Bayesian Analysis Results from JET: Thomson Scattering and Equilibrium

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3: UKAEA Fusion Association, Culham Science Centre, OX14 3DB, UK

* See the Appendix of F. Romanelli et al., Fusion Energy Conference 2008 (Proc. 22nd Int. FEC Geneva) IAEA

Forward Modelling and Bayesian Inference

The basic idea:

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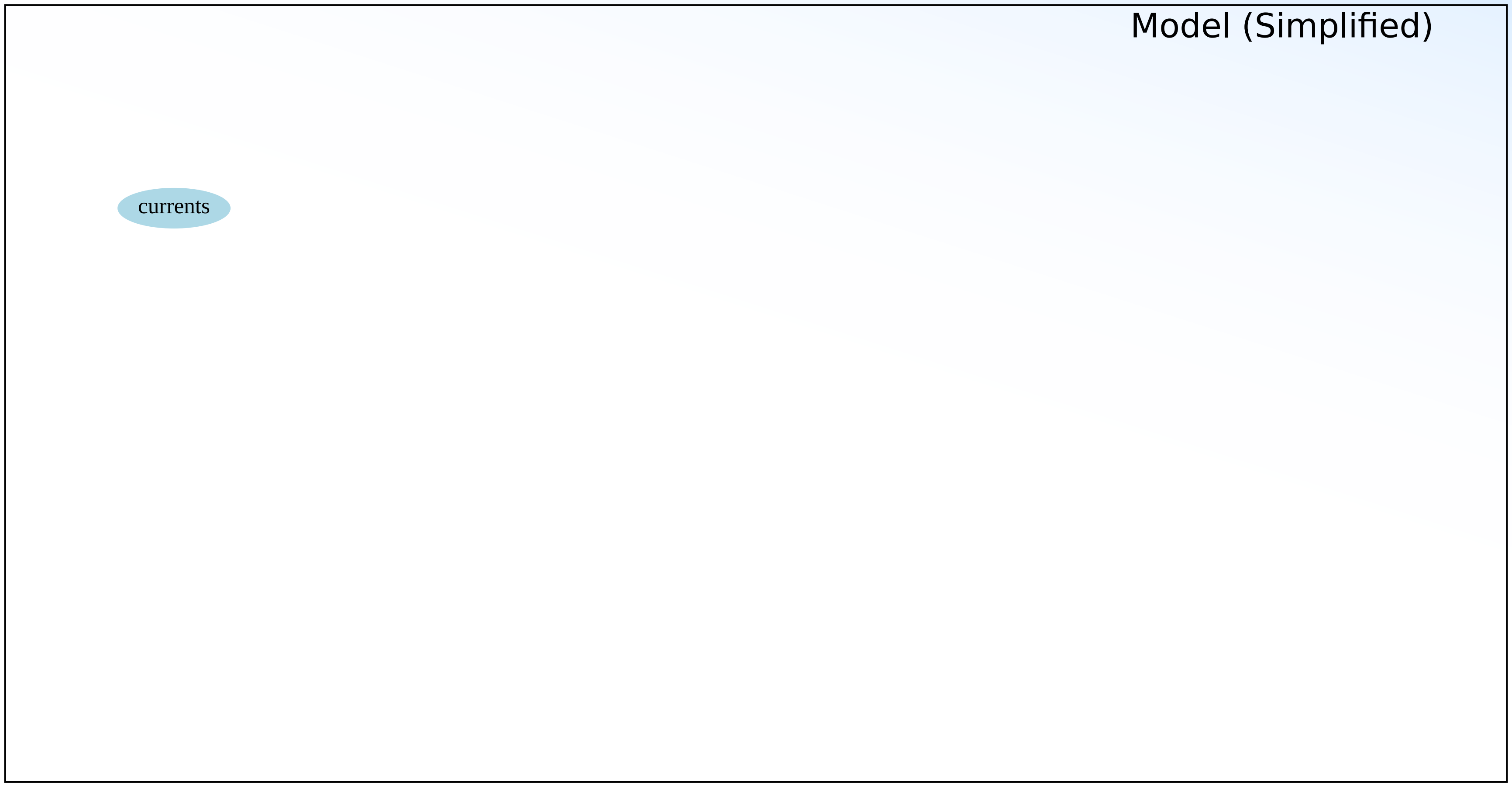
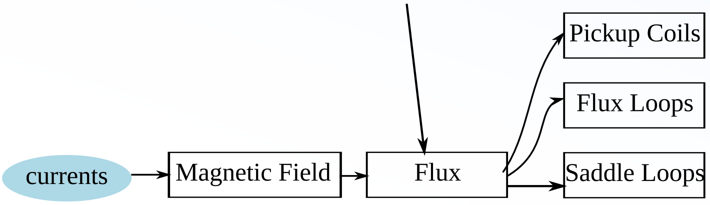


Forward Modelling and Bayesian Inference

The basic idea:

Separate/Modular code for each operation

Model (Simplified)



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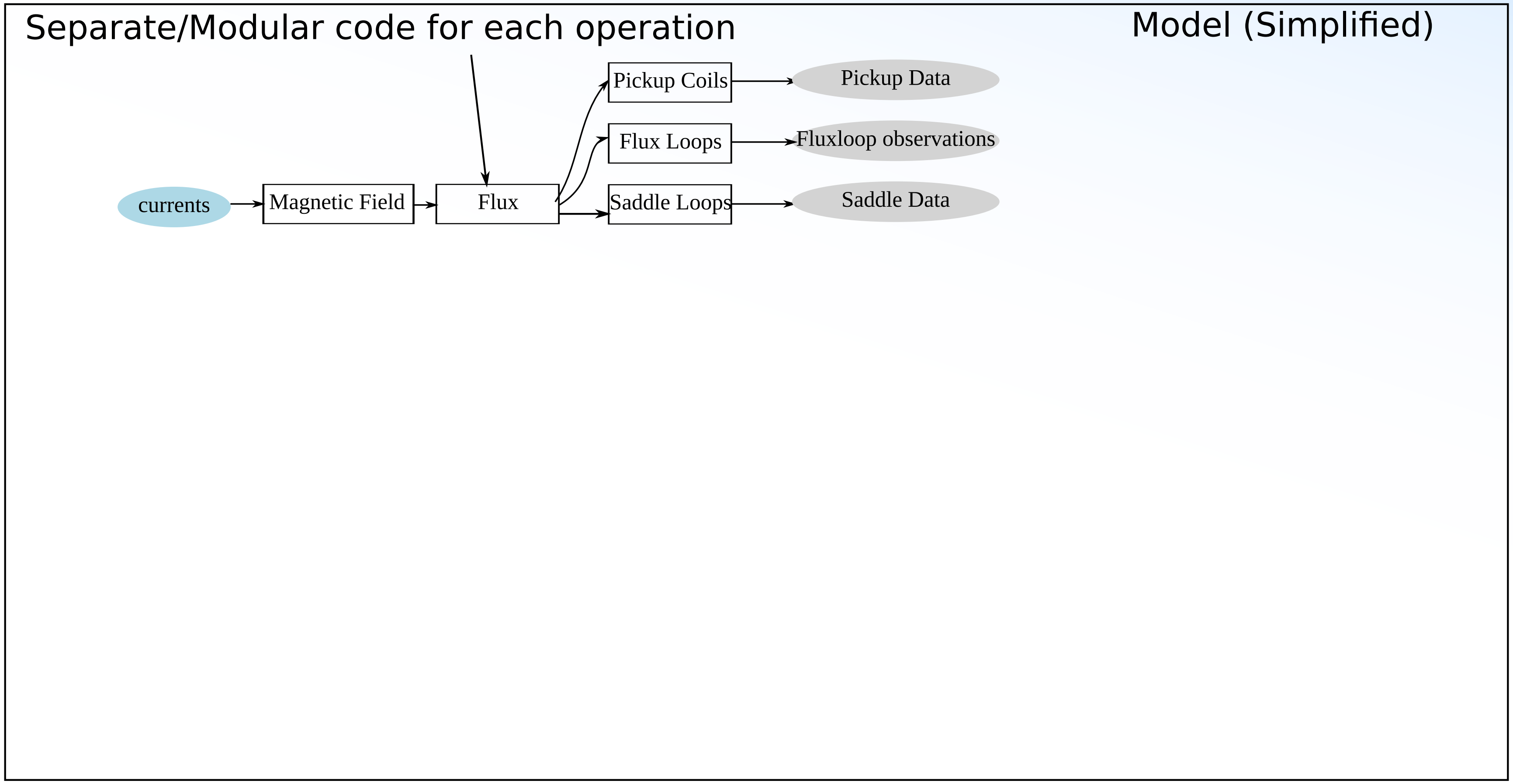

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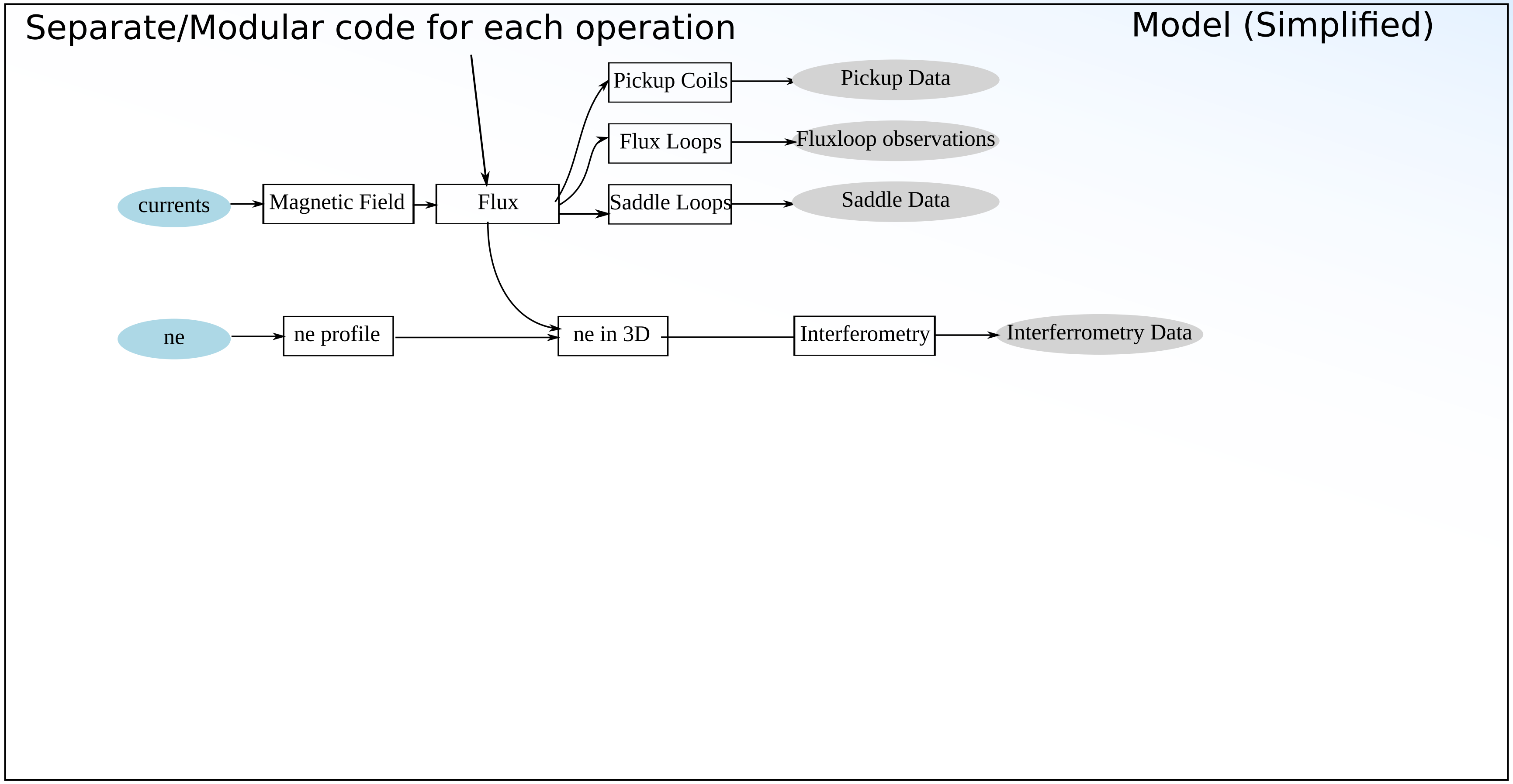

