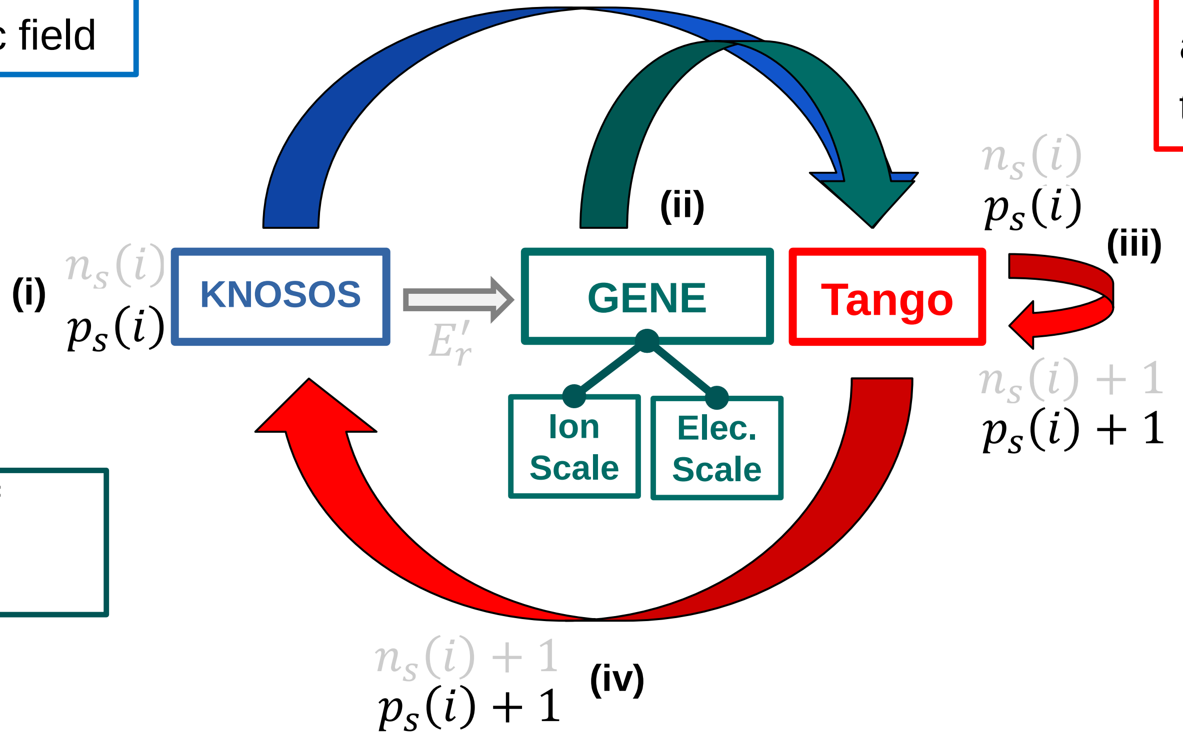

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KNOSOS: Neoclassical fluxes and the background radial electric field

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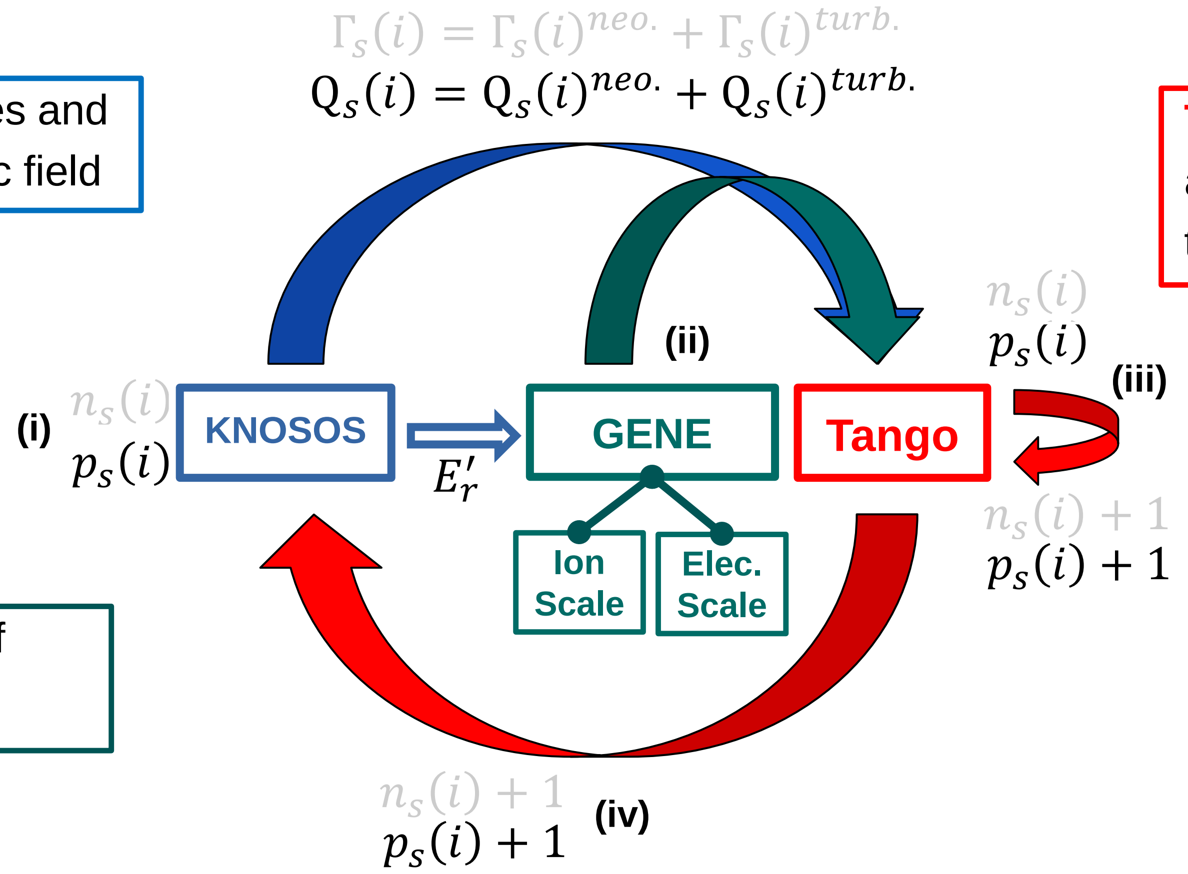

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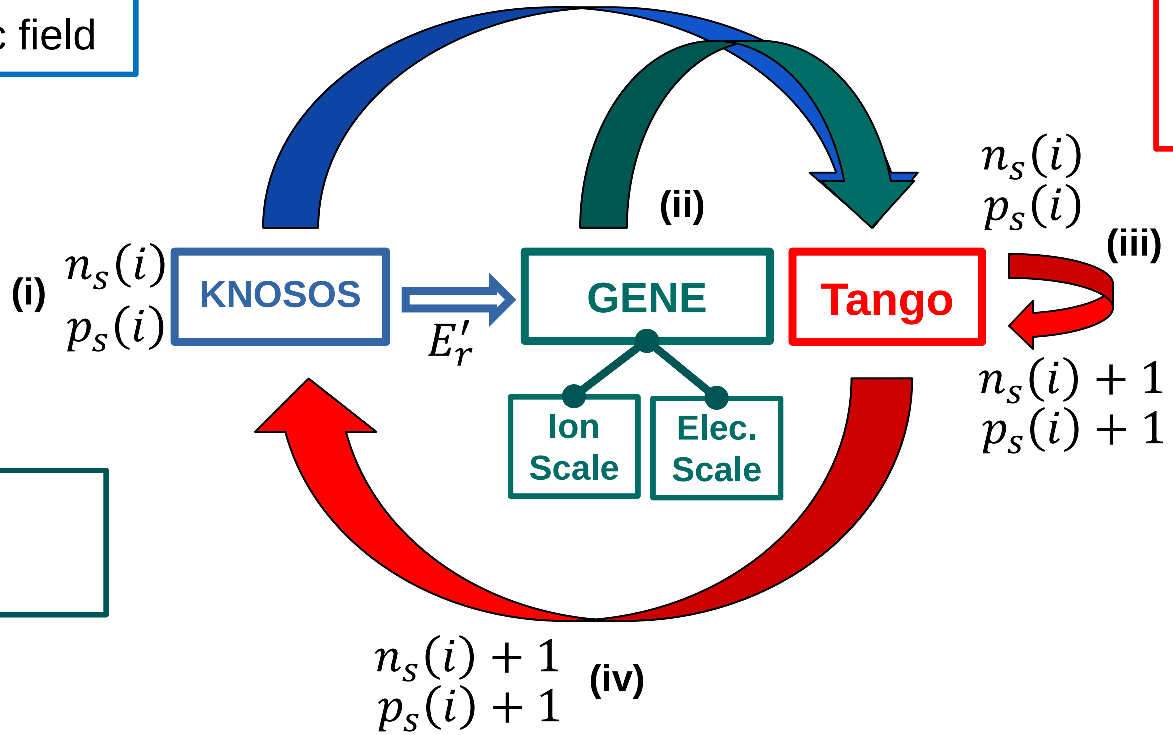

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- Model hierarchy

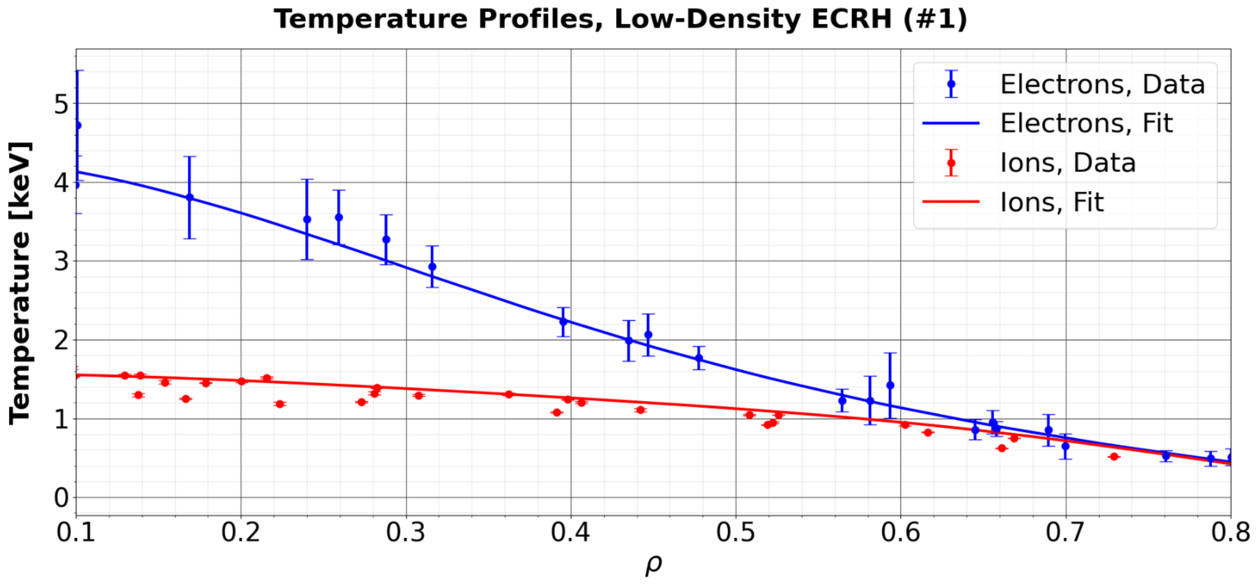
II. Results

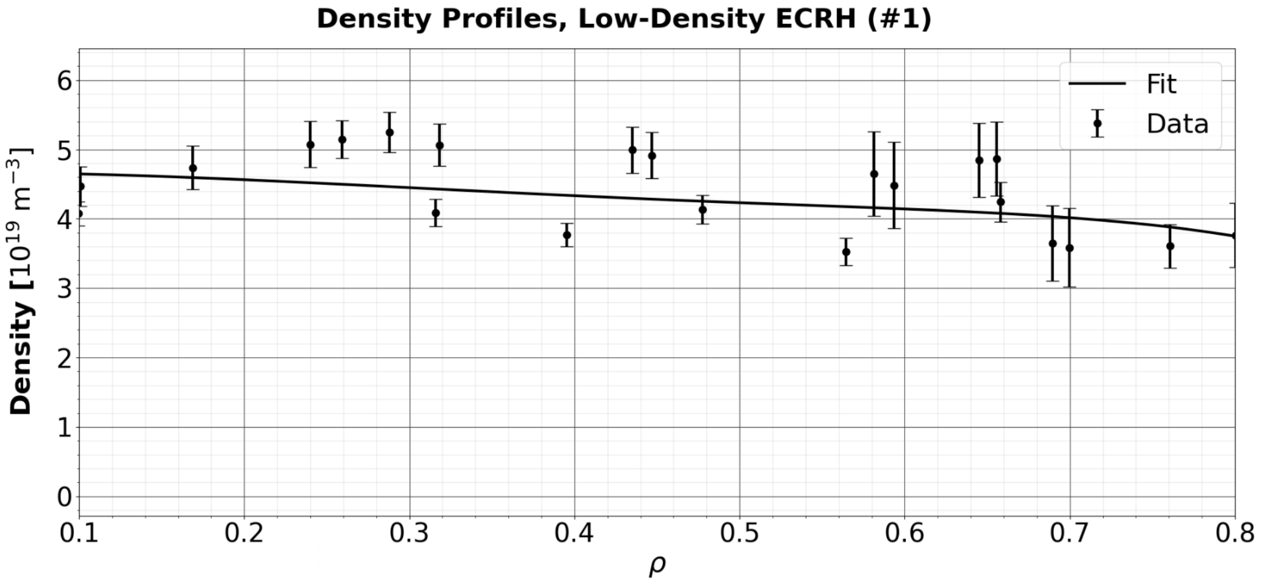
- Comparison of plasma profiles and heat fluxes
- Turbulence characteristics of the simulations & discharges

III. Summary & Outlook

RESULTS: ION-SCALE SIMULATION ONLY

LOW-DENSITY ECRH





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RESULTS: ION-SCALE SIMULATION ONLY
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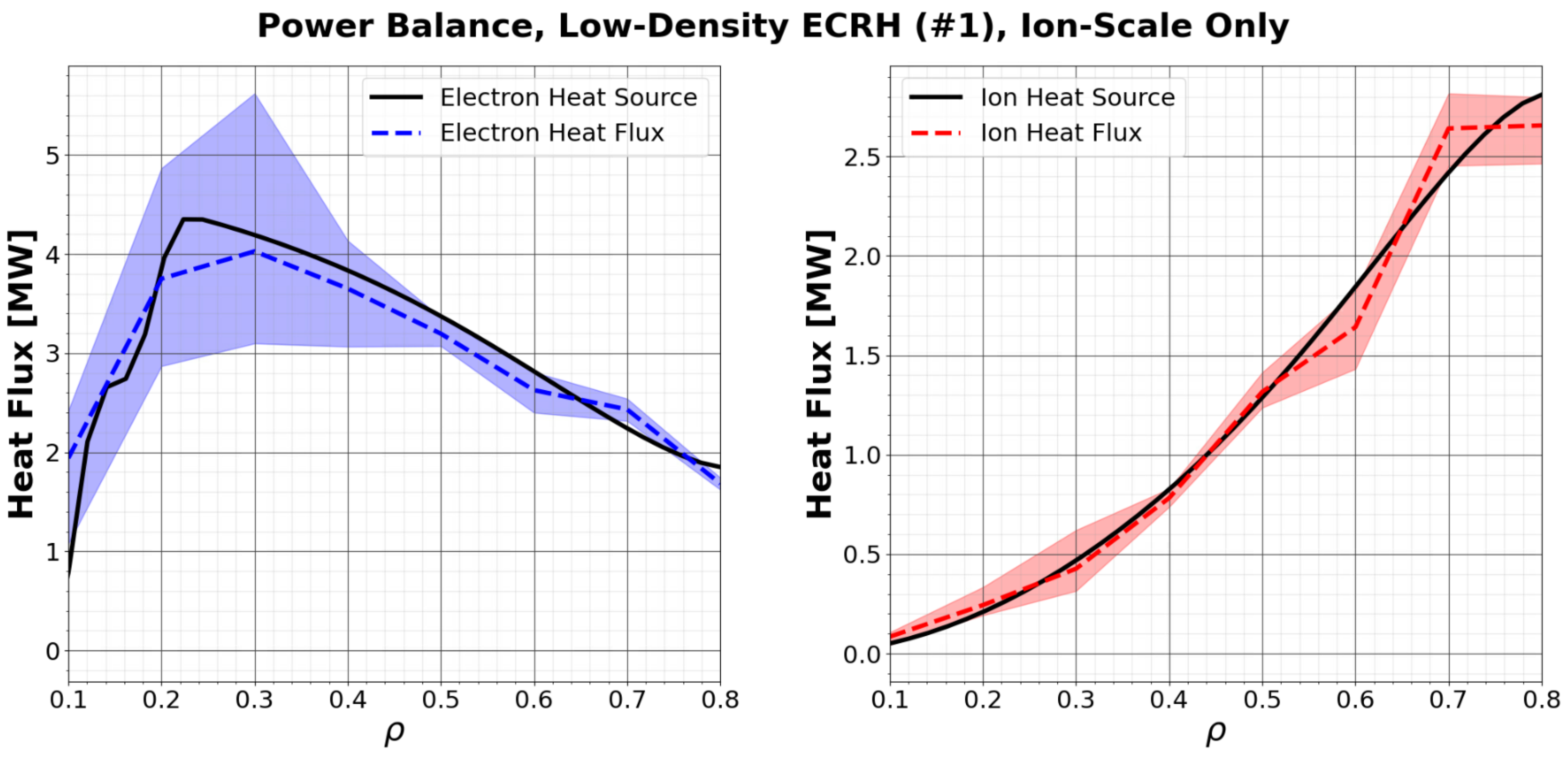

- Power balance is satisfied within 20 iterations.

