Wendelstein 7-X

IPP Max-Planck-Institut für Plasmaphysik

Status, Prospects and Validation of the Minerva Bayesian Modeling Framework at Wendelstein 7-X

MAX PLANCK GESELLSCHAFT

EUROfusion

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Outline

Introduction

Synthetic Diagnostic Models @ W7-X

- Imaging Spectrometers (*XICS / HR-XIS*)
- Thomson Scattering / Interferometer
- X-ray Tomography (*XMCTS*)
- Electron Cyclotron Emission (*ECE*)
- Charge Exchange Recombination Spectroscopy (*CXRS*)

Validation of Physics- and Diagnostic-Models

- Plasma Parameter Profile Inference from Synthetic Data (T_i, T_e, n_e, n_Z ...)
- Profile Inference from Measured Data
- Cross Comparisons to other Diagnostics / Complementary Data Analysis Tools

Summary and Outlook

Introduction

The MINERVA Modeling Framework:

- Forward modeling of several diagnostics (synthetic diagnostics) within graphical models

J. Svensson, A. Werner et al. International Symposium on Intelligent Signal Processing-WISP (2007)

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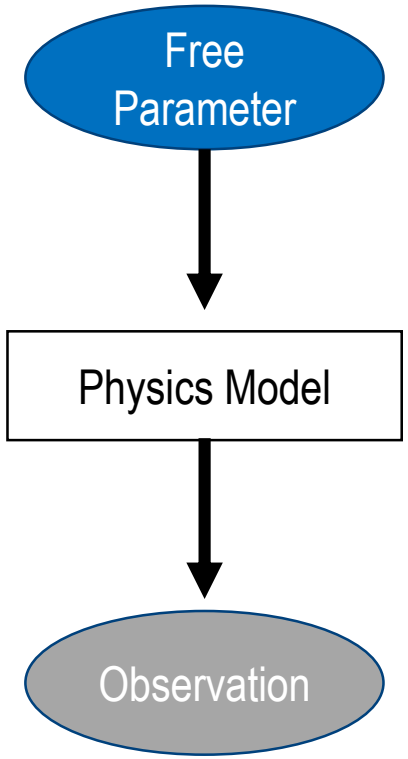
- Forward modeling of several diagnostics (synthetic diagnostics) within graphical models

Schematic Graphical Forward Model



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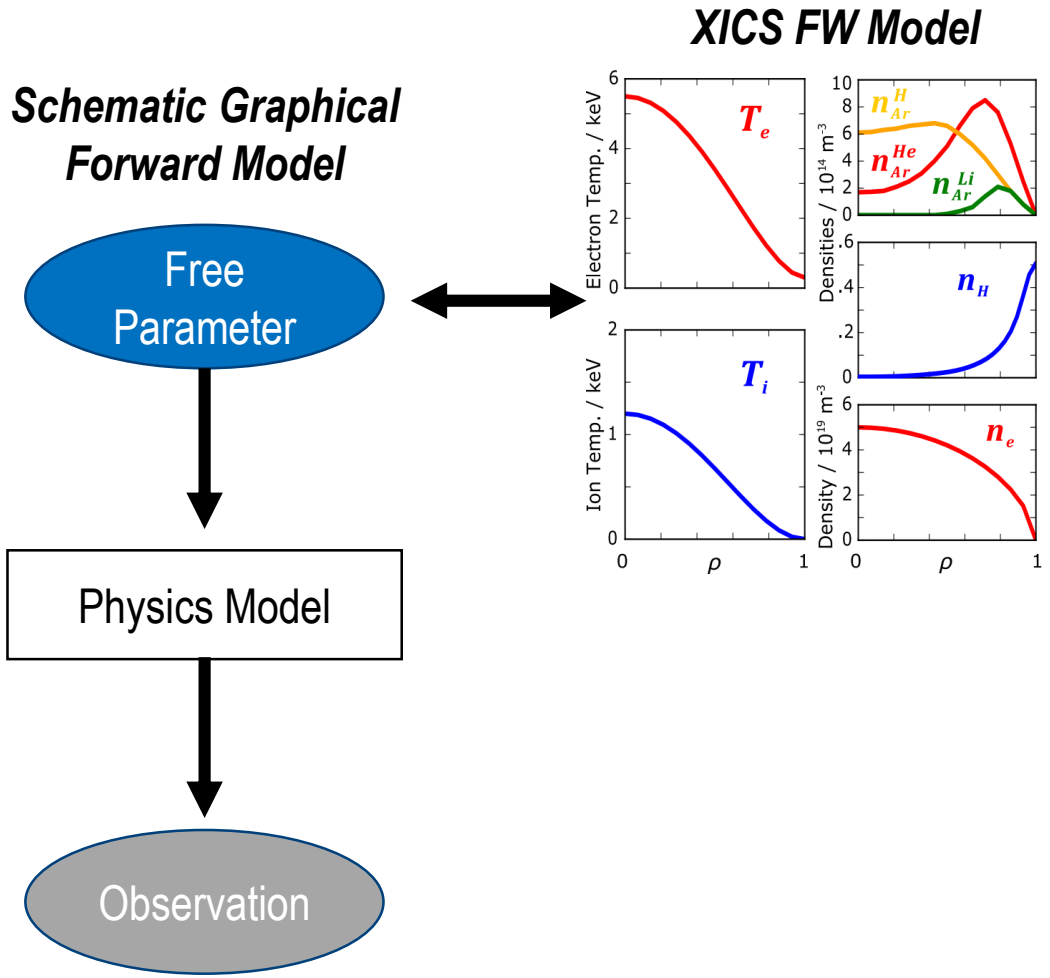

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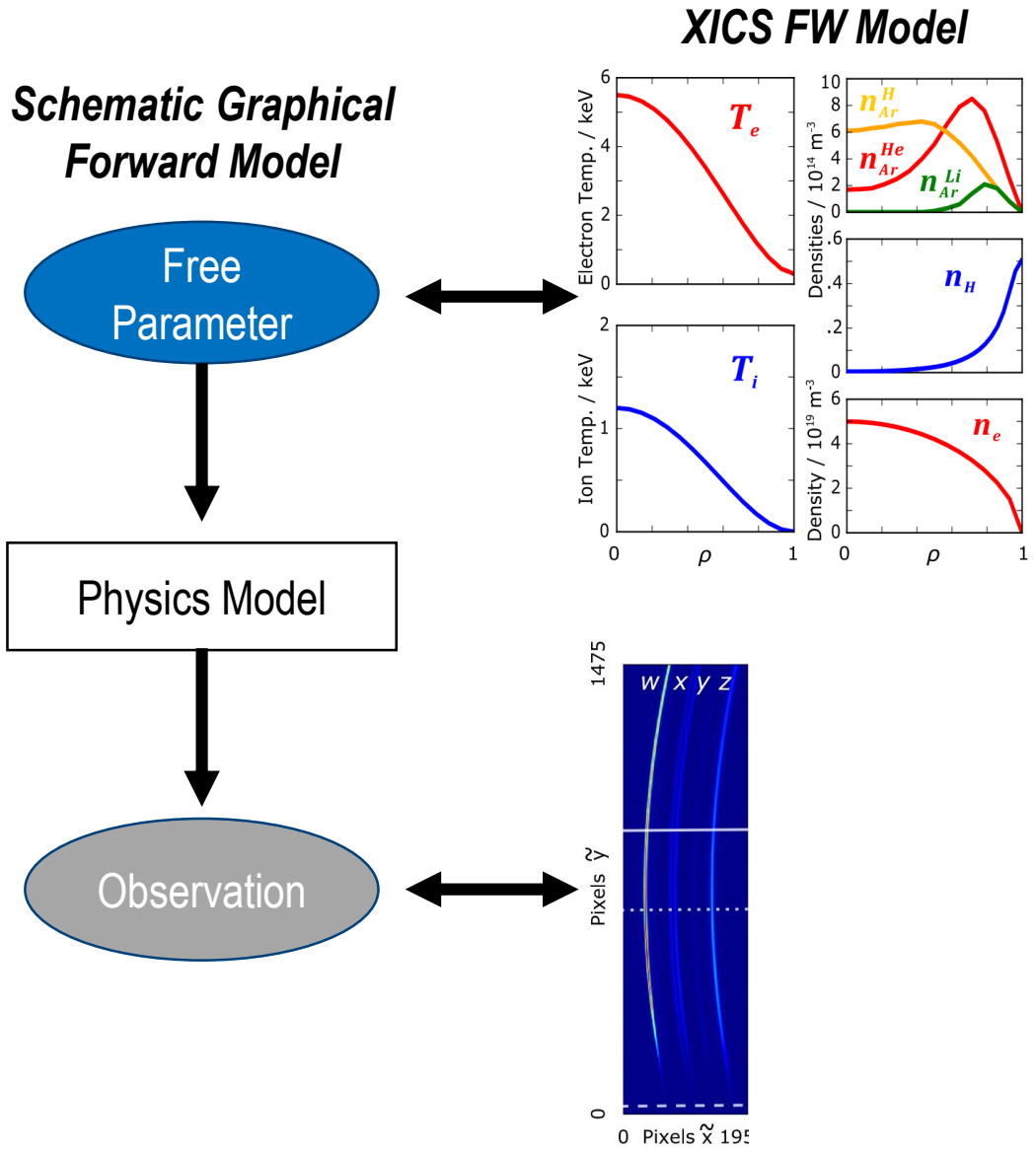

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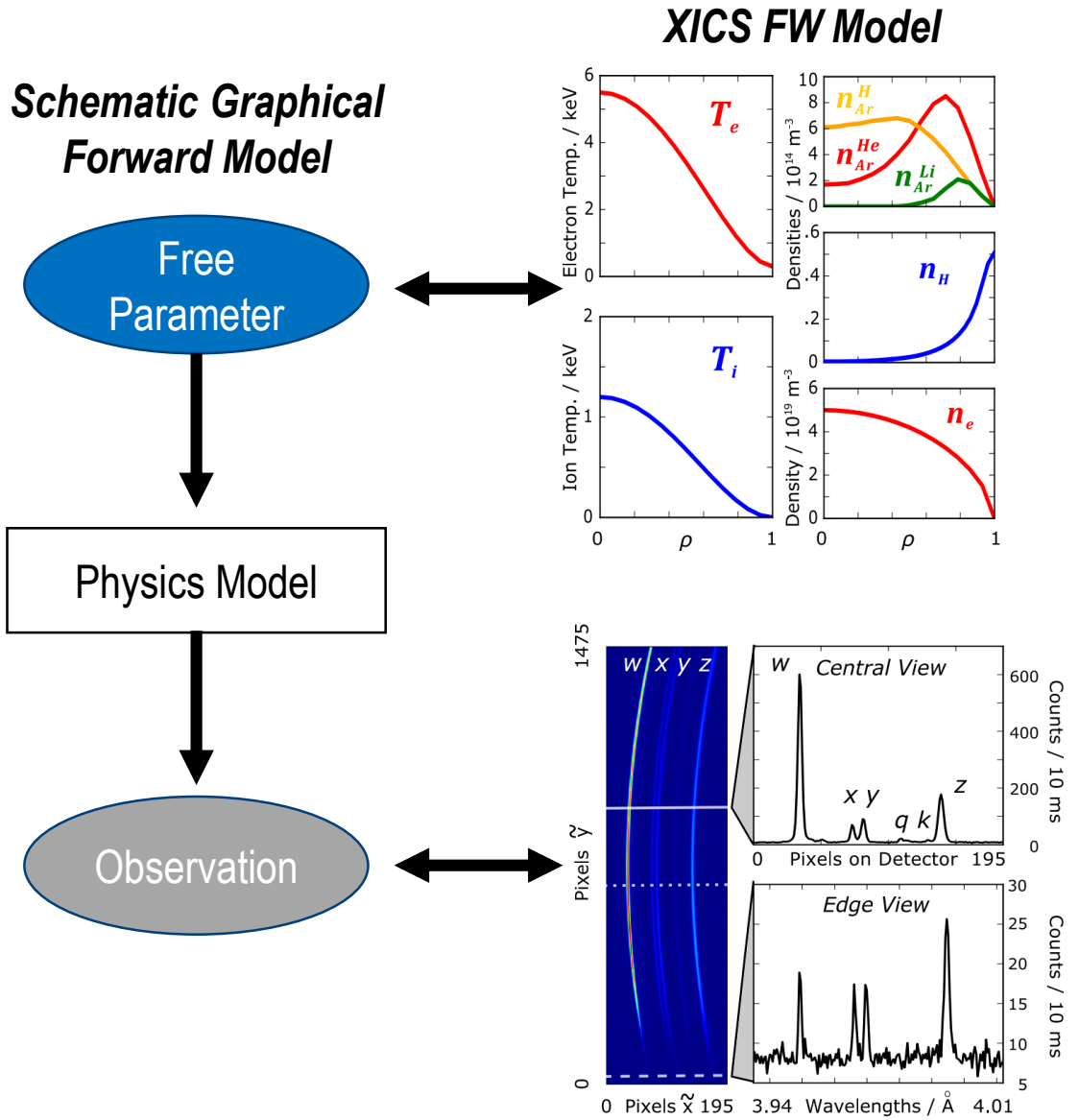
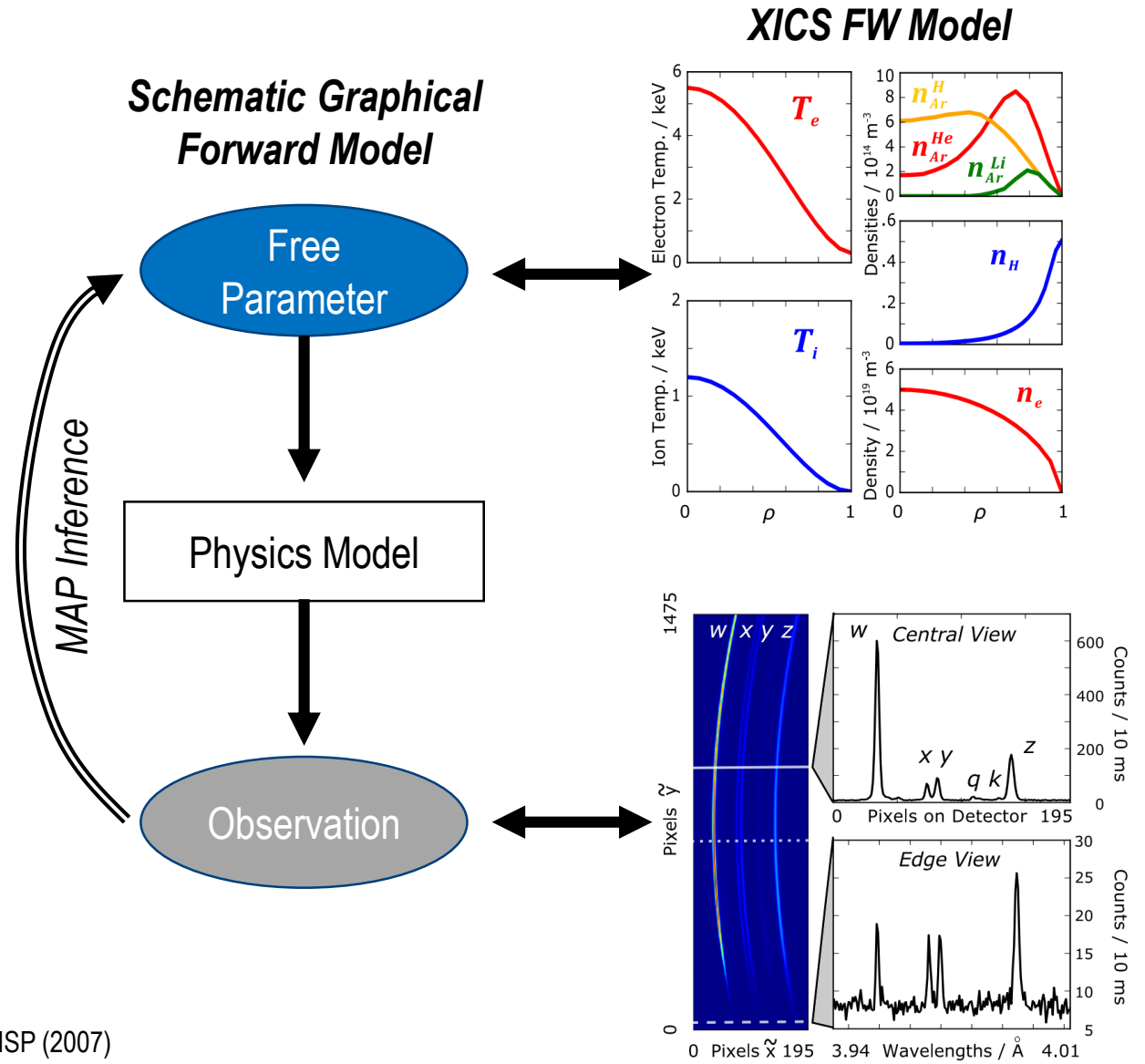


J. Svensson, A. Werner et al. International Symposium on Intelligent Signal Processing-WISP (2007)

Introduction

The MINERVA Modeling Framework:

- Forward modeling of several diagnostics (synthetic diagnostics) within graphical models
- Bayesian analysis for:
  - plasma parameter inference (MAP)
  - error calculations (MCMC sampling)
  - joint data analysis



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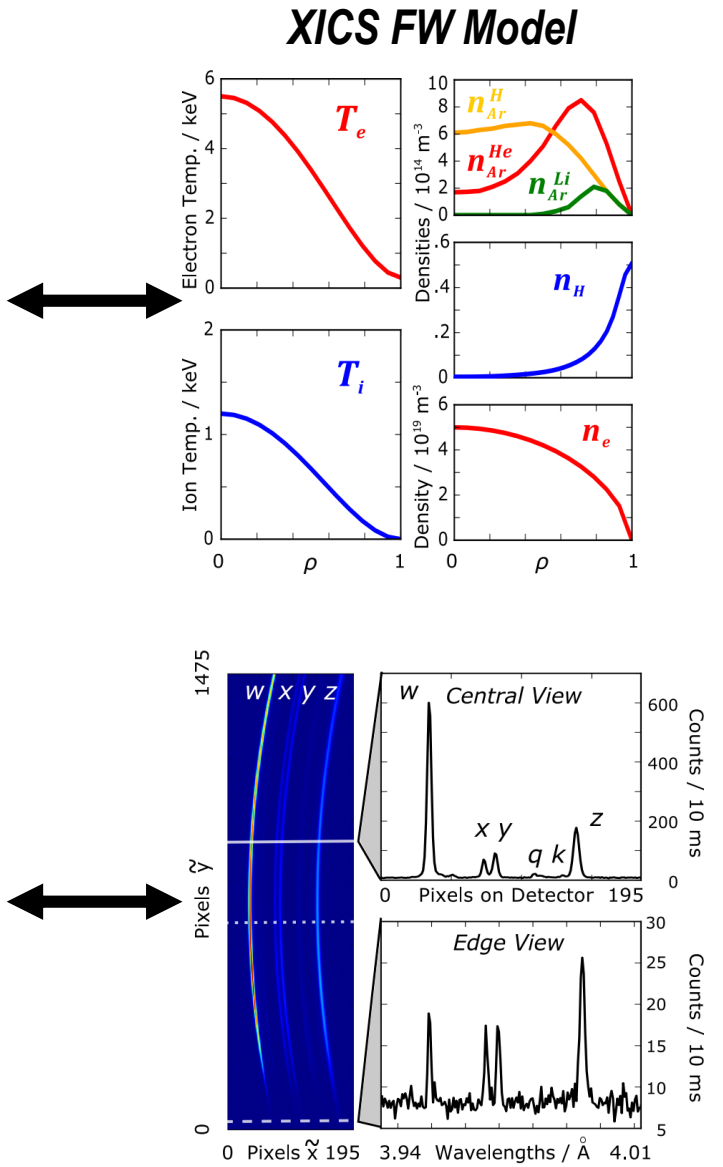
Synthetic Diagnostics @ W7-X: *Imaging Spectrometers*



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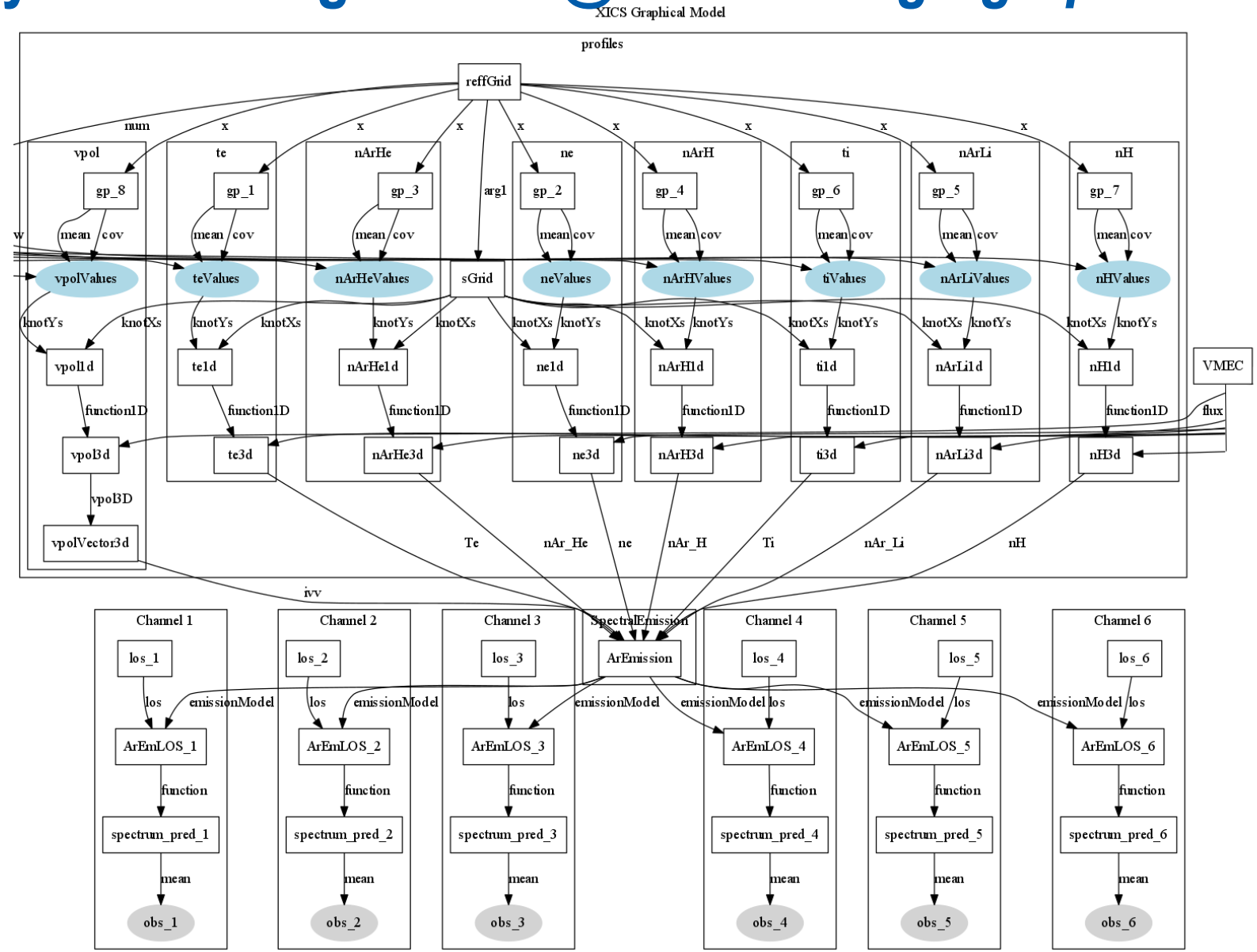
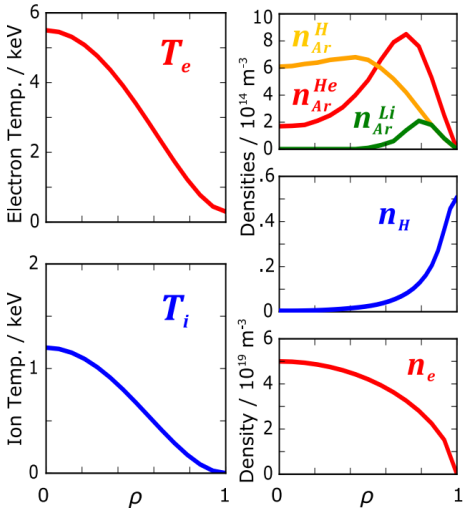
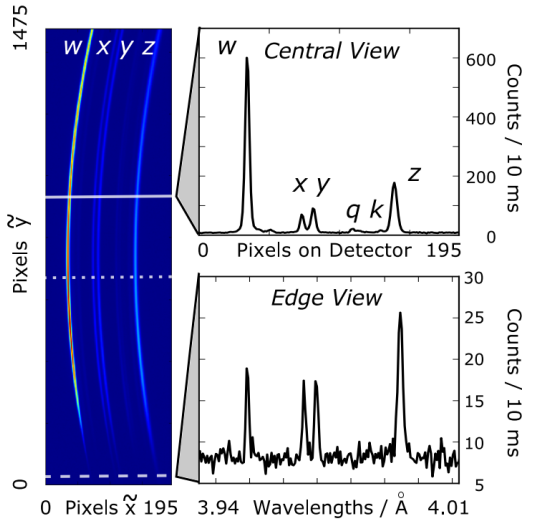