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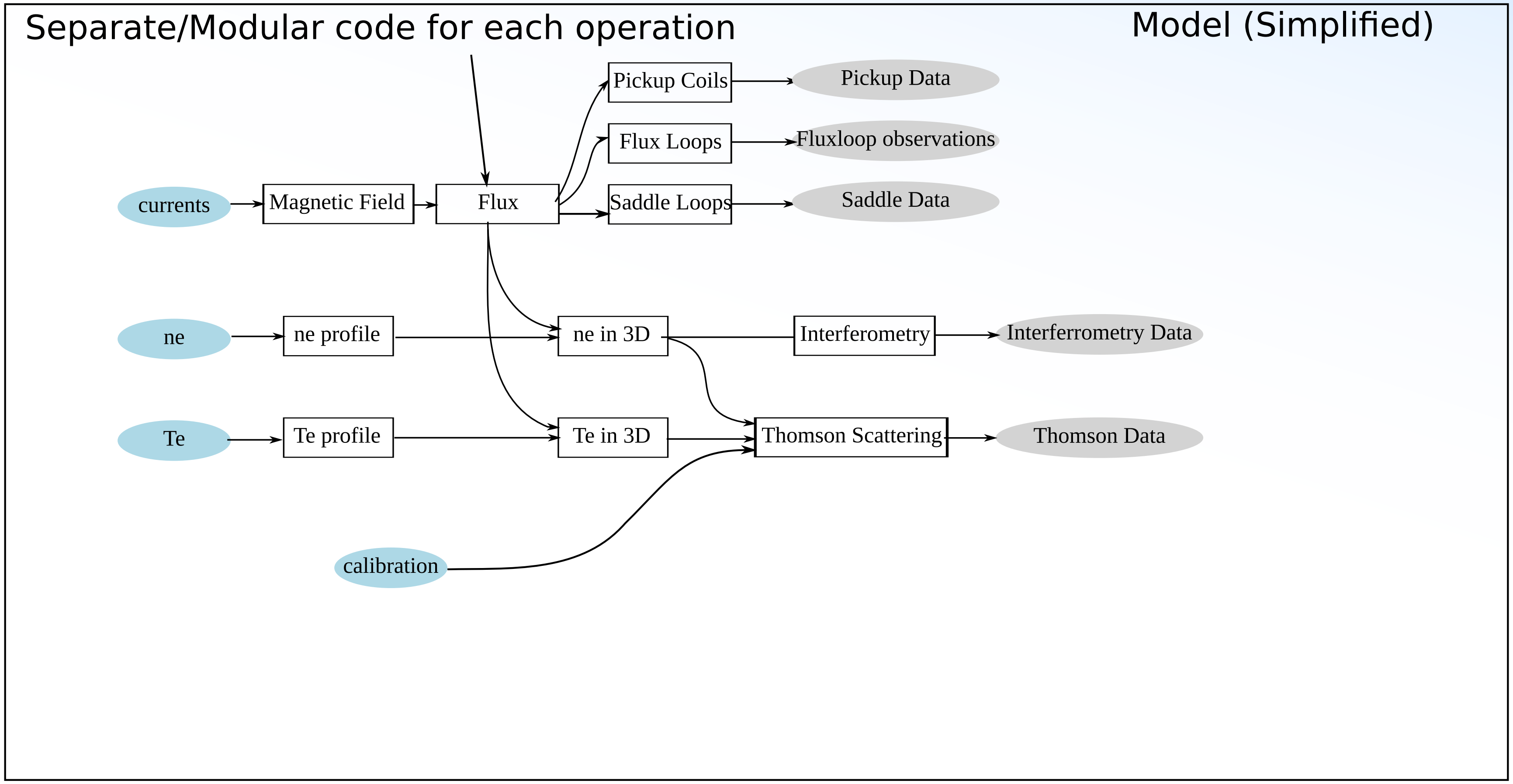

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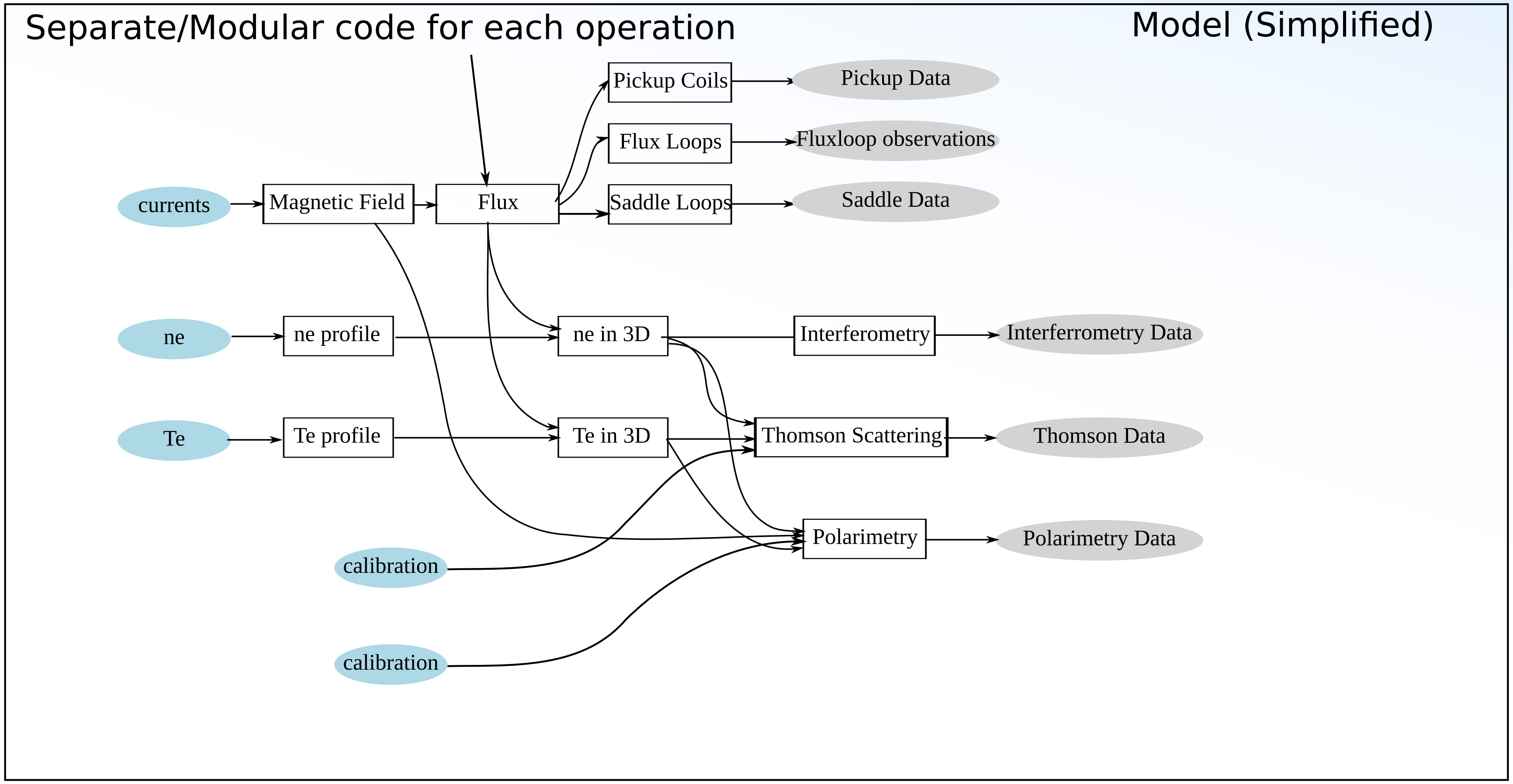

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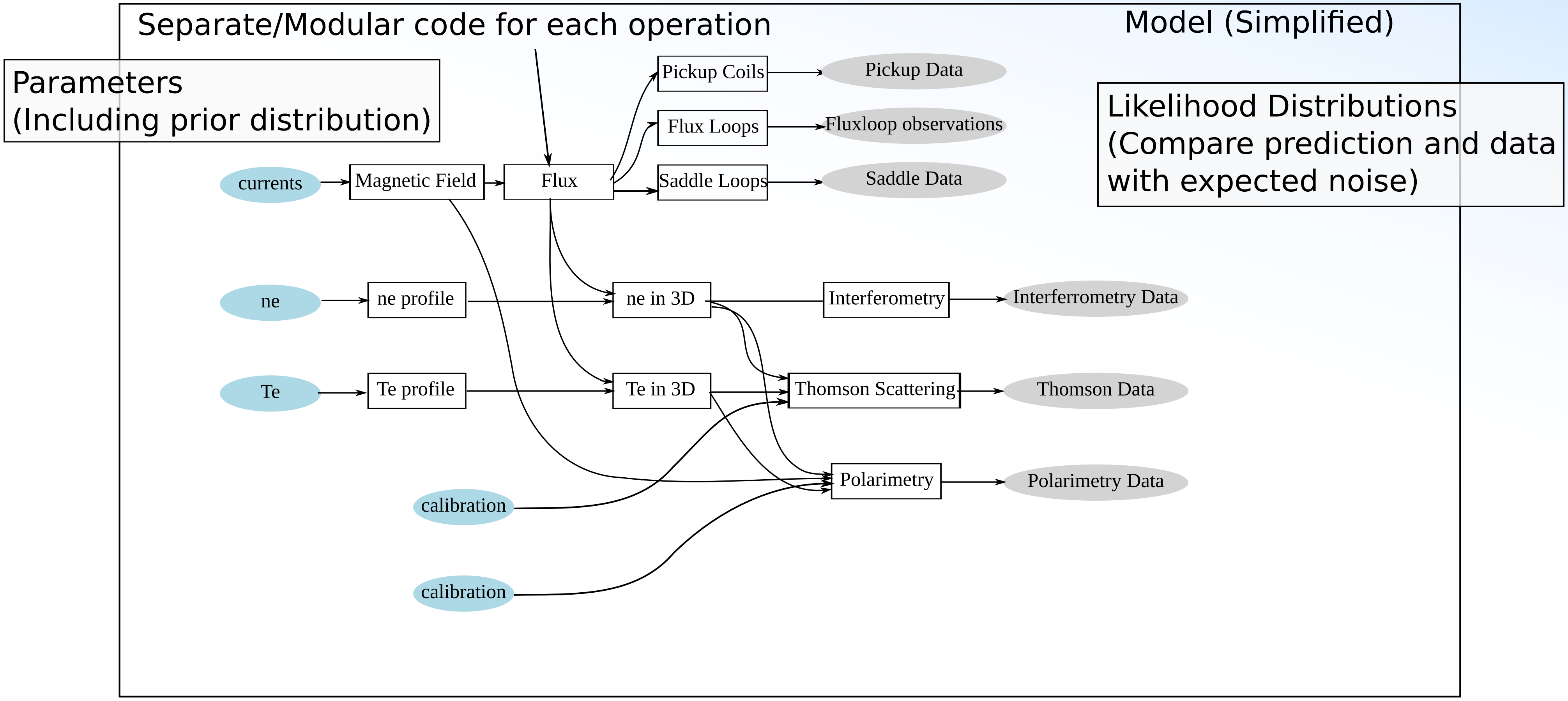