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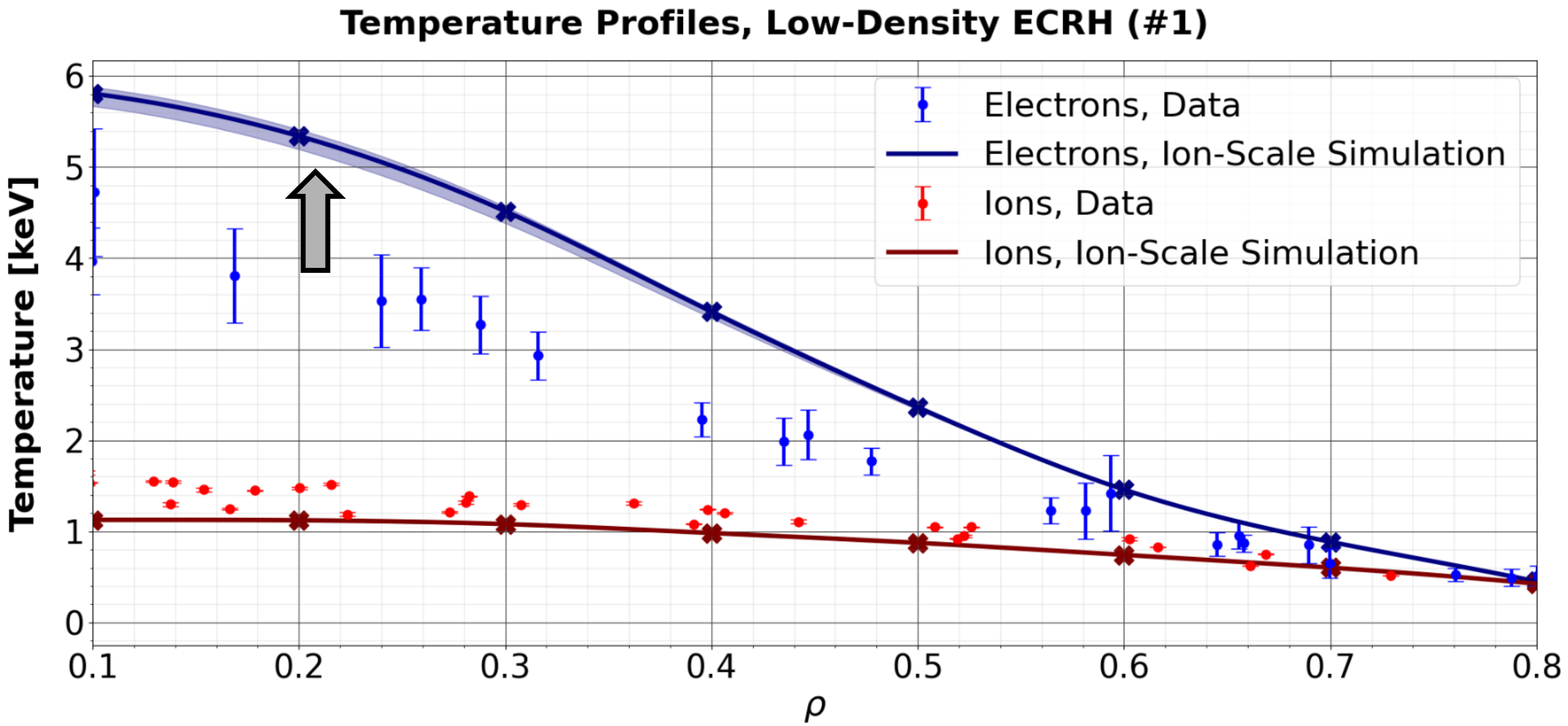
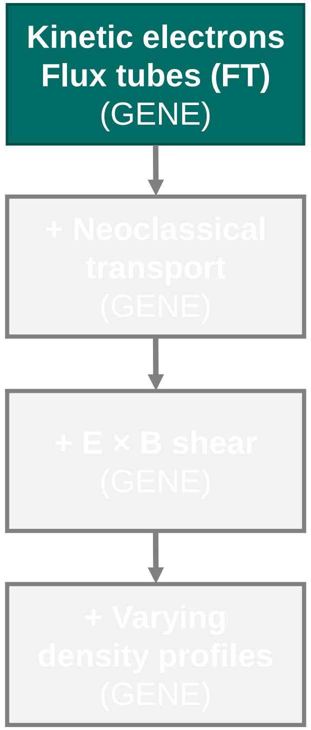
+ E × B shear (GENE)

+ Varying density profiles (GENE)

RESULTS: ION-SCALE SIMULATION ONLY

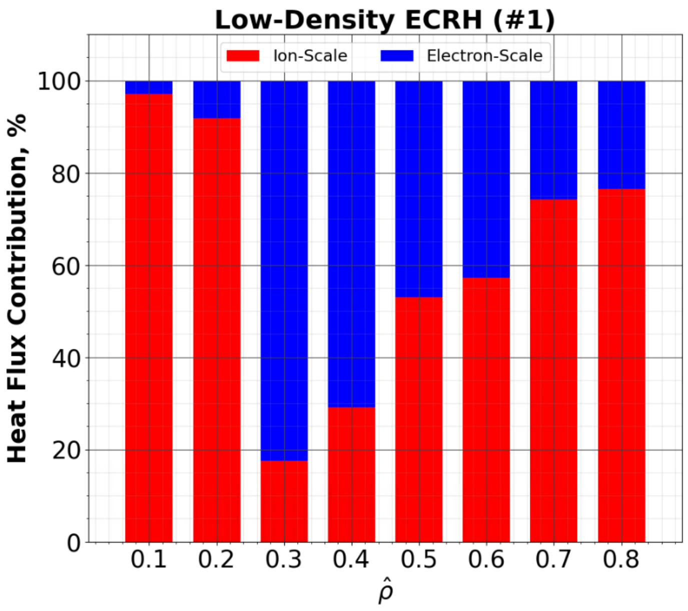
LOW-DENSITY ECRH

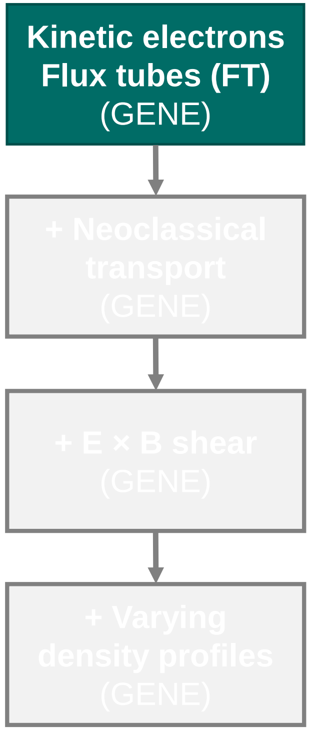




- Power balance is satisfied within 20 iterations.
- Without electron-scale turbulence, the Te profile significantly deviated from the data.

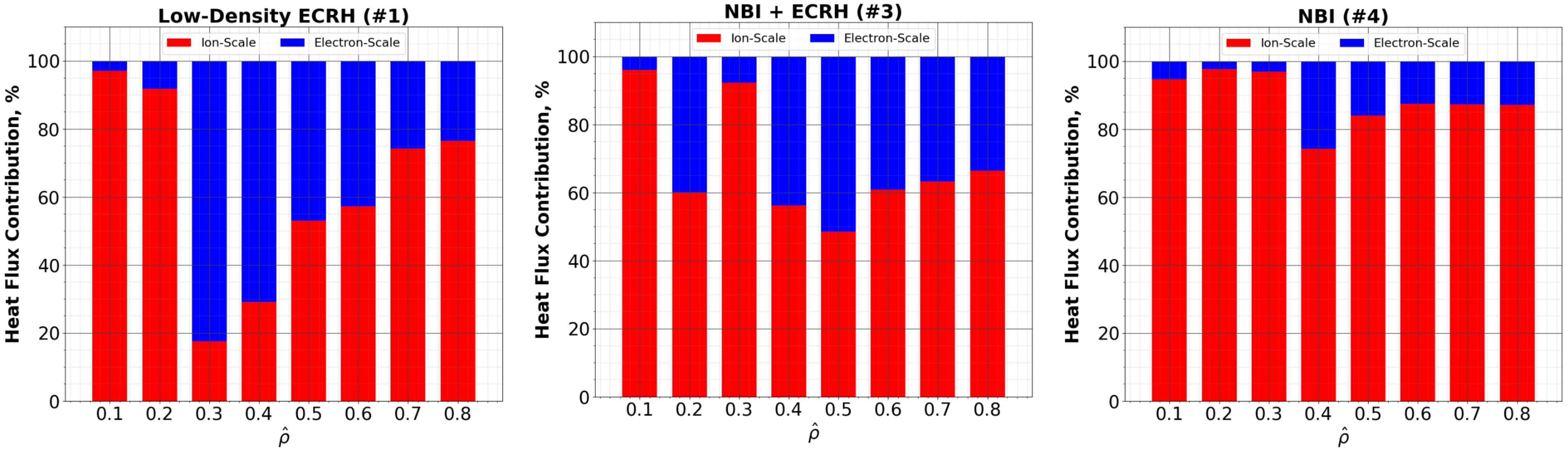
RESULTS: ION- & ELECTRON-SCALE CONTRIBUTION
LOW-DENSITY ECRH





- Power balance is satisfied within 20 iterations.
- Without electron-scale turbulence, the Te profile significantly deviated from the data
- For ρ ≥ 0.4, the contribution of electron-scale turbulence can be significant (20-80%).
- **This highlights the importance of including ETG turbulence in modelling some experiments.**

RESULTS: ION- & ELECTRON-SCALE CONTRIBUTION
LOW-DENSITY ECRH



Kinetic electrons Flux tubes (FT) (GENE)

↓

+ Neoclassical transport (GENE)

↓

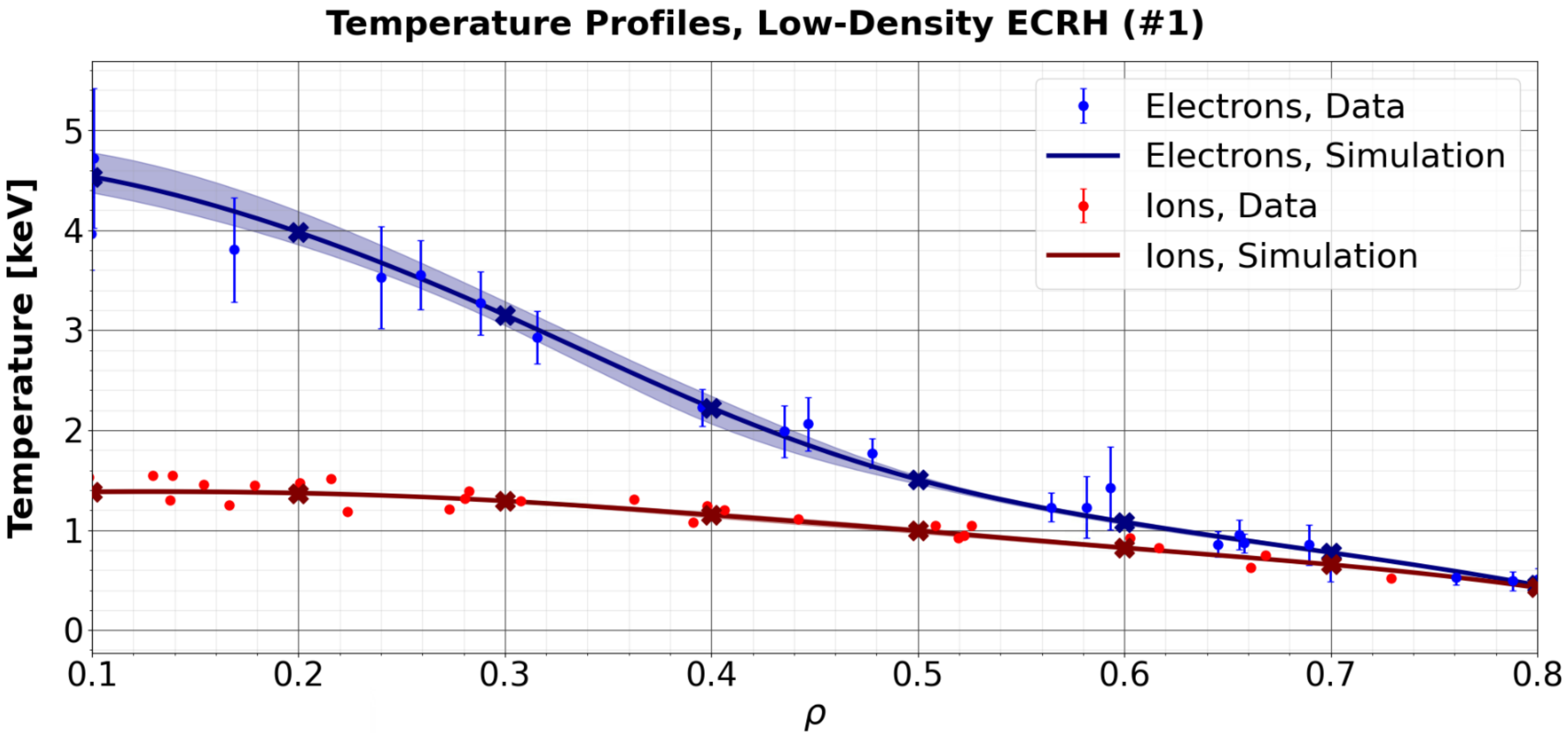
+ E × B shear (GENE)

↓

+ Varying density profiles (GENE)

- Power balance is satisfied within 20 iterations.
- Without electron-scale turbulence, the Te profile significantly deviated from the data
- For ρ ≥ 0.4, the contribution of electron-scale turbulence can be significant (20-80%).
- **This highlights the importance of including ETG turbulence in modelling some experiments.**

PHASE 1: BASE CASE
LOW-DENSITY ECRH



- With electron-scale turbulence, better agreement with experimental data is achieved but **simulations still lack several physical effects**.

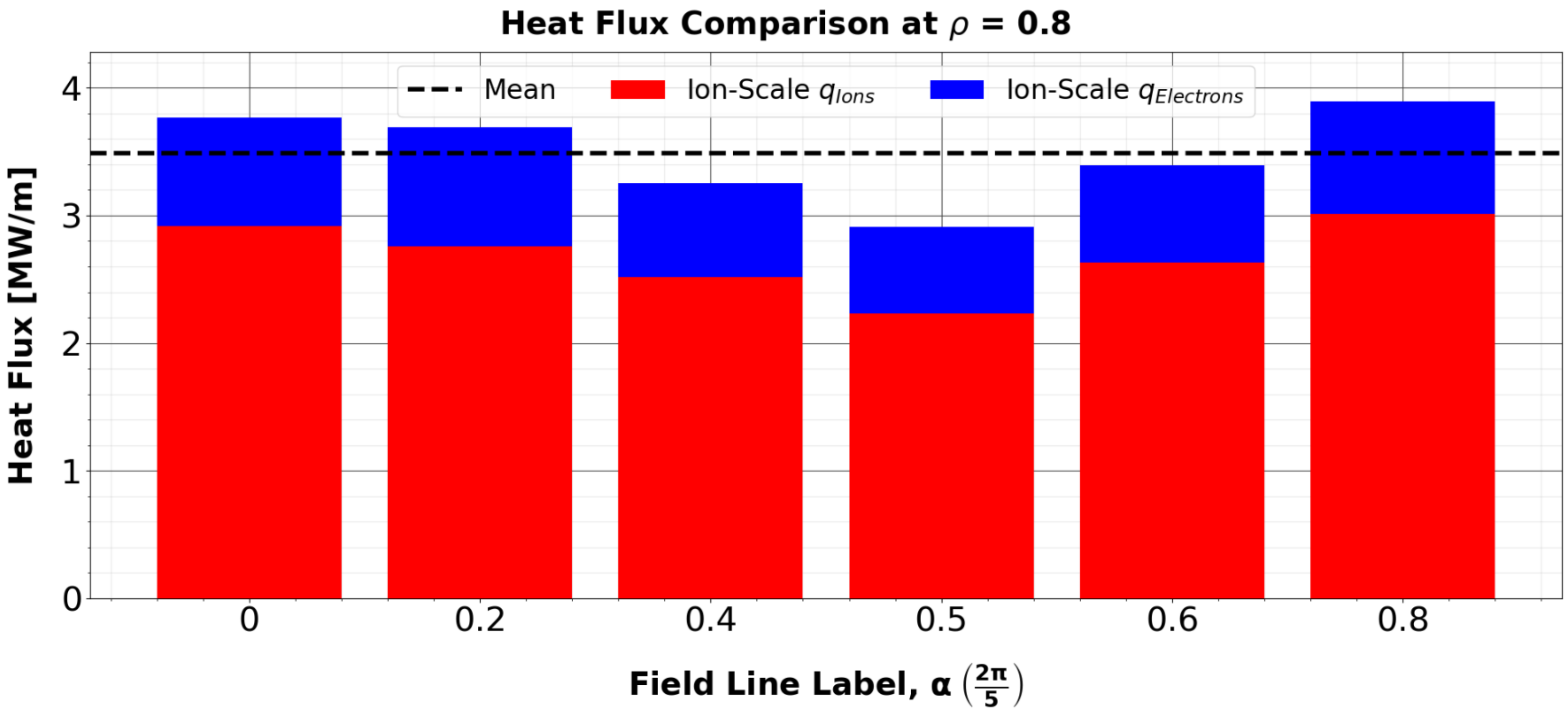
Kinetic electrons Flux tubes (FT) (GENE)

+ Neoclassical transport (GENE)

+ E × B shear (GENE)

+ Varying density profiles (GENE)

PHASE 1: HEAT FLUX COMPARISON
LOW-DENSITY ECRH



Kinetic electrons Flux tubes (FT) (GENE)

+ Neoclassical transport (GENE)

+ E × B shear (GENE)

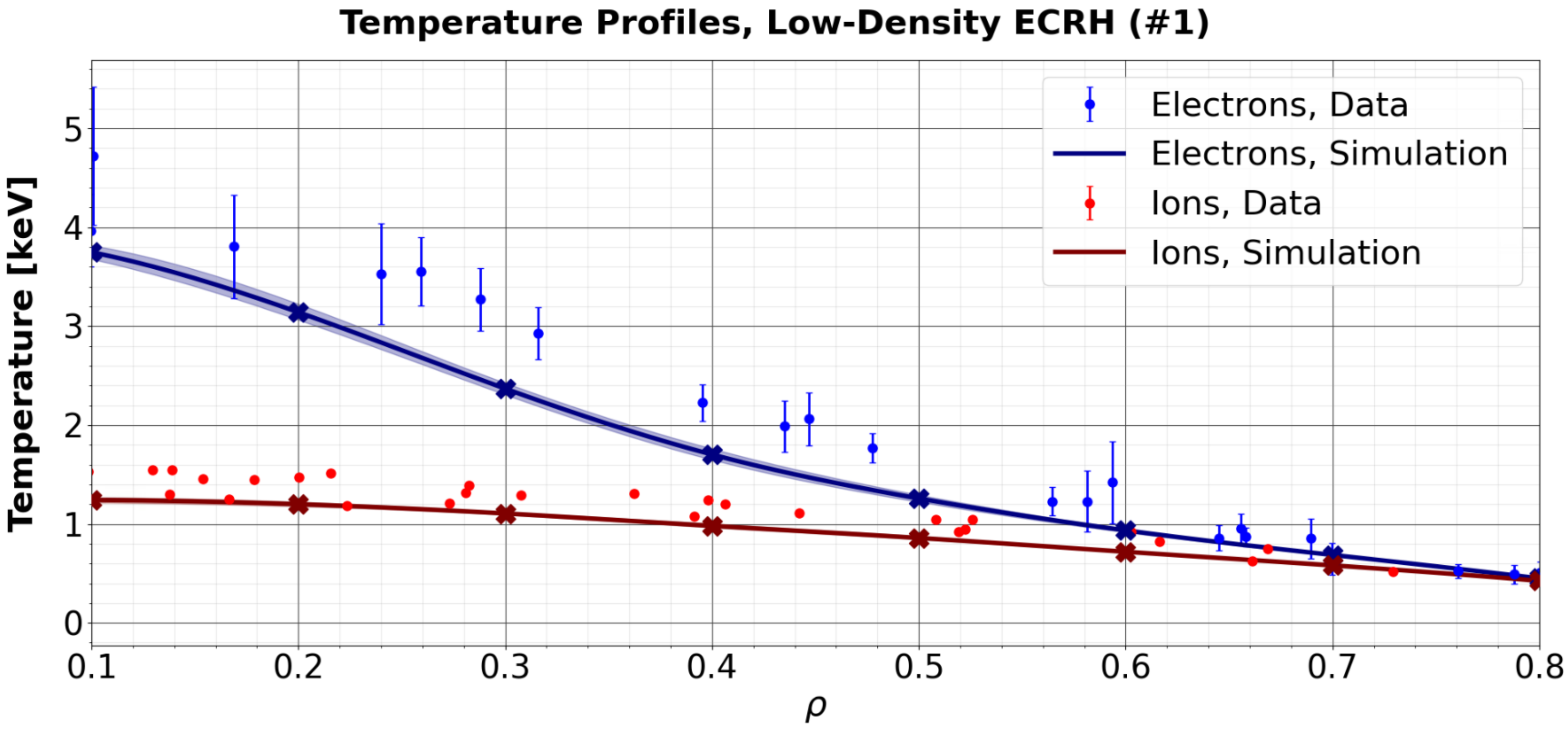
+ Varying density profiles (GENE)

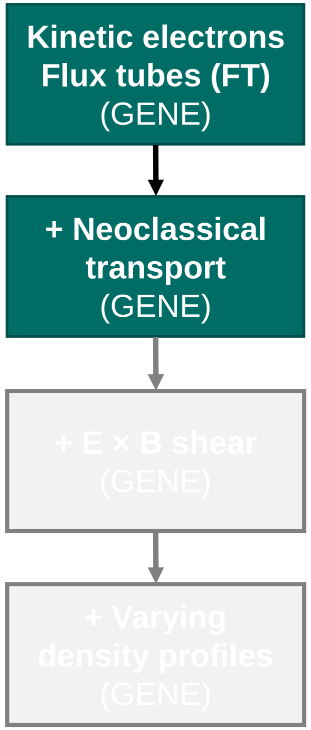
- With electron-scale turbulence, better agreement with experimental data is achieved but **simulations still lack several physical effects**.