XICS FW Model





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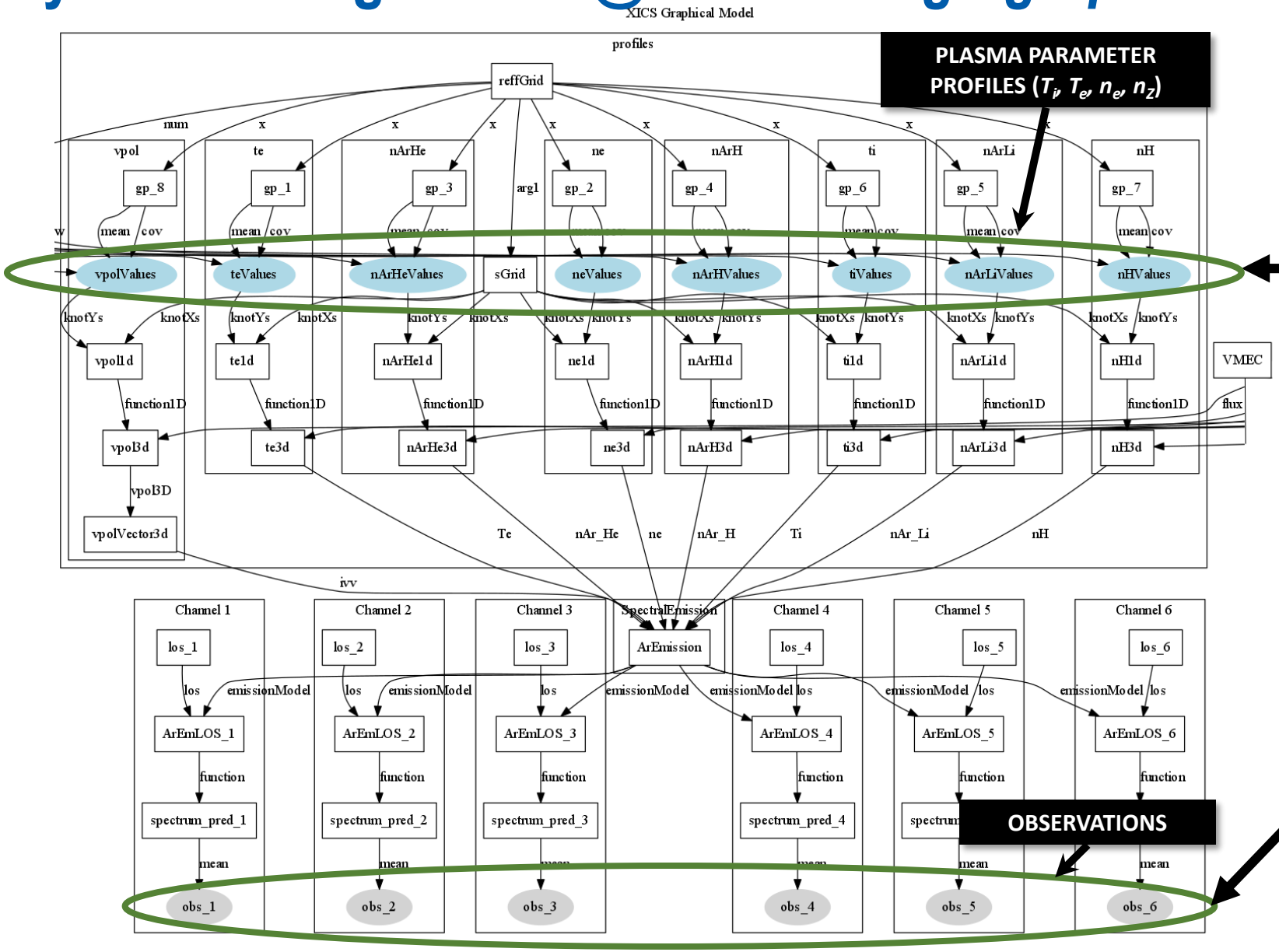

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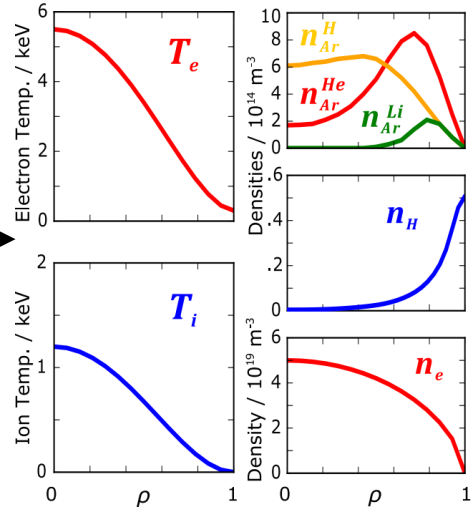

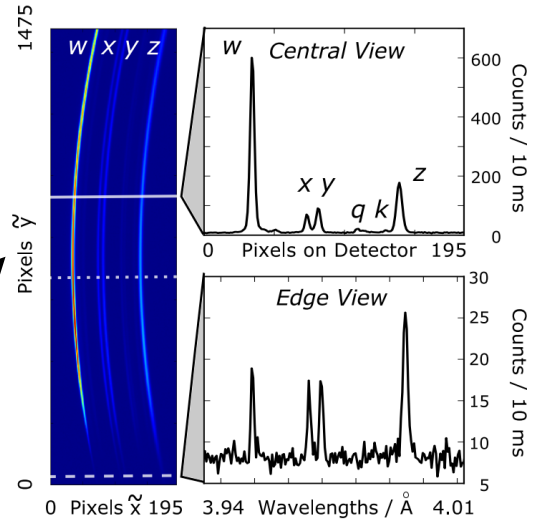

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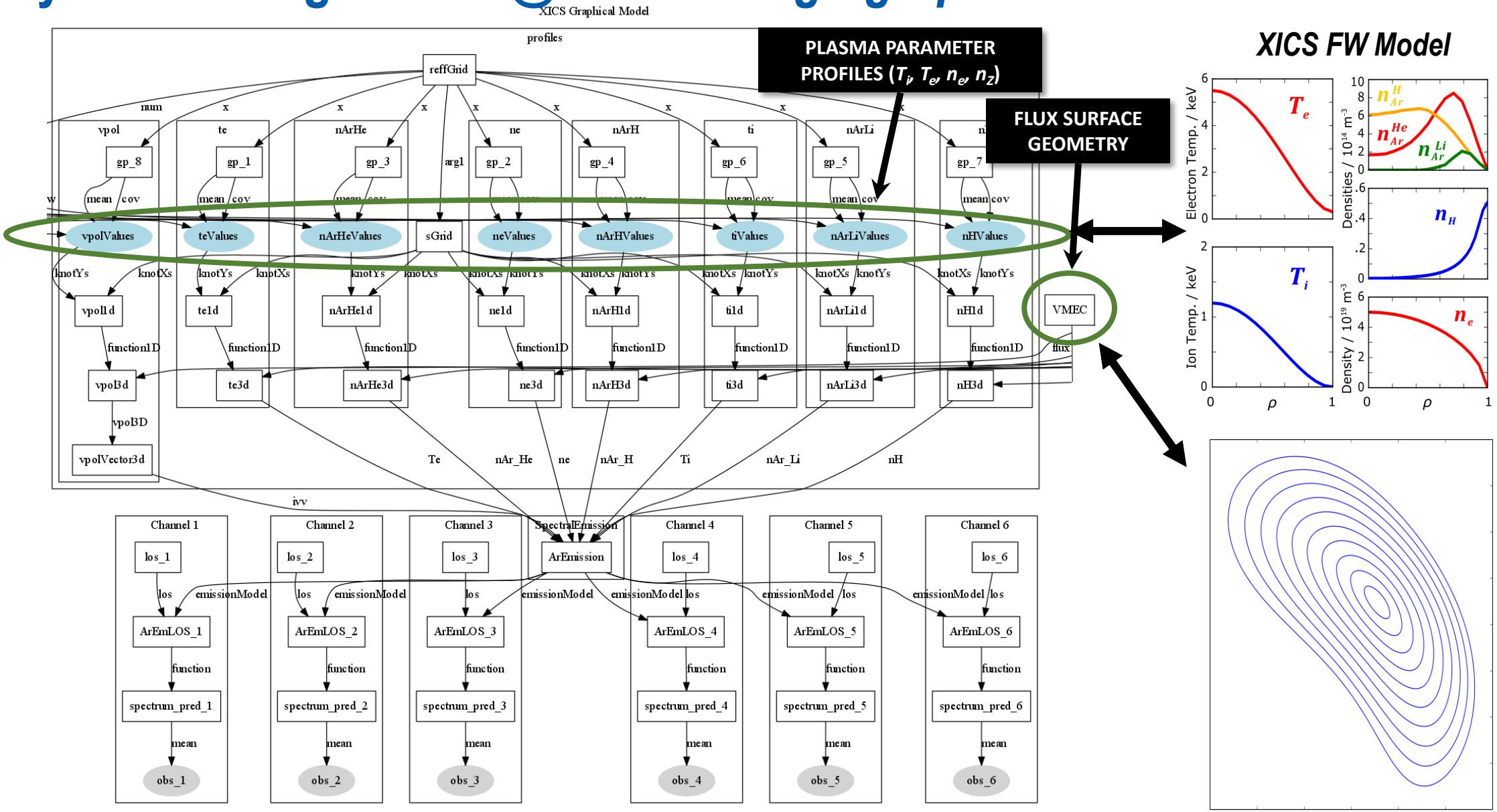

PLASMA PARAMETER PROFILES (T_i, T_e, n_e, n_Z)

FLUX SURFACE GEOMETRY

XICS FW Model

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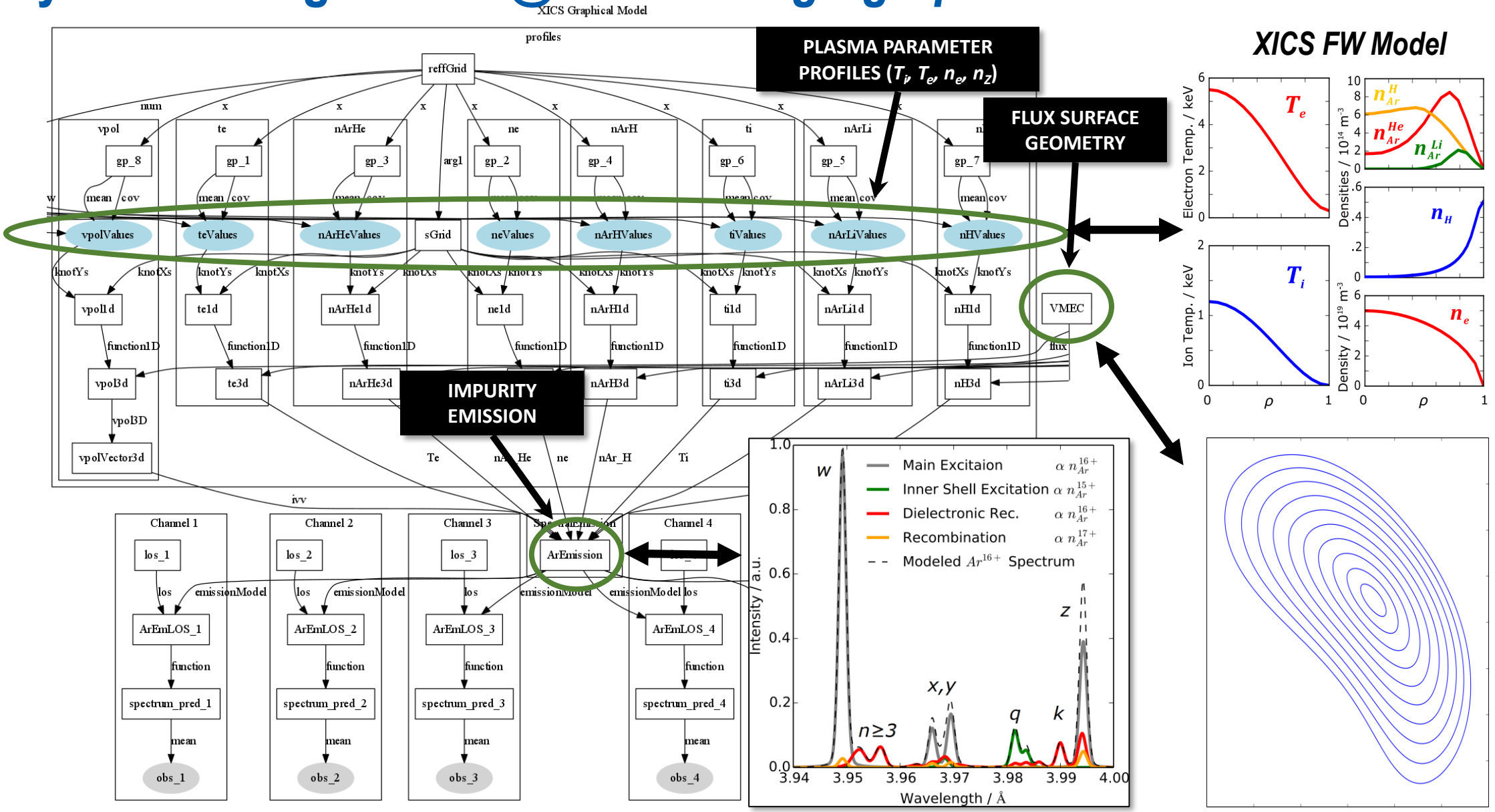

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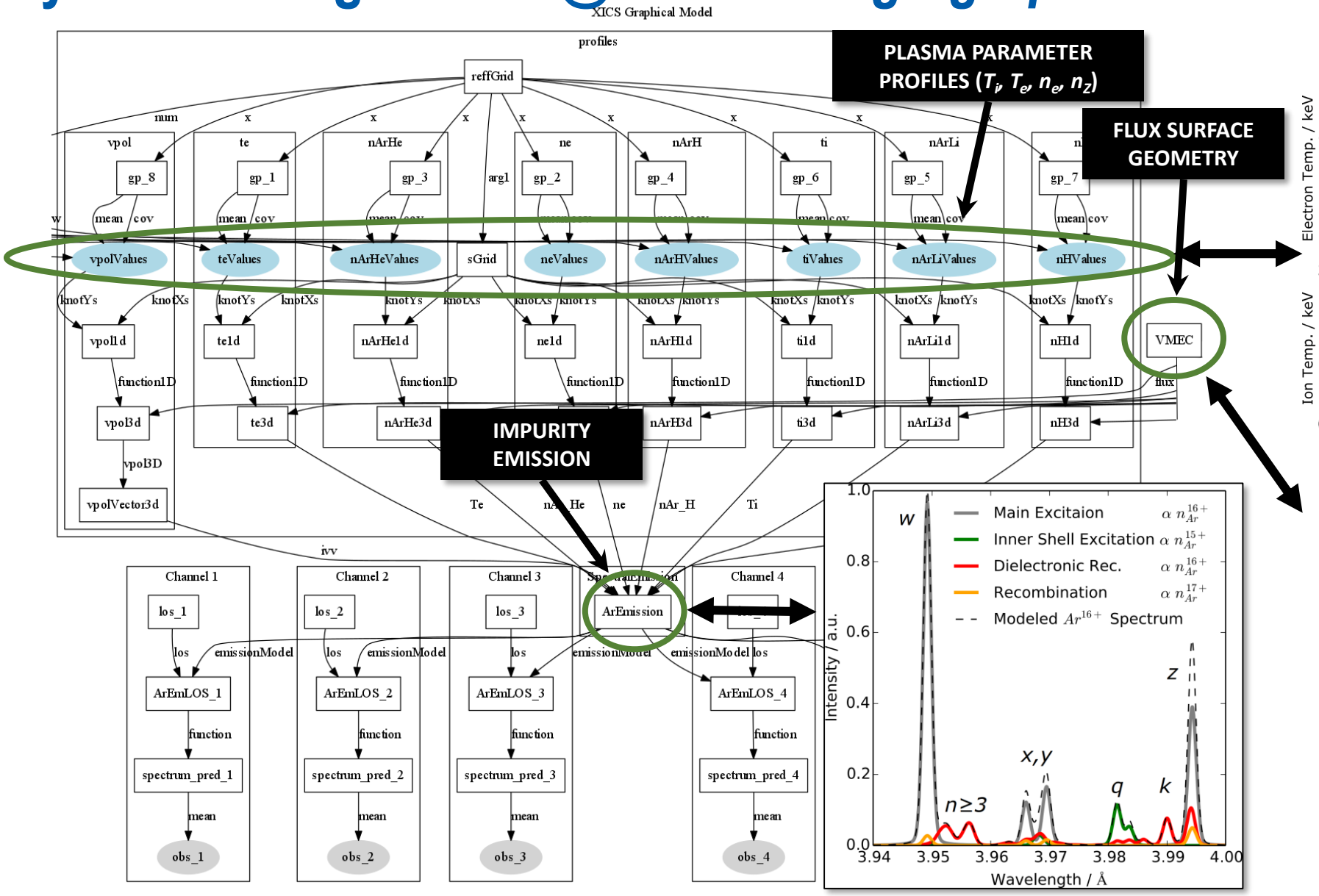

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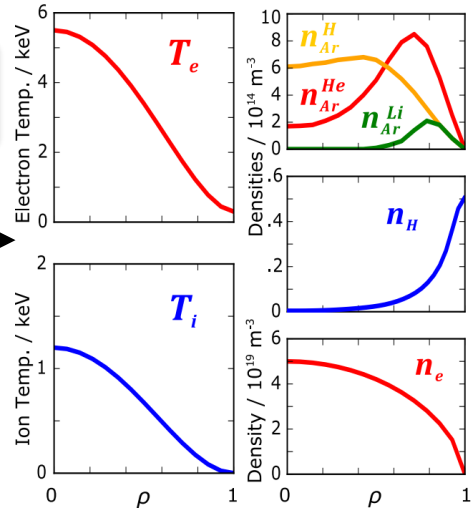
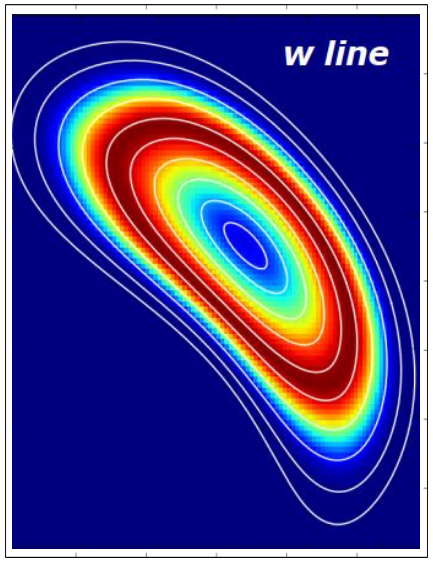
FLUX SURFACE GEOMETRY

IMPURITY EMISSION

XICS FW Model





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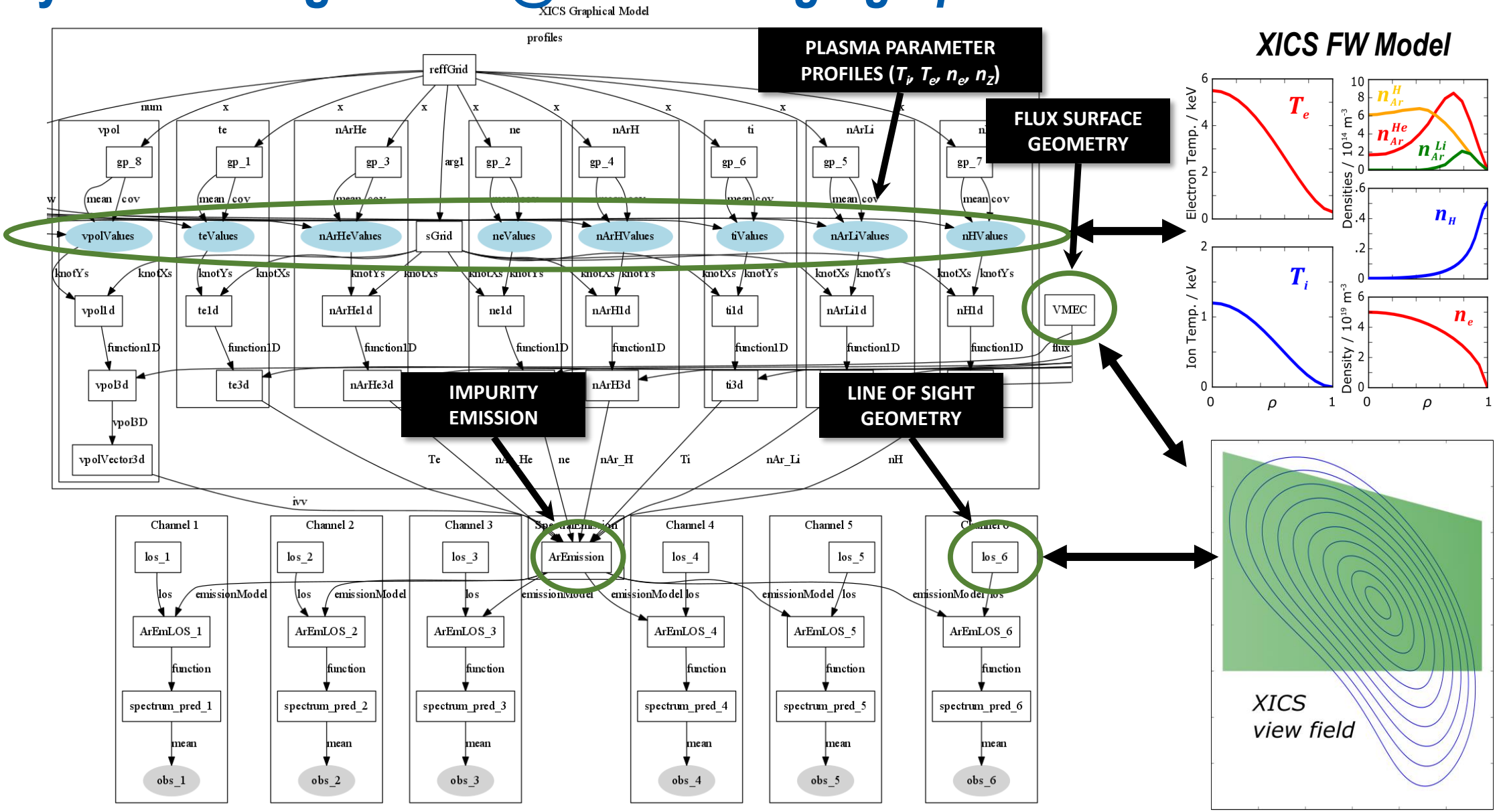