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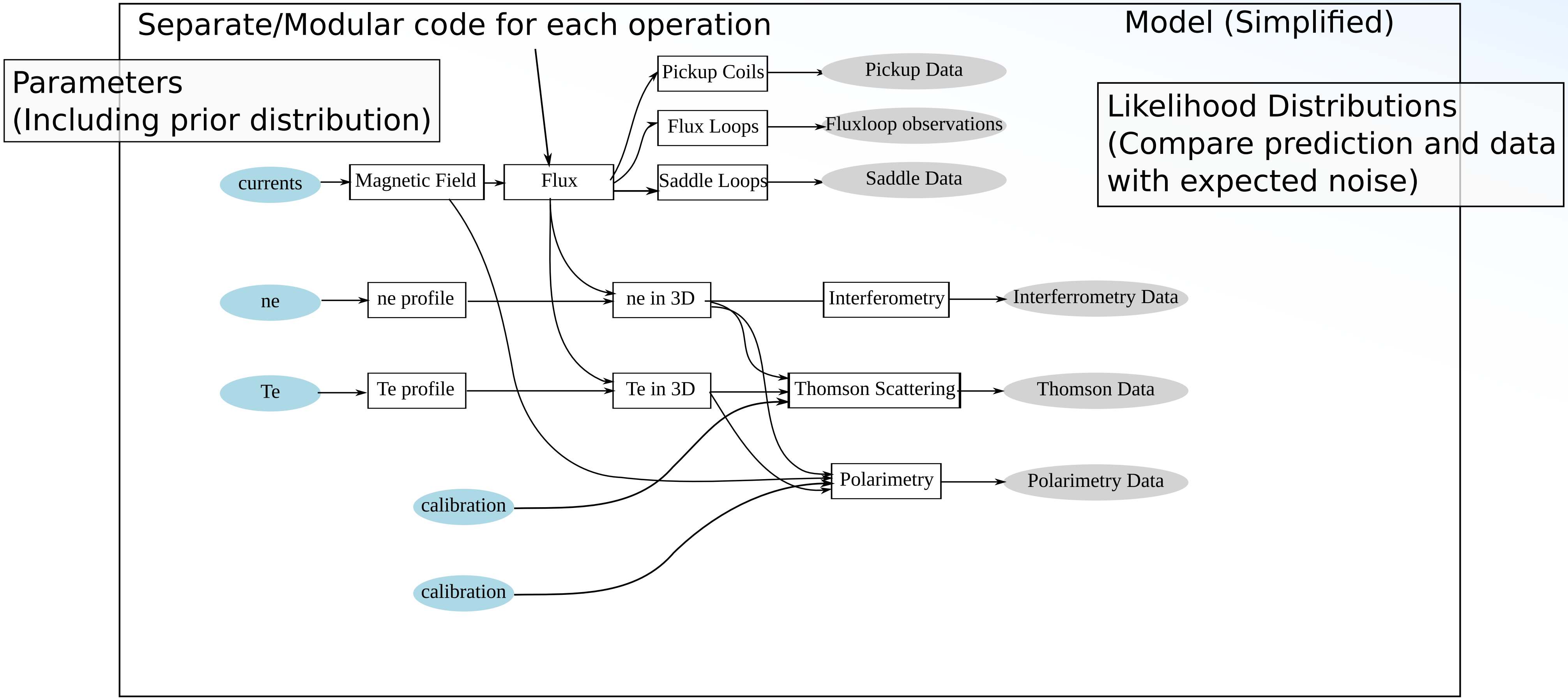

Bayes Theorem: $P(\,Te, Ne, J \mid Data\,) \sim \; P(\,D \mid Ne, Te, J\,)\; P(\,Te, Ne, J)$

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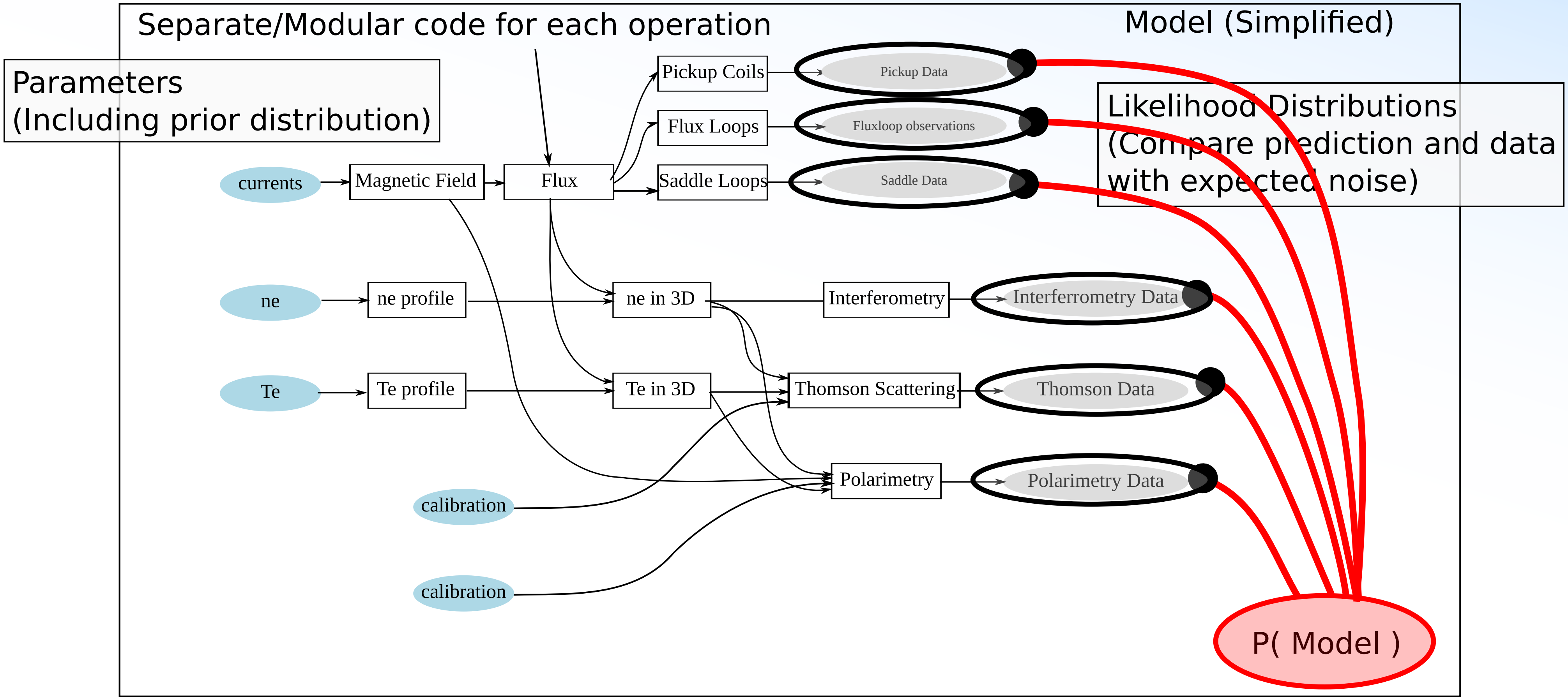

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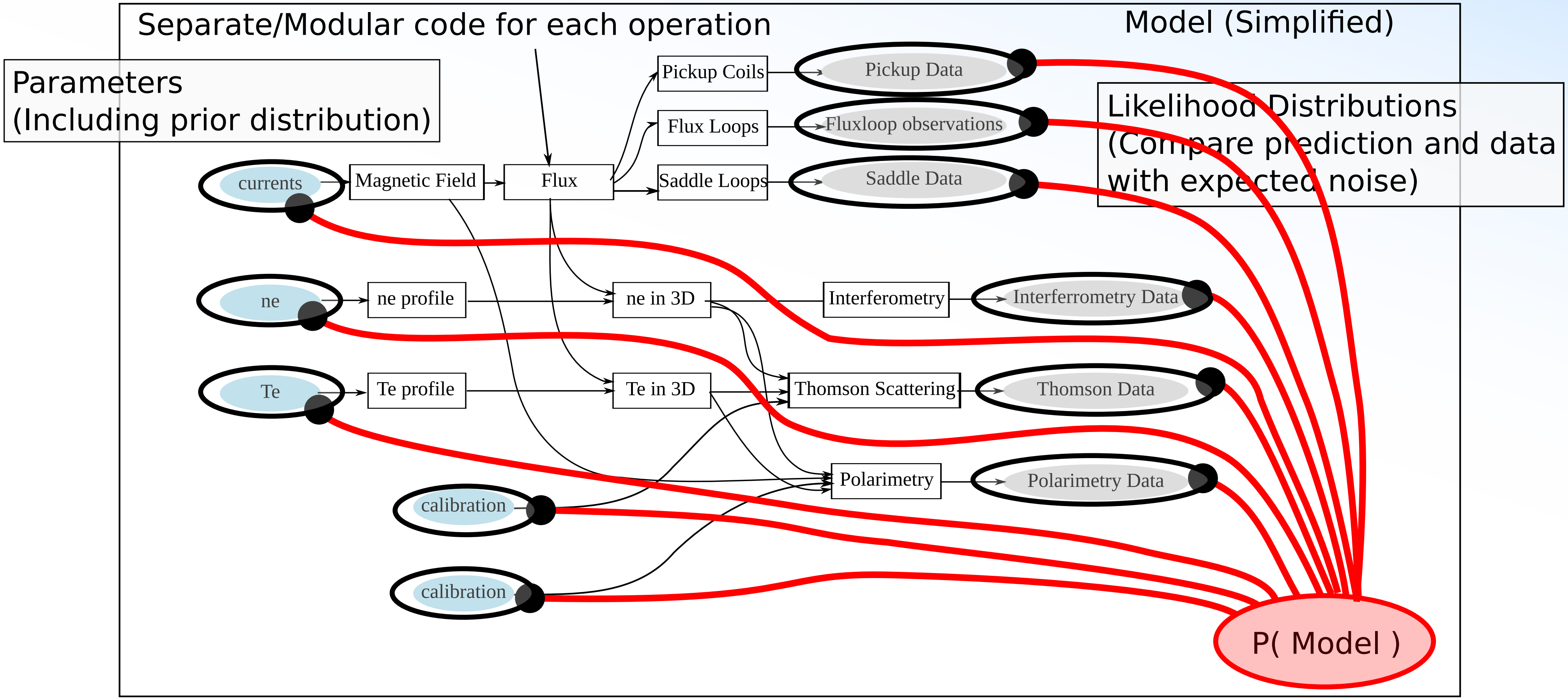