- Simulations were performed for different flux tubes as denoted by α.
  - The maximum error is 23% while the error with respect to the mean is 6%.

PHASE 2: WITH NEOCLASSICAL TRANSPORT

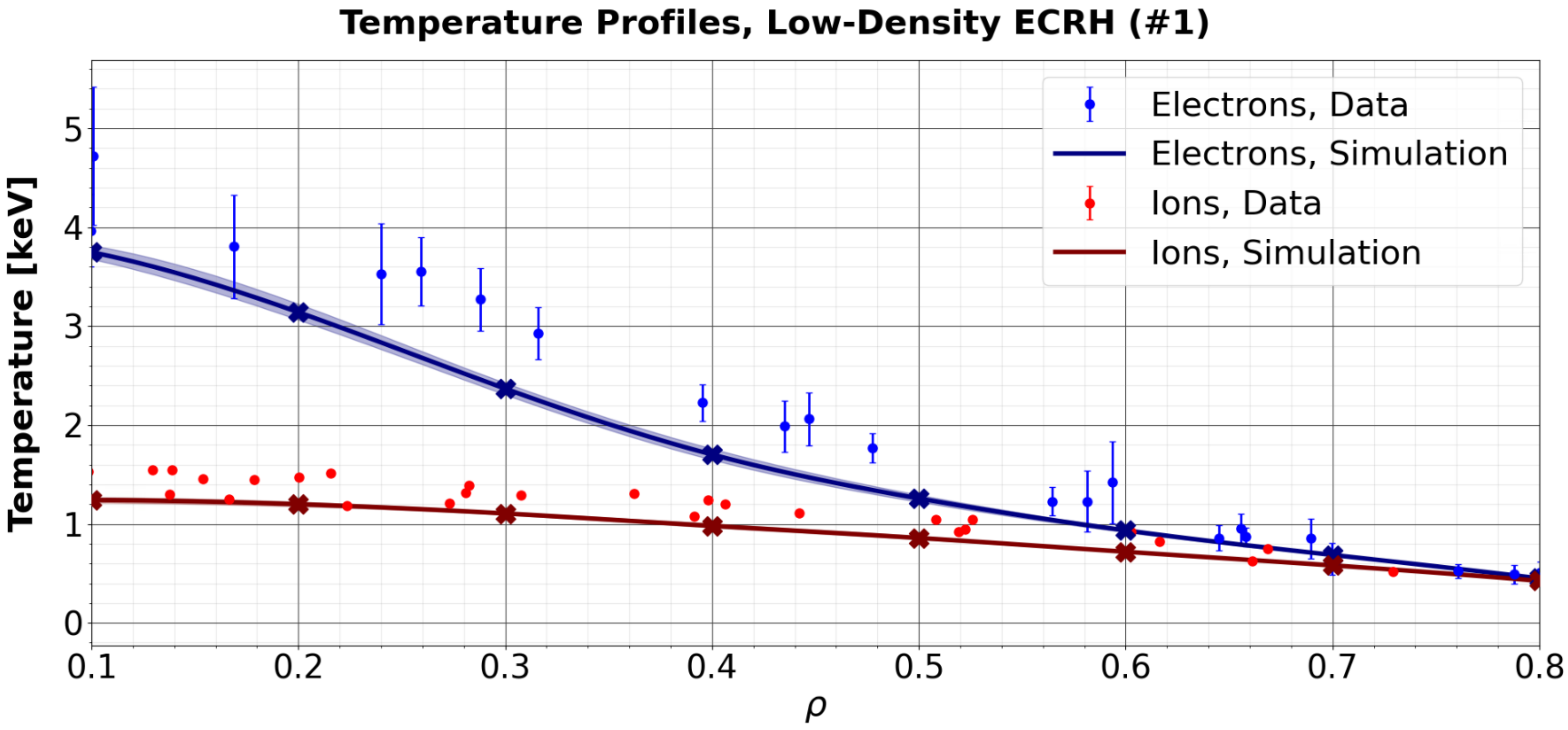
LOW-DENSITY ECRH





- ➢ With the addition of neoclassical transport, temperatures decreased.
  - The agreement worsened for $\rho < 0.5$.

PHASE 2: WITH NEOCLASSICAL TRANSPORT
LOW-DENSITY ECRH



Kinetic electrons Flux tubes (FT) (GENE)

↓

+ Neoclassical transport (GENE)

↓

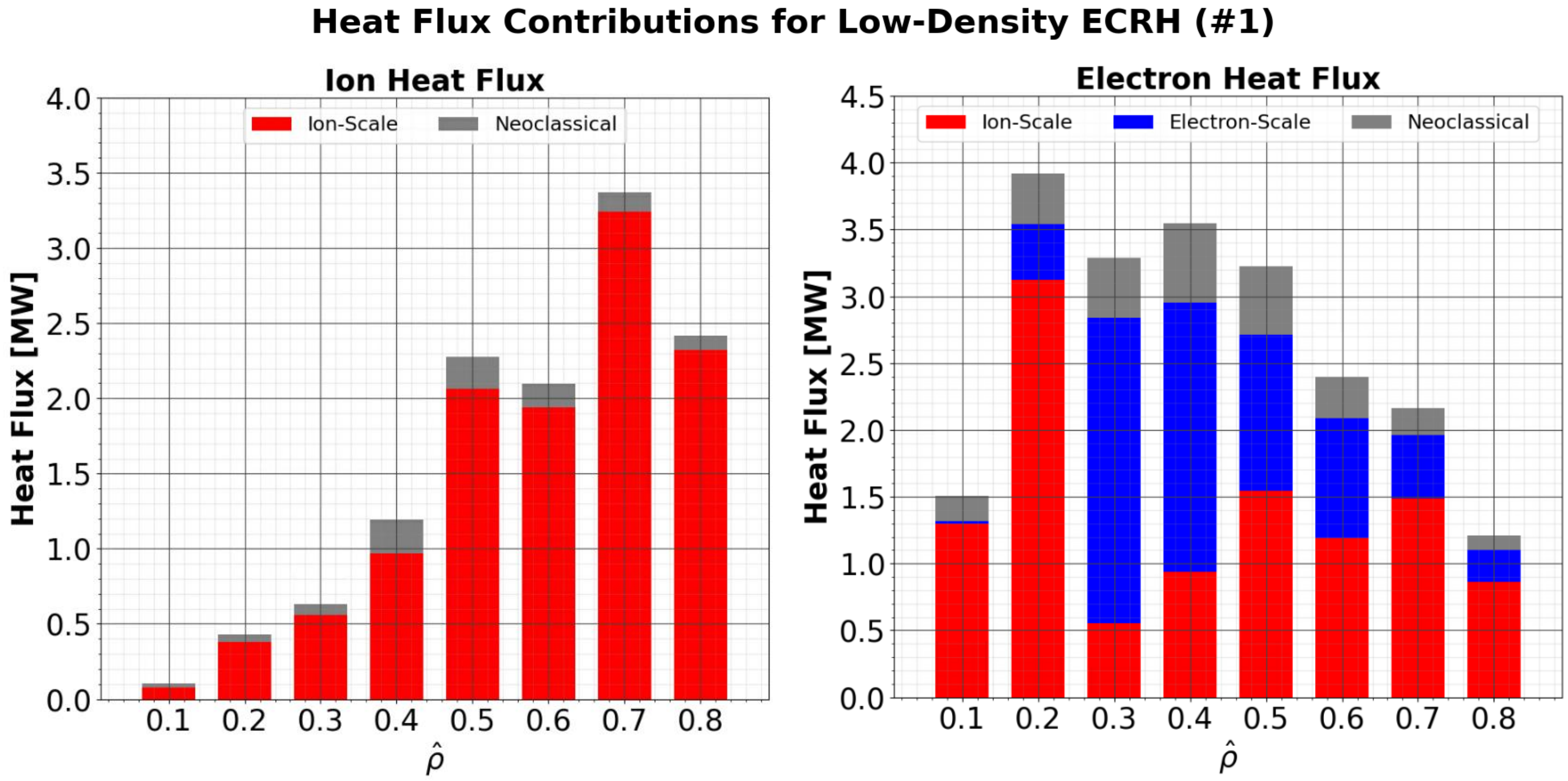
+ E × B shear (GENE)

↓

+ Varying density profiles (GENE)

- ➢ With the addition of neoclassical transport, temperatures decreased.
  - The agreement worsened for $\rho < 0.5$.
- ➢ The Ti profile exhibited a smaller reduction.

PHASE 2: WITH NEOCLASSICAL TRANSPORT
LOW-DENSITY ECRH



Kinetic electrons Flux tubes (FT) (GENE)

↓

+ Neoclassical transport (GENE)

↓

+ E × B shear (GENE)

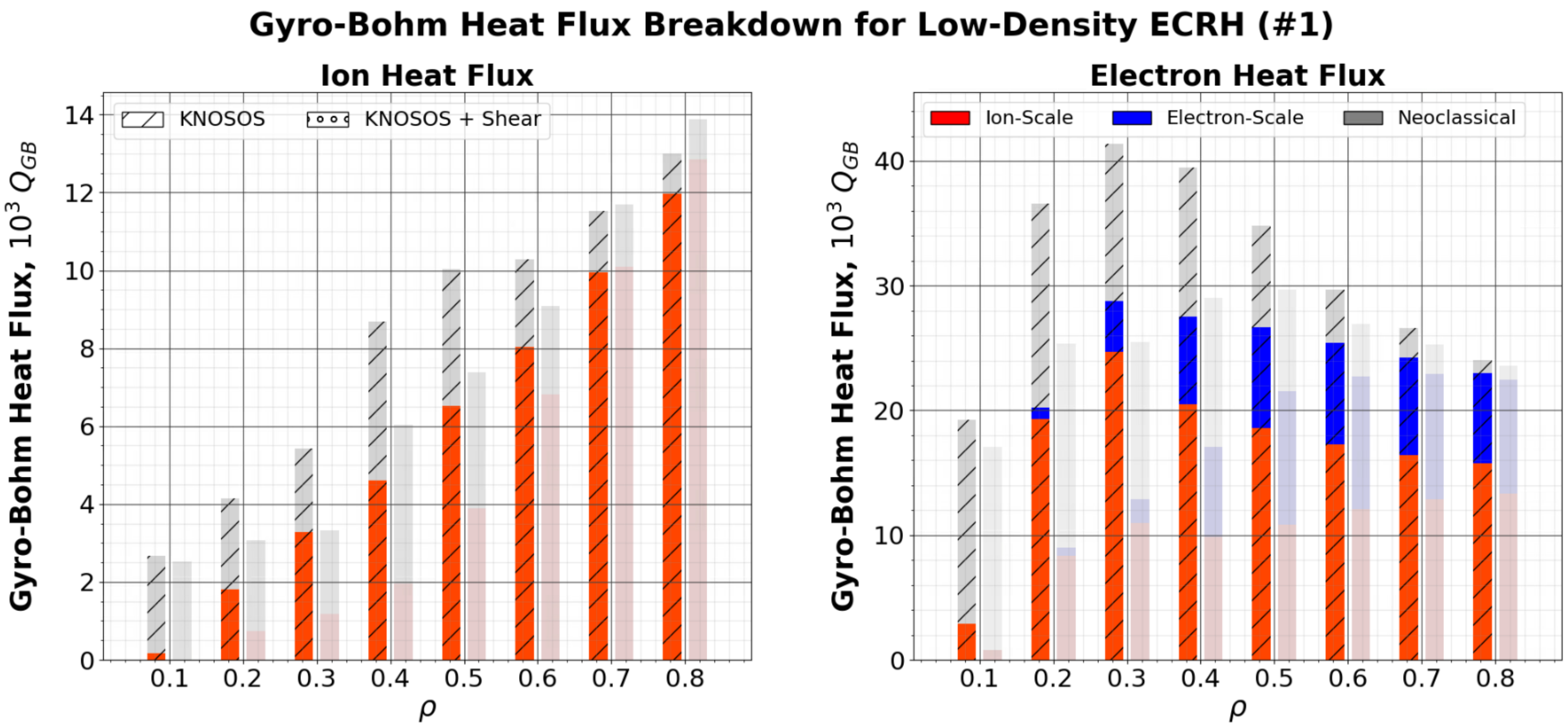
↓

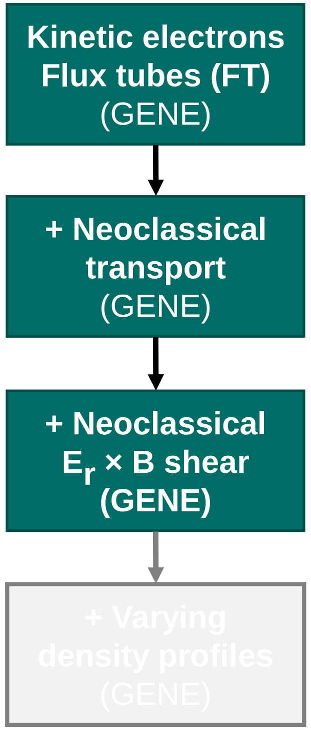
+ Varying density profiles (GENE)

- ➢ With the addition of neoclassical transport, temperatures decreased.
  - The agreement worsened for ρ < 0.5.
- ➢ The Ti profile exhibited a smaller reduction.
- ➢ The breakdown of total electron and ion heat fluxes explain both observations.

PHASE 3: WITH NEOCLASSICAL E × B SHEAR

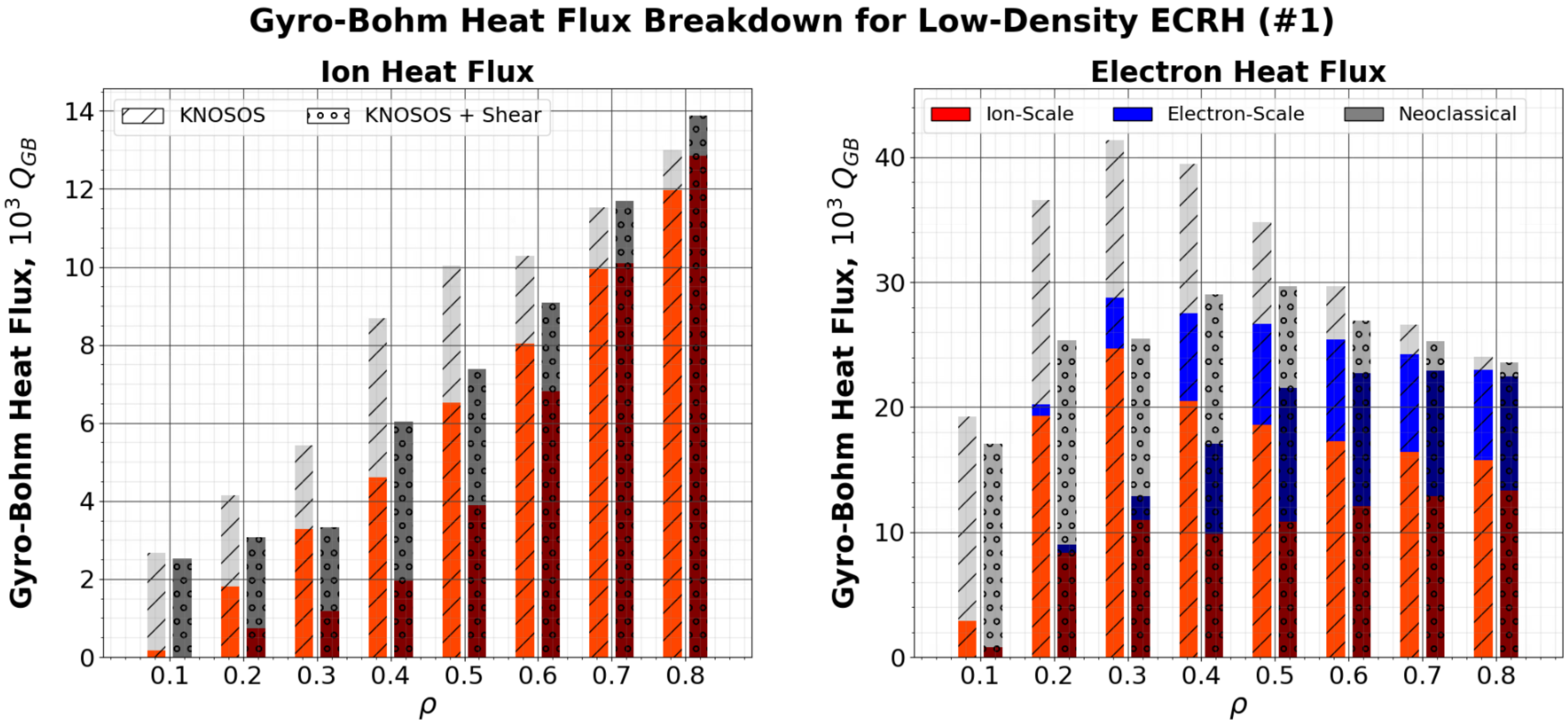
LOW-DENSITY ECRH

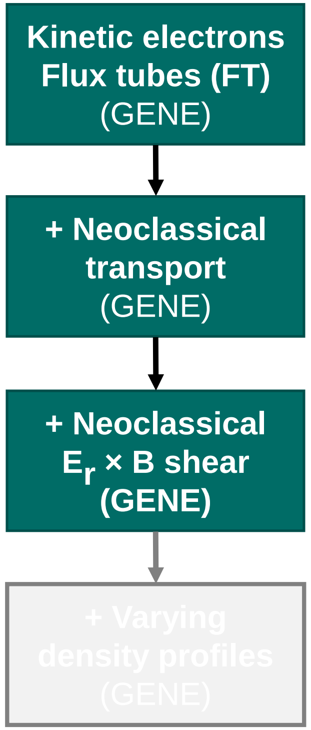




➢ With neoclassical E_r × B shear, the heat fluxes are reduced.