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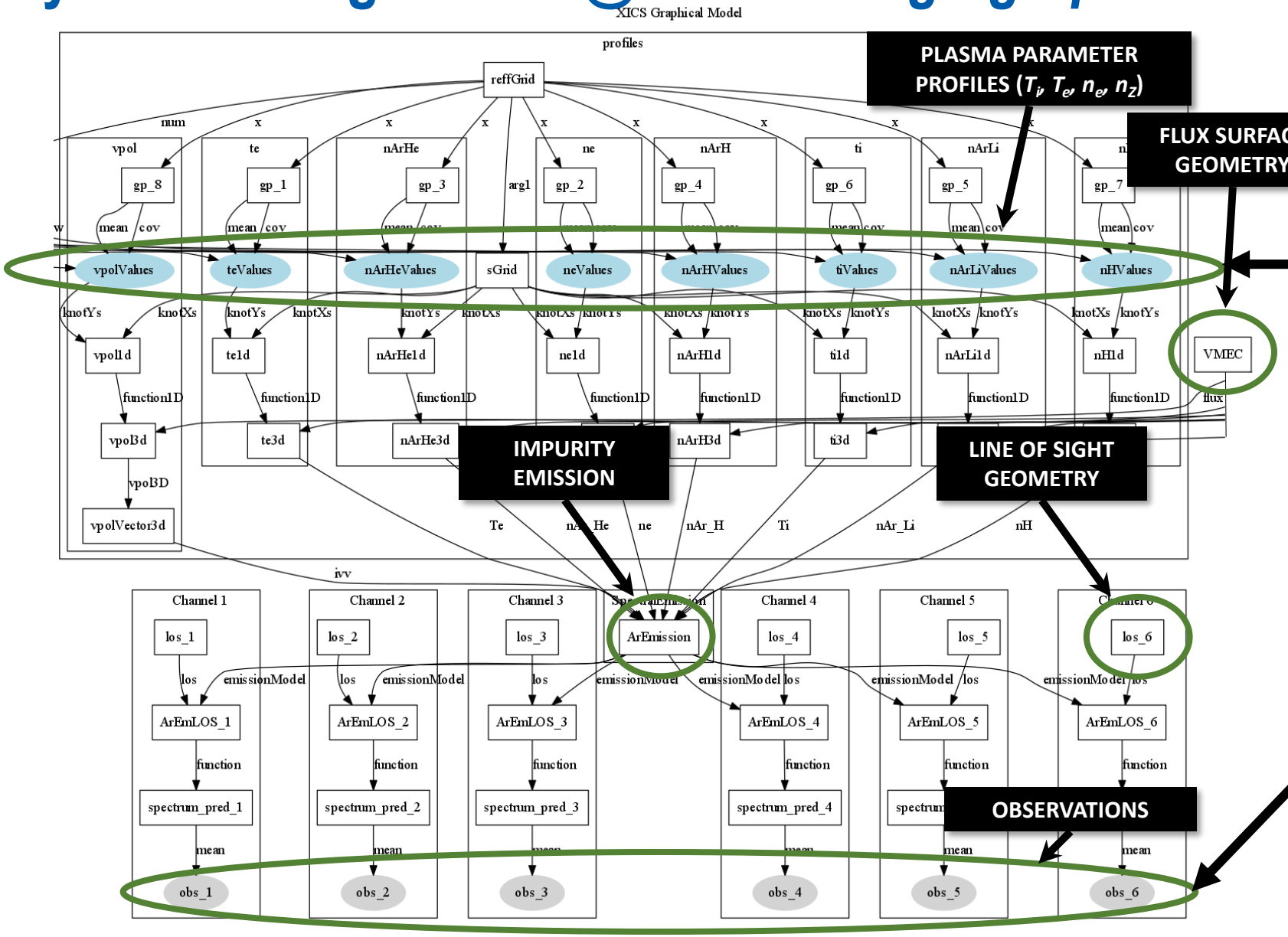

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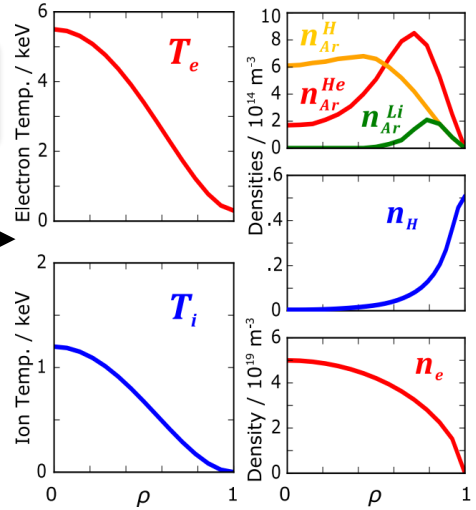

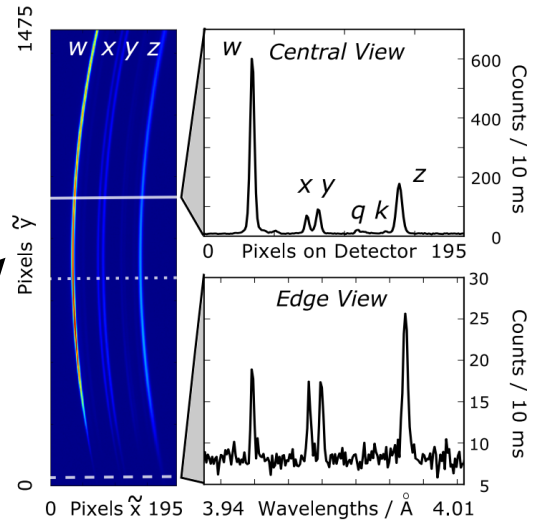

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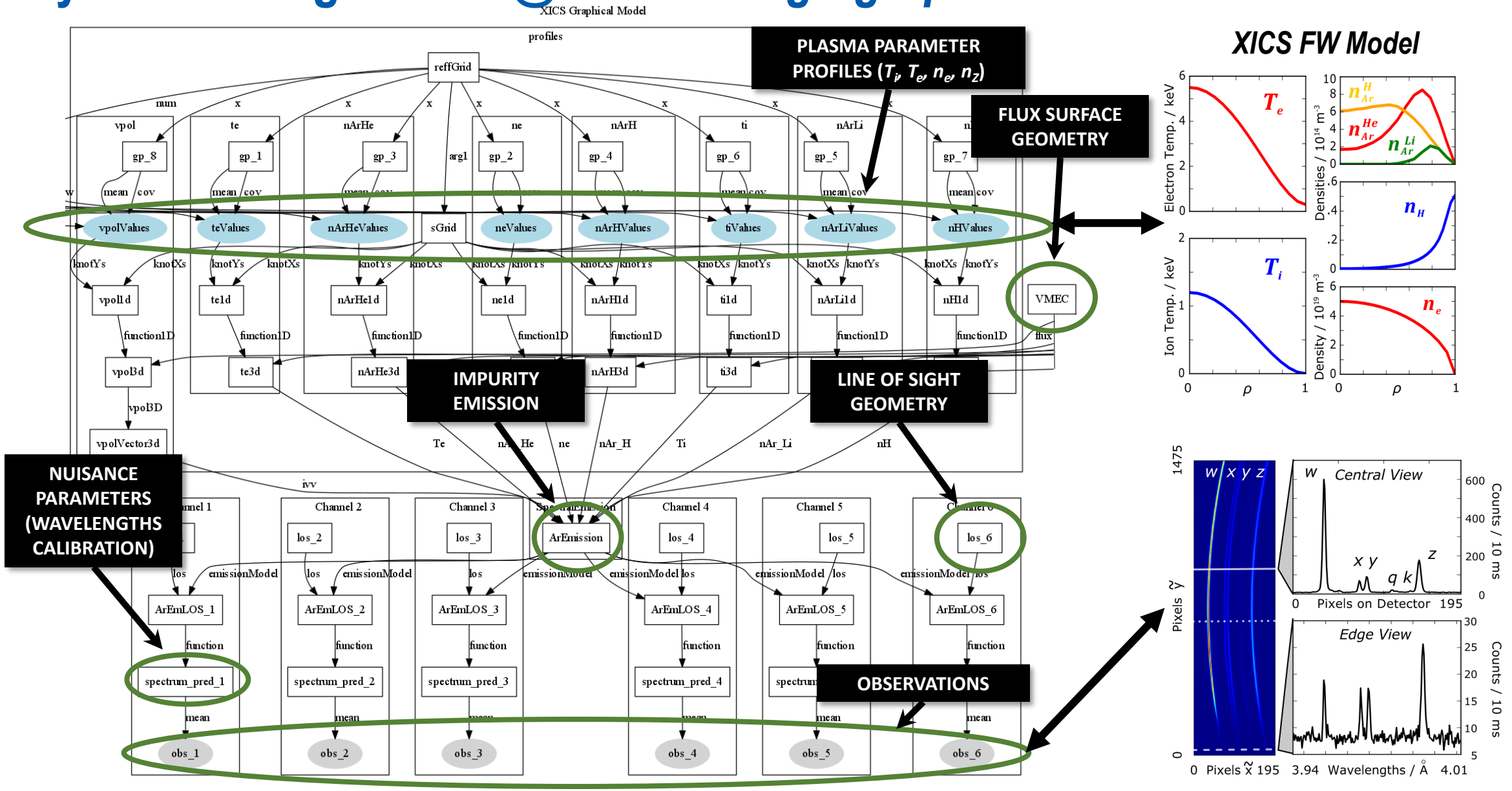

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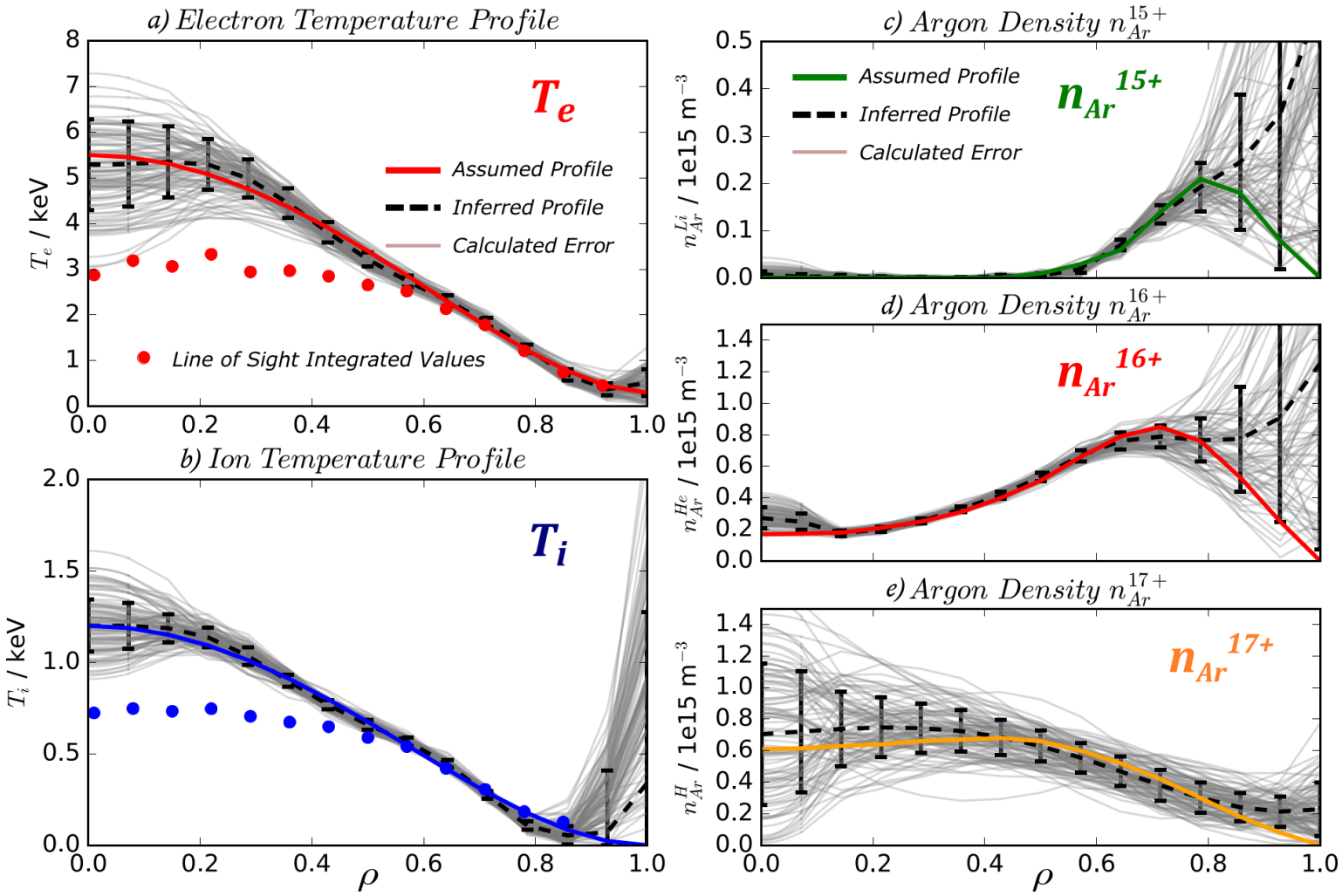
Synthetic Data Validation: *Imaging Spectrometers*

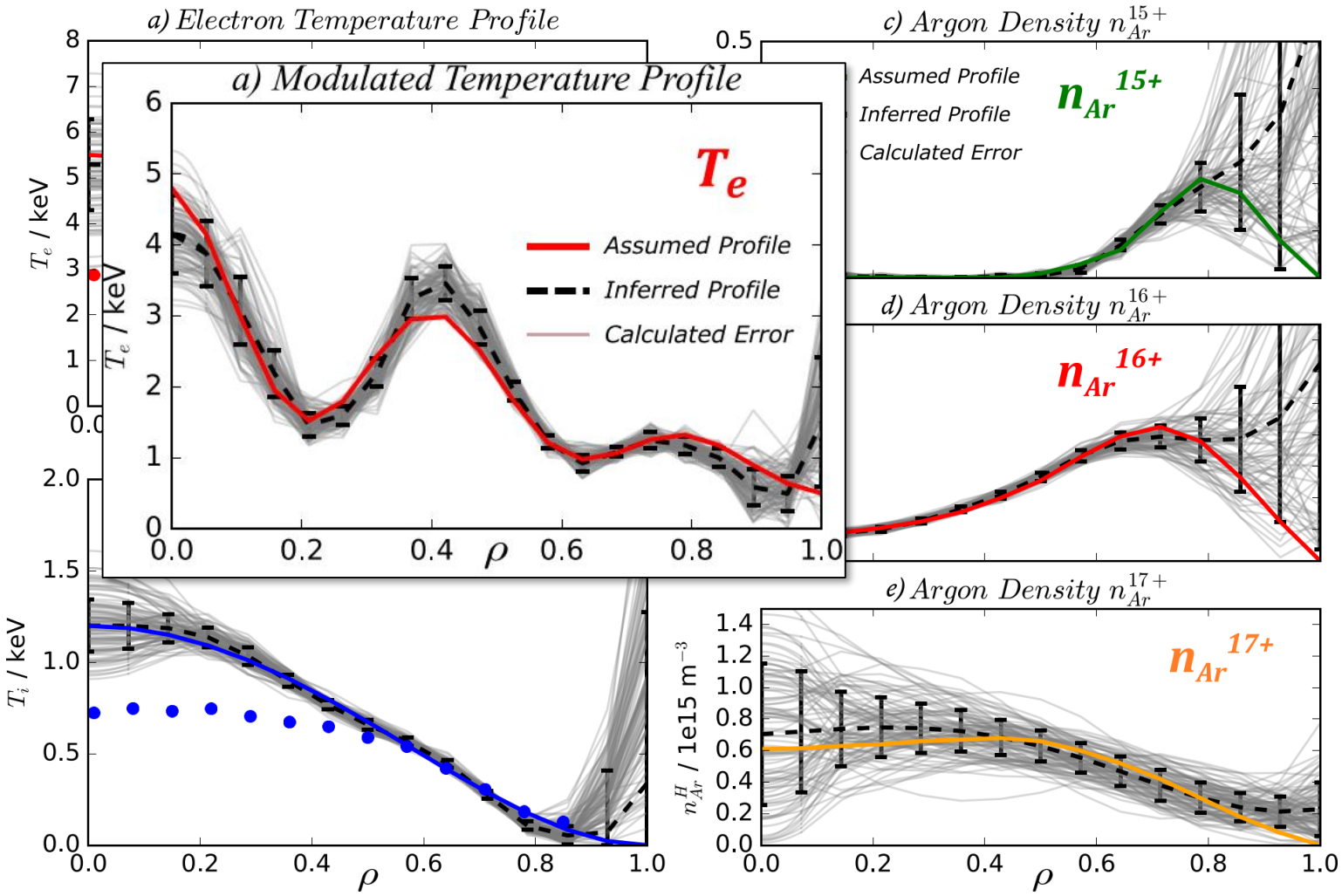


Synthetic XICS Model:

- Precise and correct profile inference incl. error calculations √
- Simulateous inference of T_e, T_i, n_{Ar}^{15+}, n_{Ar}^{16+}, and n_{Ar}^{17+} profiles √

A. Langenberg, J. Svensson, O. Marchuk et al. *Rev. Sci. Instrum.* **90** (2019)

Synthetic Data Validation: *Imaging Spectrometers*



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- Inferrence of arbitrary profile shapes √

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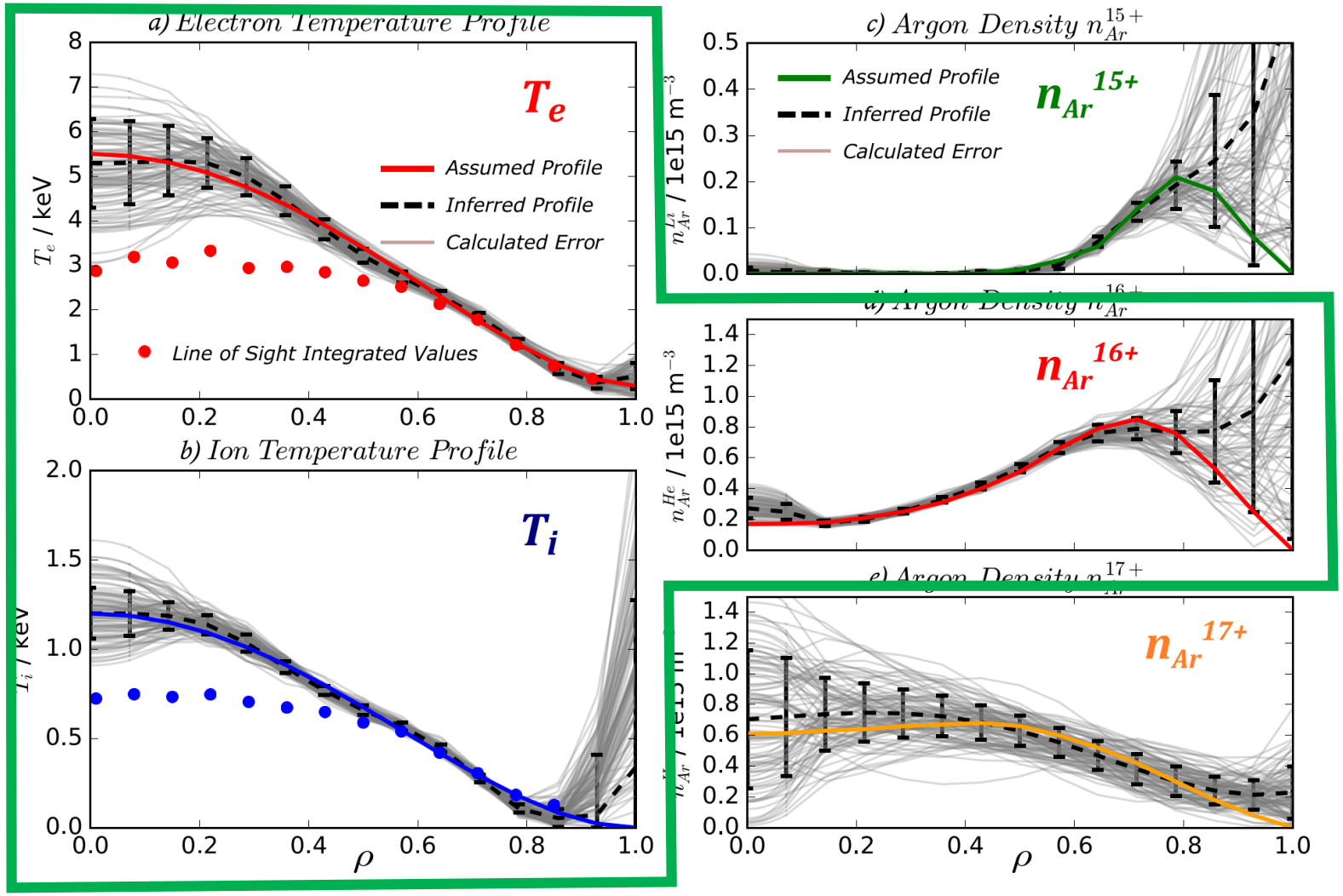

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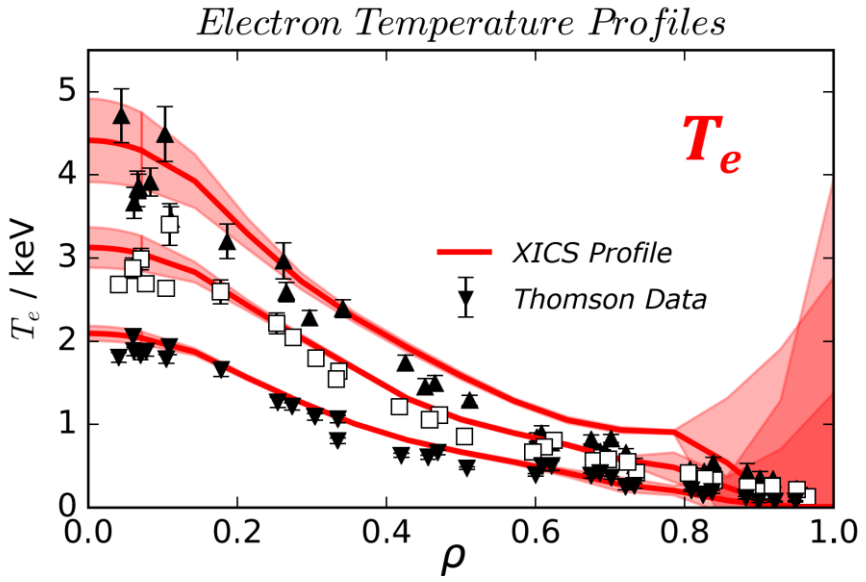
Measured Data Validation: *Imaging Spectrometers | T_e-Profile*



Validated XICS Model:

- Matching T_e profiles (XICS-Thomson) √

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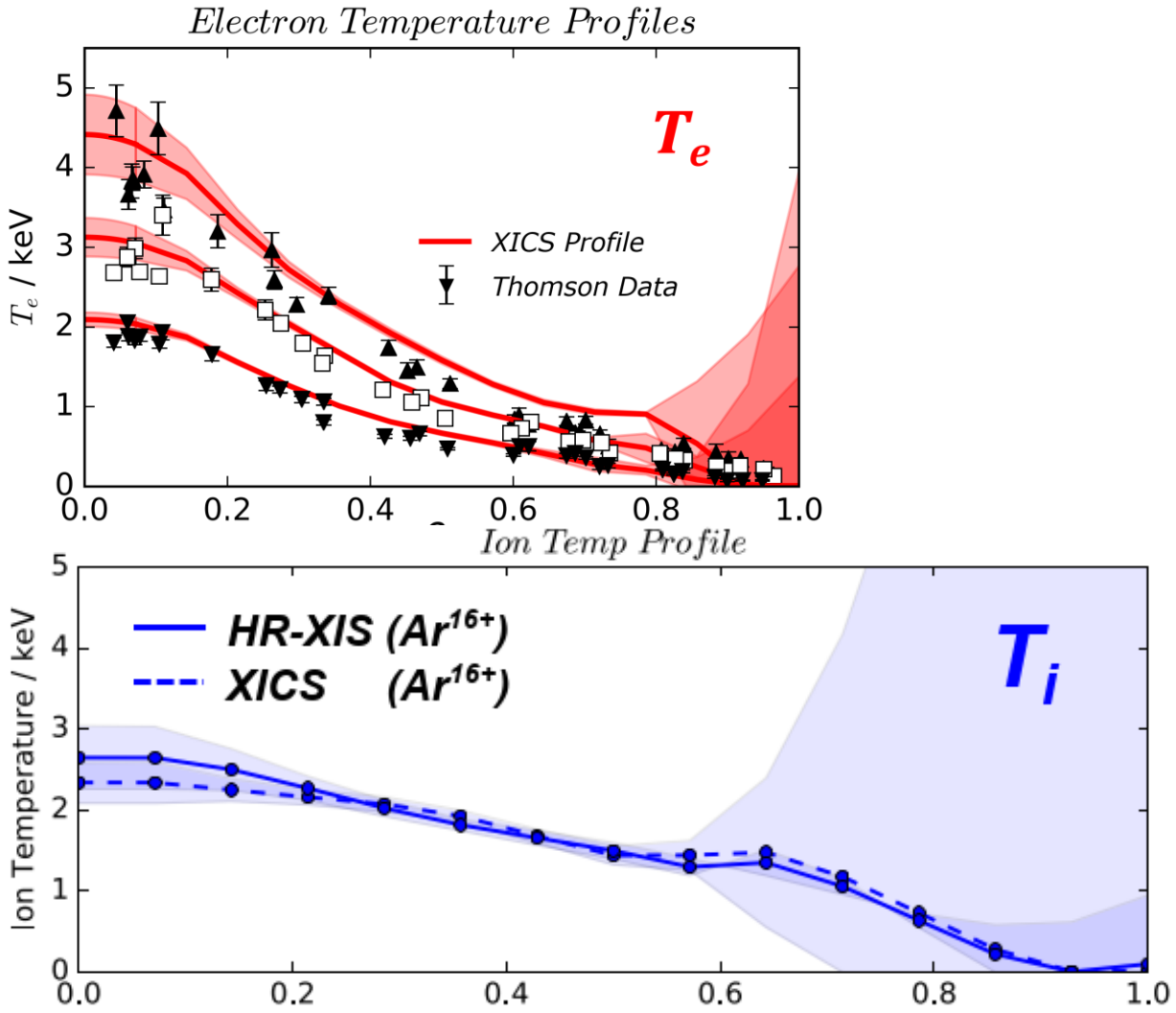
Measured Data Validation: *Imaging Spectrometers | T_i -Profile*