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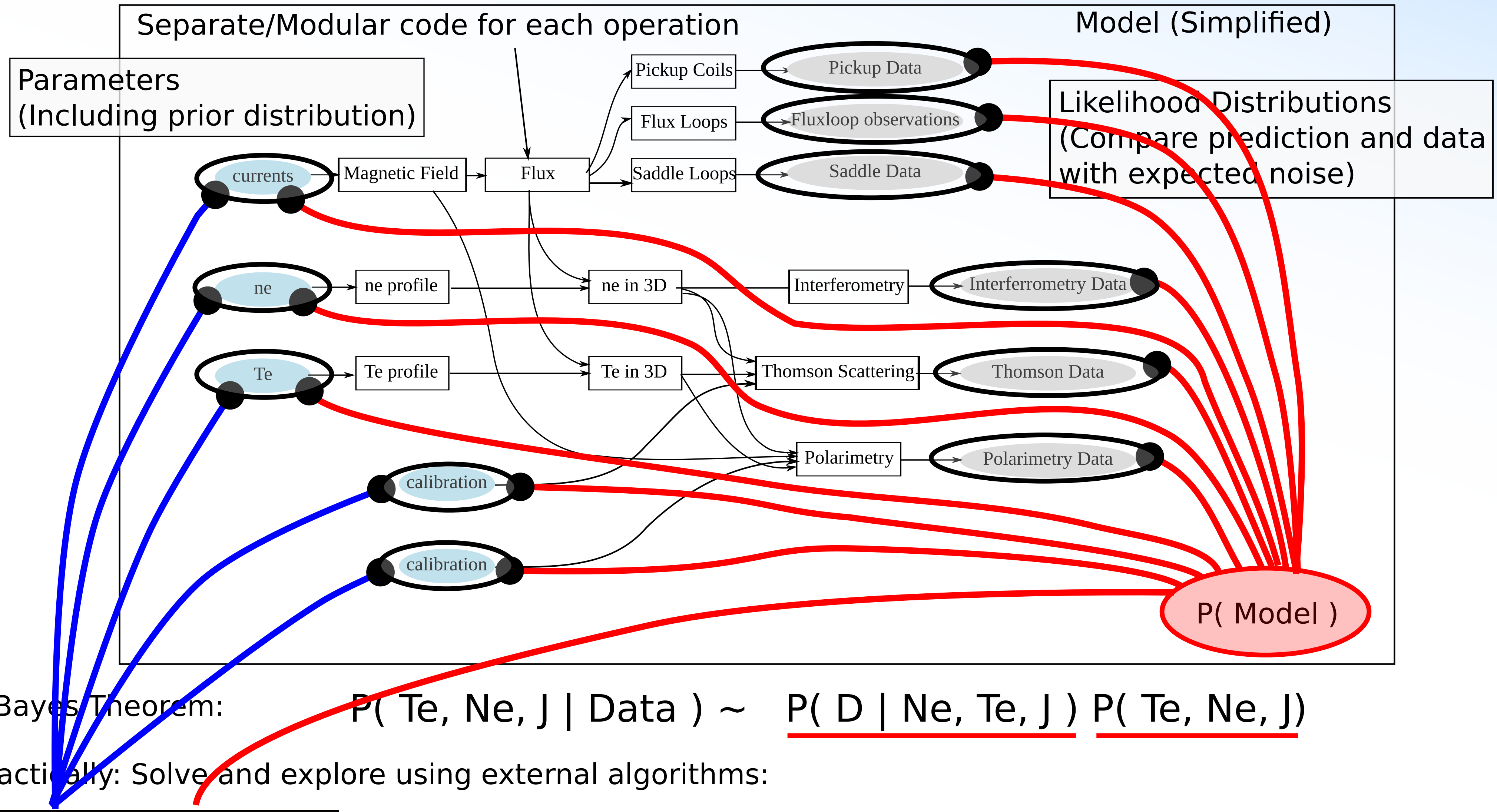

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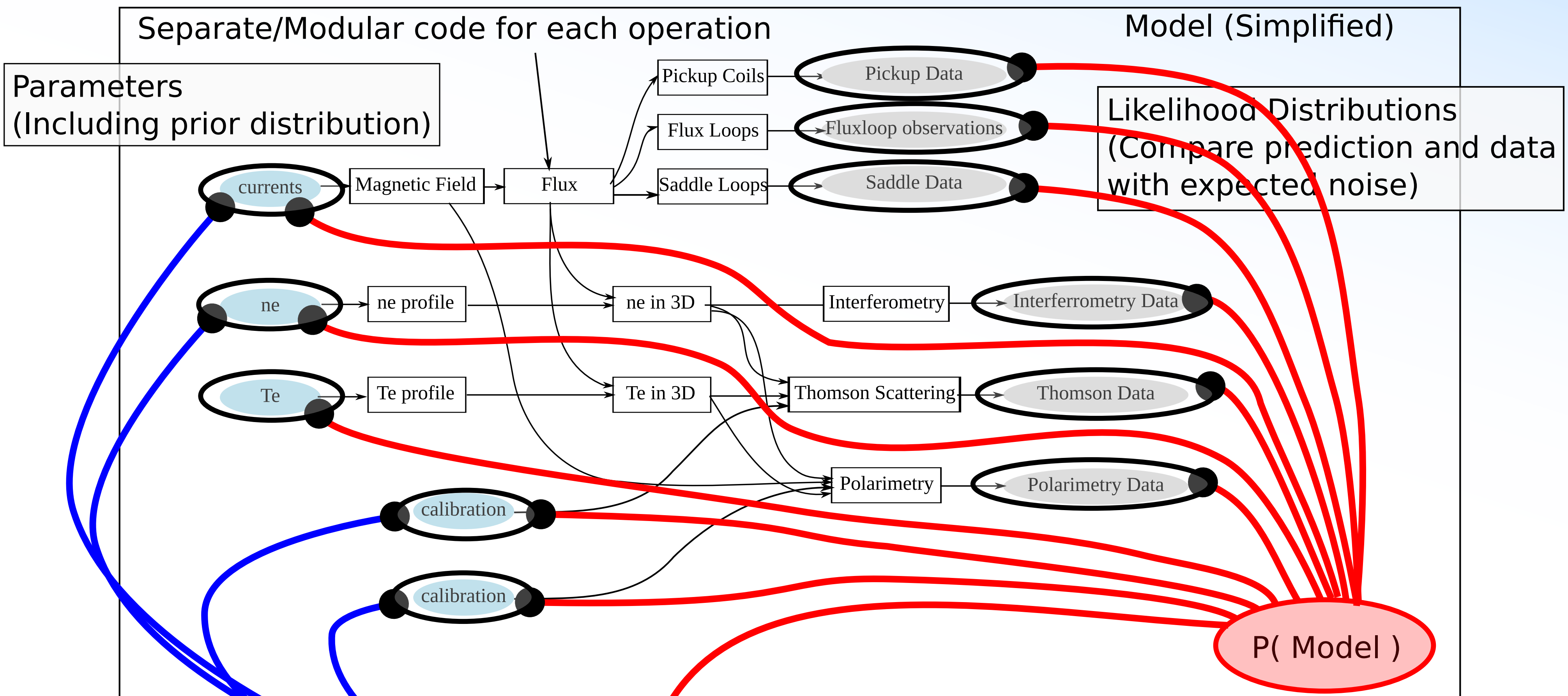

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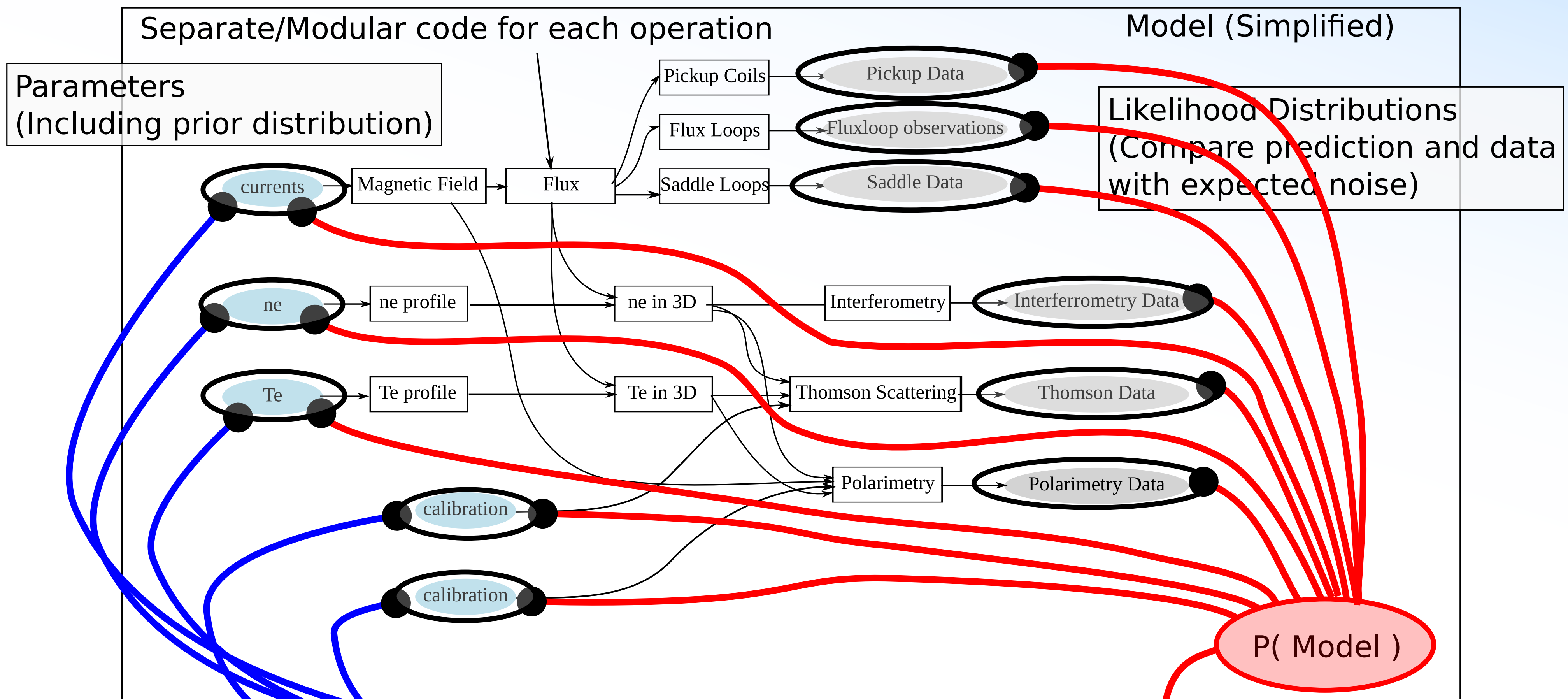

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Genetic Algorithms
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Metropolis Hastings
MCMC Non-linear Exploration:
--> Uncertainty

Software and Models

Write nodes and wire them together.
Software framework handles the rest.