PHASE 3: WITH NEOCLASSICAL E × B SHEAR
LOW-DENSITY ECRH

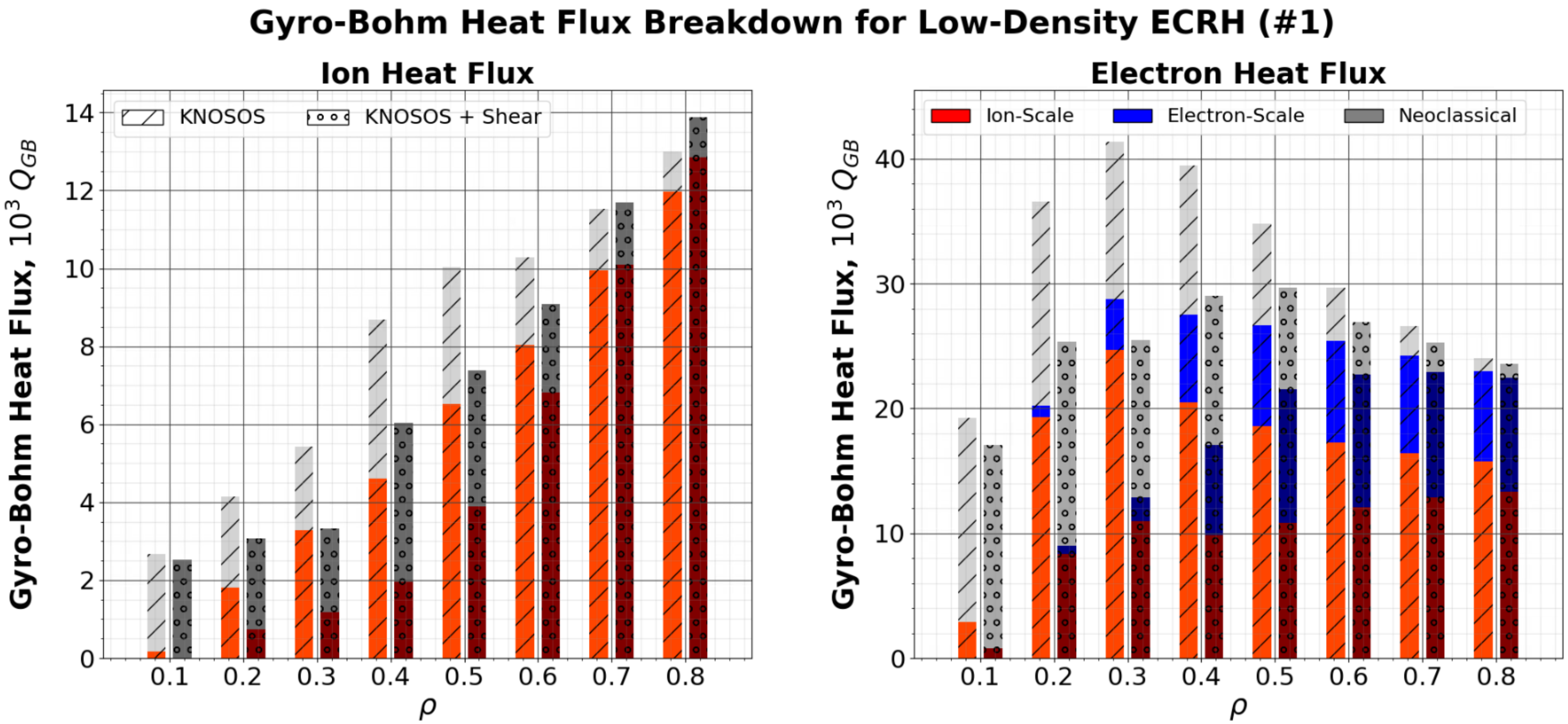




- With neoclassical E_r × B shear, the heat fluxes are reduced.
  - The reduction is more significant in the inner and intermediate positions (ρ < 0.6).

PHASE 3: WITH NEOCLASSICAL E × B SHEAR

LOW-DENSITY ECRH



Kinetic electrons Flux tubes (FT) (GENE)

↓

+ Neoclassical transport (GENE)

↓

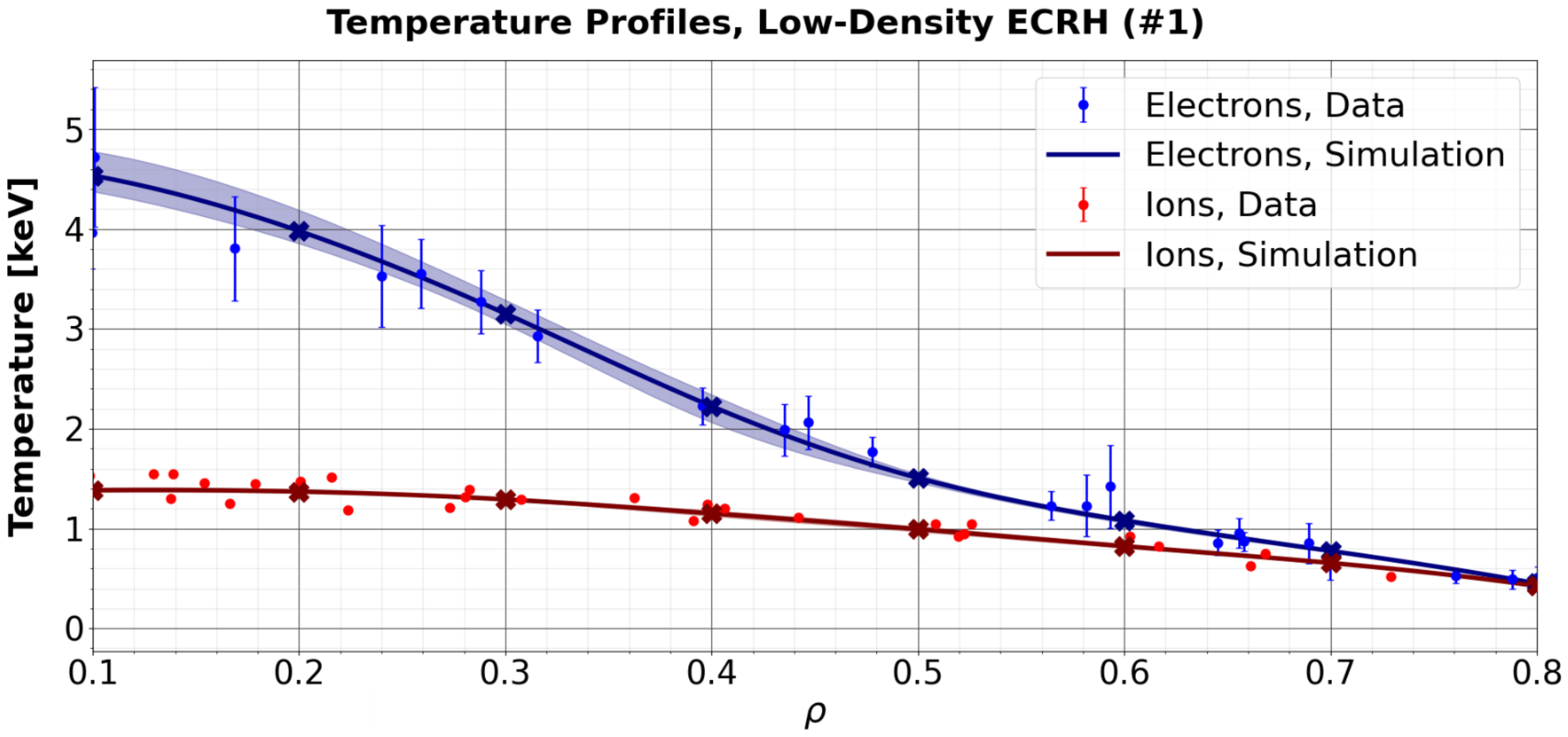
+ Neoclassical E_r × B shear (GENE)

↓

+ Varying density profiles (GENE)

- With neoclassical E_r × B shear, the heat fluxes are reduced.
  - The reduction is more significant in the inner and intermediate positions (ρ < 0.6).
  - Large decrease in ion-scale fluxes

PHASE 3: WITH NEOCLASSICAL E × B SHEAR
LOW-DENSITY ECRH



Kinetic electrons Flux tubes (FT) (GENE)

↓

+ Neoclassical transport (GENE)

↓

+ Neoclassical E_r × B shear (GENE)

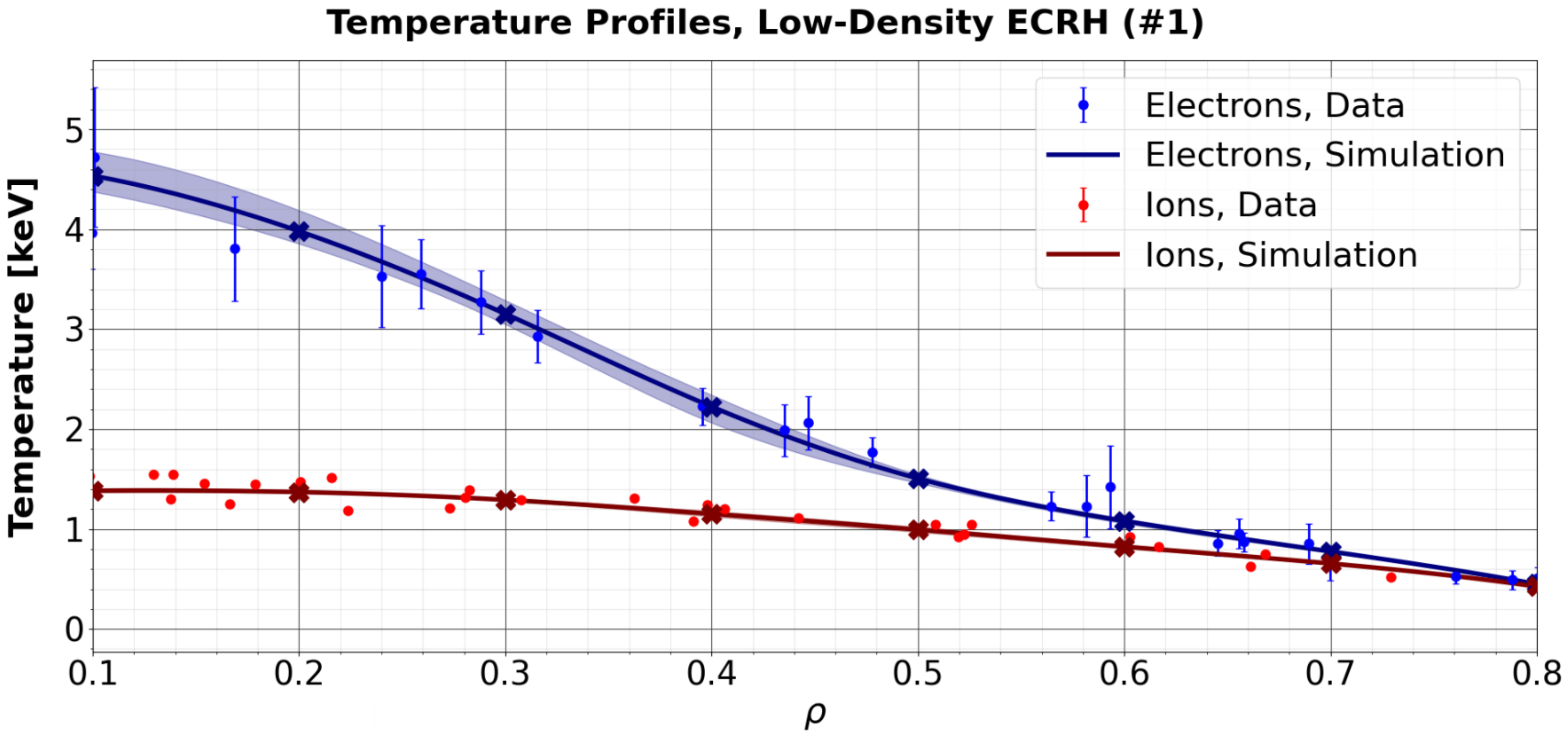
↓

+ Varying density profiles (GENE)

➢ With neoclassical E_r × B shear, which reduces turbulence, temperature profiles increased.

PHASE 3: WITH NEOCLASSICAL E × B SHEAR

LOW-DENSITY ECRH



Kinetic electrons Flux tubes (FT) (GENE)

↓

+ Neoclassical transport (GENE)

↓

+ Neoclassical E_r × B shear (GENE)

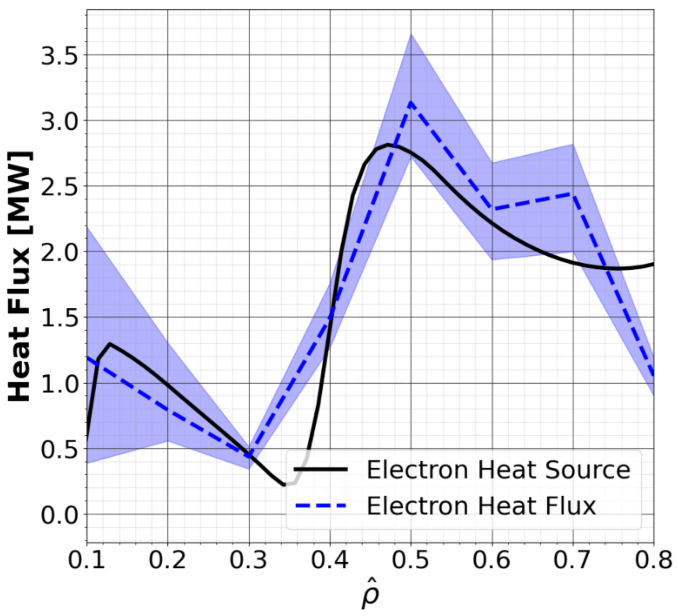
↓

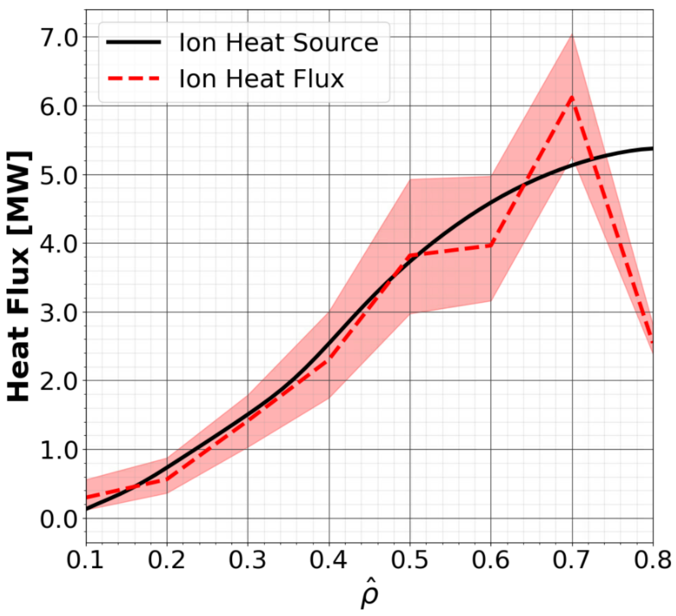
+ Varying density profiles (GENE)

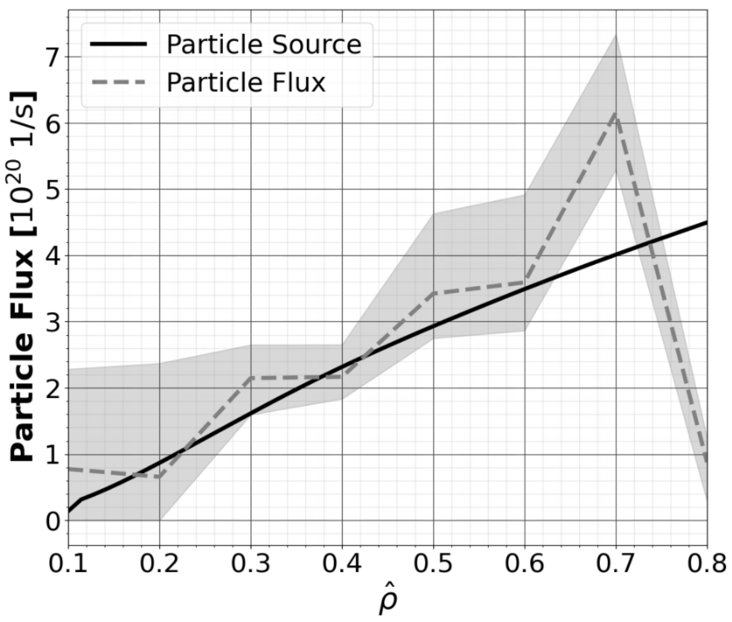
- With neoclassical E_r × B shear, which reduces turbulence, temperature profiles increased.
- Agreement with experimental temperature data improved significantly.
  - Experimental temperatures are both recovered well by simulations.

PHASE 4: WITH VARYING DENSITY PROFILE

NBI + ECRH







Kinetic electrons Flux tubes (FT) (GENE)

↓

+ Neoclassical transport (GENE)

↓

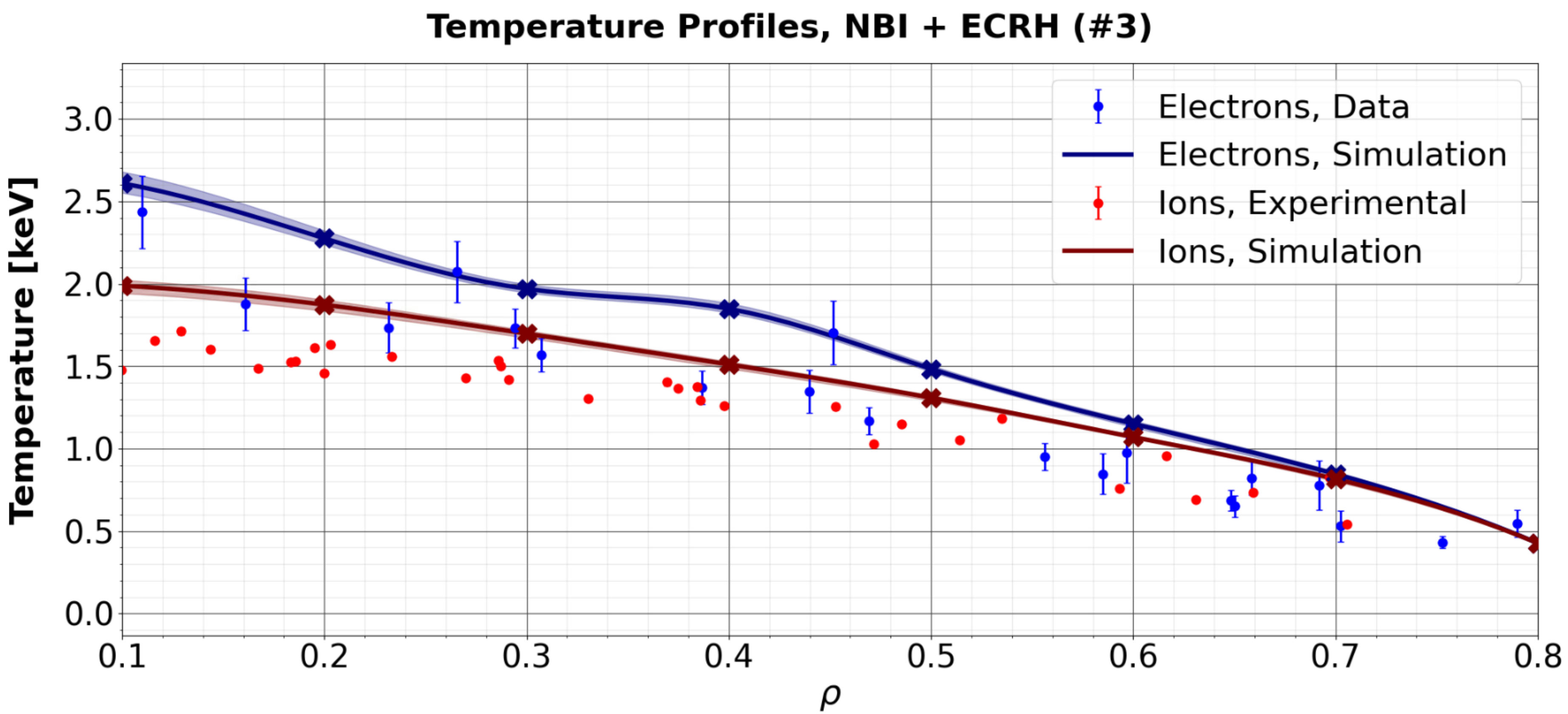
+ Neoclassical $E_r \times B$ shear (GENE)