Validated XICS Model:

- Matching T_e profiles (XICS-Thomson) √
- Matching T_i profiles (XICS-HR-XIS) √

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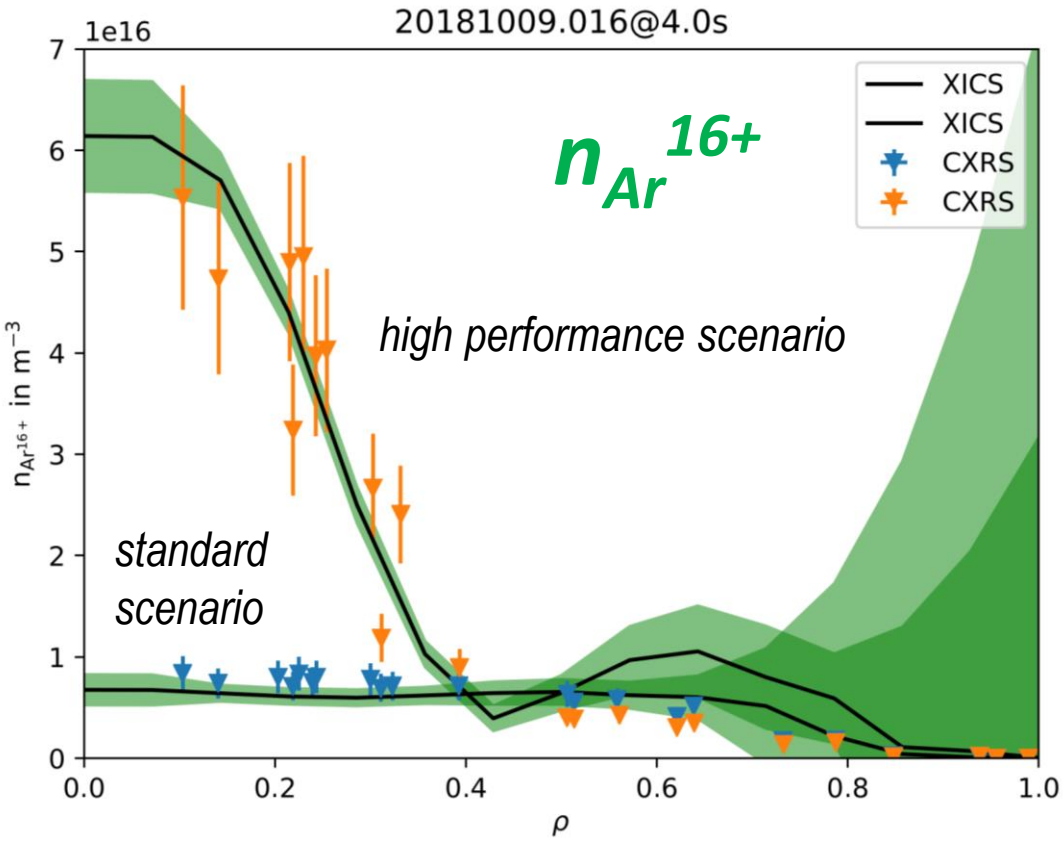
Measured Data Validation: *Imaging Spectrometers | n_z-Profile*



Validated XICS Model:

- Matching T_e profiles (XICS-Thomson) √
- Matching T_i profiles (XICS-HR-XIS) √
- Matching n_Z profiles (XICS-CXRS) √

Courtesy of Thilo Romba

A. Langenberg, J. Svensson, O. Marchuk et al. *Rev. Sci. Instrum.* **90** (2019)

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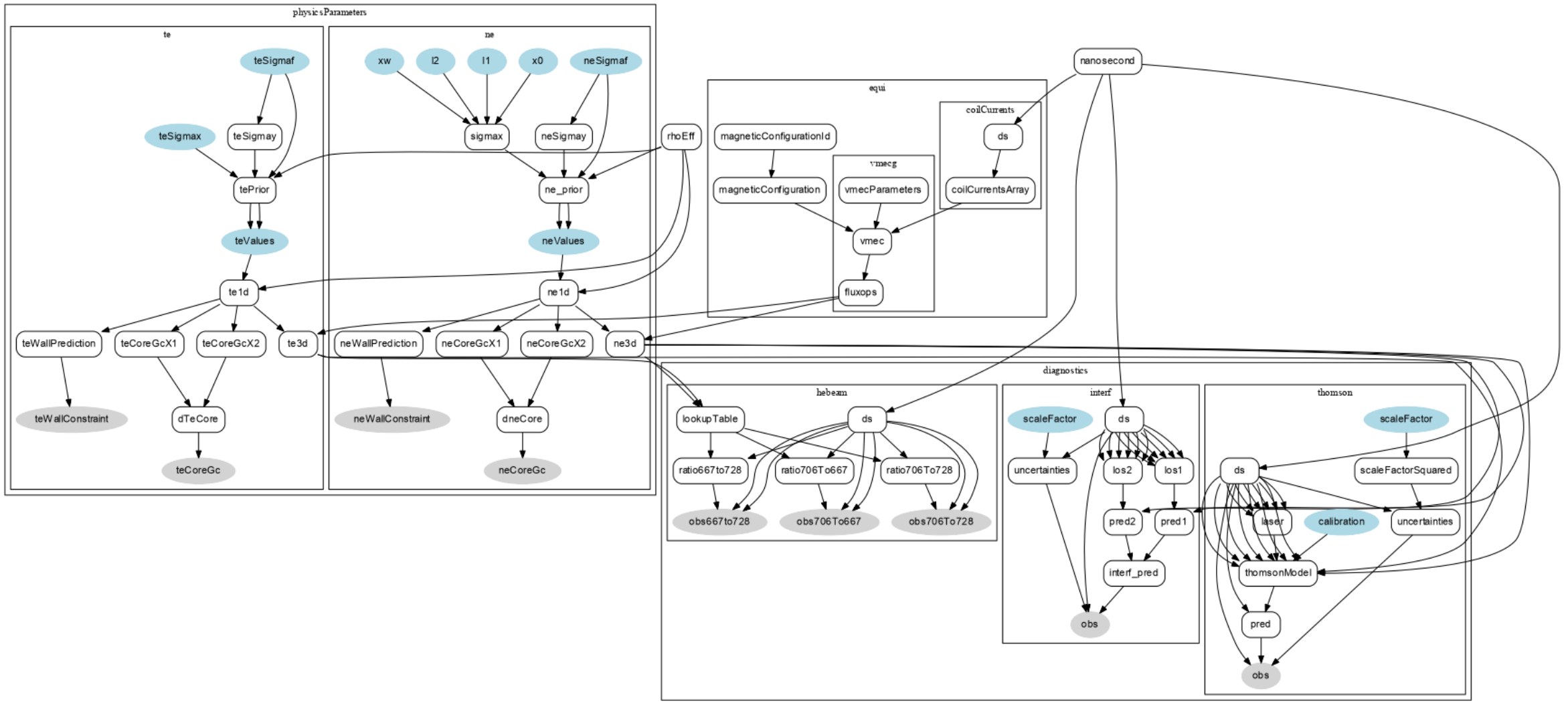

S. Kwak, J. Svensson, S. Bozhenkov et al. *To be published.*

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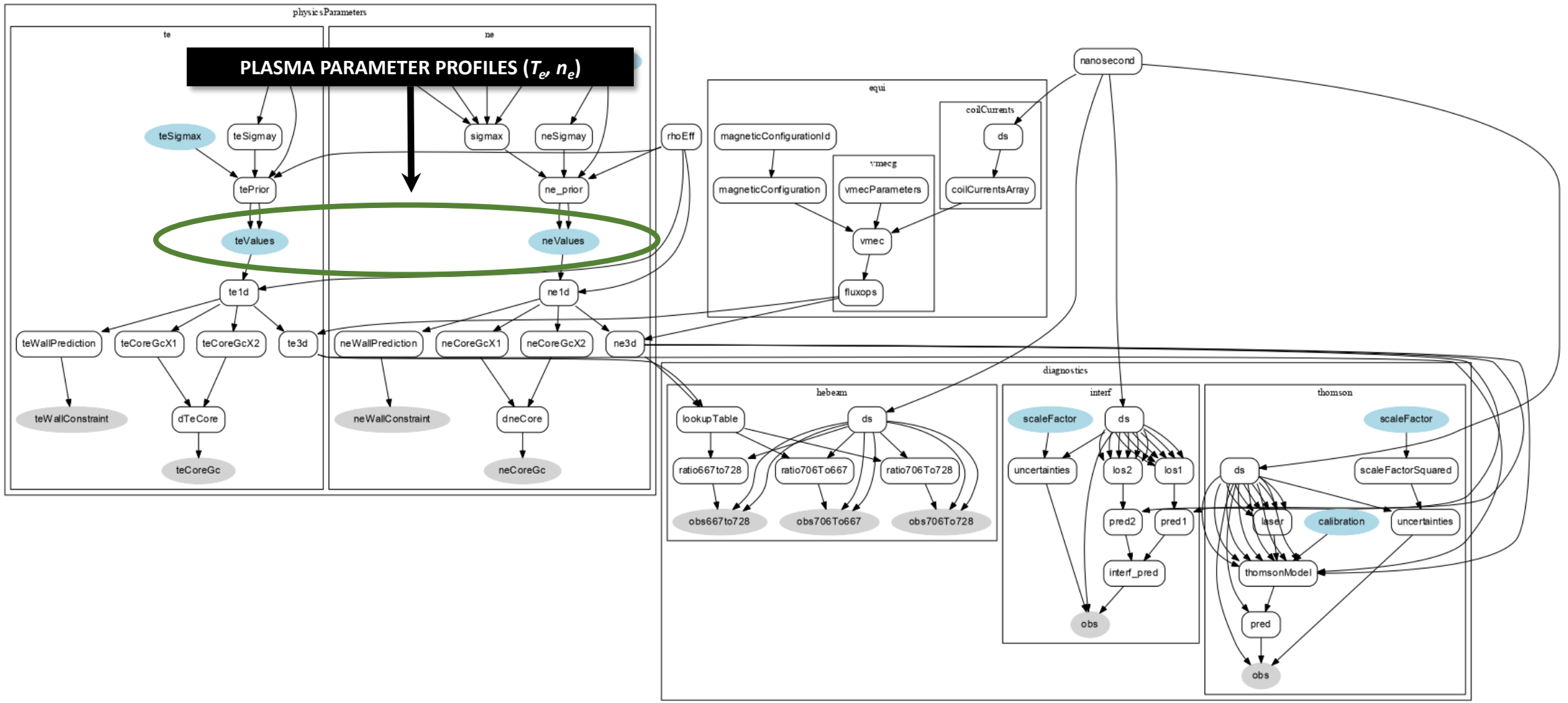

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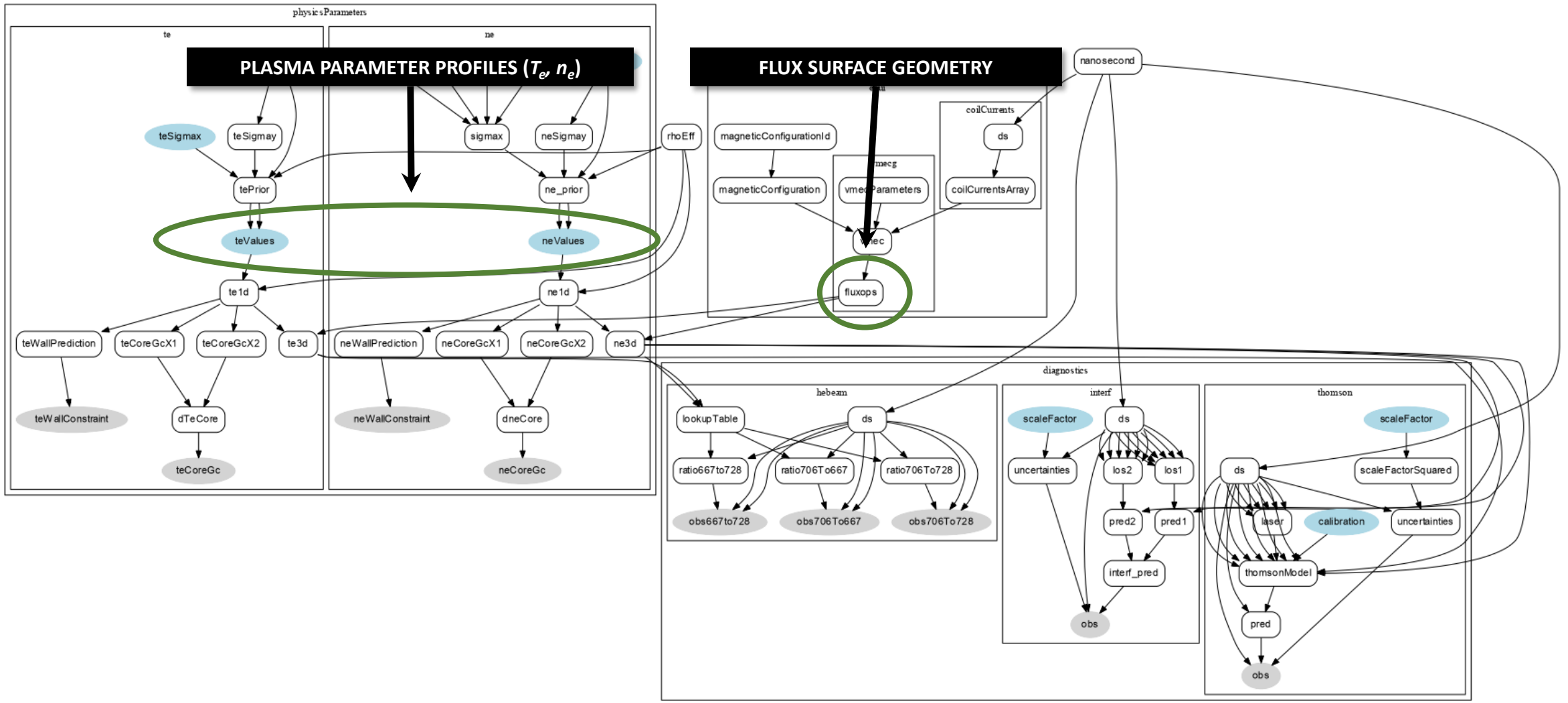

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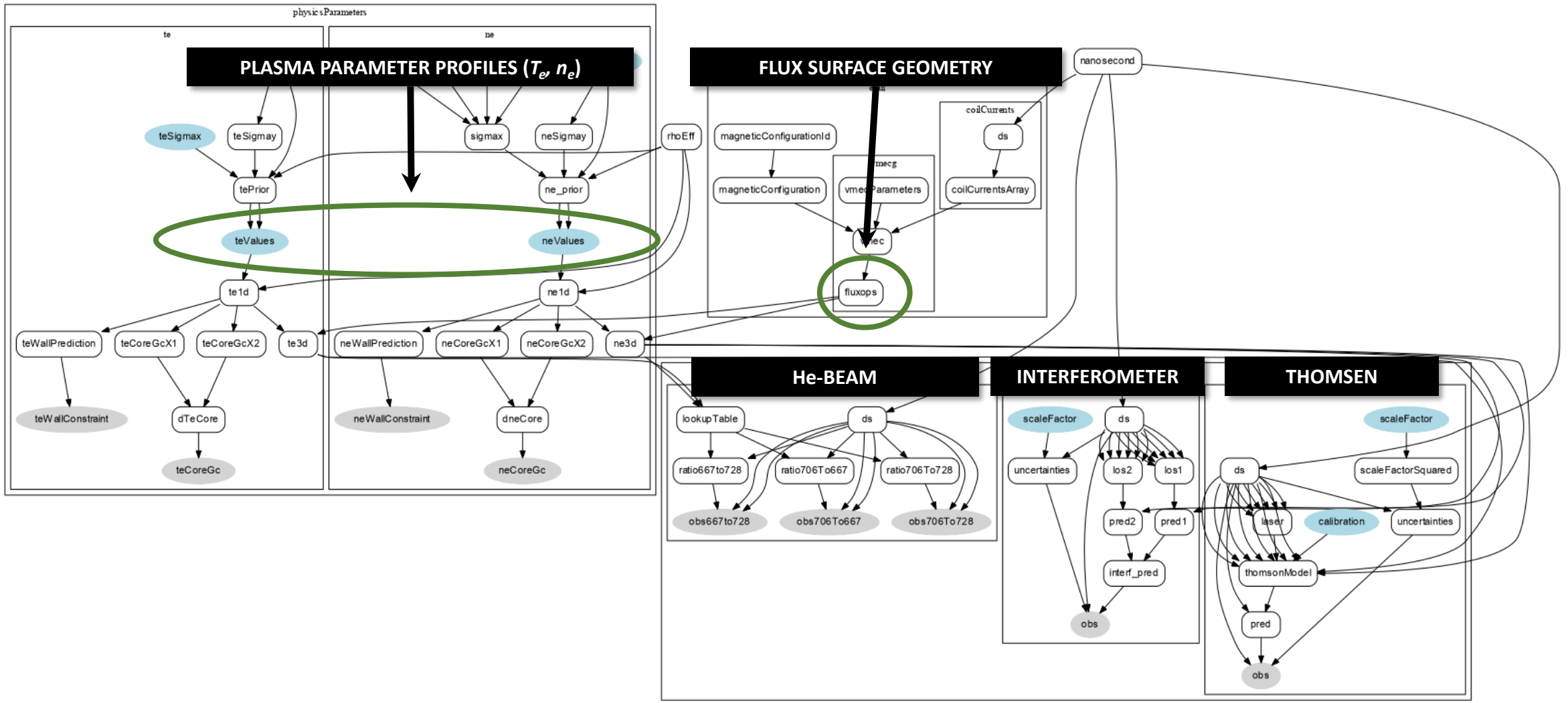

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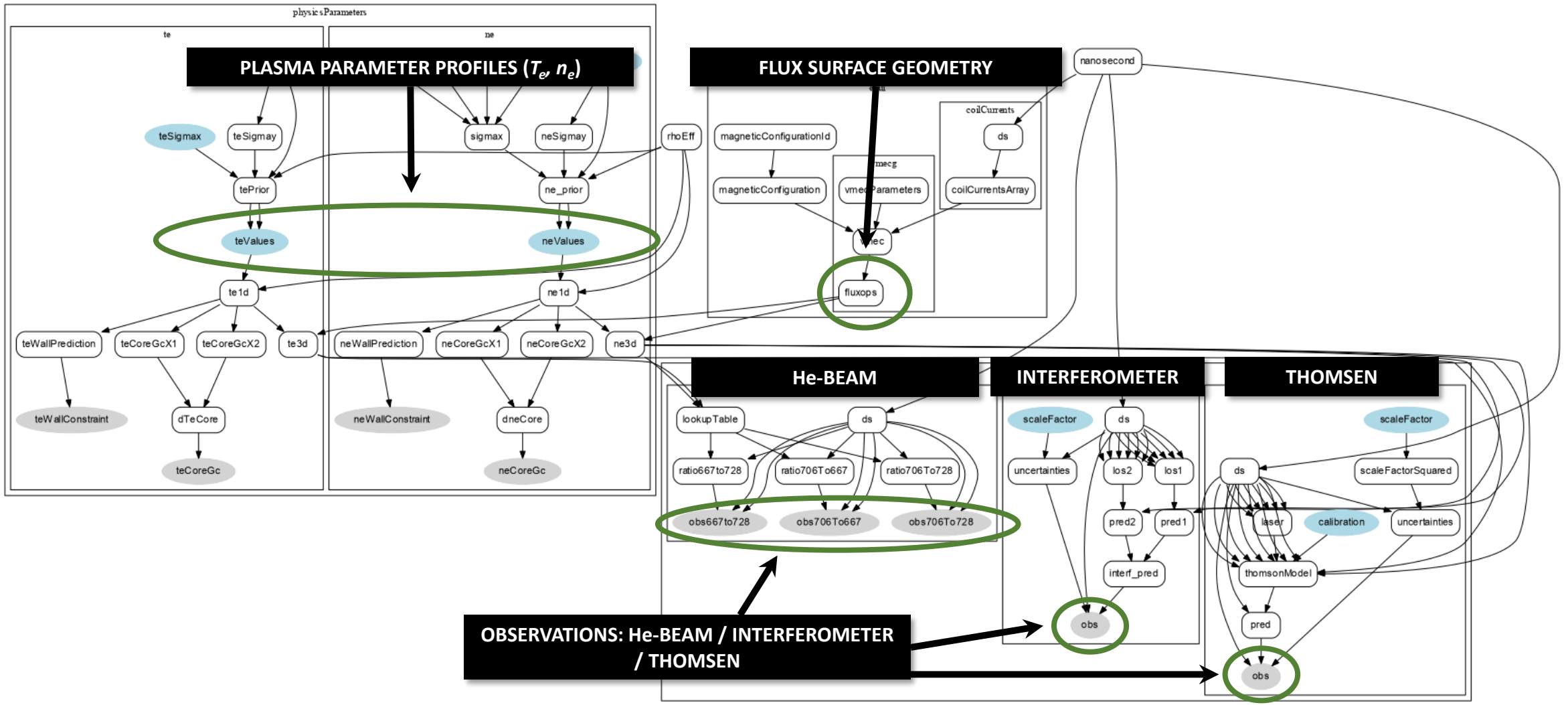

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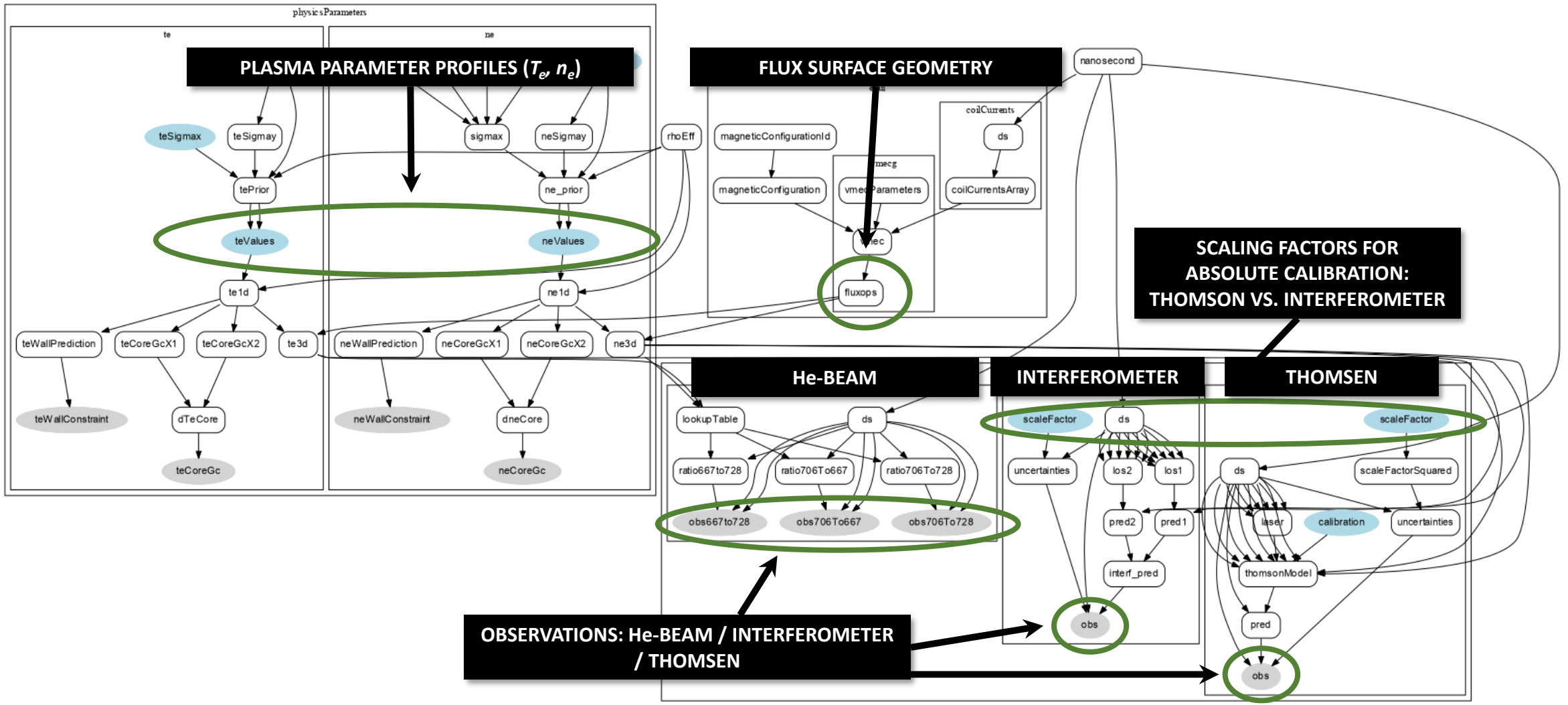