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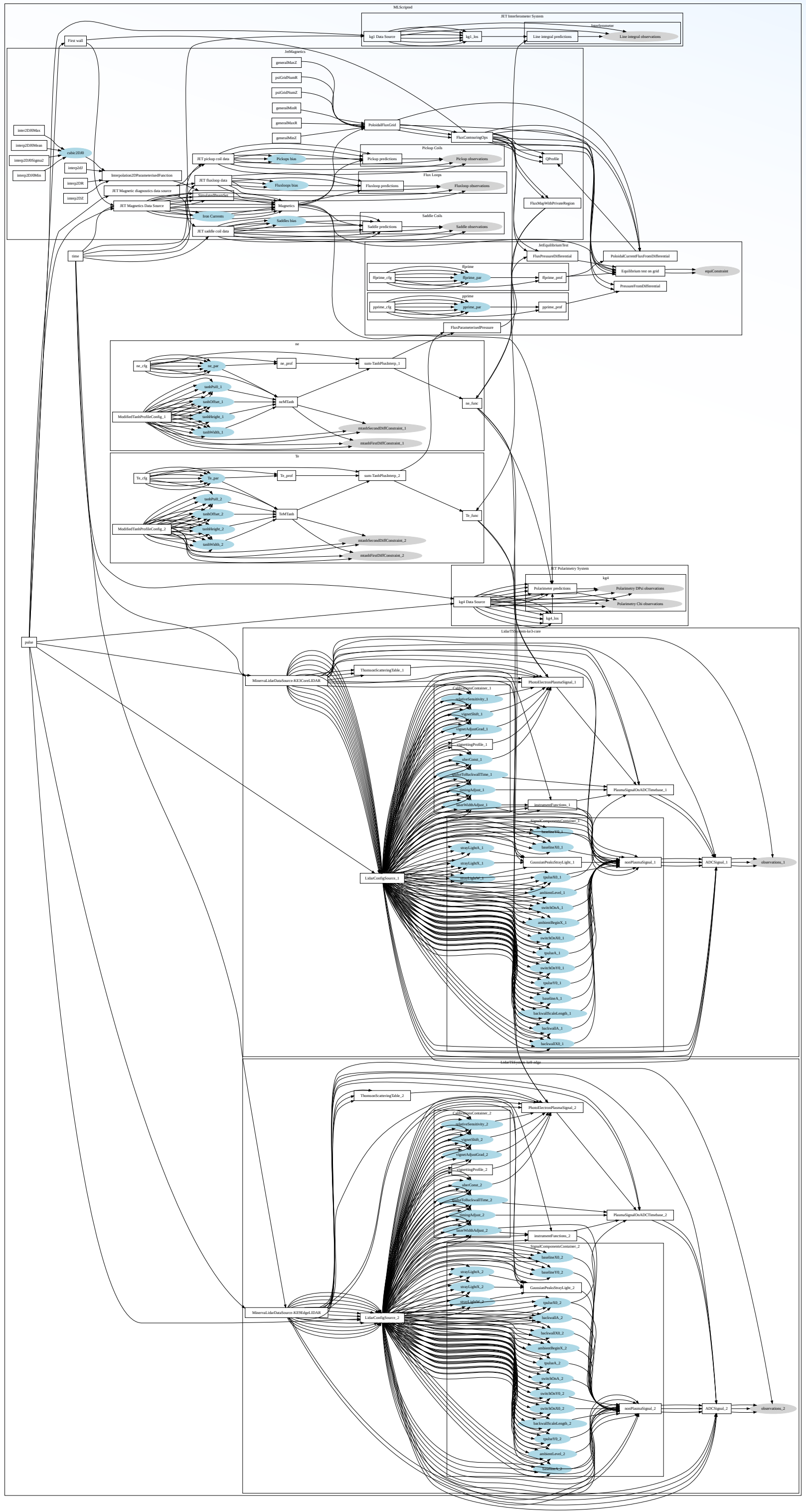

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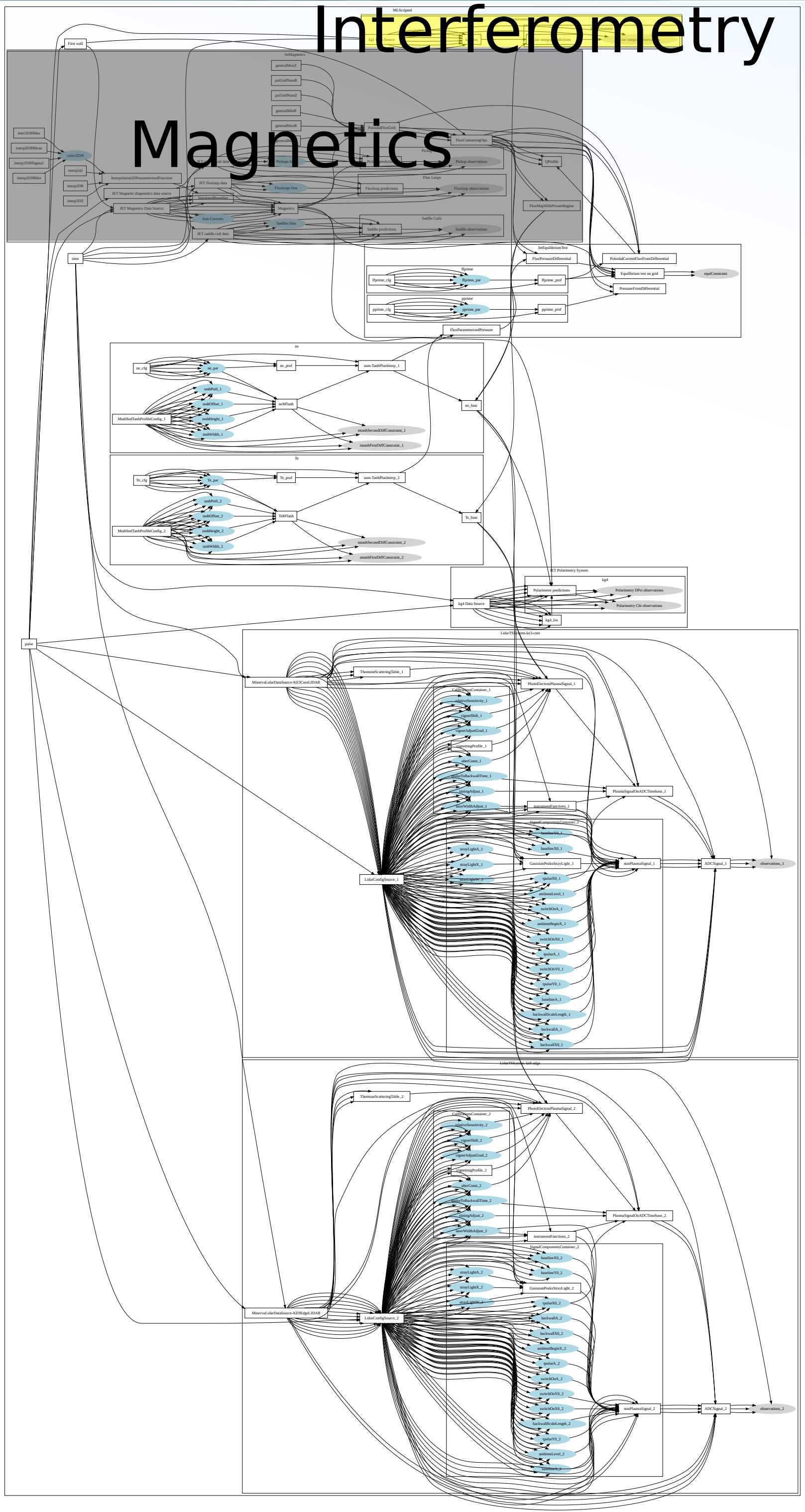

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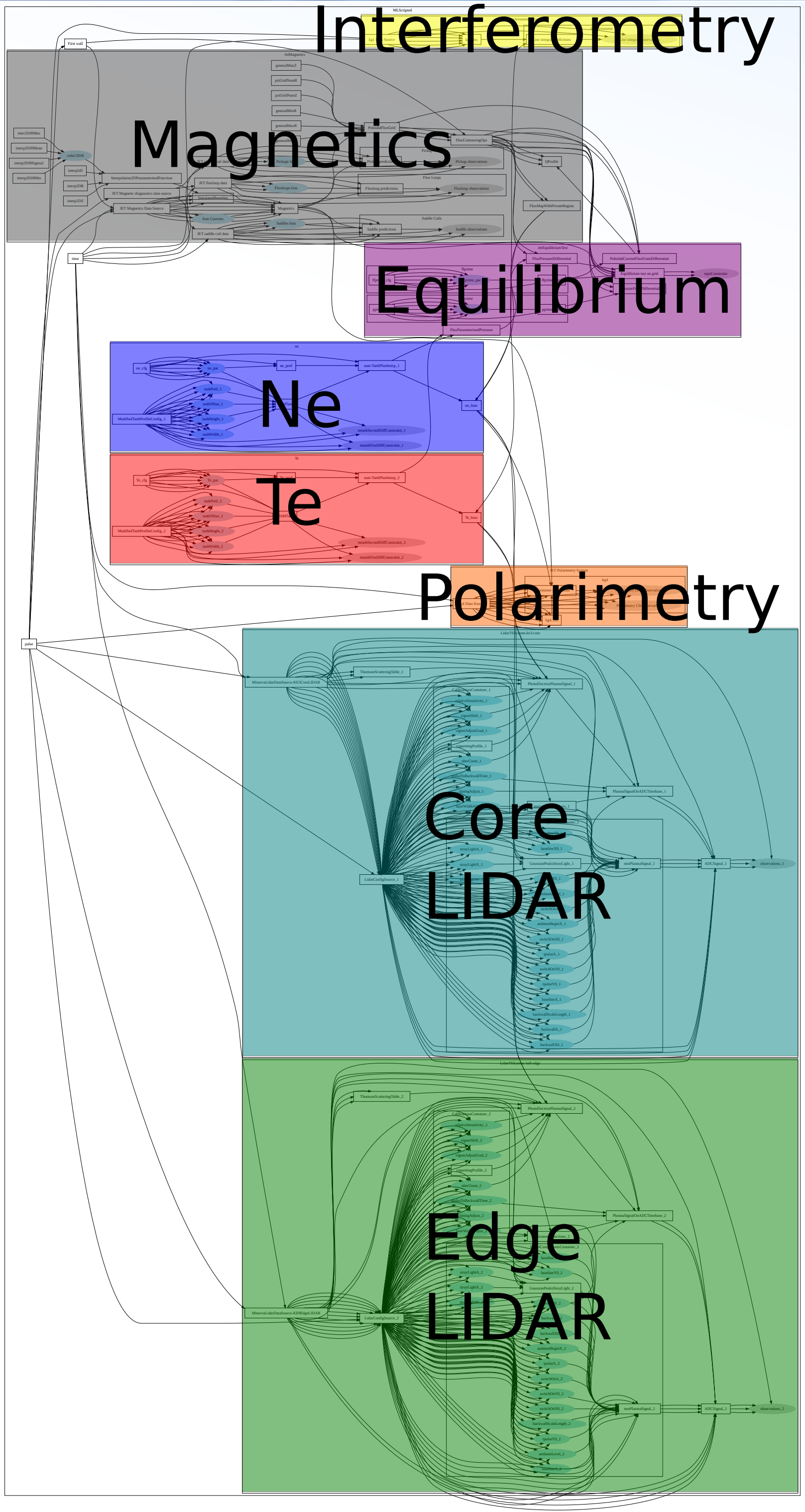