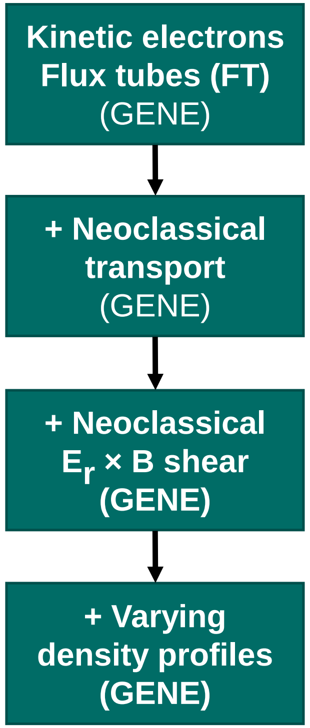
↓

+ Varying density profiles (GENE)

➢ Using the boundaries set by the data fit, power and particle balances are both matched well

PHASE 4: WITH VARYING DENSITY PROFILE
NBI + ECRH

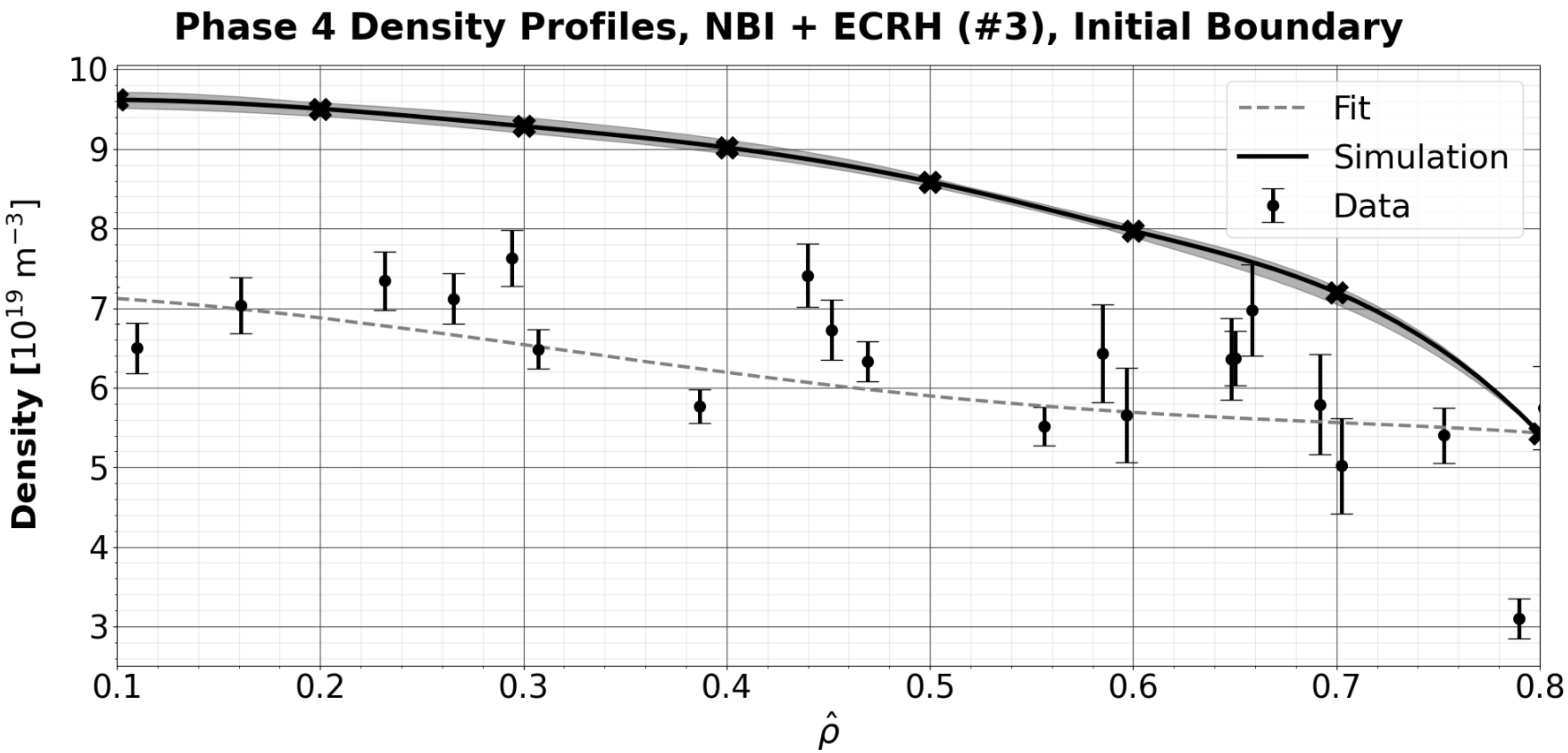


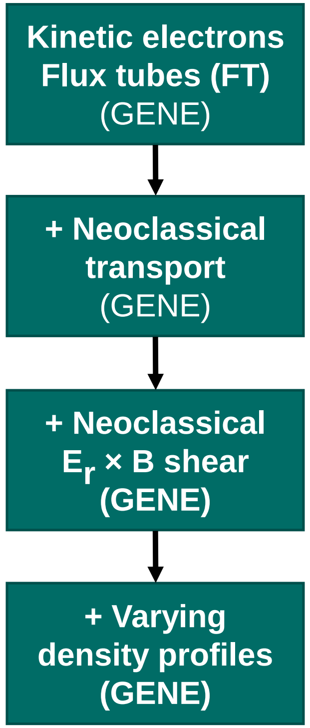


- Using the boundaries set by the data fit, power and particle balances are both matched well but disagreements are observed.
  - In some cases, the converged profiles diverge from the data.

PHASE 4: WITH VARYING DENSITY PROFILE

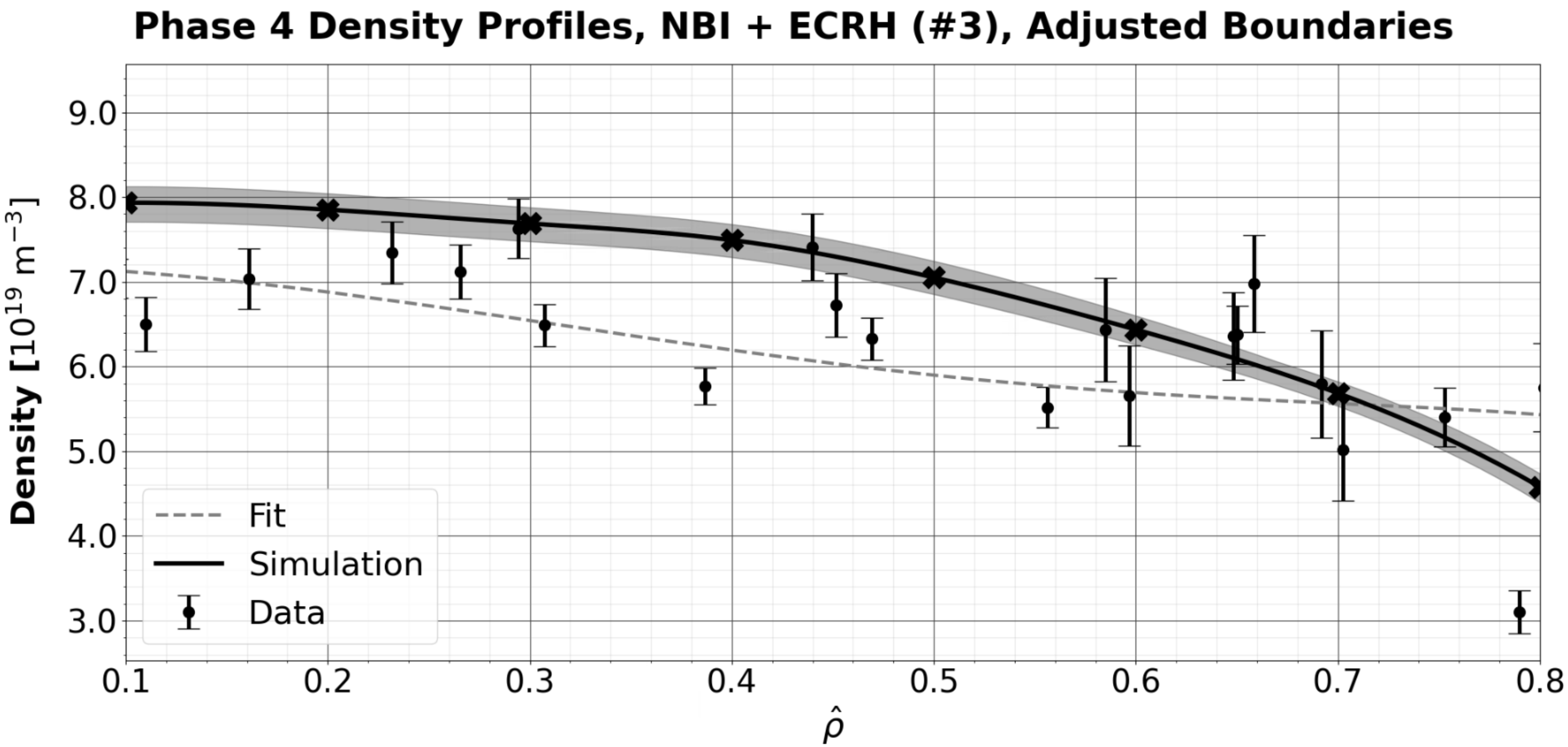
NBI + ECRH





- Using the boundaries set by the data fit, power and particle balances are both matched well but disagreements are observed.
  - In some cases, the converged profiles diverge from the data.
  - Primary challenge with matching the density profile: Negative particle fluxes for outer ρ

PHASE 4: WITH VARYING DENSITY PROFILE
NBI + ECRH



Kinetic electrons Flux tubes (FT) (GENE)

↓

+ Neoclassical transport (GENE)

↓

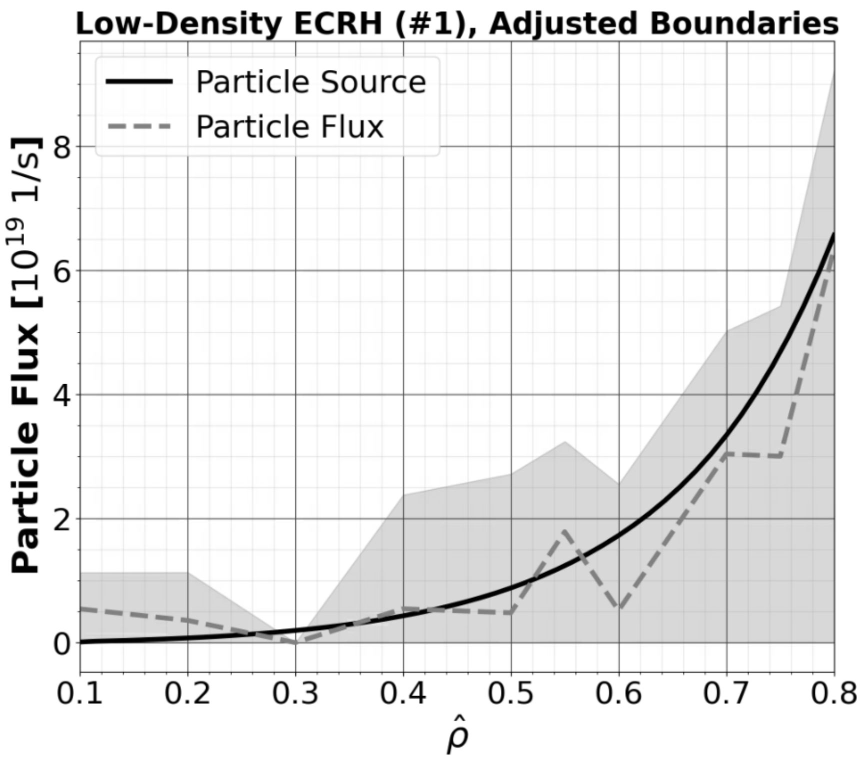
+ Neoclassical $E_r \times B$ shear (GENE)

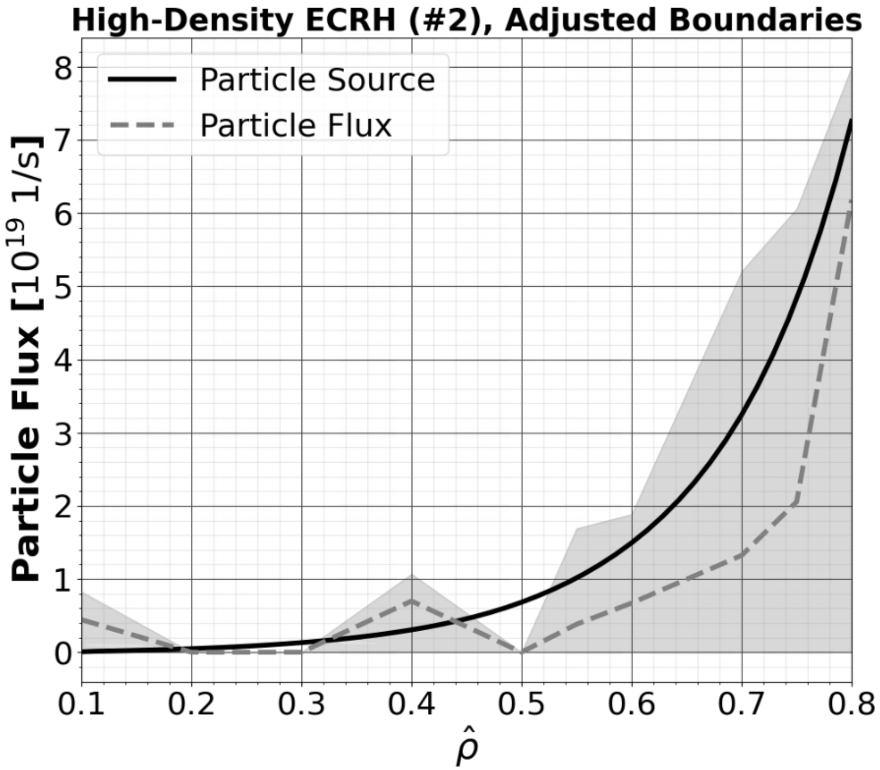
↓

+ Varying density profiles (GENE)

- Using the boundaries set by the data fit, power and particle balances are both matched well but disagreements are observed.
  - In some cases, the converged profiles diverge from the data.
  - Primary challenge with matching the density profile: Negative particle fluxes for outer ρ
  - Emphasizes the importance of the **boundary condition and the plasma edge**.

PHASE 4: WITH VARYING DENSITY PROFILE
ECRH SCENARIOS





Kinetic electrons Flux tubes (FT) (GENE)

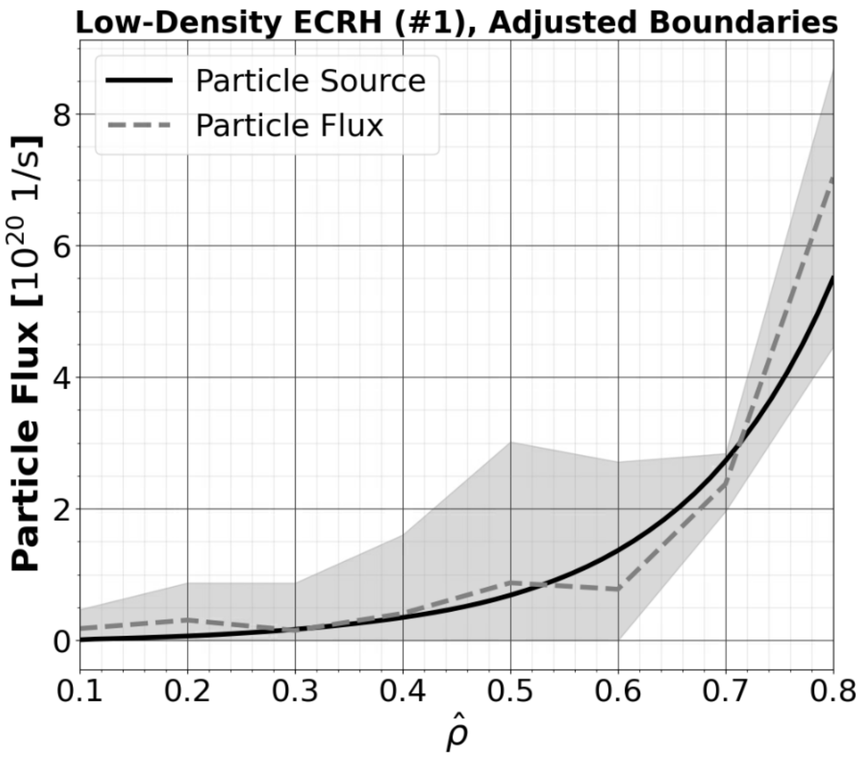
+ Neoclassical transport (GENE)

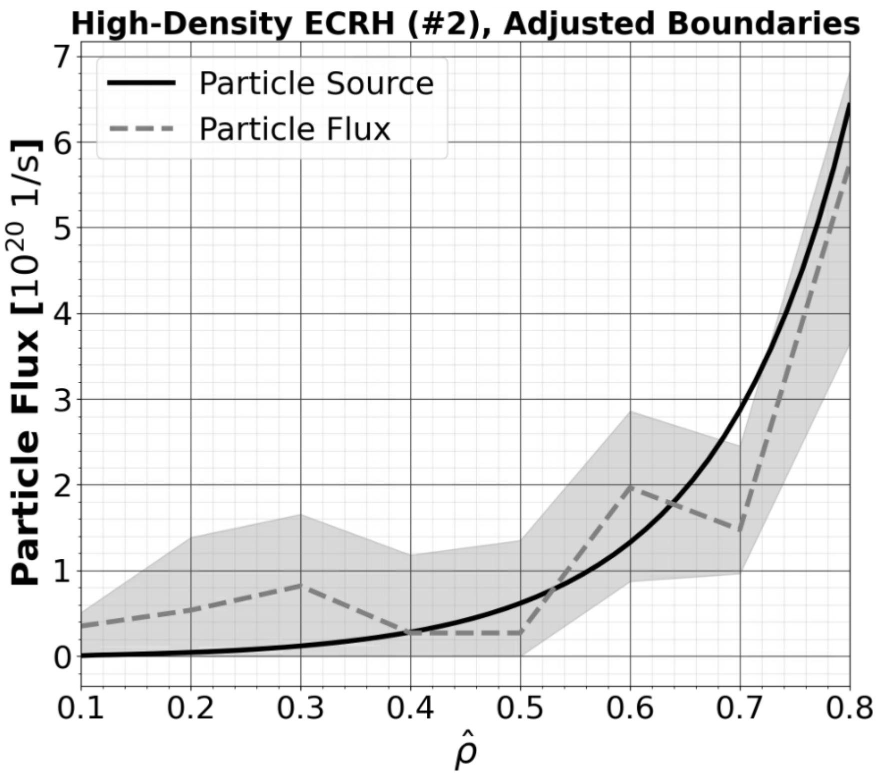
+ Neoclassical $E_r \times B$ shear (GENE)

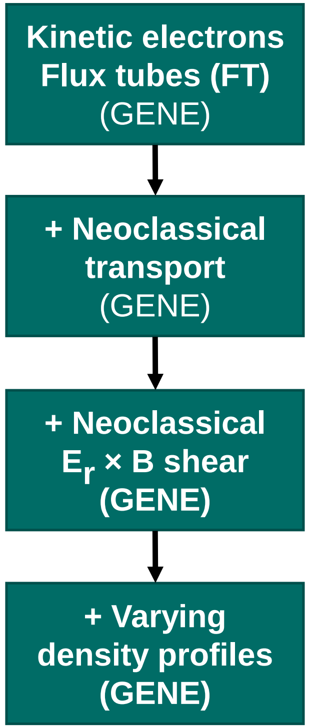
+ Varying density profiles (GENE)

- Besides the profile boundaries, the assumption on boundary neutrals concentration (**n_0**) is also important.
  - The particle fluxes of the ECRH scenarios were very sensitive to small changes in the profiles.
  - It was supposed that this arises from the lower particle source magnitude relative to the NBI cases.