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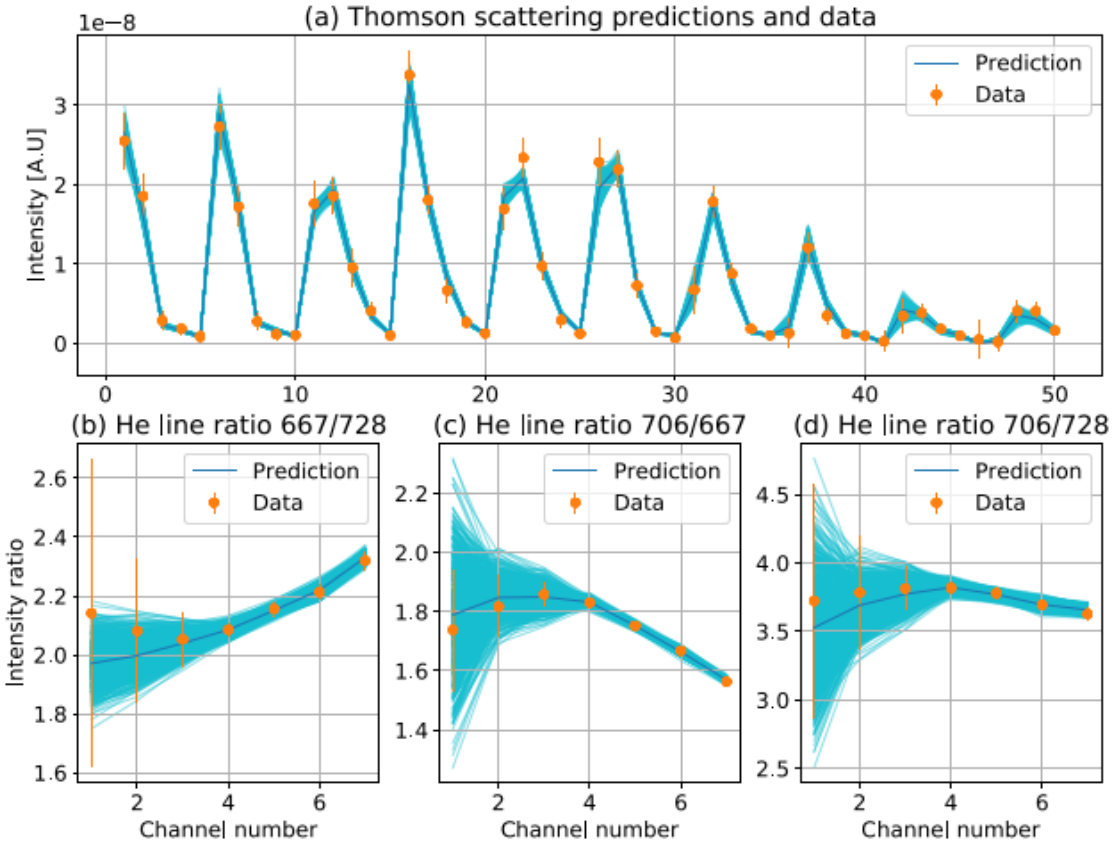

Combined Thomson / He-Beam / Interferometer Model:

- Matching predictions and observations (Thomson-HeBeam) √

S. Kwak, J. Svensson, S. Bozhenkov et al. *To be published.*

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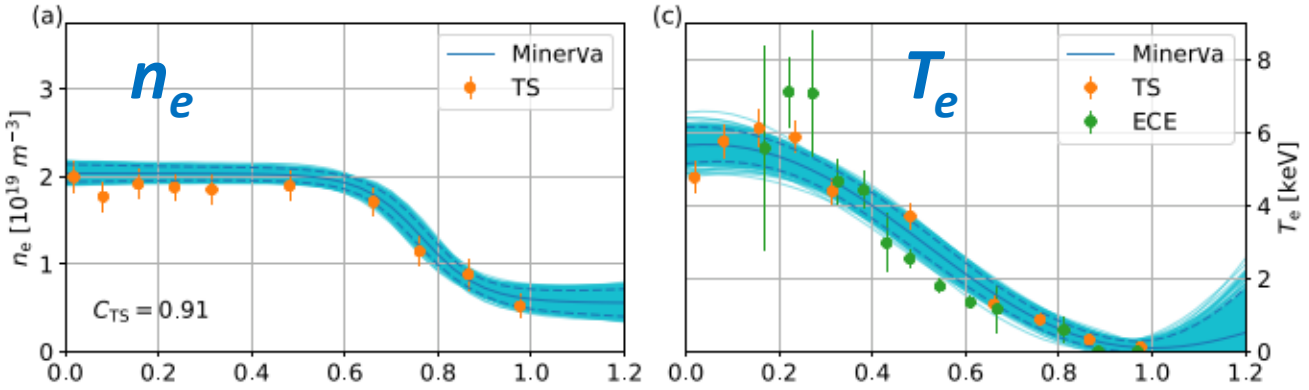

Combined Thomson / He-Beam / Interferometer Model:

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- Thomson only: large edge uncertanties

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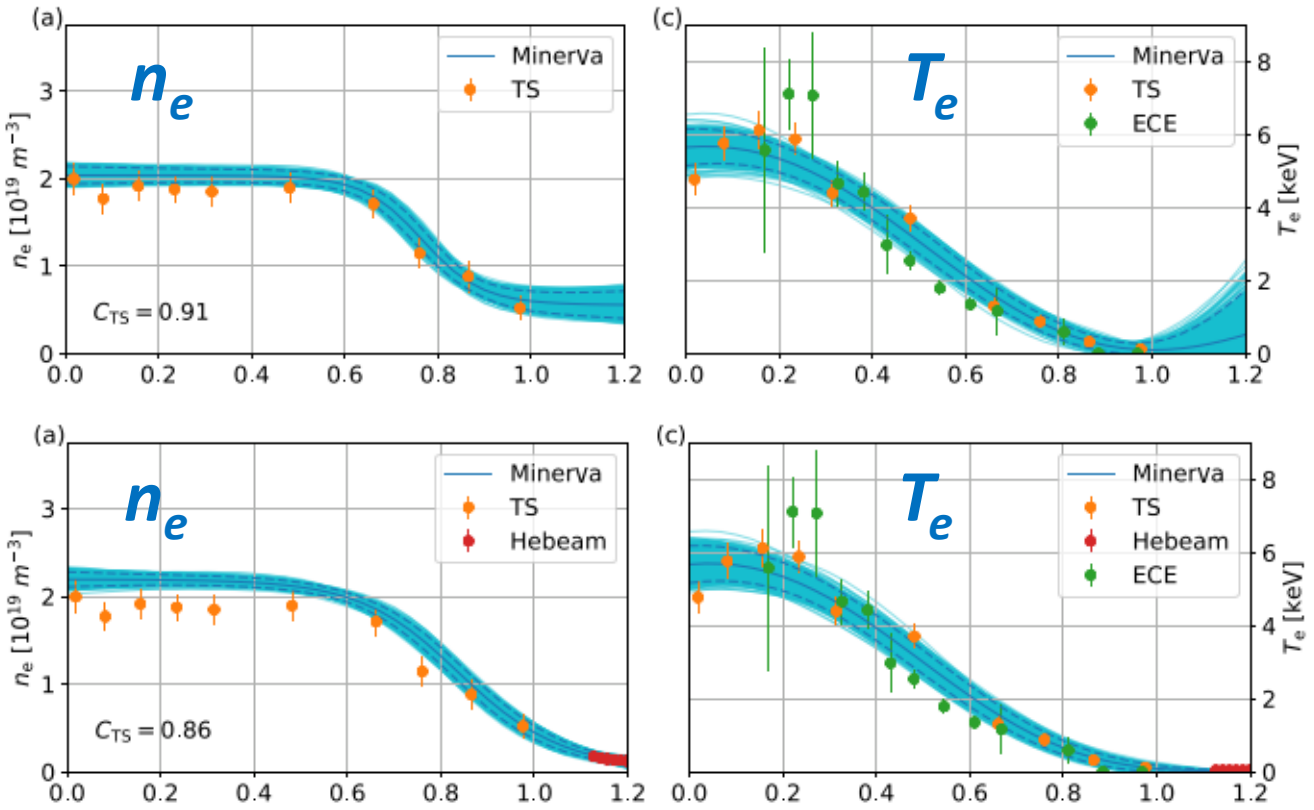

Combined Thomson / He-Beam / Interferometer Model:

- Matching predictions and observations (Thomson-HeBeam) √
- Thomson only: large edge uncertanties
- Combined Thomson / He-Beam:
  - Defined edge T_e and n_e √

S. Kwak, J. Svensson, S. Bozhenkov et al. *To be published.*

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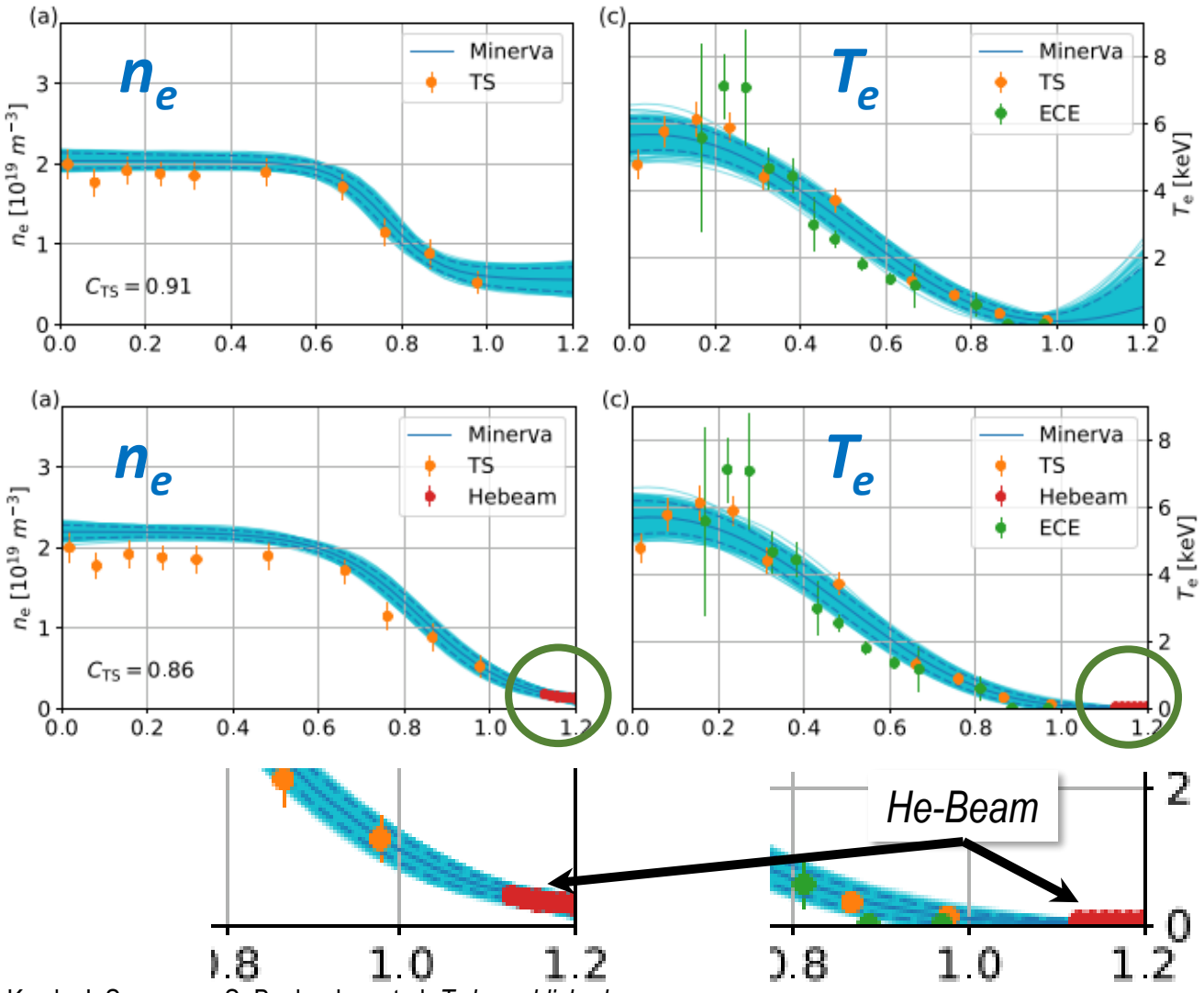

S. Kwak, J. Svensson, S. Bozhenkov et al. *To be published.*

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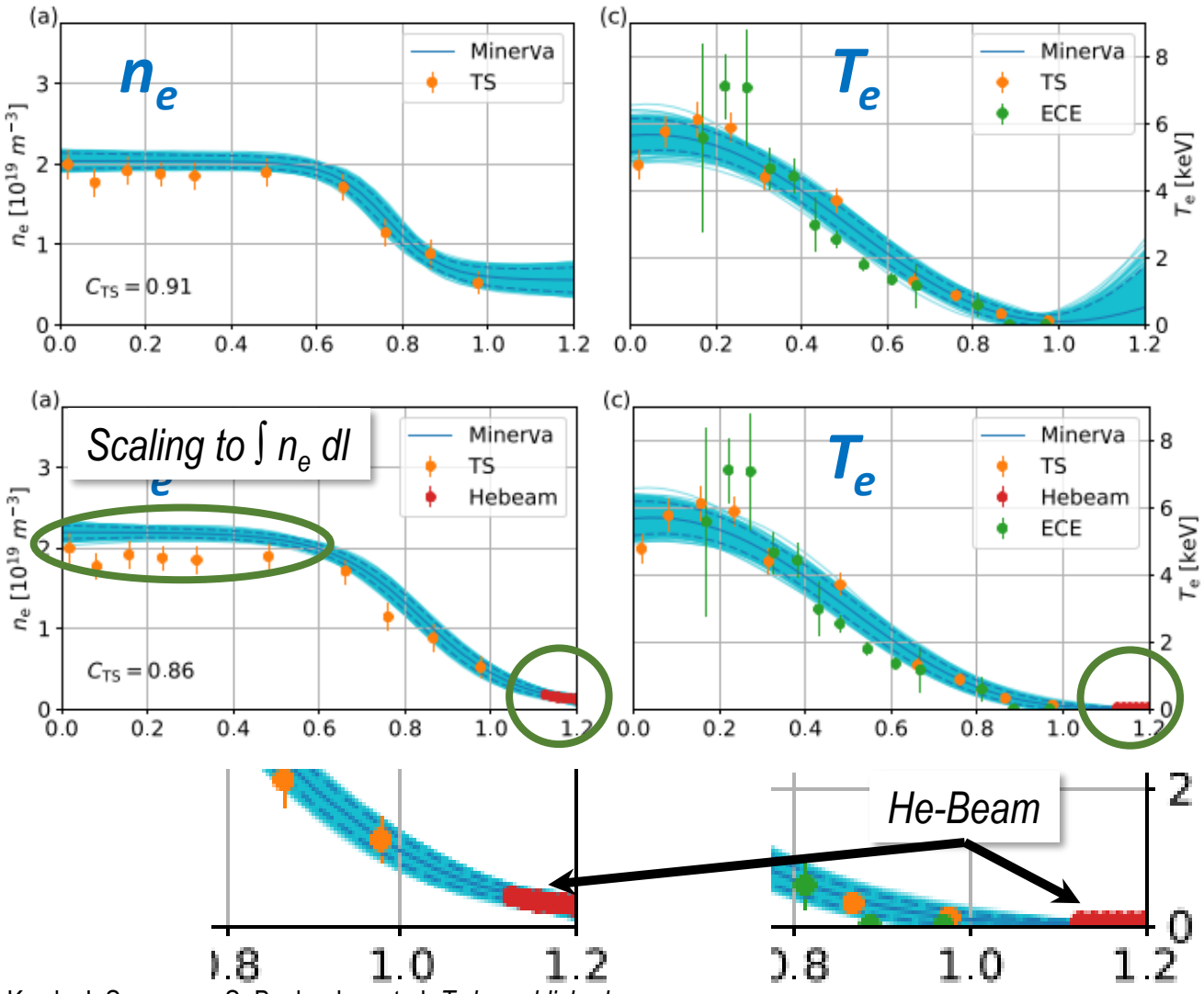


S. Kwak, J. Svensson, S. Bozhenkov et al. *To be published.*

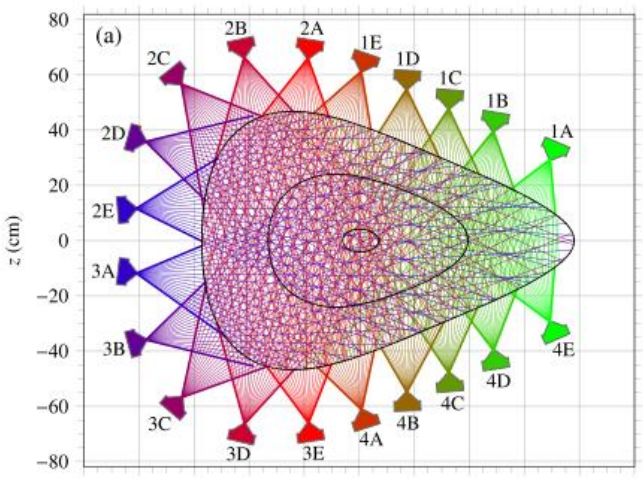
Combined Thomson / He-Beam / Interferometer Model:

- Matching predictions and observations (Thomson-HeBeam) √
- Thomson only: large edge uncertanties
- Combined Thomson / He-Beam:
  - Defined edge T_e and n_e √
- Including interferometer:
  - Corrected absolute n_e scaling √

Synthetic Diagnostics @ W7-X: *X-ray Tomography*

C. Brandt et al. *Plasma Phys. Control. Fusion* **62** (2020).

Synthetic Diagnostics @ W7-X: *X-ray Tomography*



- ***XMCTS:*** 20 cameras with movable shutters

C. Brandt et al. *Plasma Phys. Control. Fusion* **62** (2020).

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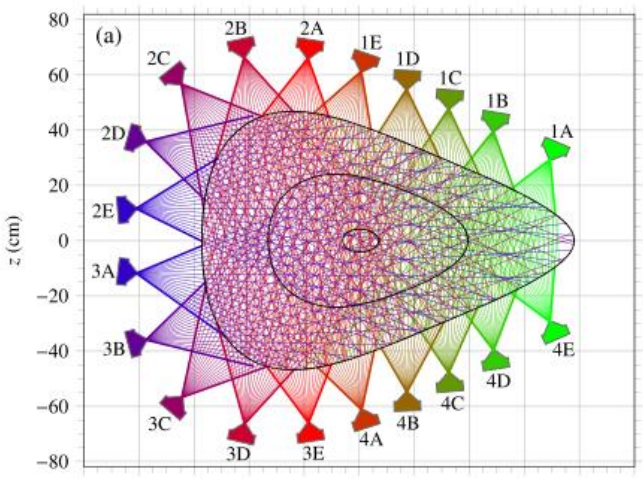

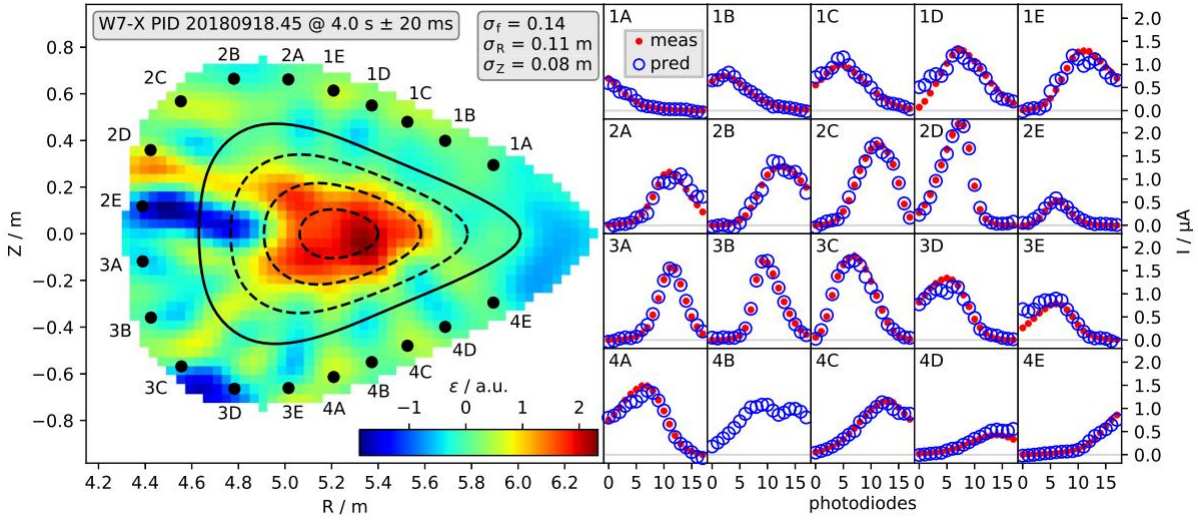

- ***XMCTS:*** 20 cameras with movable shutters
- Weired intensity patterns on XMCTS tomograms

J. Schilling et al. *Plasma Phys. Control. Fusion* **63** (2021)
C. Brandt et al. *Plasma Phys. Control. Fusion* **62** (2020)

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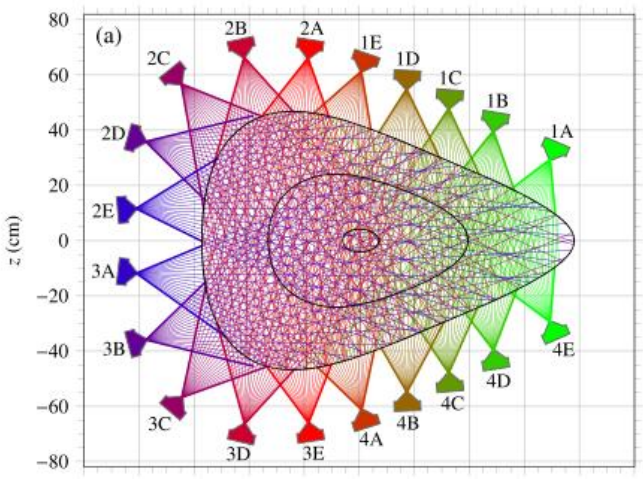