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- Equilibrium (Grad-Shafranov Test)
- Various Ne/Te profile models.
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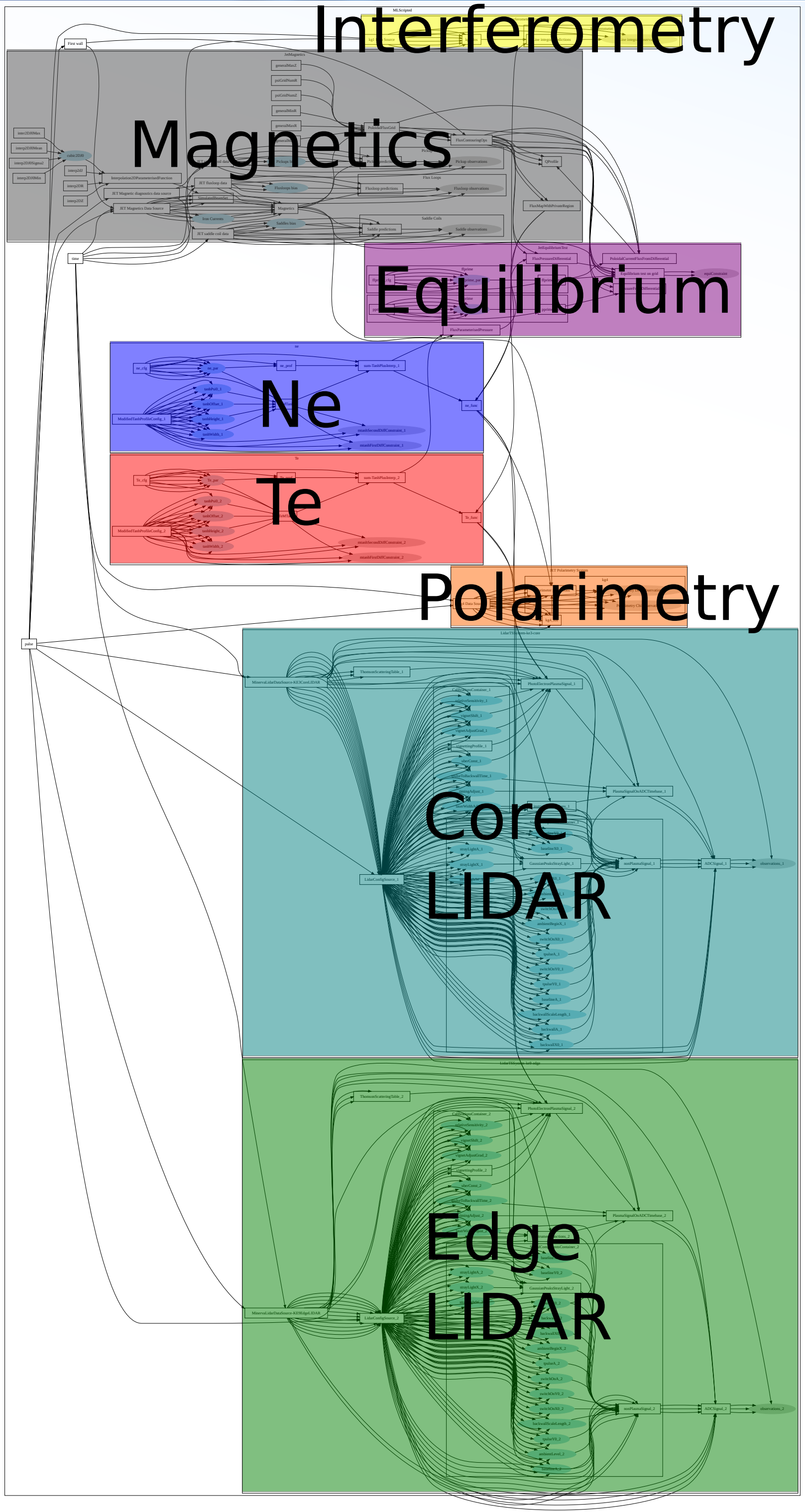

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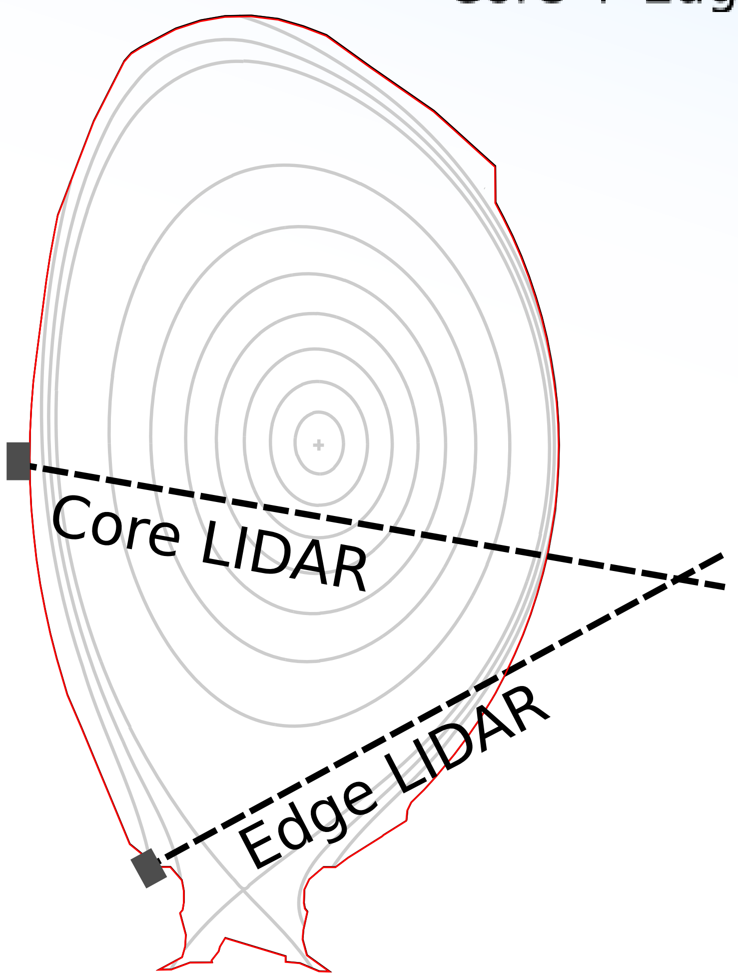
Other parts written during the past 3 years:

- JET MSE
- JET Reflectometry
- JET Infrared strikepoint camera
- MAST Magnetics
- MAST MSE
- MAST Thomson Scattering
- ... and a few others ...

Core + Edge LIDAR: The systems and the problem



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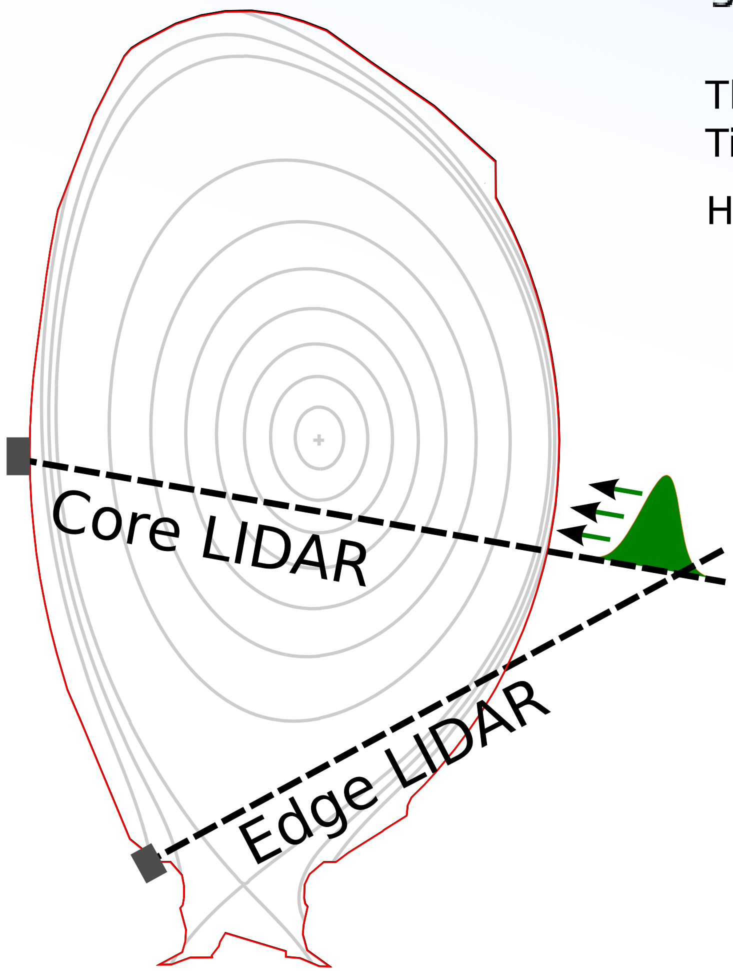

Thomson Scattering diagnostics with single spectrometer.
Time of flight for positioning.

Hardware system very complex.