PHASE 4: WITH VARYING DENSITY PROFILE
ECRH SCENARIOS







- Besides the profile boundaries, the assumption on boundary neutrals concentration ($\mathbf{n_0}$) is also important.
    - The particle fluxes of the ECRH scenarios were very sensitive to small changes in the profiles.
    - It was supposed that this arises from the lower particle source magnitude relative to the NBI cases.
    - With an increase of an order of magnitude for $\mathbf{n_0}$, the particle balances are more consistently satisfied.

PHASE 4: WITH VARYING DENSITY PROFILE
FLUX BREAKDOWN

Kinetic electrons
Flux tubes (FT)
(GENE)

↓

+ Neoclassical transport
(GENE)

↓

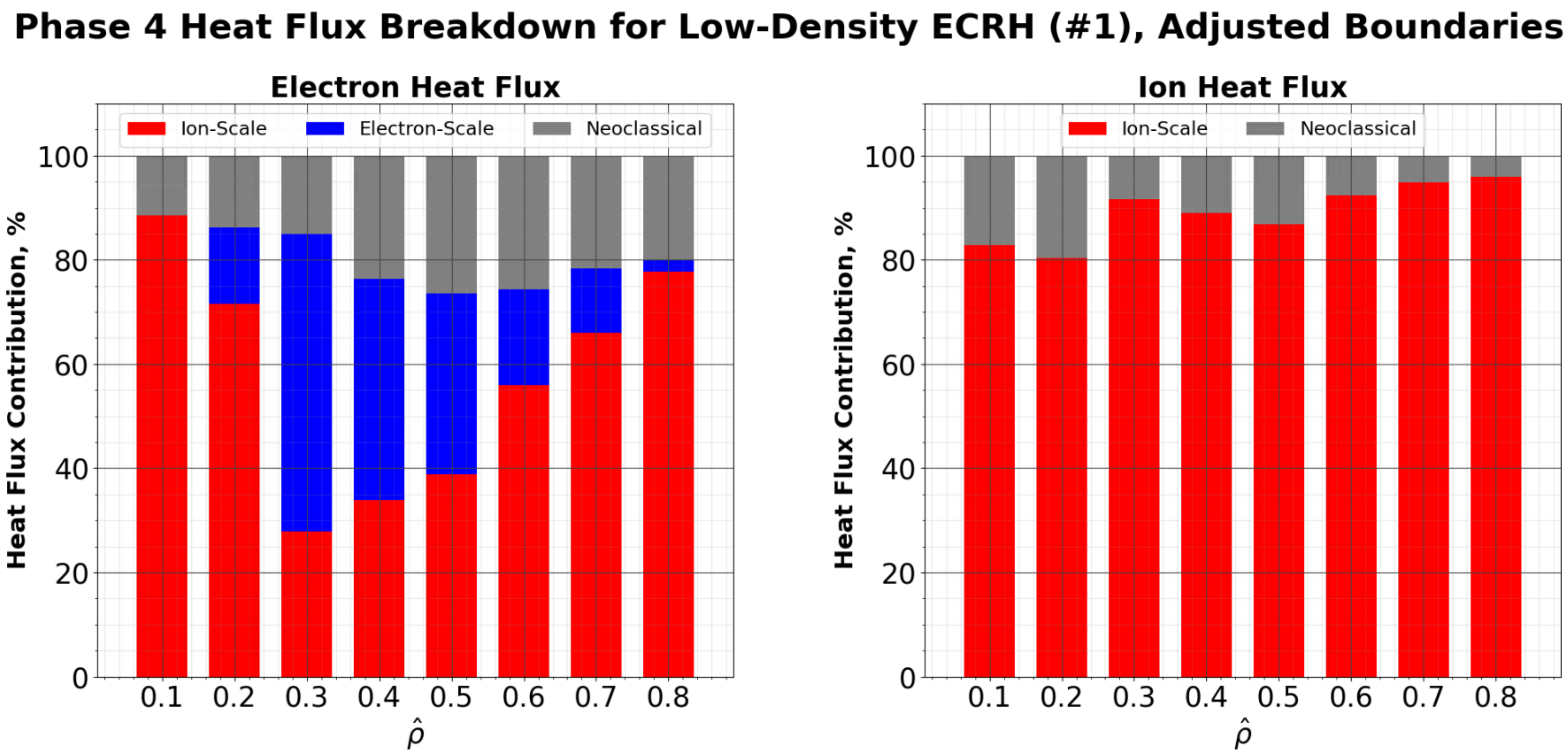
+ Neoclassical E_r × B shear
(GENE)

↓

+ Varying density profiles
(GENE)

- Revisiting the breakdown of heat fluxes for each scenario:

PHASE 4: WITH VARYING DENSITY PROFILE
FLUX BREAKDOWN



Kinetic electrons Flux tubes (FT) (GENE)

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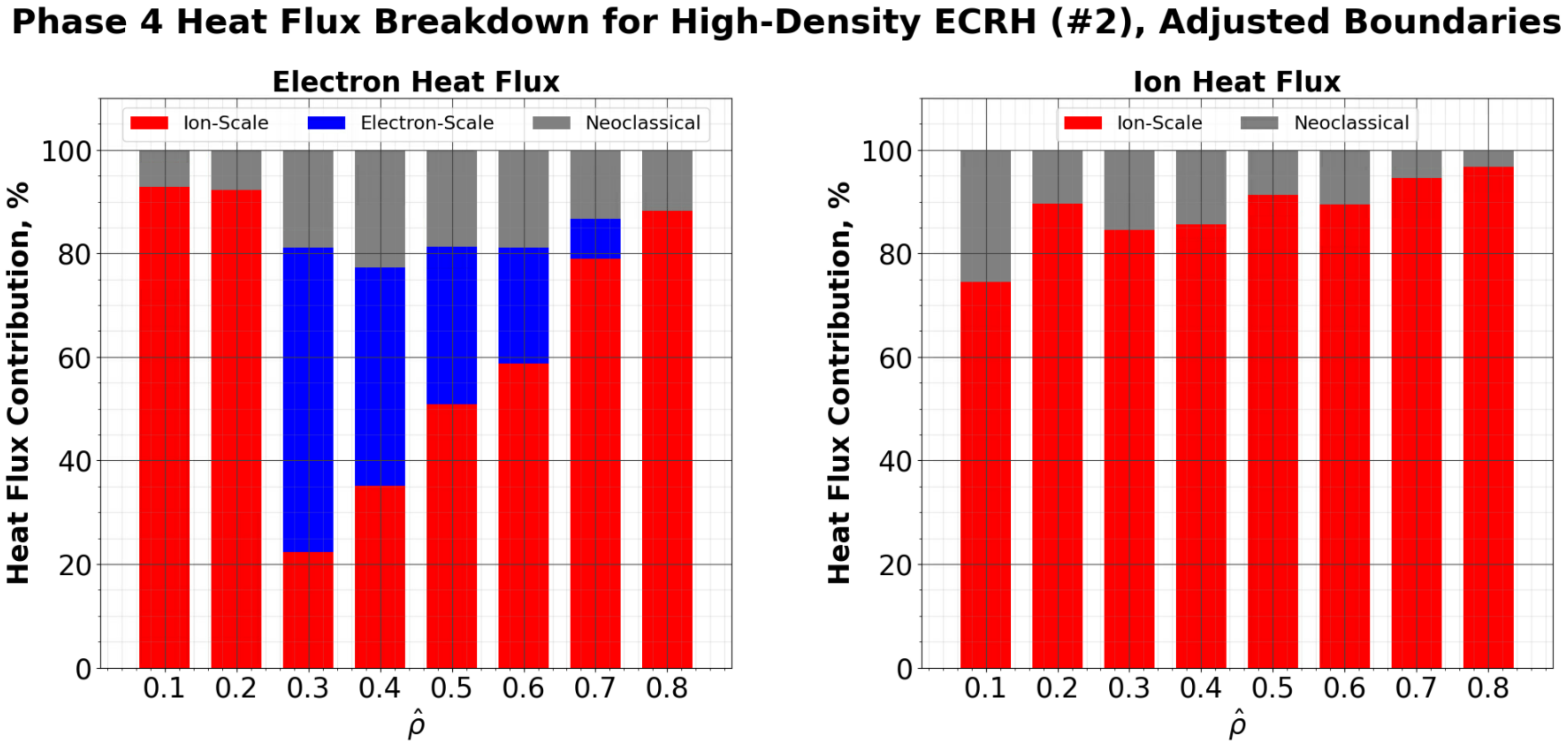
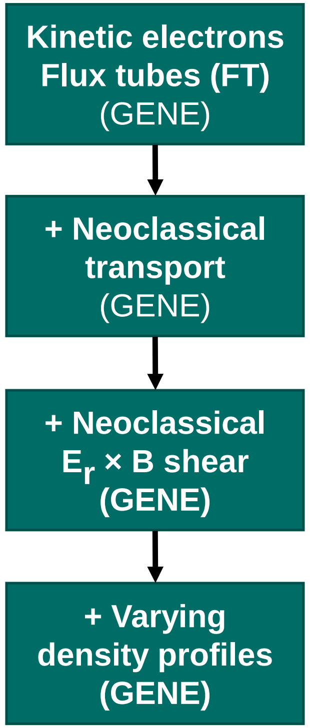
+ Neoclassical $E_r \times B$ shear (GENE)

+ Varying density profiles (GENE)

- Revisiting the breakdown of heat fluxes for each scenario:
  - The ECRH scenarios were have large electron-scale contributions to the total electron heat flux.

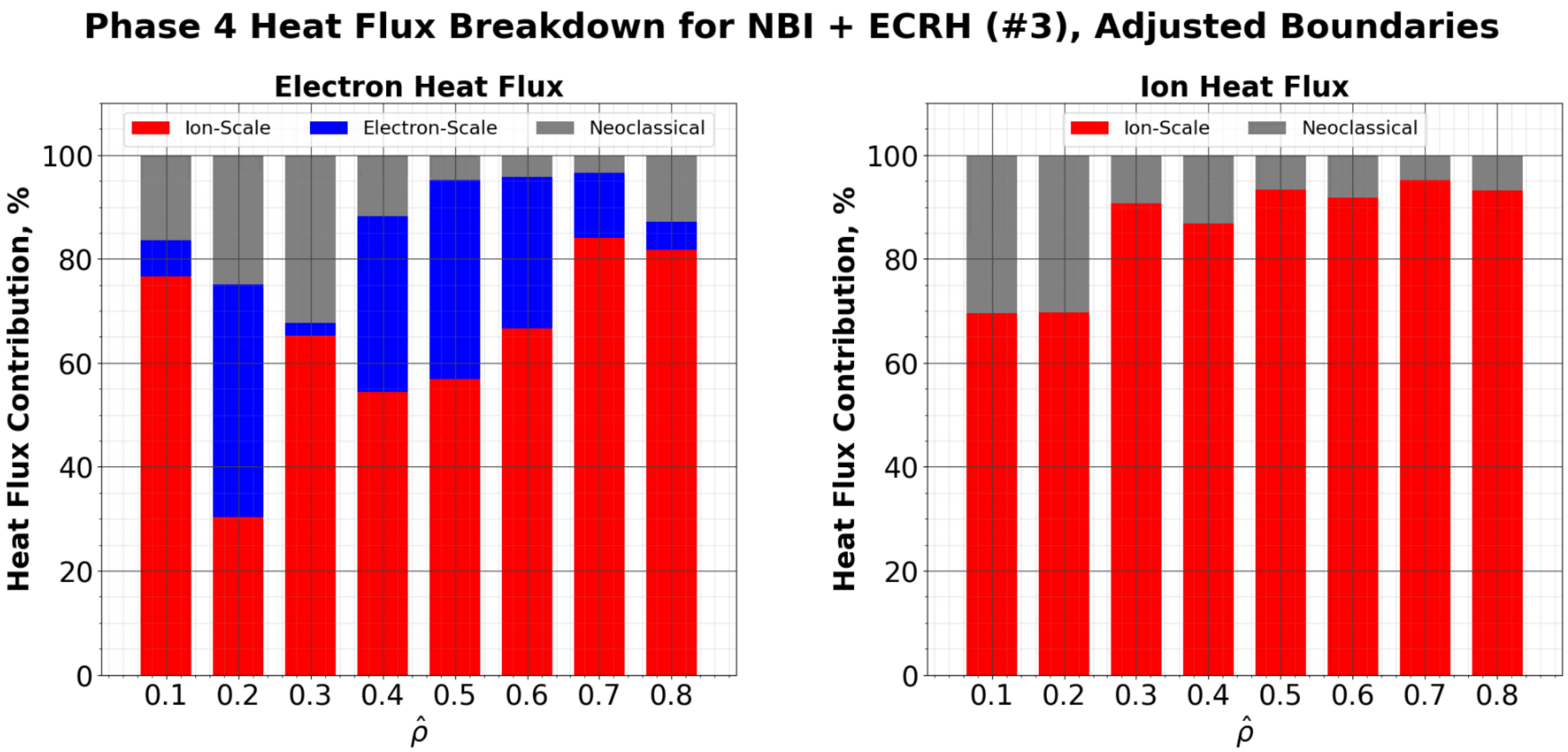
PHASE 4: WITH VARYING DENSITY PROFILE
FLUX BREAKDOWN

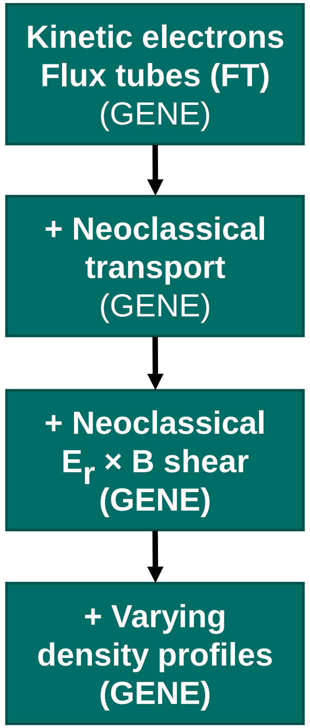




- Revisiting the breakdown of heat fluxes for each scenario:
  - The ECRH scenarios were have large electron-scale contributions to the total electron heat flux.
  - The upward trend with ρ can be explained by $\boldsymbol{\omega_{Te}}$ and $\boldsymbol{\tau}$, while the decreasing trend is explained by $\boldsymbol{\omega_n}$.

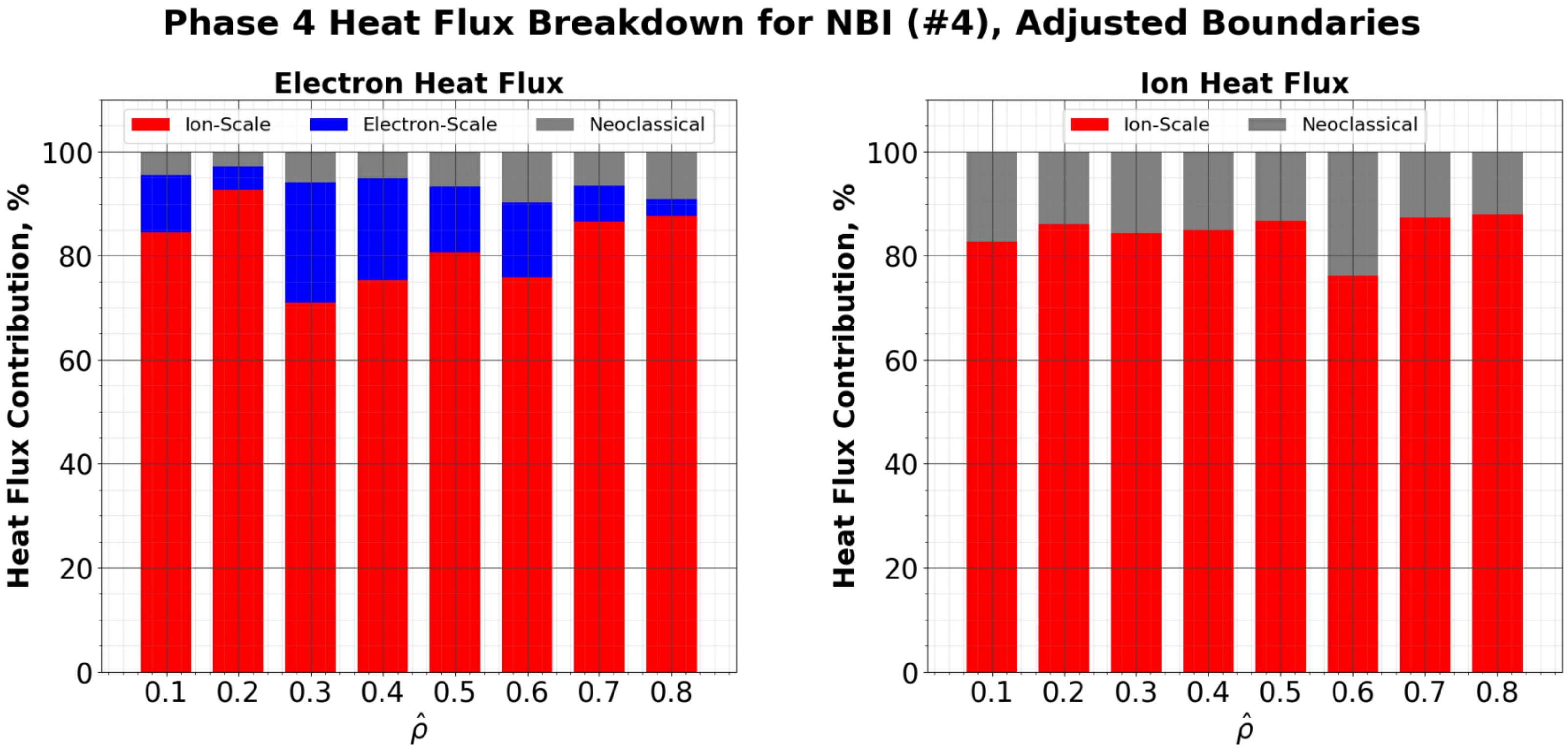
PHASE 4: WITH VARYING DENSITY PROFILE
FLUX BREAKDOWN





- Revisiting the breakdown of heat fluxes for each scenario:
  - The ECRH scenarios were have large electron-scale contributions to the total electron heat flux.
  - The upward trend with ρ can be explained by $\boldsymbol{\omega_{Te}}$ and $\boldsymbol{\tau}$, while the decreasing trend is explained by $\boldsymbol{\omega_n}$.
  - The NBI cases show relatively less electron-scale contribution to the total electron heat flux.