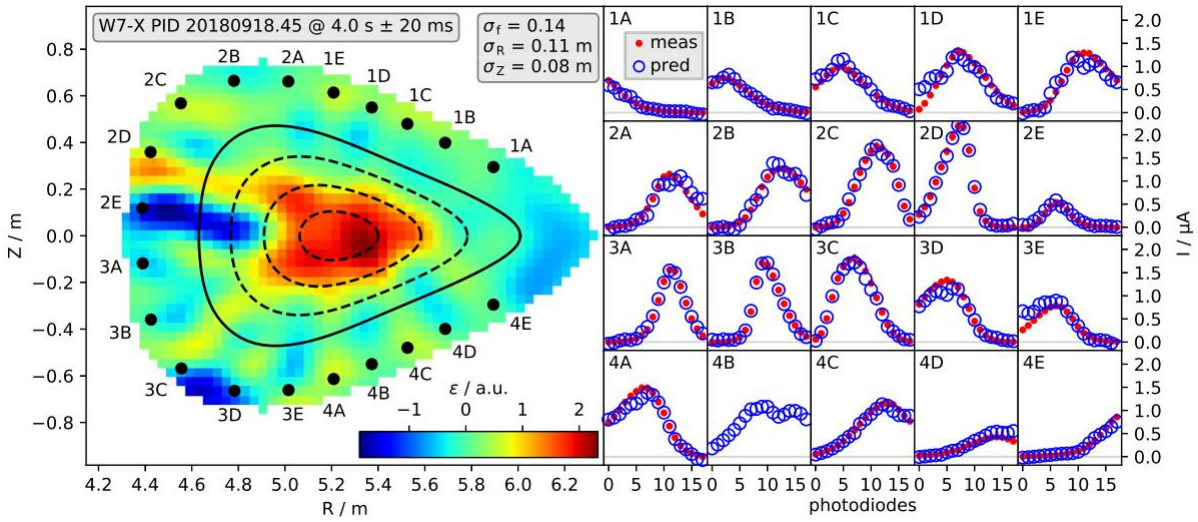

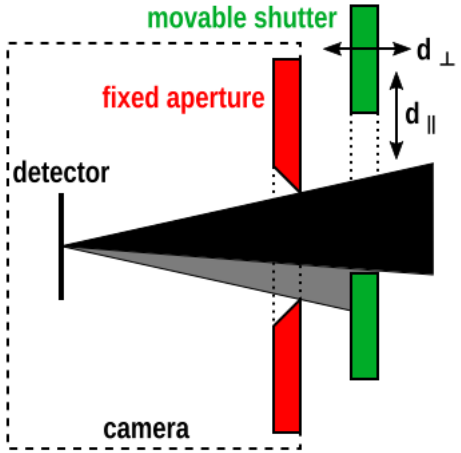

- ***XMCTS:*** 20 cameras with movable shutters
- Weired intensity patterns on XMCTS tomograms
- Several shutters 2E,3C,3D partially closed

Issue: *Unknown shutter state during expermiental campaign*

Solution: *XMCTS forward model with shutter positions, camera calibration factors, and emissivity profile as free parameters*

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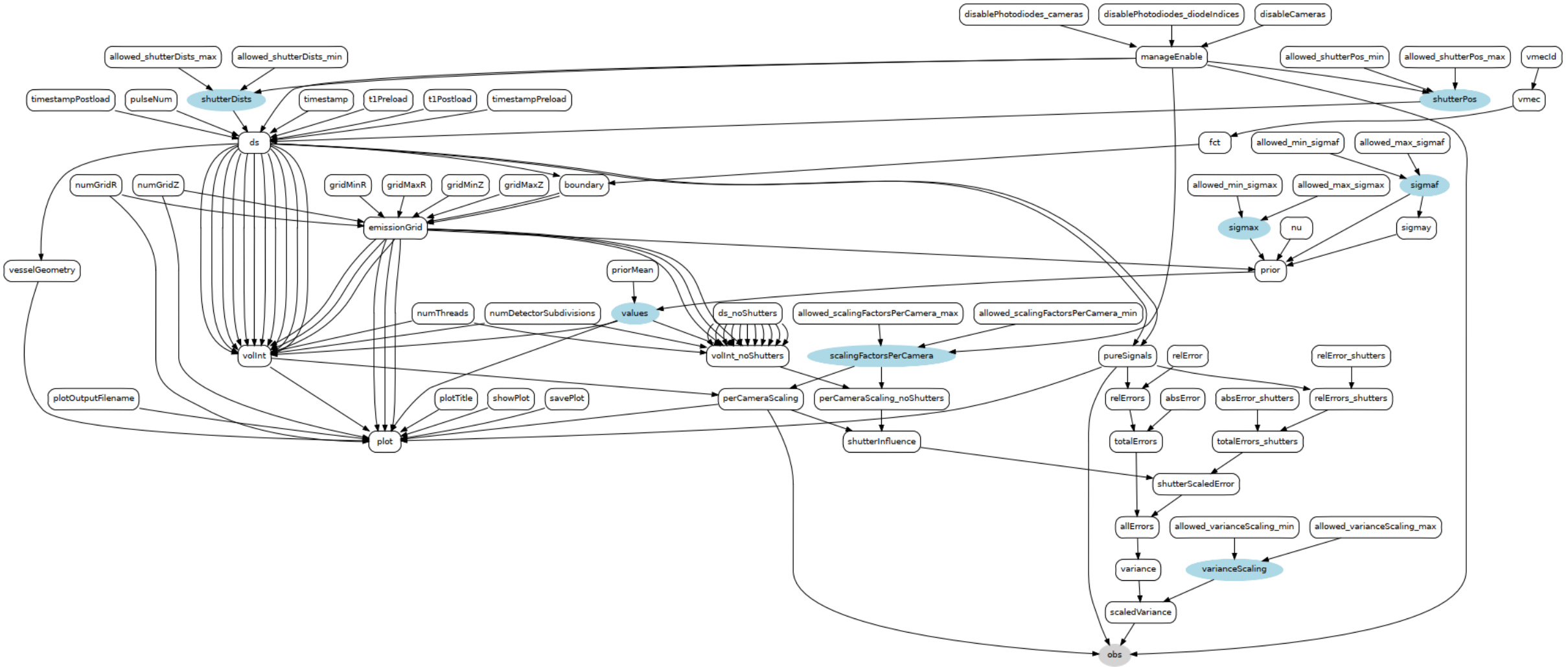
C. Brandt et al. *Plasma Phys. Control. Fusion* **62** (2020)

Synthetic Diagnostics @ W7-X: *X-ray Tomography*



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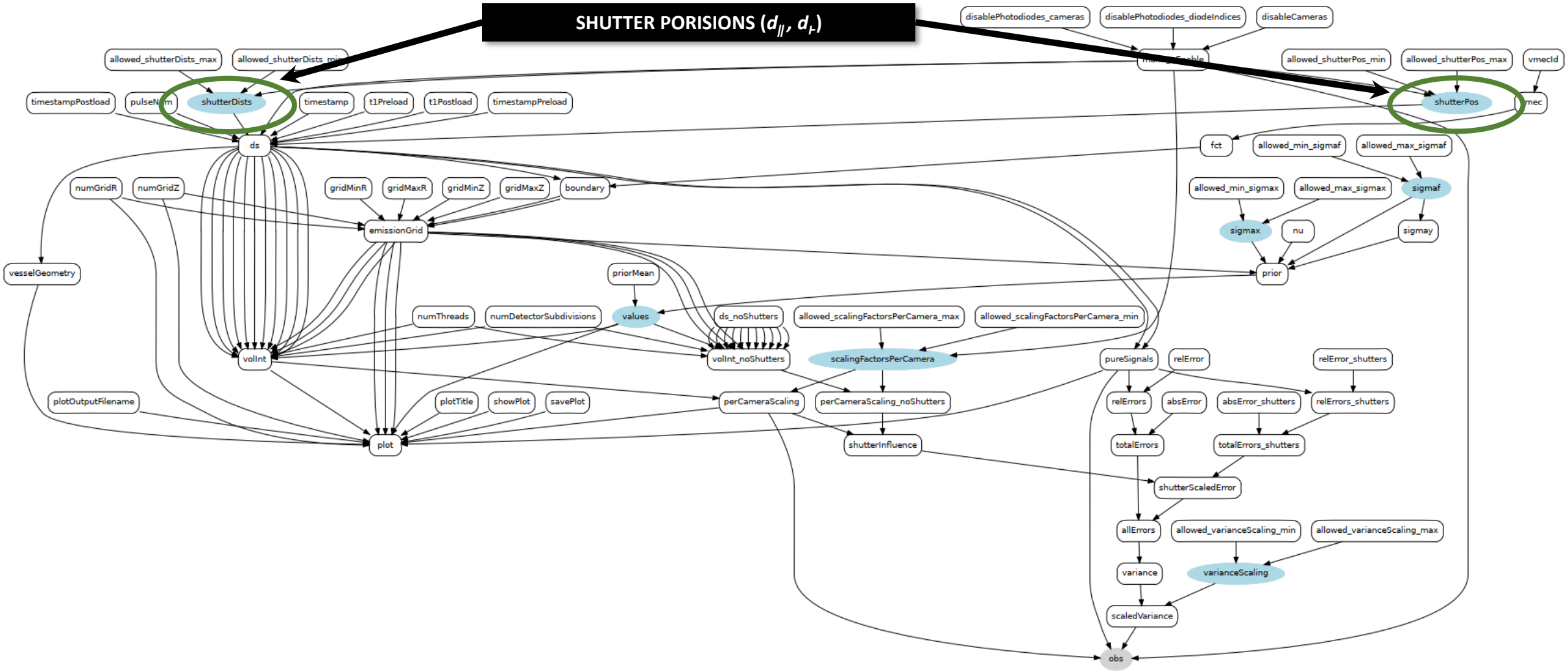

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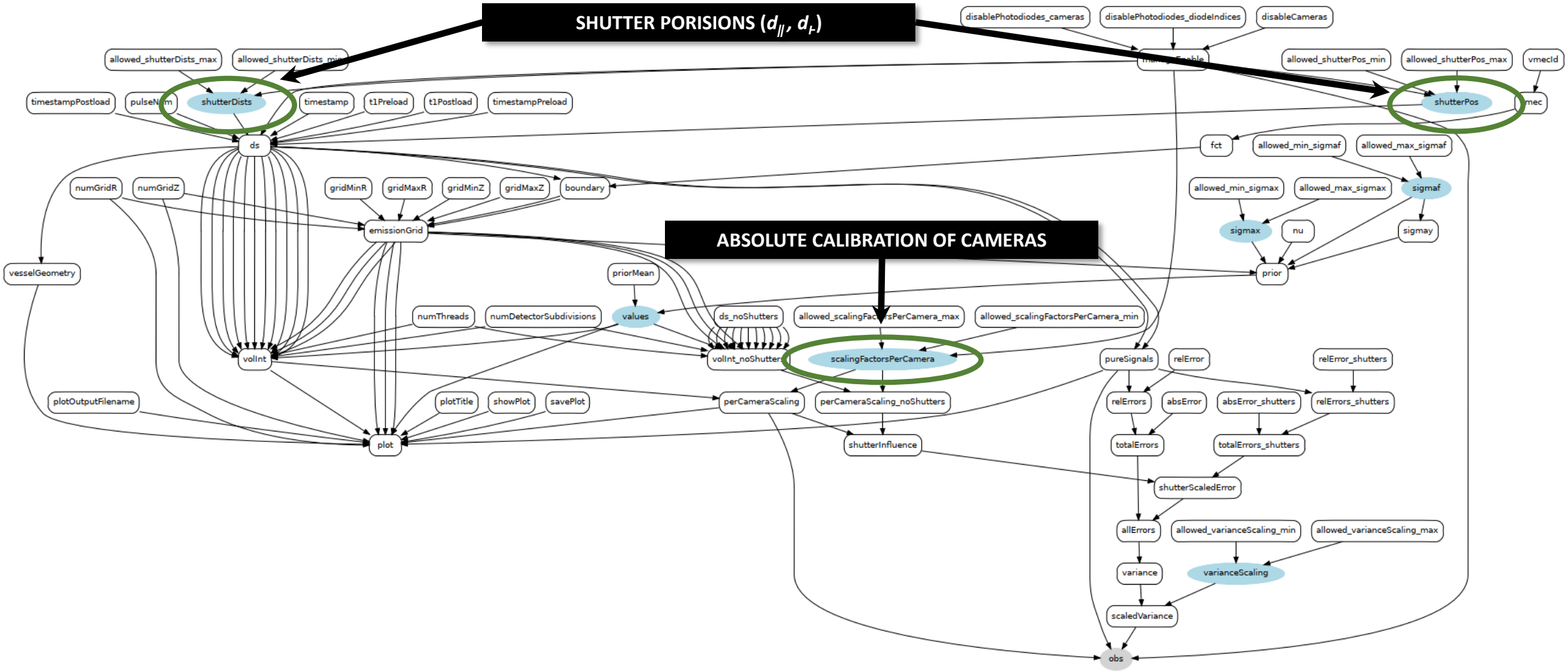

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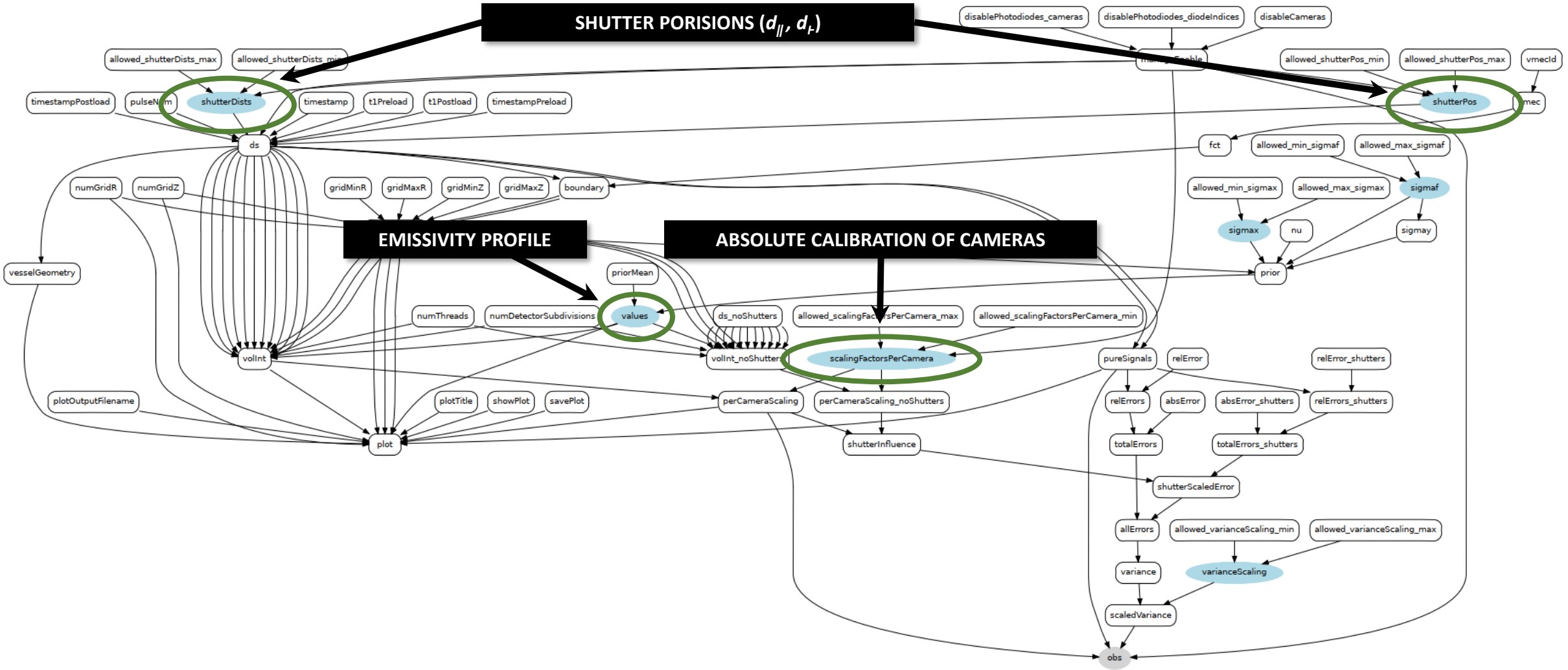

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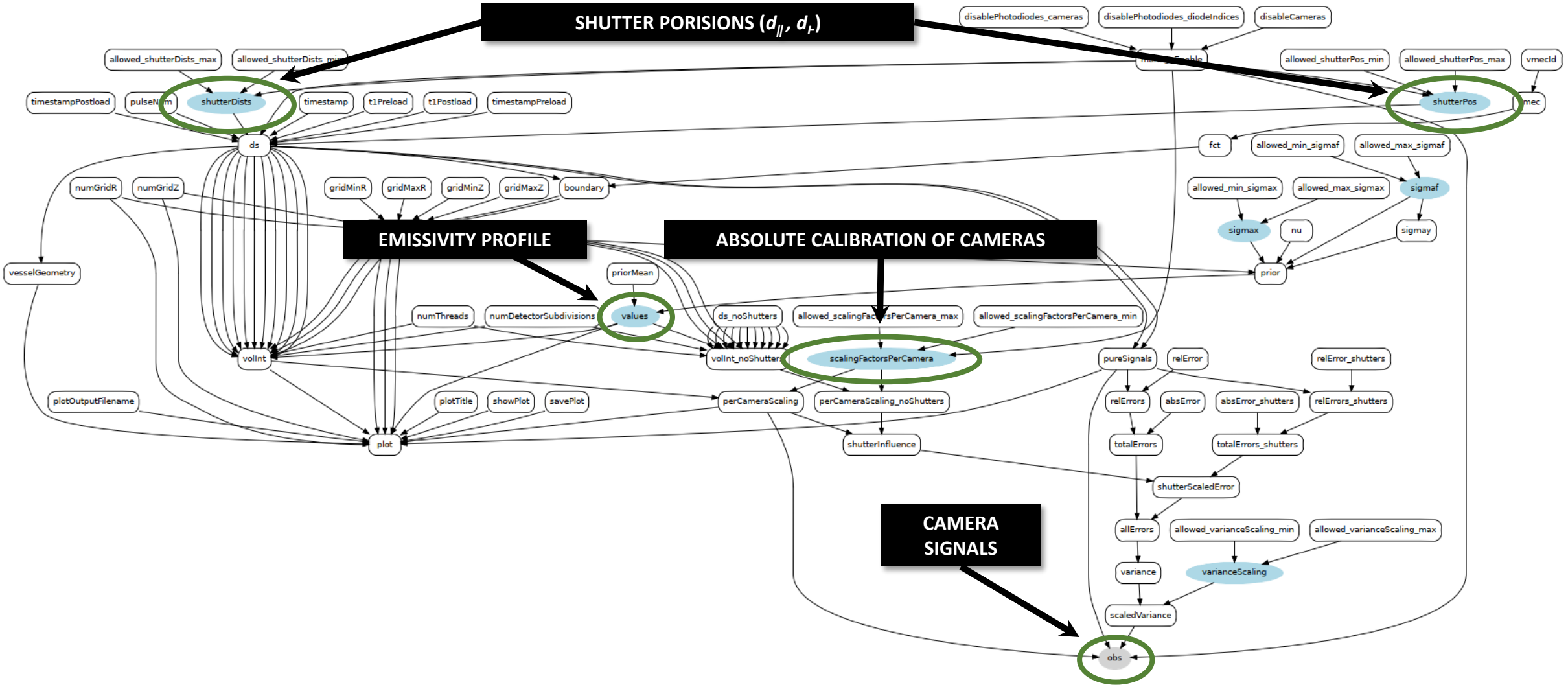

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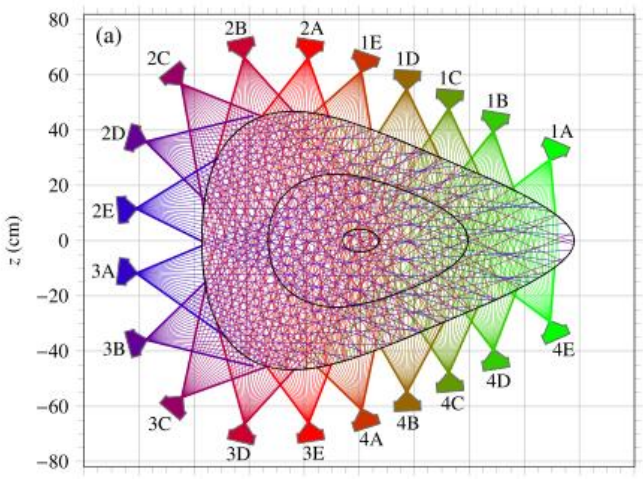
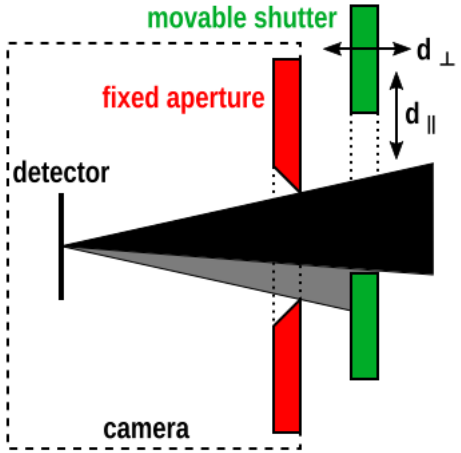
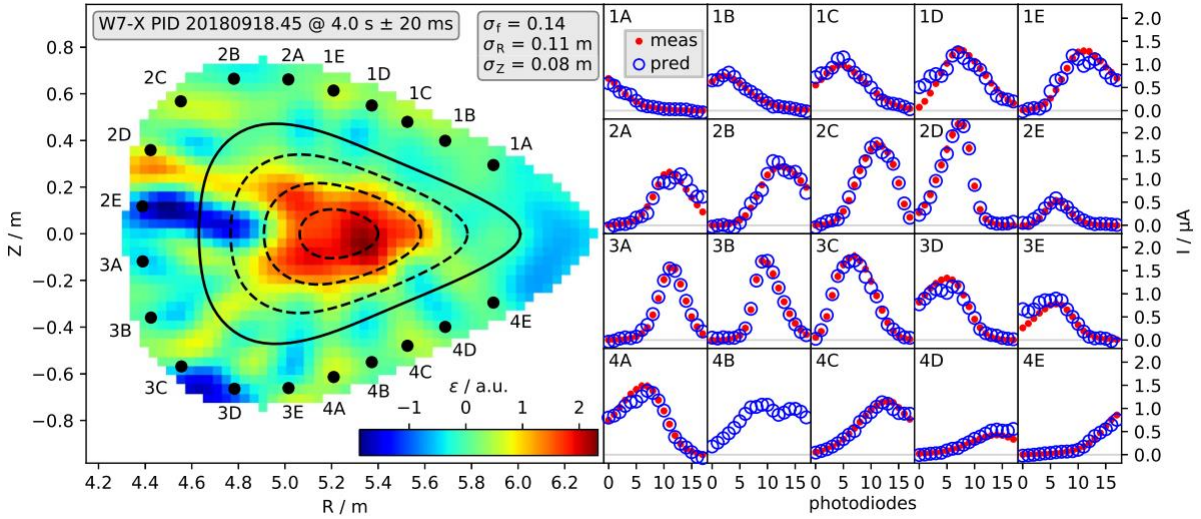
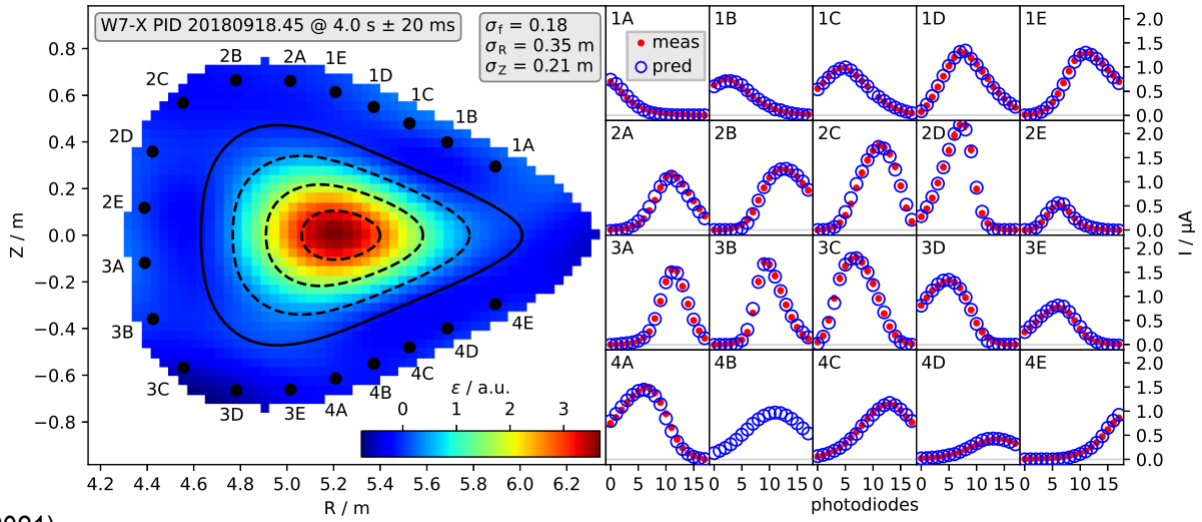