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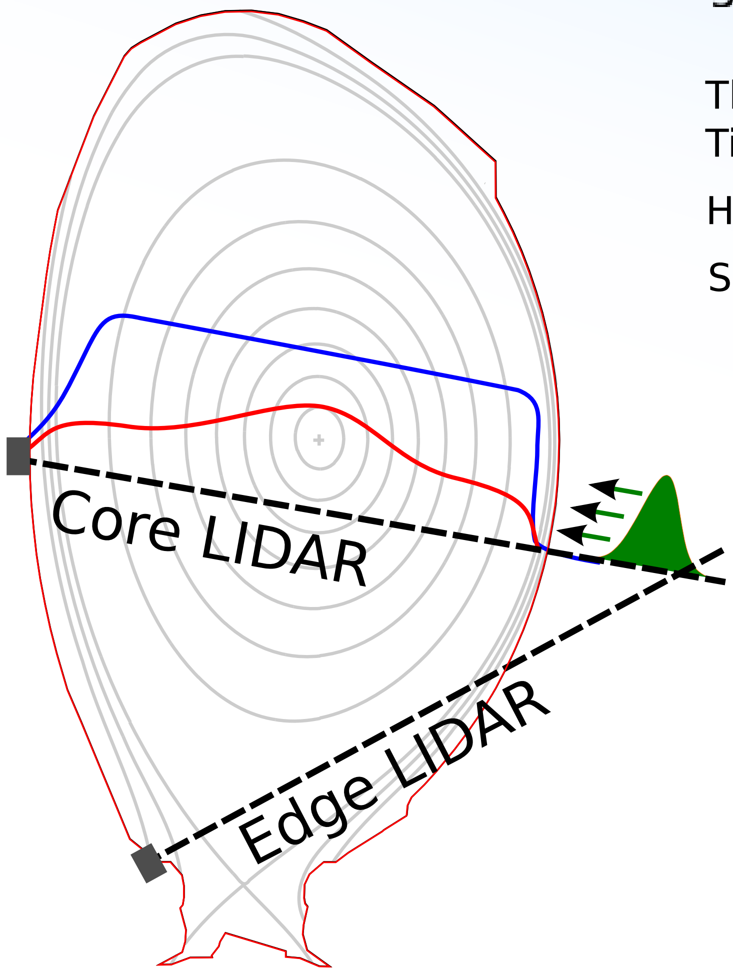

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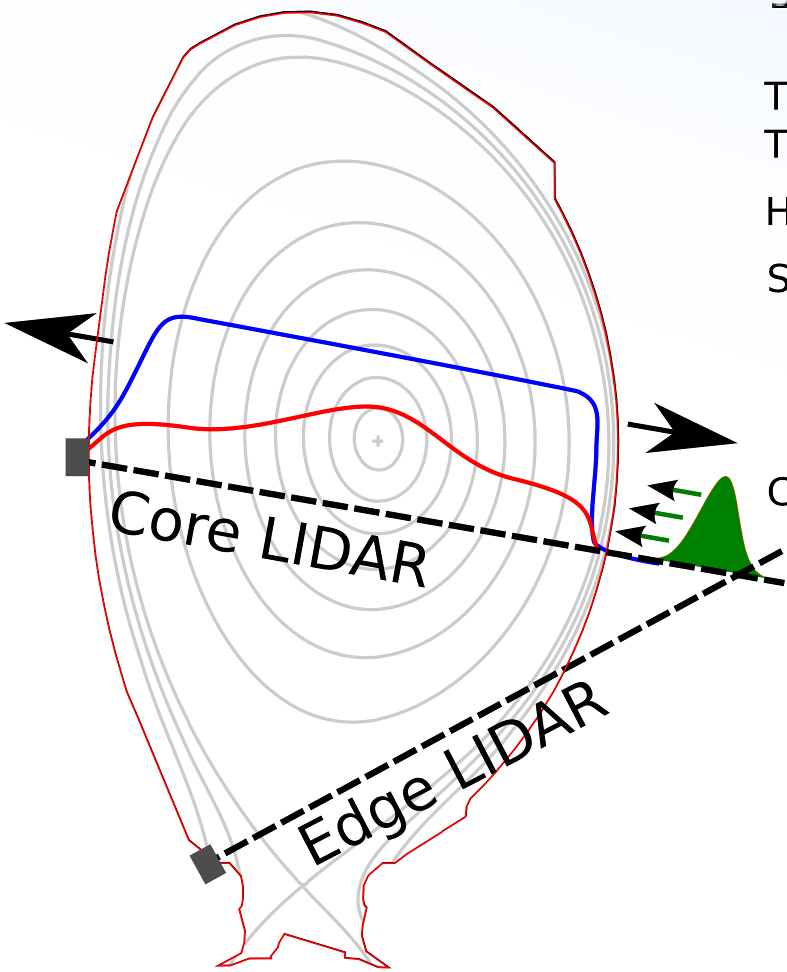

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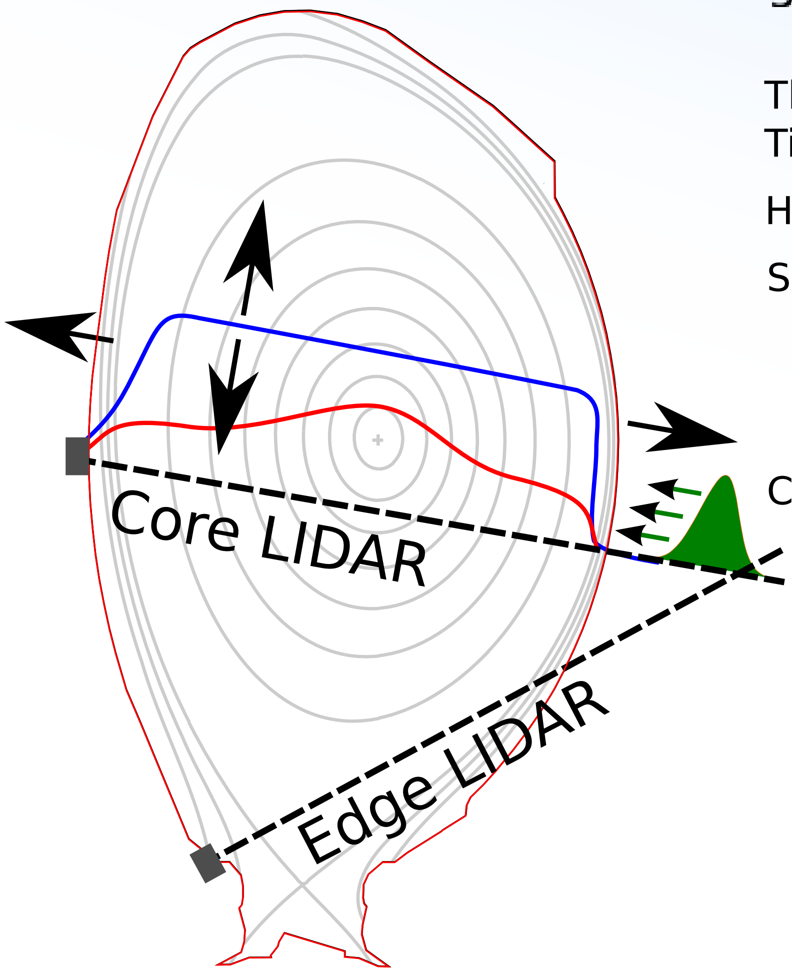

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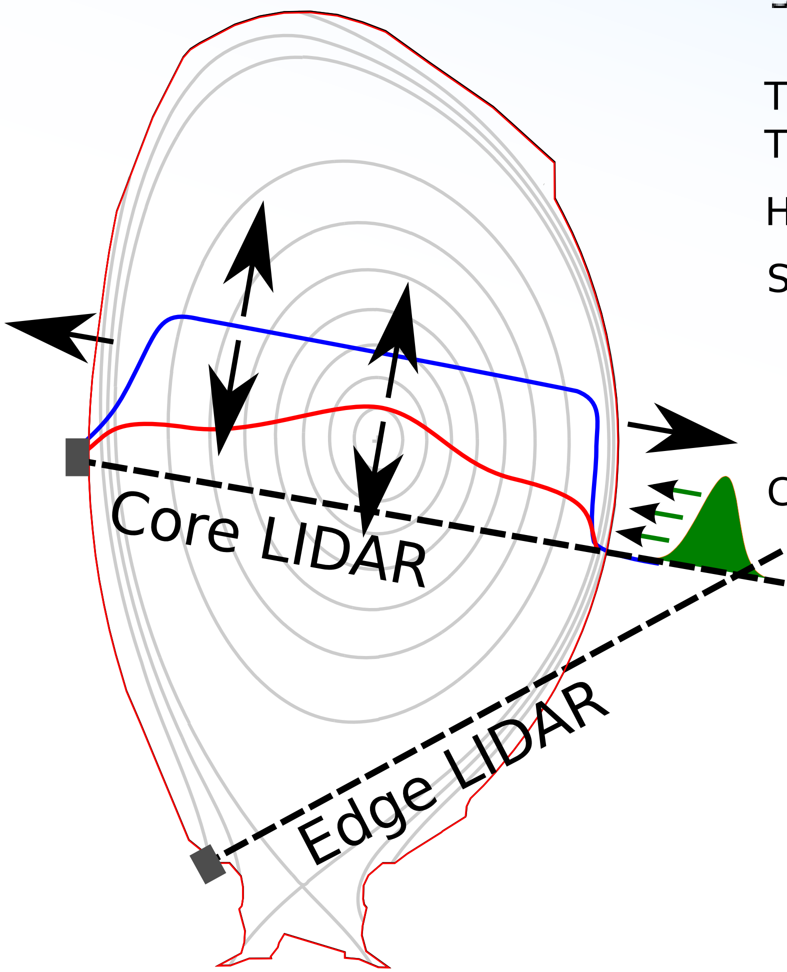

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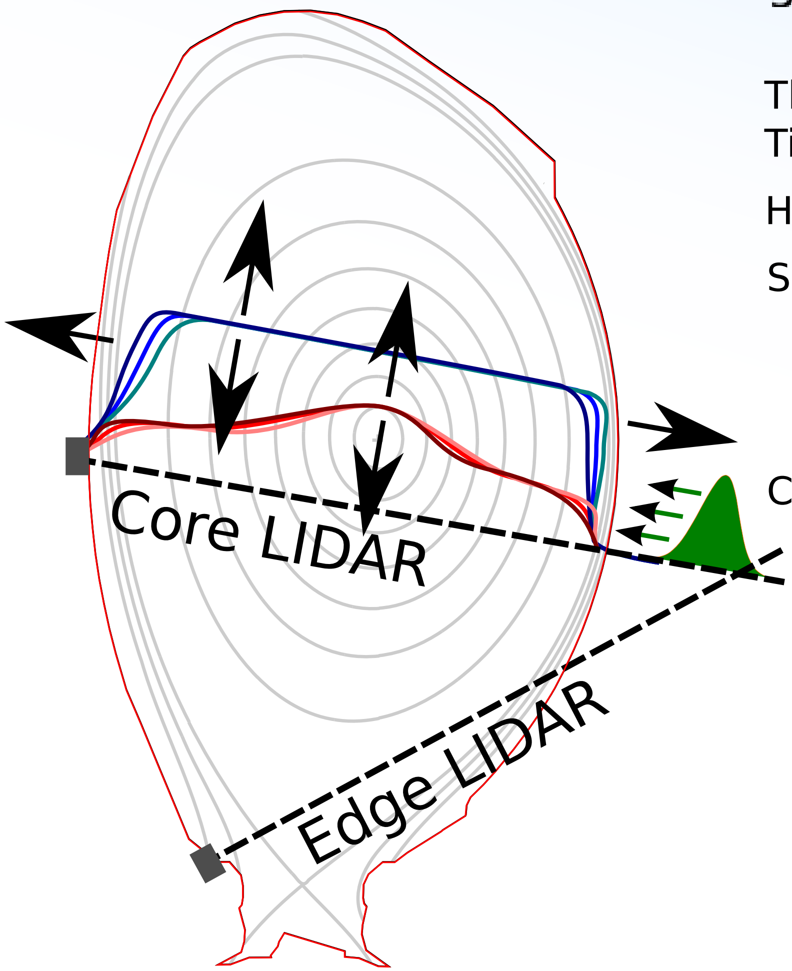