PHASE 4: WITH VARYING DENSITY PROFILE
FLUX BREAKDOWN



Kinetic electrons Flux tubes (FT) (GENE)

↓

+ Neoclassical transport (GENE)

↓

+ Neoclassical $E_r \times B$ shear (GENE)

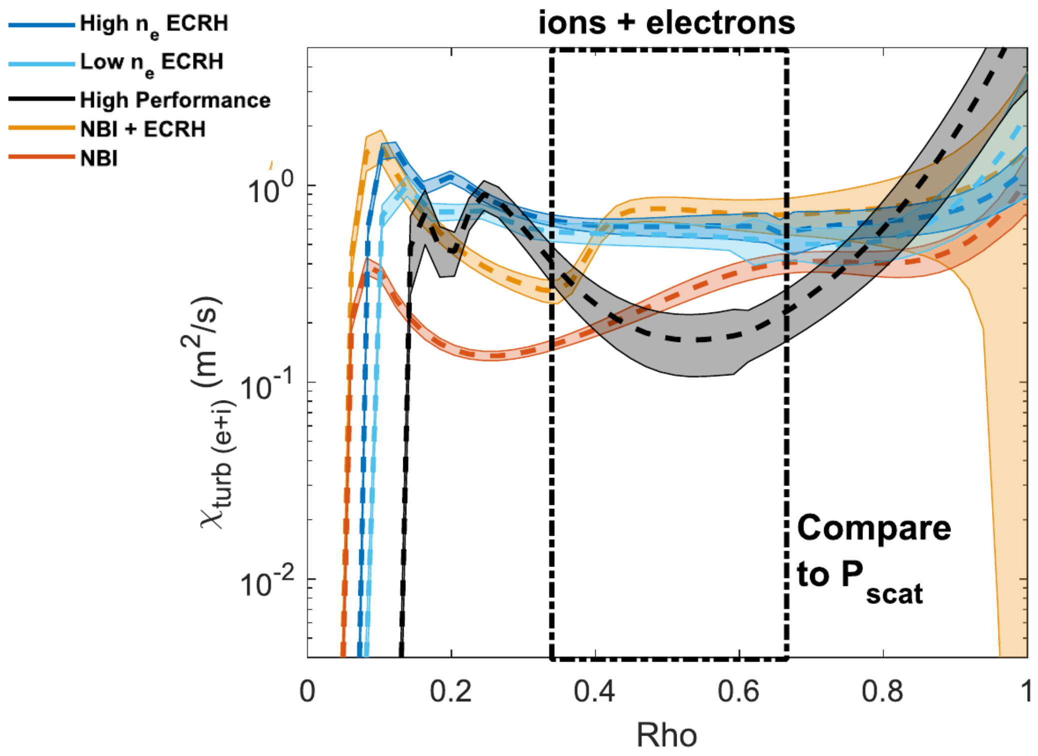
↓

+ Varying density profiles (GENE)

- Revisiting the breakdown of heat fluxes for each scenario:
  - The ECRH scenarios were have large electron-scale contributions to the total electron heat flux.
  - The upward trend with ρ can be explained by $\boldsymbol{\omega_{Te}}$ and **τ**, while the decreasing trend is explained by $\boldsymbol{\omega_{n}}$.
  - The NBI cases show relatively less electron-scale contribution to the total electron heat flux.
  - This is consistent with previous findings for cases with **Ti ~ Te** and $\boldsymbol{\omega_{Ti} \sim \omega_{Te}}$.

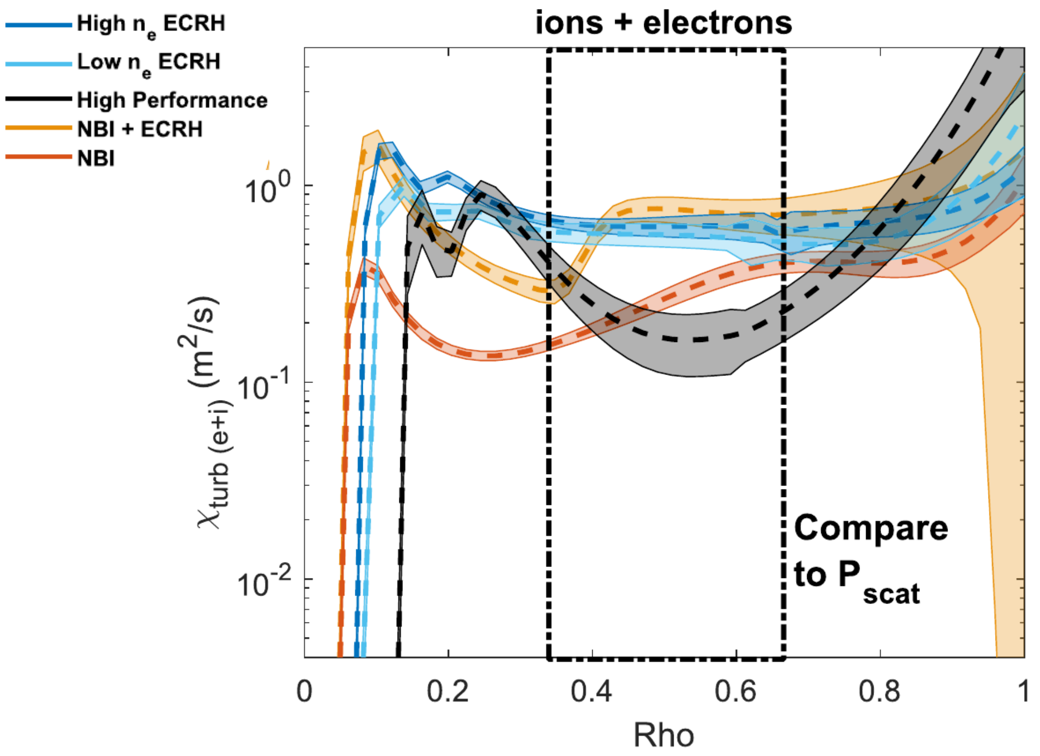
RESULTS
TURBULENCE PROPERTIES

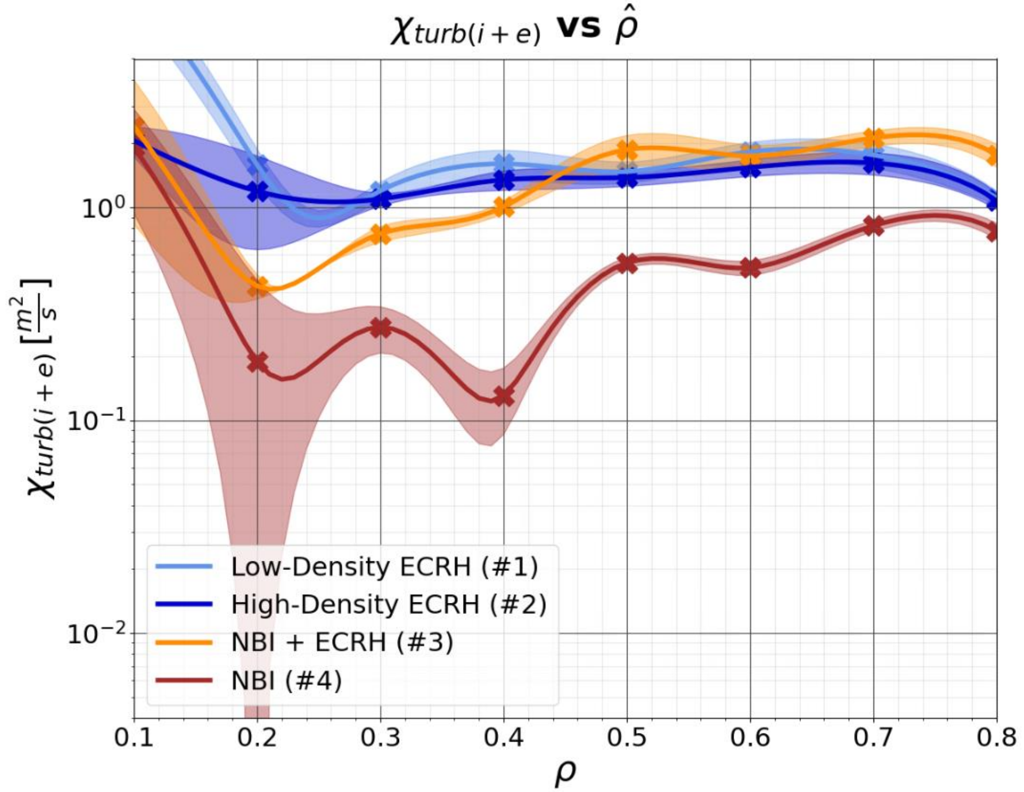
D. Carralero, et. al., 2022, Plasma Phys. Control. Fusion



RESULTS
TURBULENCE PROPERTIES

D. Carralero, et. al., 2022, Plasma Phys. Control. Fusion





RESULTS
TURBULENCE PROPERTIES

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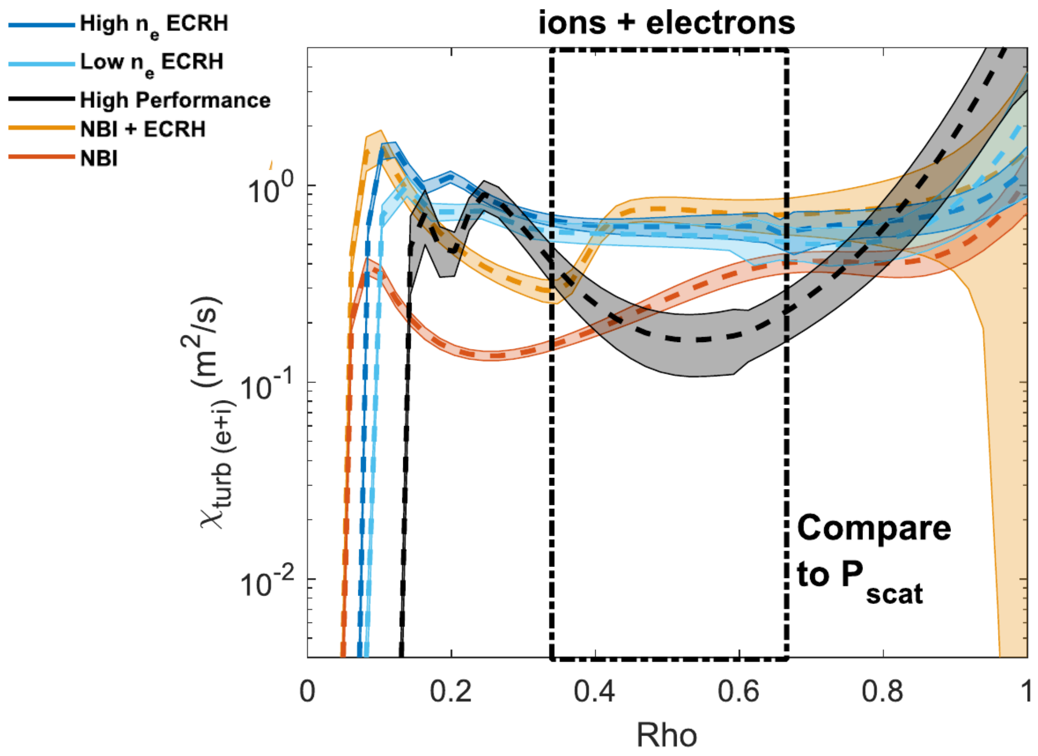
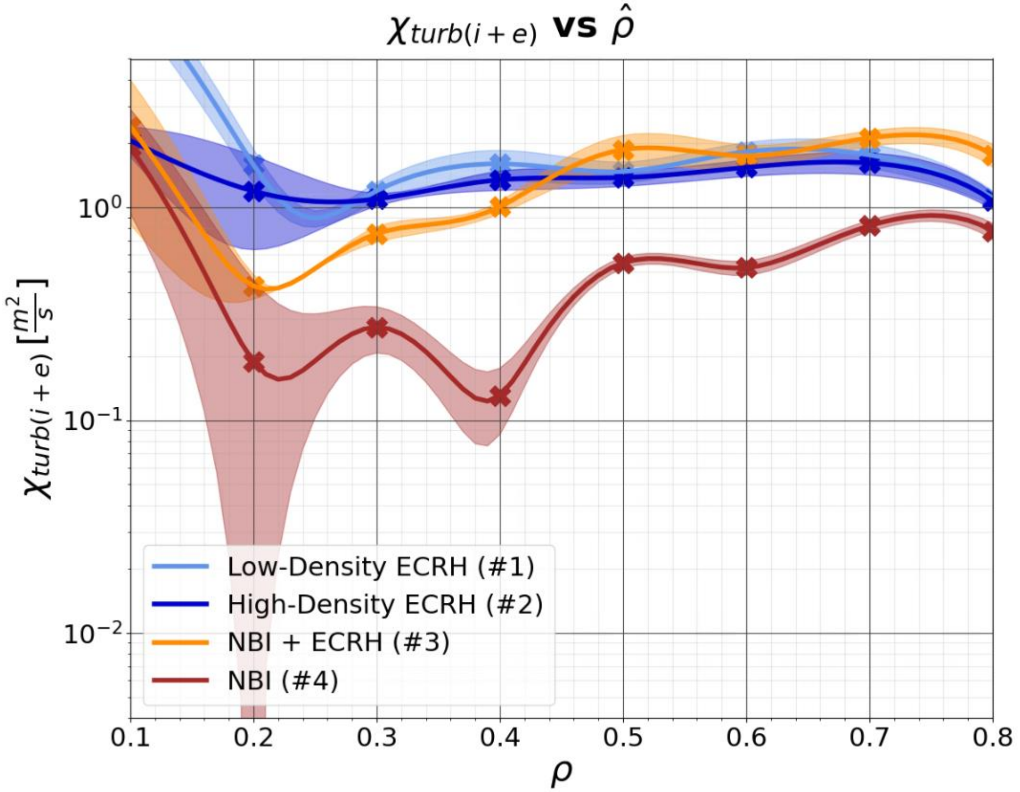
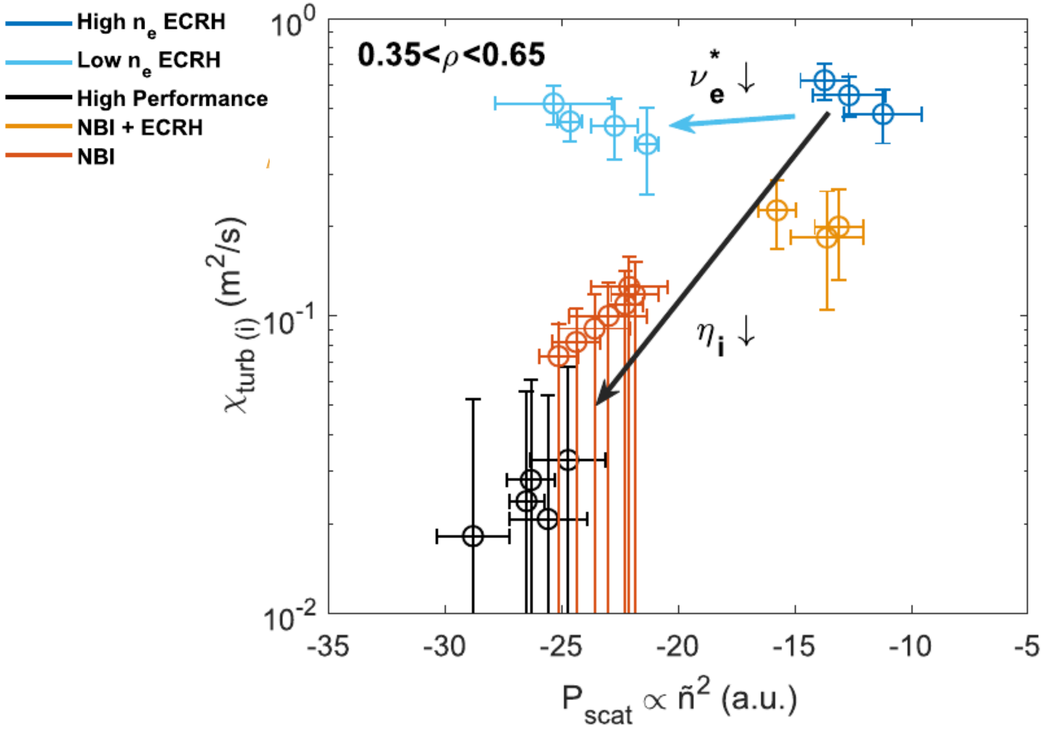




- The NBI case exhibited the lowest turbulent heat diffusivity χ among the 4 scenarios.

RESULTS
TURBULENCE PROPERTIES

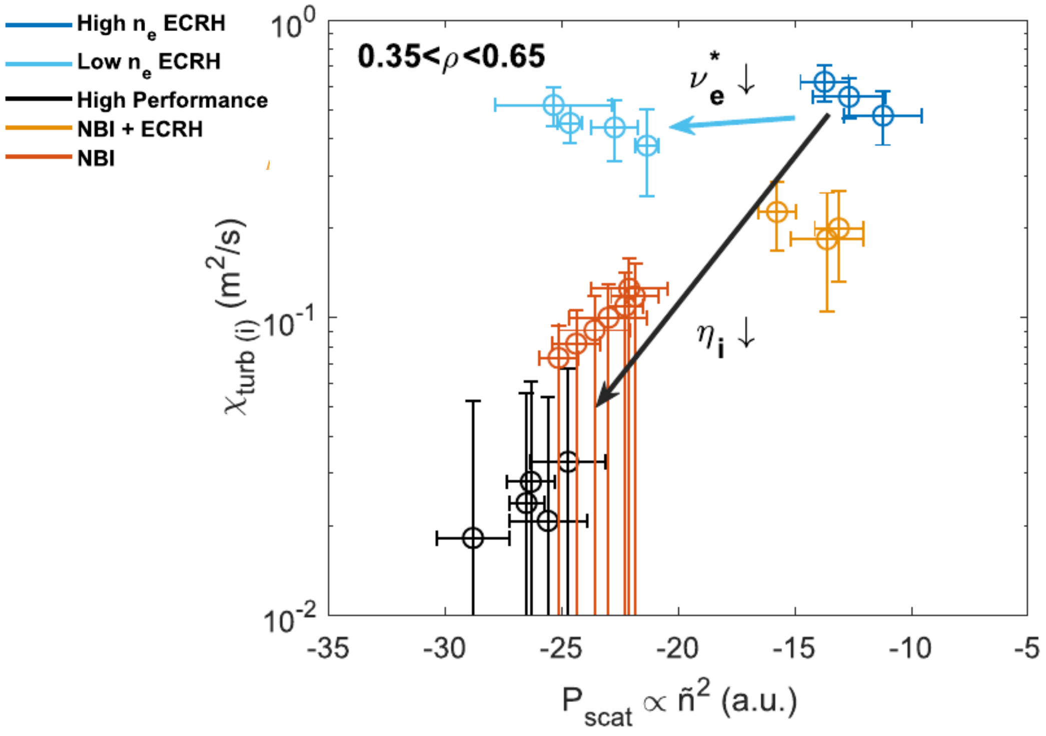
D. Carralero, et. al., 2022, Plasma Phys. Control. Fusion

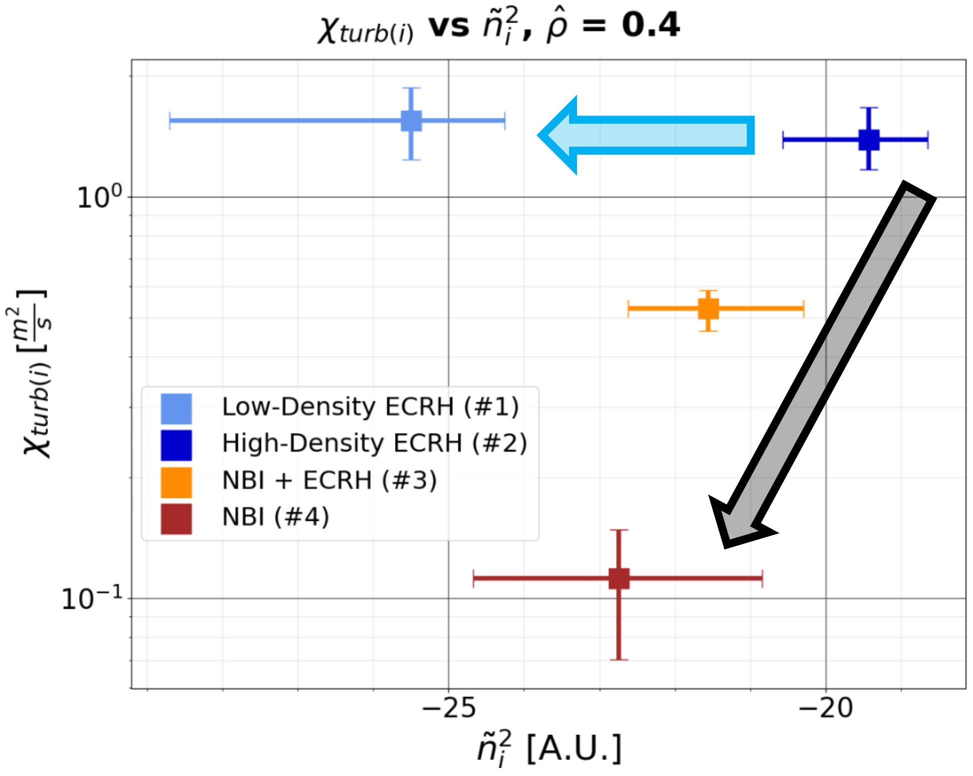


- The NBI case exhibited the lowest turbulent heat diffusivity **χ** among the 4 scenarios.