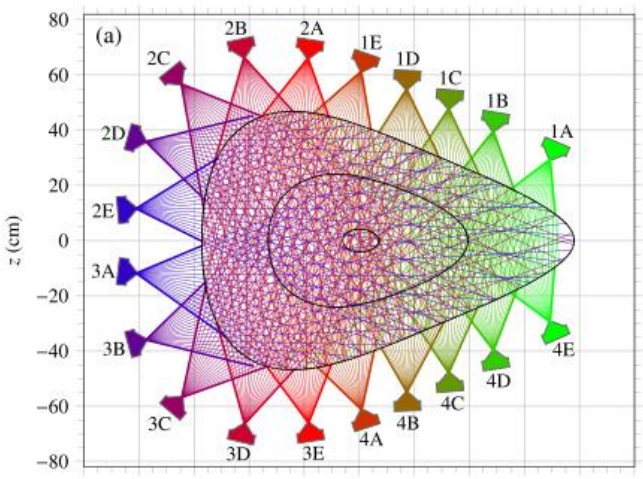


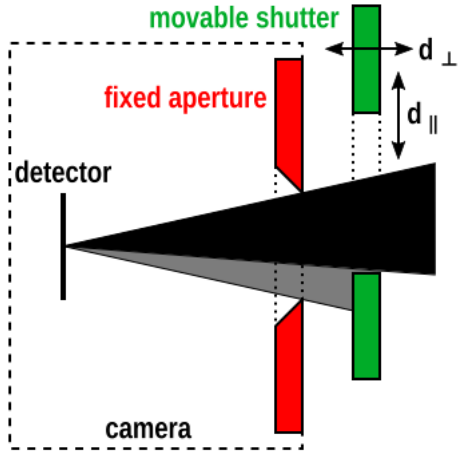


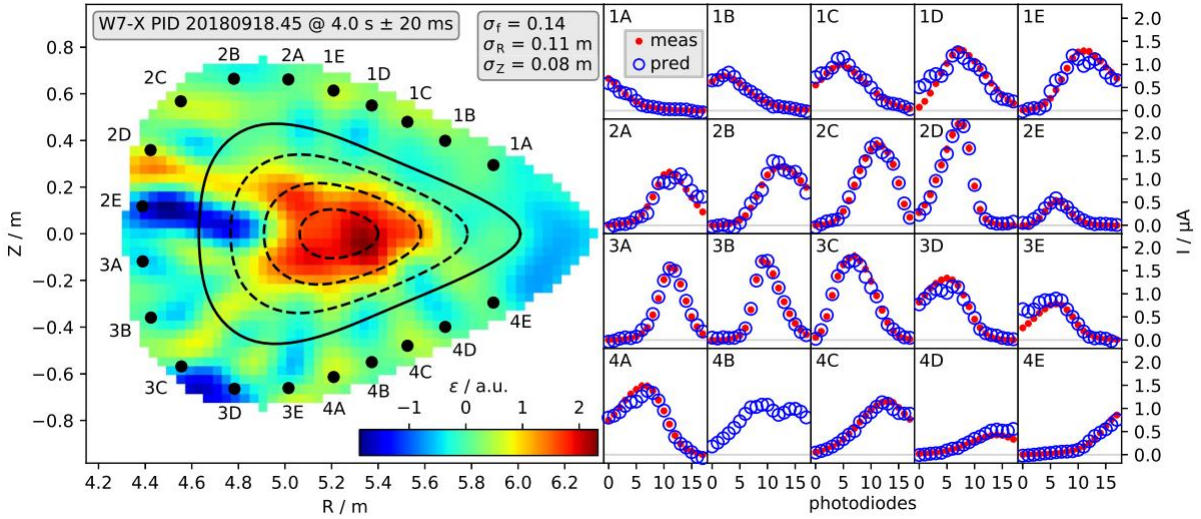
- ***XMCTS:*** 20 cameras with movable shutters
- Weired intensity patterns on XMCTS tomograms
- Several shutters 2E,3C,3D partially closed
- Identification of shutter states and camera calibrations (60 params!) √

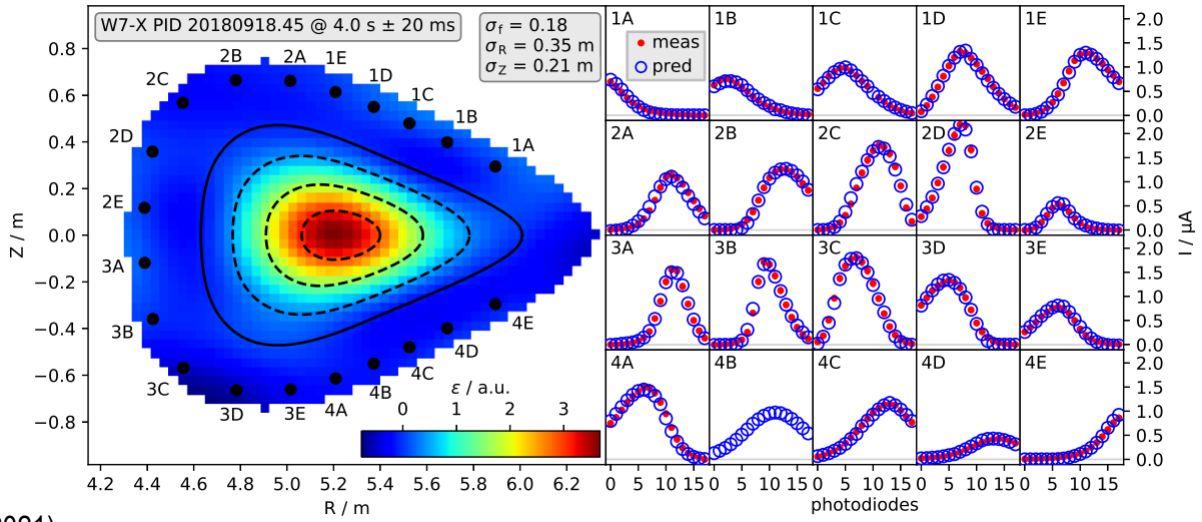
J. Schilling et al. *Plasma Phys. Control. Fusion* **63** (2021)
C. Brandt et al. *Plasma Phys. Control. Fusion* **62** (2020)

Synthetic Diagnostics @ W7-X: *X-ray Tomography*









- ***XMCTS:*** 20 cameras with movable shutters
- Weired intensity patterns on XMCTS tomograms
- Several shutters 2E,3C,3D partially closed

- Identification of shutter states and camera calibrations (60 params!) √
- No unphysical, static patterns in tomograms √

J. Schilling et al. *Plasma Phys. Control. Fusion* **63** (2021)
C. Brandt et al. *Plasma Phys. Control. Fusion* **62** (2020)

Synthetic Diagnostics @ W7-X: *Electron Cyclotron Emission*

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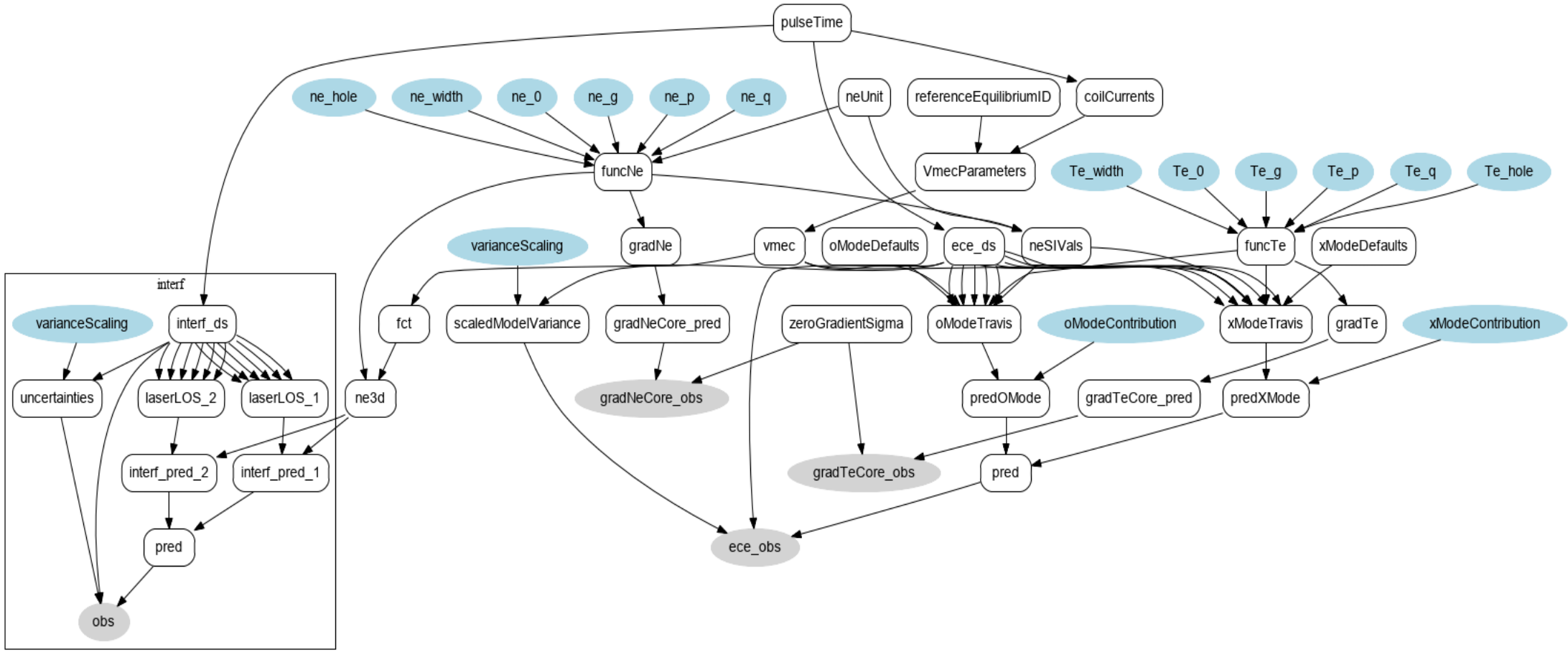
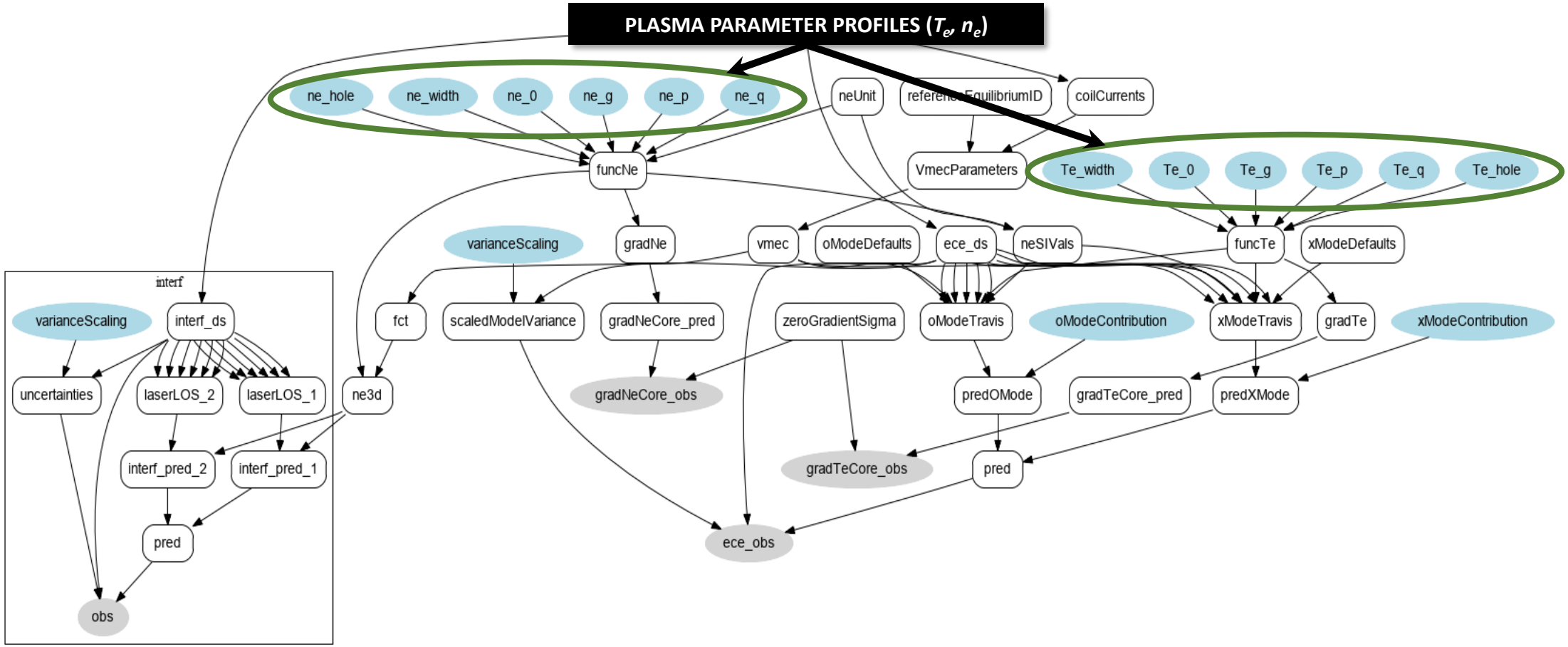


U. Höfel, „*Bayesian Analysis of Electron Cyclotron Emission Measurements at Wendelstein 7-X* “ PhD thesis (2020)

Synthetic Diagnostics @ W7-X: *Electron Cyclotron Emission*



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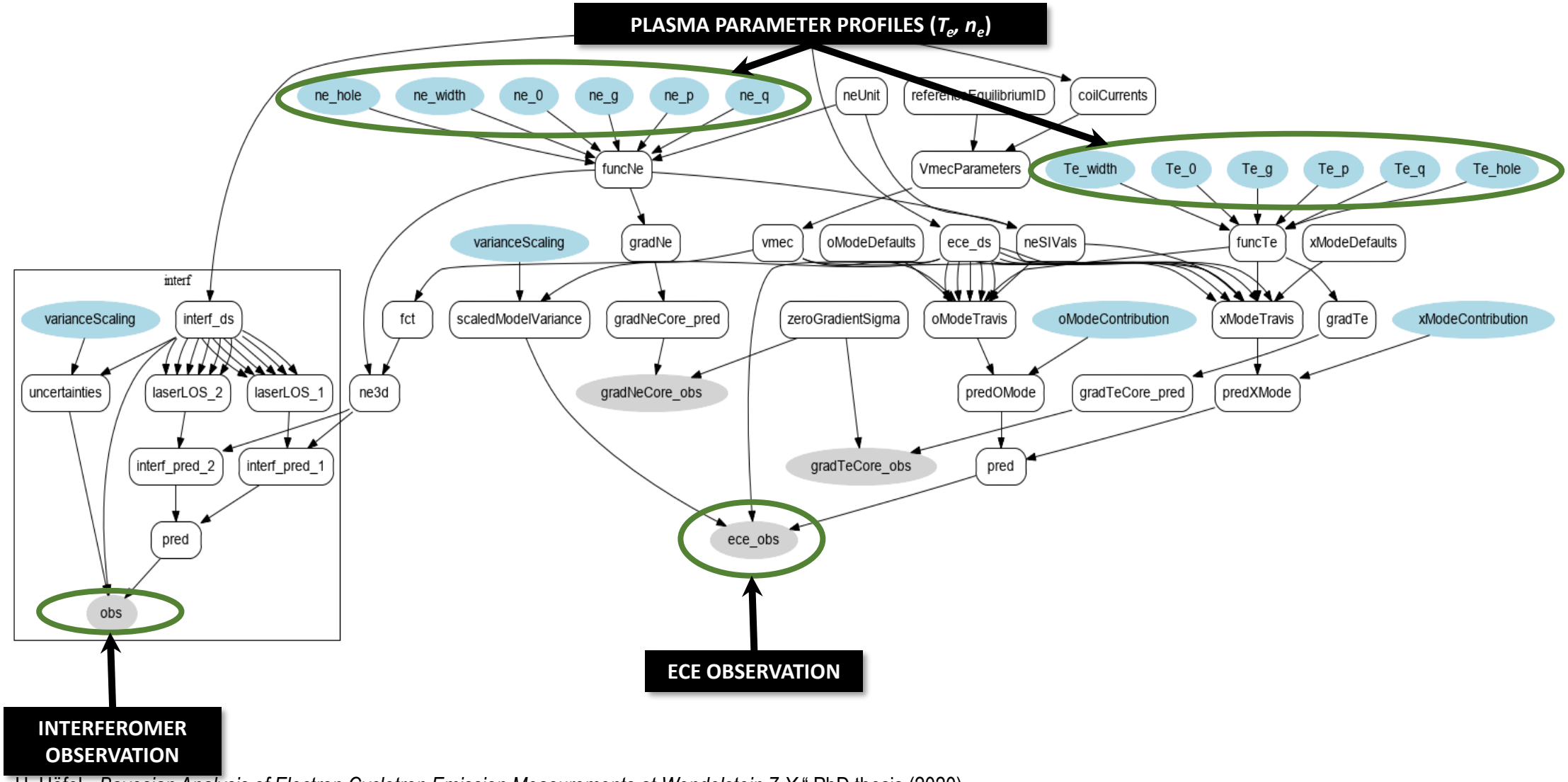
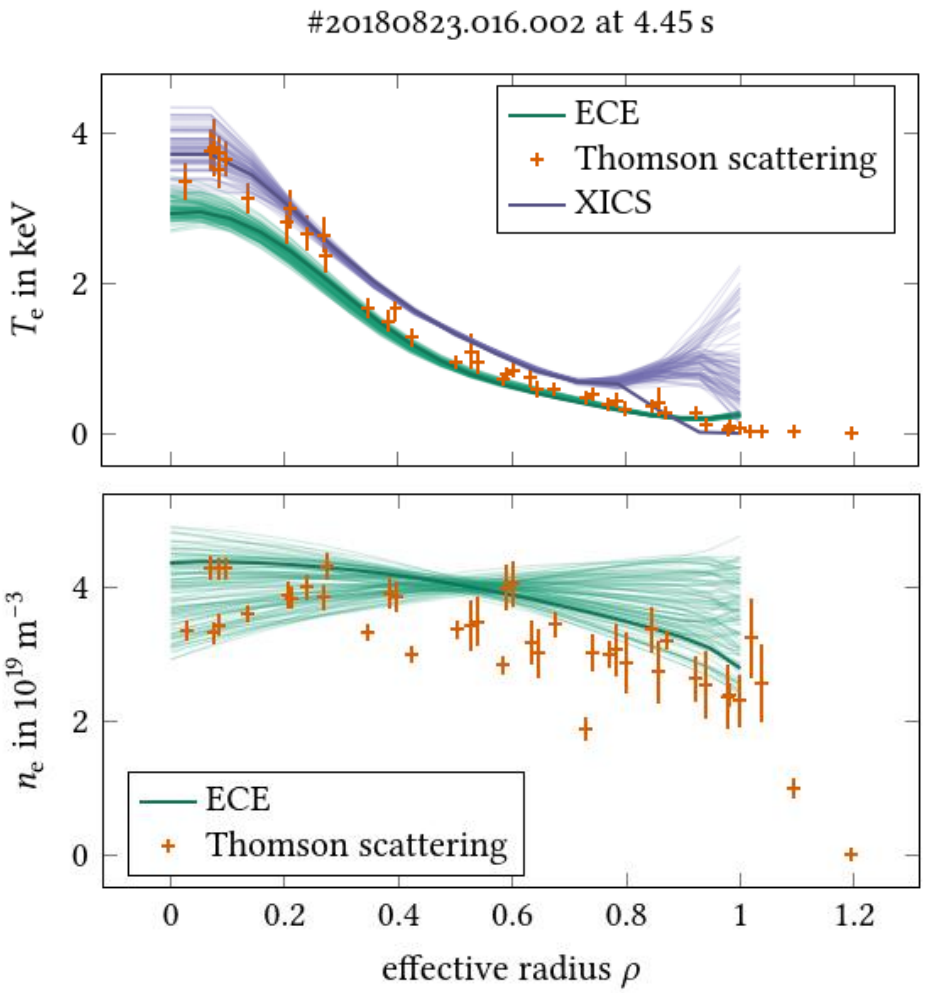


U. Höfel, „*Bayesian Analysis of Electron Cyclotron Emission Measurements at Wendelstein 7-X* “ PhD thesis (2020)

Synthetic Diagnostics @ W7-X: *ECE | T_e and n_e -Profiles*

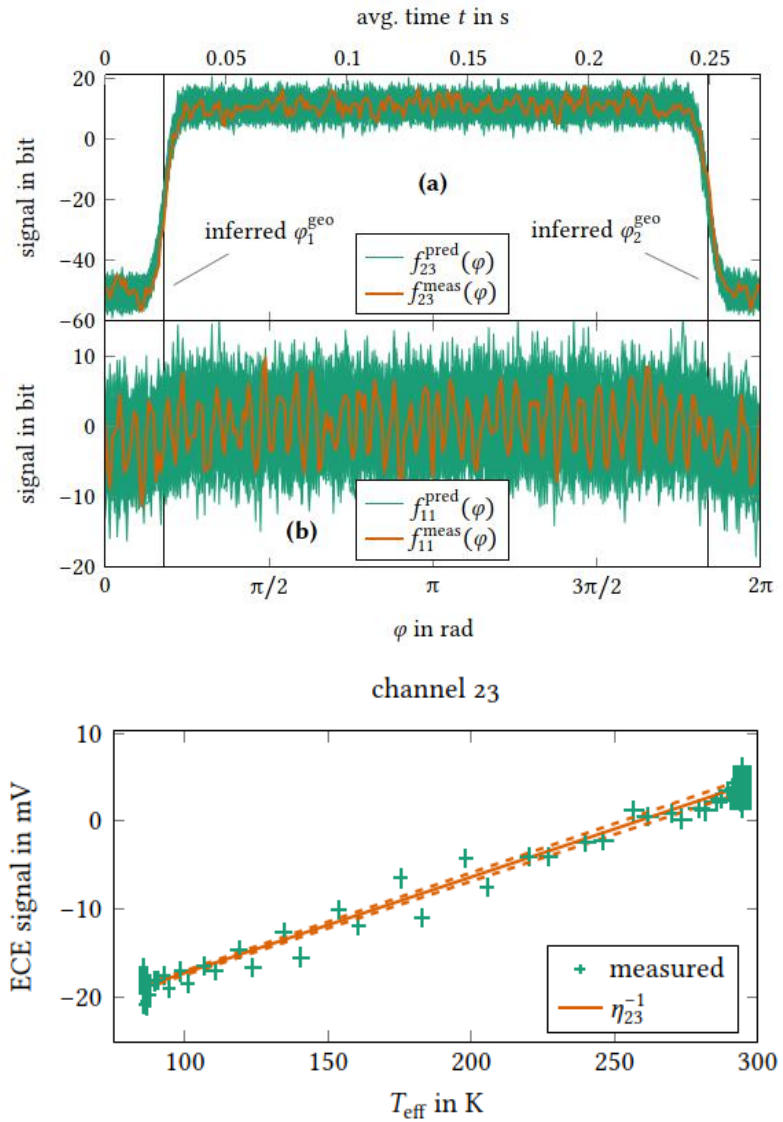


ECE Profiles:

- T_e and n_e profiles match Thomson data within errorbars
- Slight missmatch (~300 eV) between ECE and XICS T_e , under investigation

U. Höfel, „*Bayesian Analysis of Electron Cyclotron Emission Measurements at Wendelstein 7-X* “ PhD thesis (2020)

Synthetic Diagnostics @ W7-X: *ECE | Calibration*



ECE Profiles:

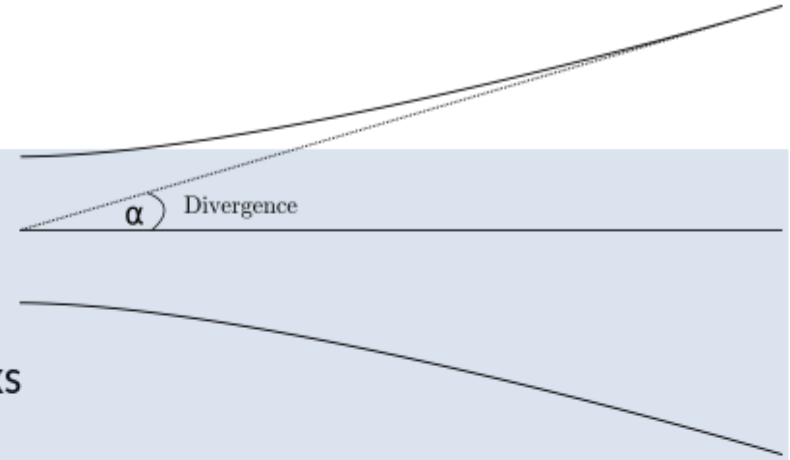
- T_e and n_e profiles match Thomson data within errorbars
- Slight missmatch (~300 eV) between ECE and XICS T_e , under investigation
- Minerva Model for precise temperature calibration including temperature rise/fall phases

U. Höfel, „*Bayesian Analysis of Electron Cyclotron Emission Measurements at Wendelstein 7-X* “ PhD thesis (2020)

Synthetic Diagnostics @ W7-X: *Charge Exchange Spectr.*

Synthetic Diagnostics @ W7-X: *Charge Exchange Spectr.*

Free parameters for optimisation in Minerva model



Beam model:

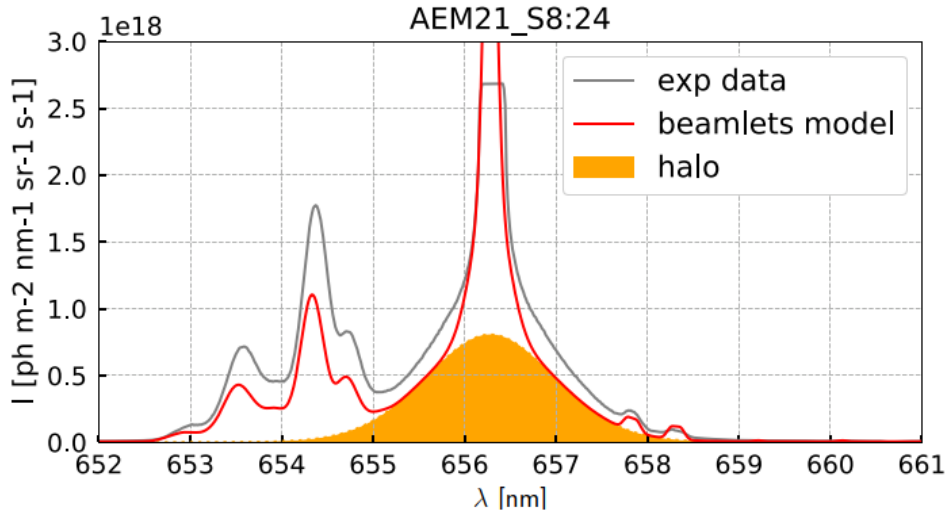
- Beamlet divergence → Beam shape
- Beam component power fractions → Halo emission, BES peaks
- Total beam power → Absolute intensity

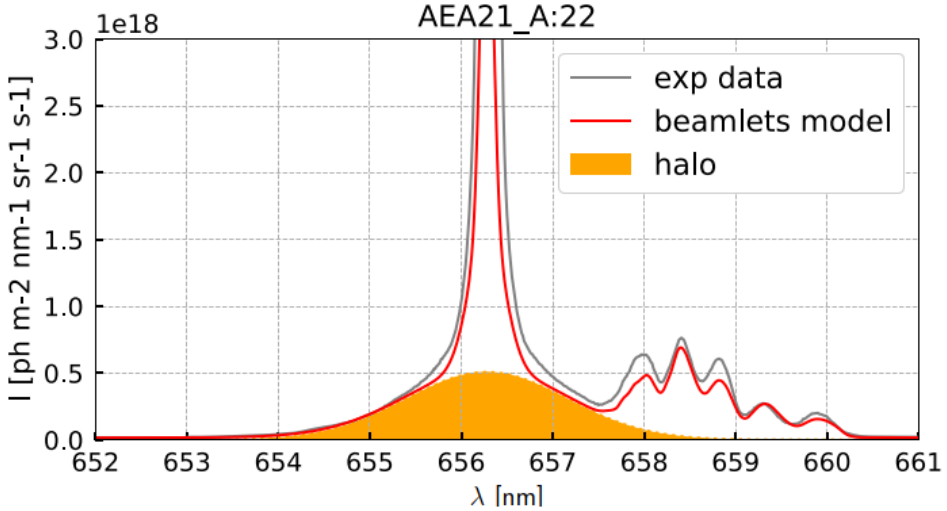
Optical system:

- Head orientation (yaw, pitch, roll) → Moves BES peaks (Doppler shift changes) and changes intensities
- Polariser contrast → Relative weight of sigma to pi ratio of emitted light

Courtesy of Sebastian Bannmann.

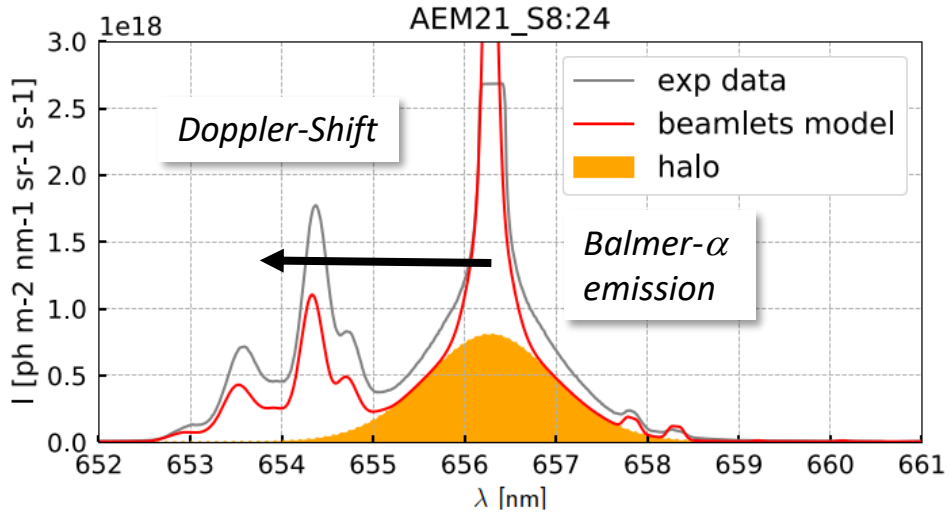
Synthetic Diagnostics @ W7-X: *Charge Exchange Spectr.*

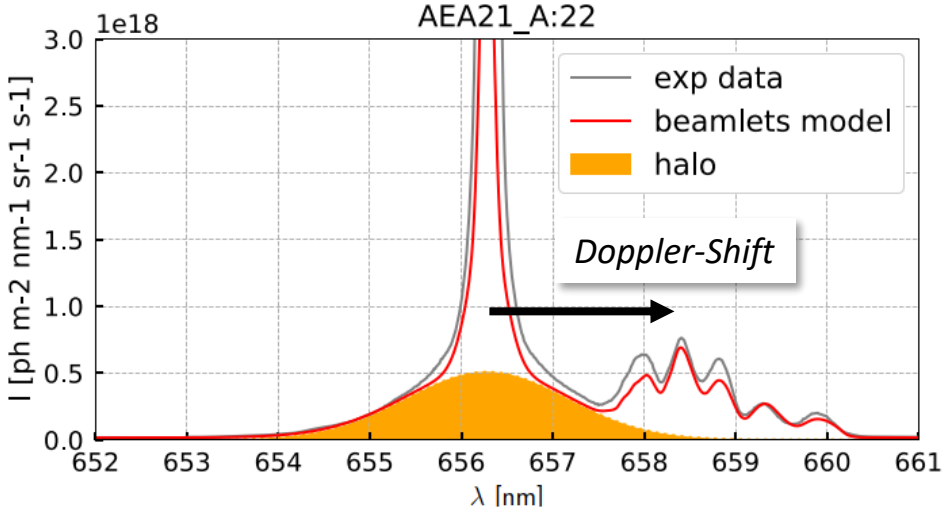




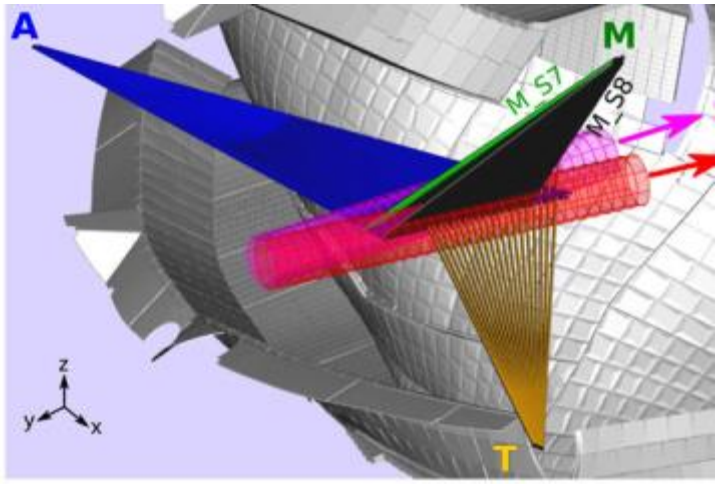
Courtesy of Sebastian Bannmann.

Synthetic Diagnostics @ W7-X: *Charge Exchange Spectr.*



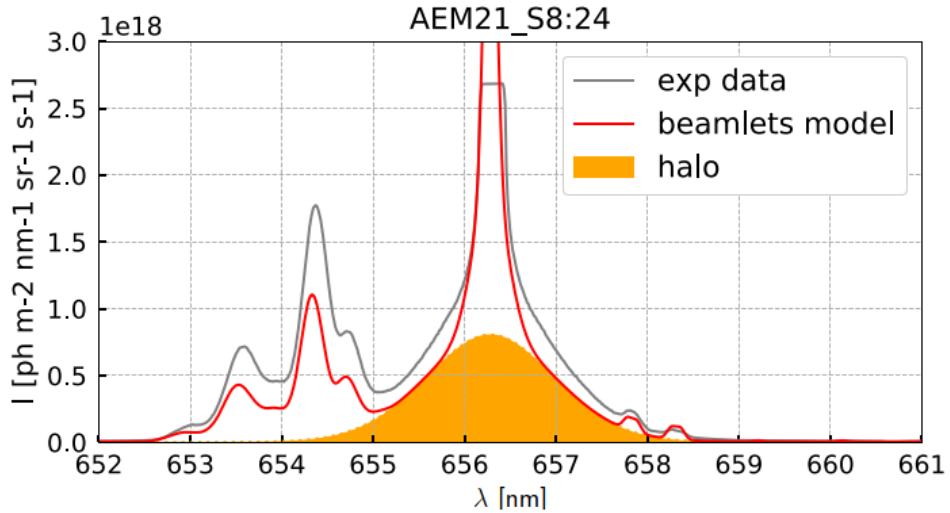


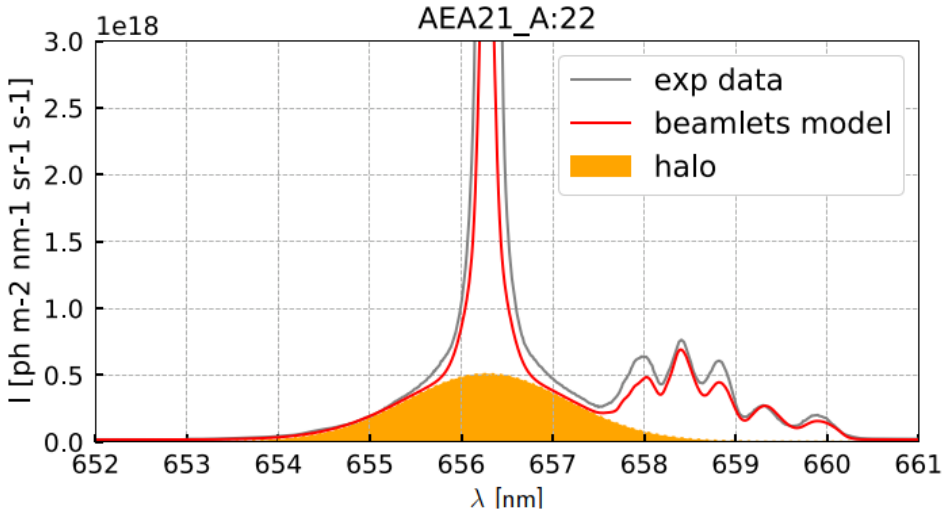
CXRS Observation Ports: ***A,M****,T*



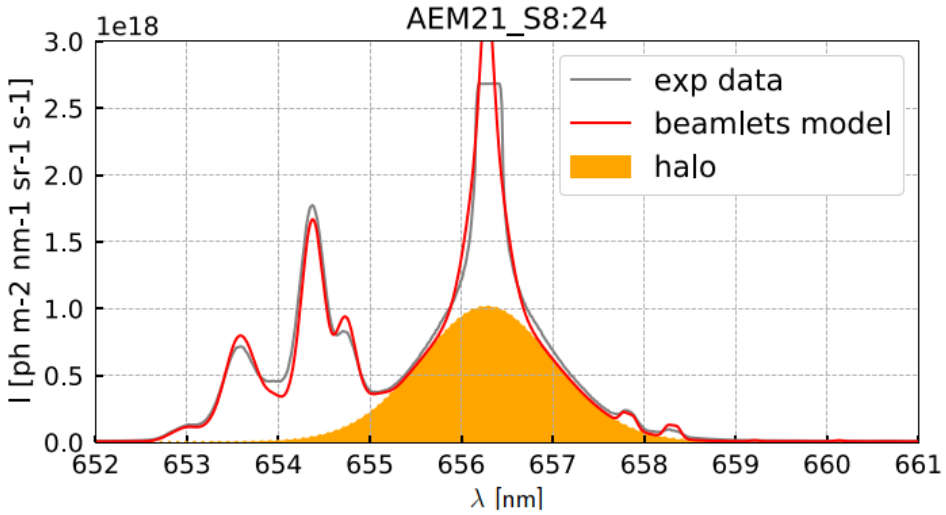
Courtesy of Sebastian Bannmann.

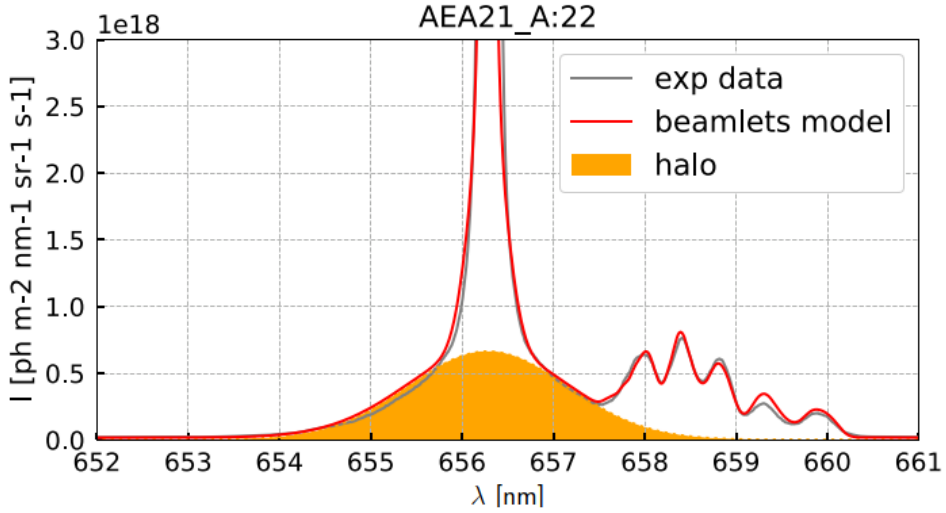
Synthetic Diagnostics @ W7-X: *Charge Exchange Spectr.*





First try MAP inversion





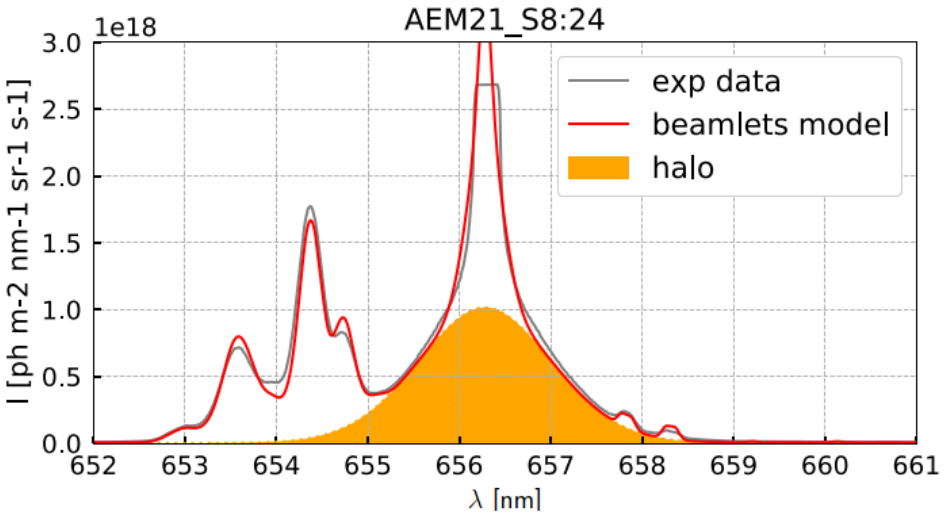
Courtesy of Sebastian Bannmann.

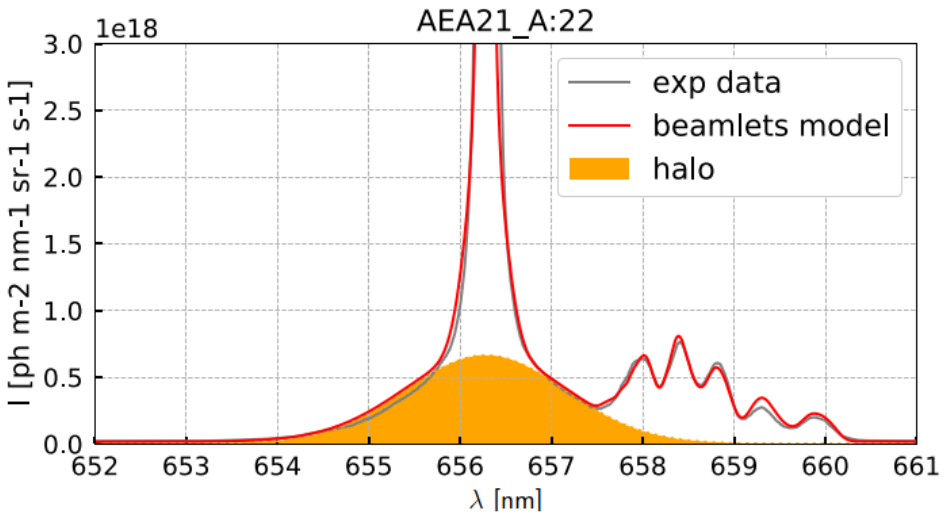
Synthetic Diagnostics @ W7-X: *Charge Exchange Spectr.*

CXRS Sensitivity Study:

- Minerva model including neutral beam and optics parameters
- Variation of model parameters shows convergency with good match of modeled / measured data

First try MAP inversion





Courtesy of Sebastian Bannmann.

Summary and Outlook

Diagnostic	***Inferred Plasma- and Diagnostics-Parameters***	***Cross Validation*** ***Minerva*** */ alternative Analysis*	***# Joint Observ.***
Imaging Spectrometers	▪ T_i, T_e, n_Z *profiles* ▪ *Defocusing error*	***Synthetic data validation*** T_e ***(XICS)*** *vs.* T_e *(Thomson)* T_i ***(XICS)*** *vs.* T_i ***(HR-XIS)*** n_Z***(XICS)*** *vs.* n_Z*(CXRS)*	***1***
Thomson Scattering, Interferometer, He-beam	▪ *Combined* T_e */* n_e *profile analysis* ▪ *Scaling of Thomson* n_e *profiles*	T_e *and* n_e ***(Thomson)*** *vs.* ***He-Beam***	***3***
X-ray Tomography	▪ 2D X-ray Emissivity of impurities ▪ Scaling / Vignetting of camera views	***Synthetic data validation***	***1***
Electron Cyclotron Emission	▪ T_e, n_e *profiles* ▪ *Hot-cold calibration*	T_e ***(ECE)*** *vs.* T_e *(Thomson + XICS)* n_e ***(ECE)*** *vs.* n_e *(Thomson)*	***2***
Charge Exchange	▪ *Predictions / Observations matching*	*To be done.*	***2***

Summary and Outlook

Computation time of large and complex models

e.g. ***XICS Profile inference:*** 20 min MAP inference, 3.5 h for MCMC sampling

- 10x faster after simple parallelization
- $1x10^6$ faster using artificial neural networks (ANN)

Acknowledgements

Minerva Modelling Framework:
Jakob Svensson

XICS / HR-XIS:
Andrea Pavone
Oleksandr Marchuk

Thomson:
Sehyun Kwak
Sergey Bozhenkov
Golo Fuchert

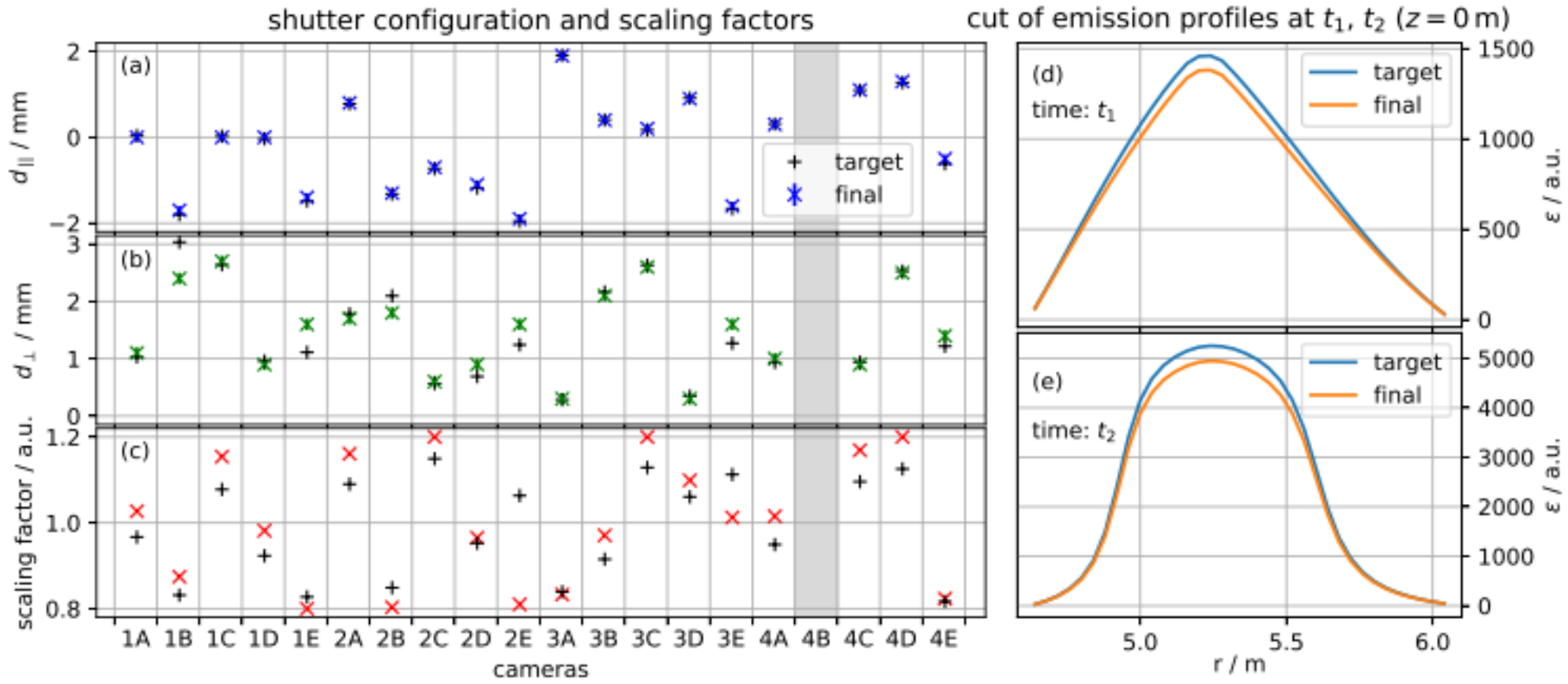
XMCTS:
J. Schilling
C. Brandt
H. Thomsen

ECE:
U. Höfel
M. Hirsch

CXRS:
Oliver Ford
Sebastian Bannmann
Lila Vano

Backup Slides

Synthetic Diagnostics @ W7-X: *X-ray Tomography*



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Backup Slides

ToDo‘s

- Ti validation for XICS vs. CXRS in backups
- XICS+HR-XIS Model: switch from XICS to HR-XIS using new los nodes