RESULTS
TURBULENCE PROPERTIES

D. Carralero, et. al., 2022, Plasma Phys. Control. Fusion

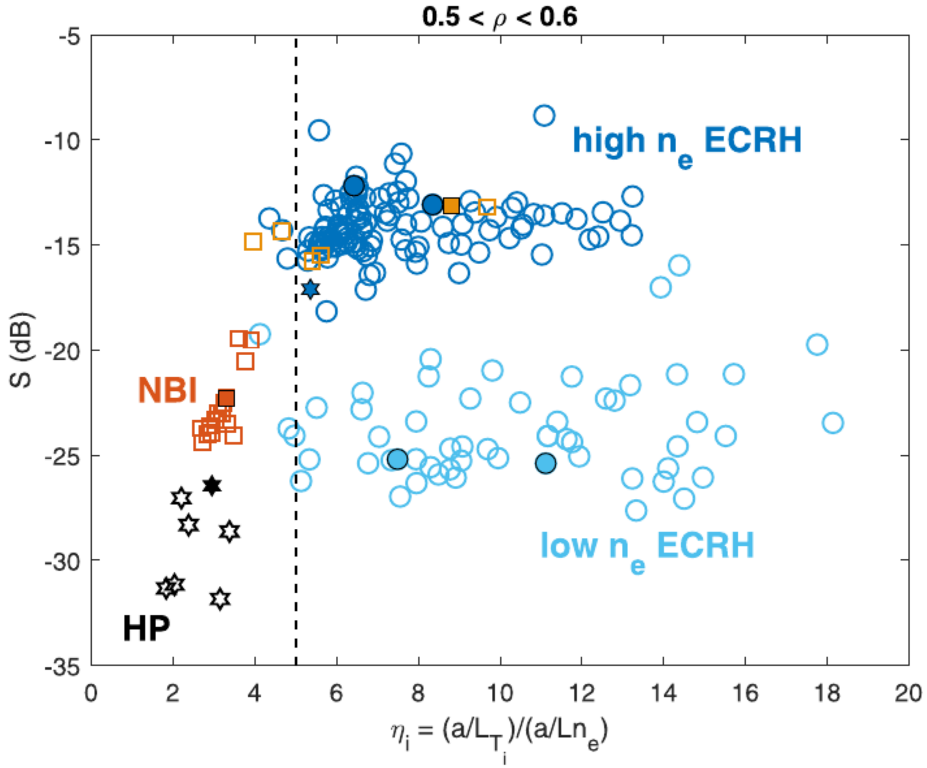




- The NBI case exhibited the lowest turbulent heat diffusivity χ among the 4 scenarios.
- The simulations qualitatively confirm the relationship between χ and squared density fluctuations.

RESULTS
TURBULENCE PROPERTIES

D. Carralero, et. al., 2021, Nuclear Fusion



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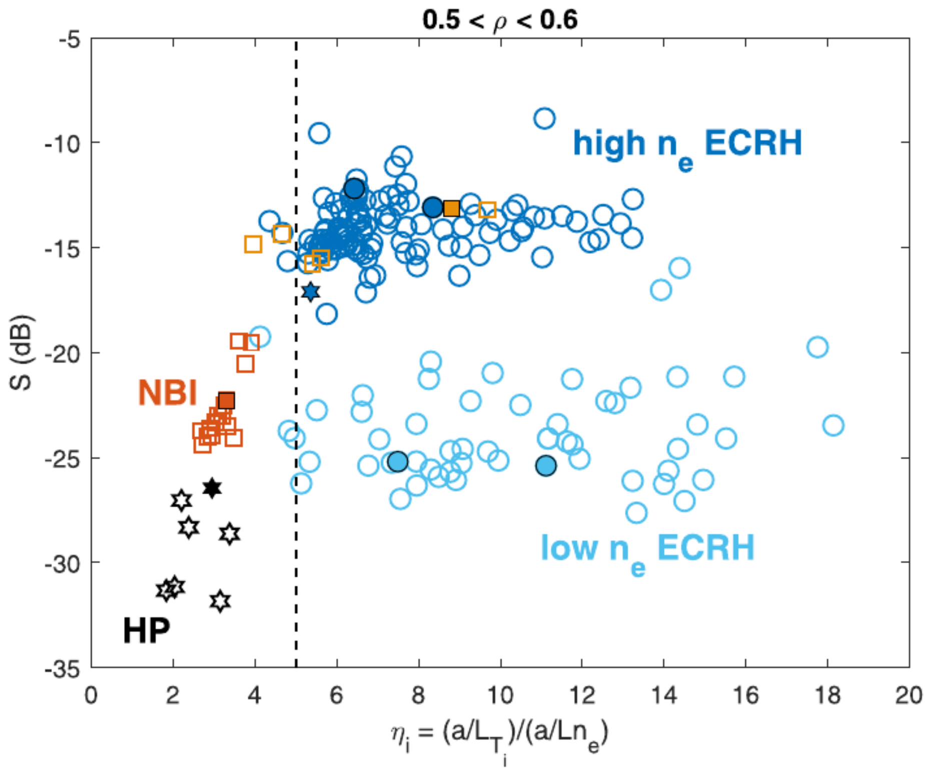
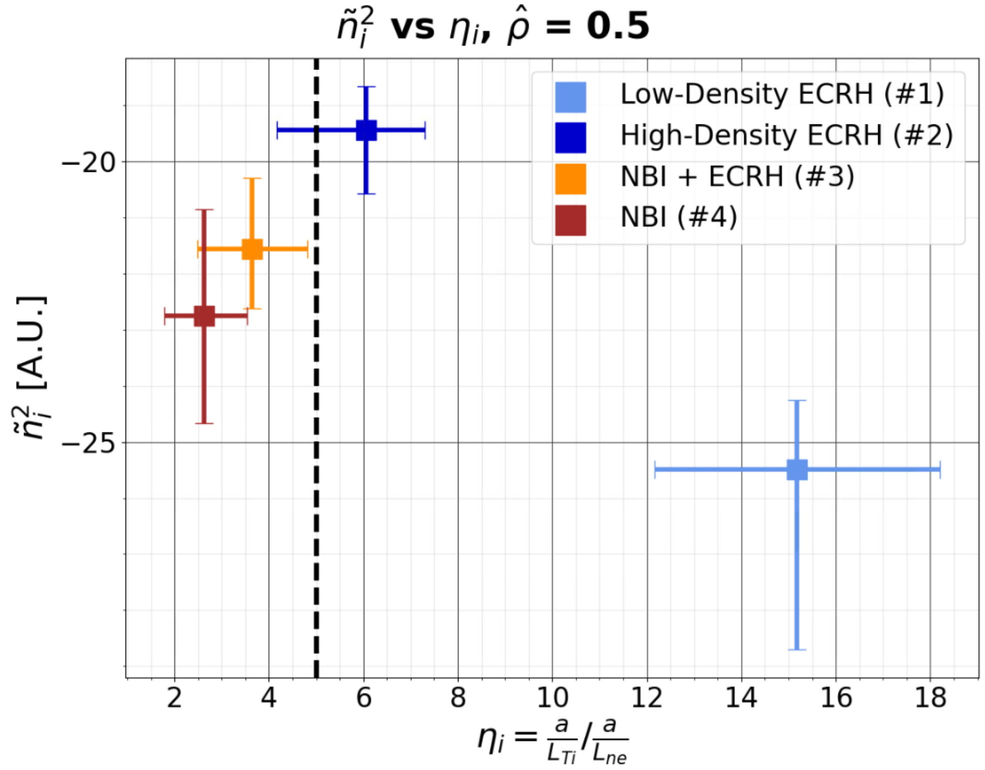
RESULTS
TURBULENCE PROPERTIES

D. Carralero, et. al., 2021, Nuclear Fusion





- The NBI case exhibited the lowest turbulent heat diffusivity χ among the 4 scenarios.
- The simulations qualitatively confirm the relationship between χ and squared density fluctuations.
- A reduction in the gradient ratio leads to a reduction in the density fluctuations. The ITG is stabilized by higher density gradients.

RESULTS
TURBULENCE PROPERTIES

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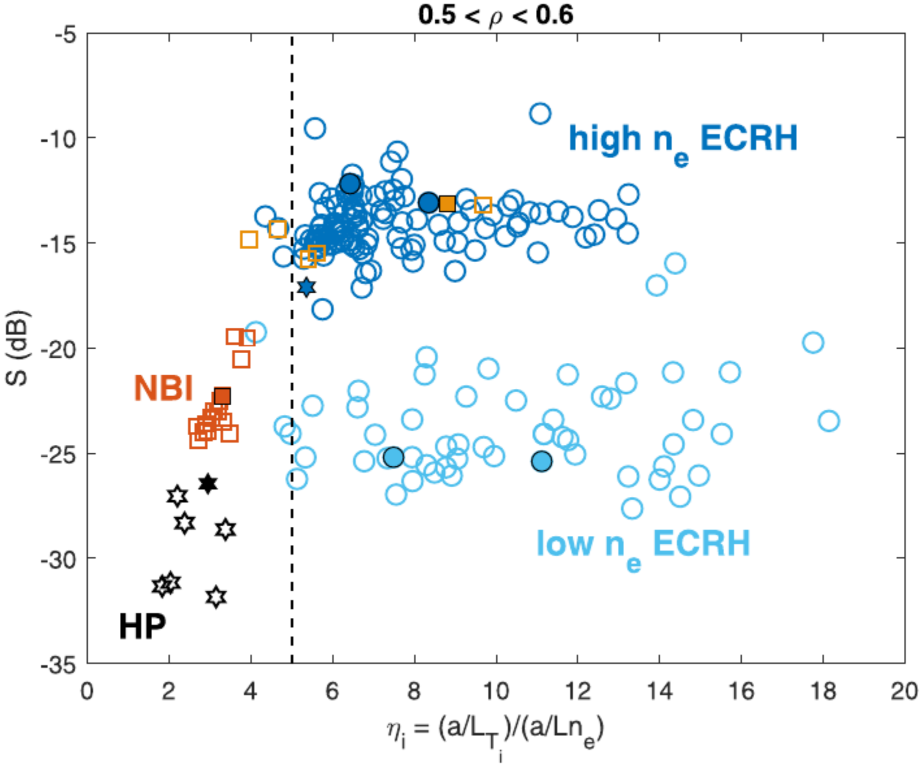

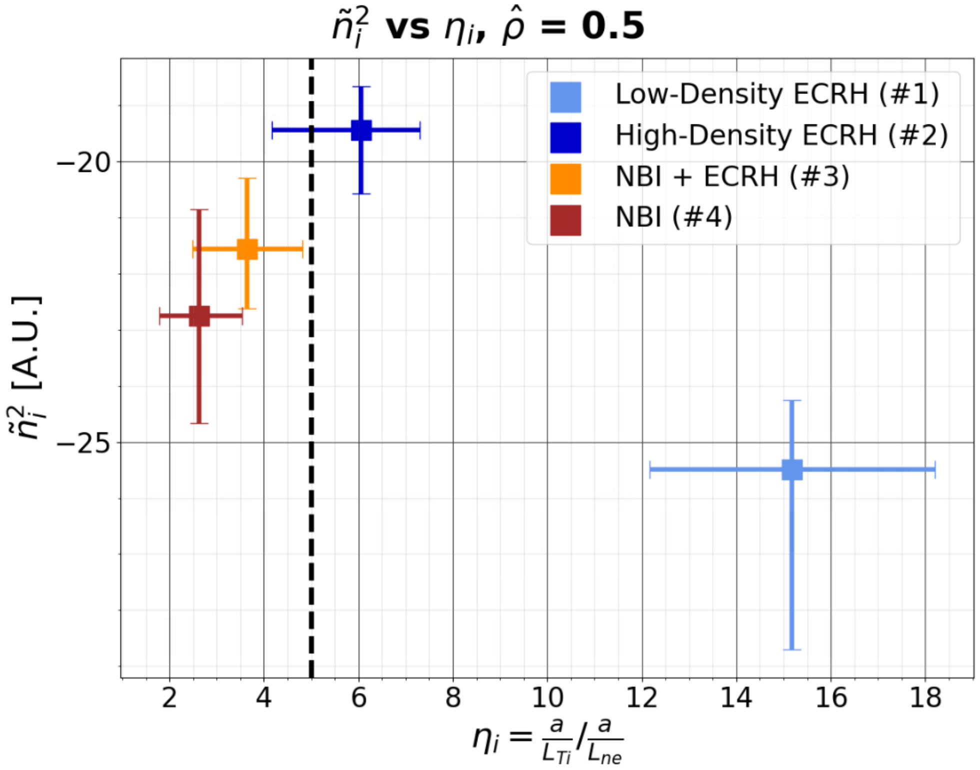

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- Further analysis for the different turbulent properties of the low- and high-density ECRH cases.

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- Perform radially global GENE-3D simulations with the converged GENE plasma profiles.

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Kinetic electrons Flux tubes (FT) (GENE) → **+ Neoclassical transport** (KNOSOS) → **+ E × B shear** (KNOSOS & GENE) → **+ Varying density profiles** (GENE) → **+ Global effects (GENE-3D)**

This study | **Separate study**

MODEL HIERARCHY
PHASE 4

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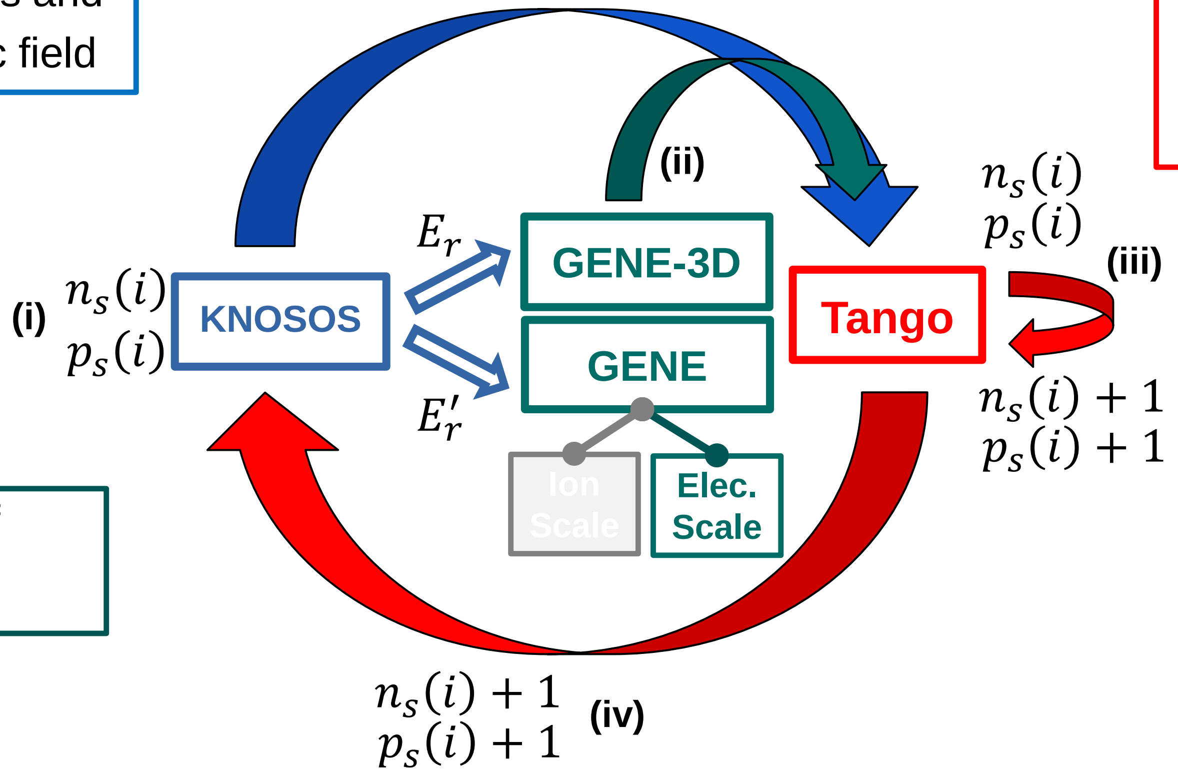
$$\Gamma_s(i) = \Gamma_s(i)^{neo.} + \Gamma_s(i)^{turb.}$$
$$Q_s(i) = Q_s(i)^{neo.} + Q_s(i)^{turb.}$$

KNOSOS: Neoclassical fluxes and the background radial electric field



GENE: Turbulent transport of plasma species

Tango: New plasma profiles accounting for both the total transport and the injected sources

$$\frac{3}{2}A\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}AQ = AS_Q$$

$$\frac{3}{2}A\frac{\partial n}{\partial t} + \frac{\partial}{\partial x}A\Gamma = AS_\Gamma$$

$$\bar{X}^l = \alpha X^l + (1-\alpha)\bar{X}^{l-1}$$

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- Continue validation studies for other discharges beyond the parameter space covered in this study (pellet fuelling scenarios, etc.)

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Wendelstein 7-X

Validation of a Comprehensive First-Principles-Based Framework for Predicting the Performance of Future Stellarators

Don Lawrence Carl Agapito Fernando[1], Alejandro Banon Navarro[1], Daniel Carralero[2], Jose Luis Velasco[2], Alessandro Di Siena[1], Felix Wilms[1], Frank Jenko[1,4], Sergey Bozhenkov[3], Ekkehard Pasch[3], Golo Fuchert[3], Kai Jacob Brunner[3], Jens Knauer[3], Andreas Langenberg[3], Novimir Pablant[3], Tomas Gonda[3], Oliver Ford[3], Lila Vano[3], and the W7-X Team[3]

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