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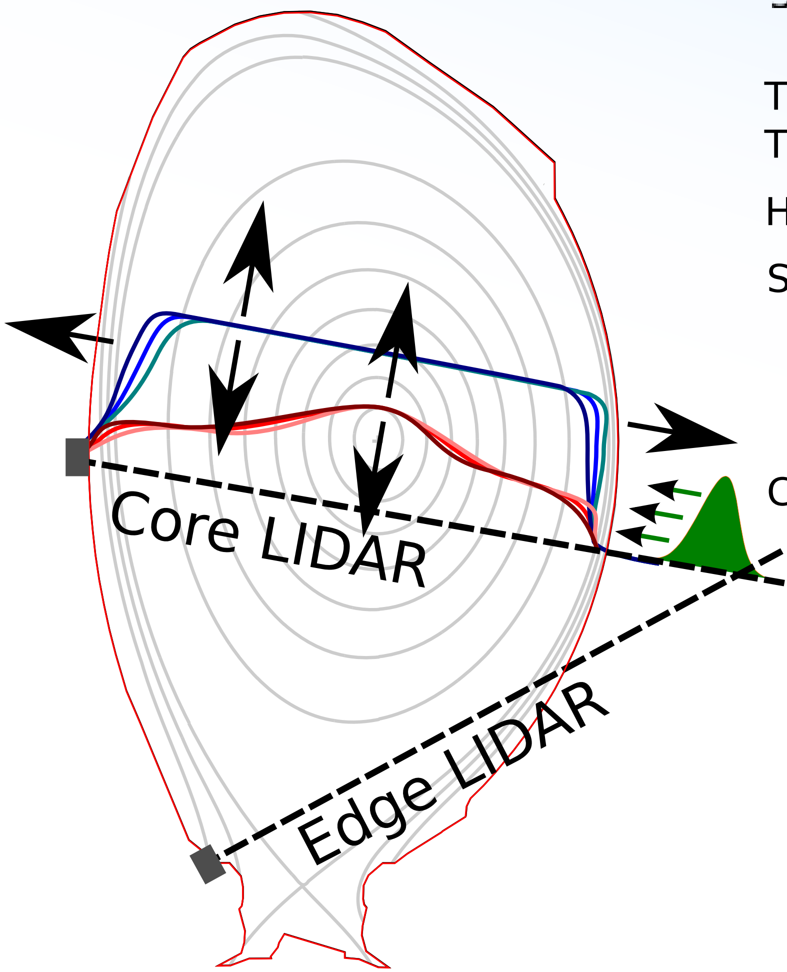

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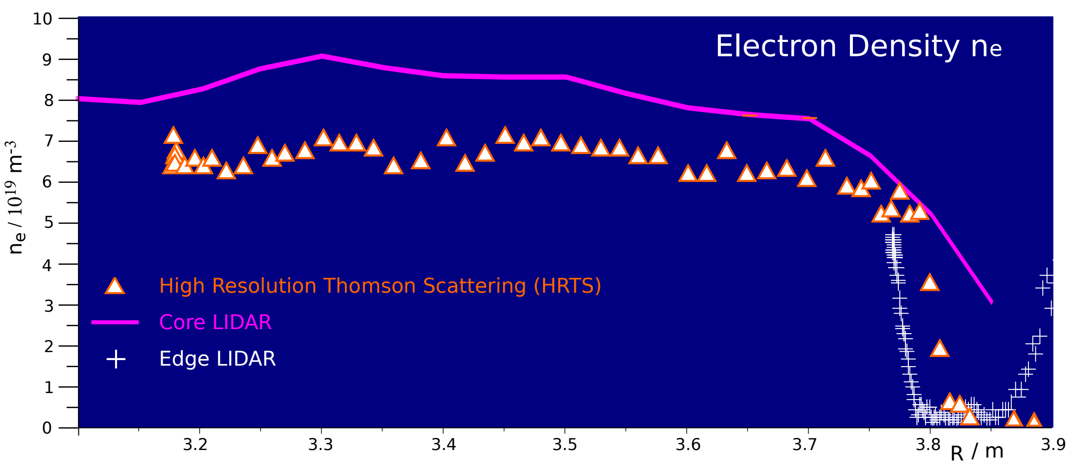

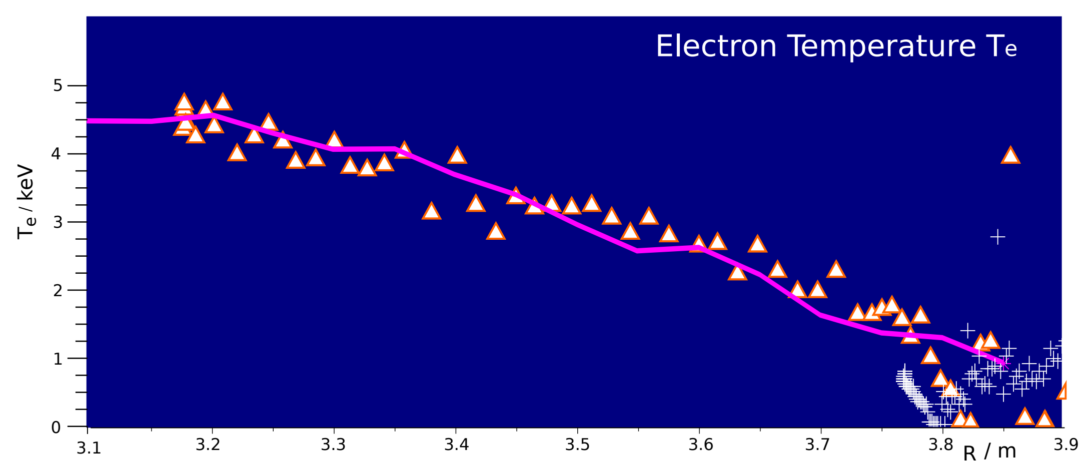

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We must really understand each part of the system:
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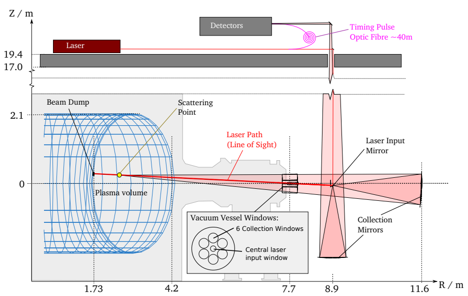

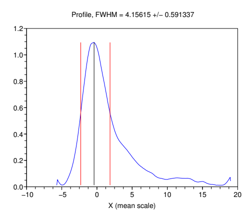

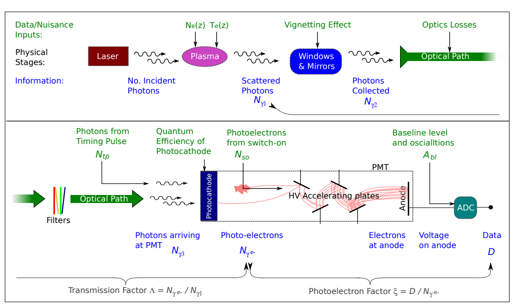

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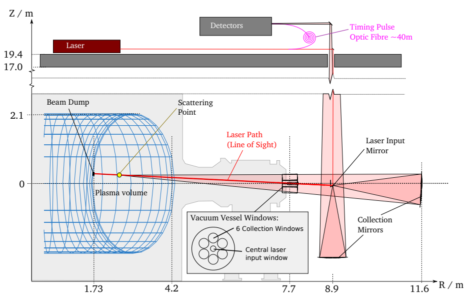

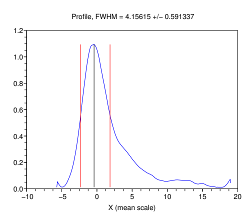

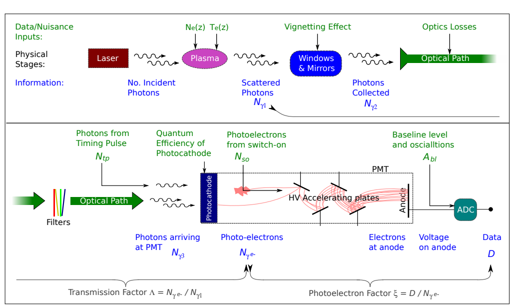

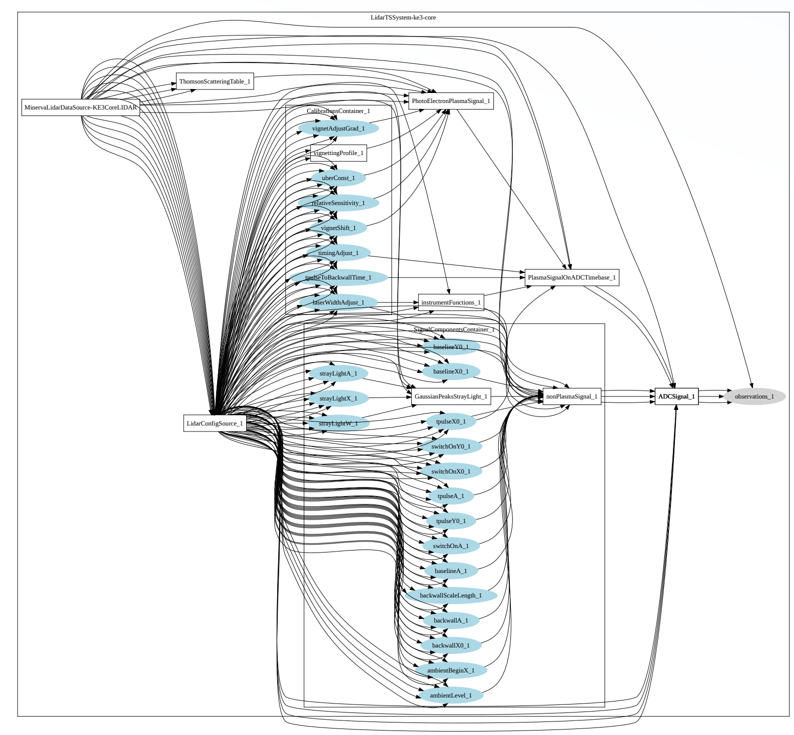

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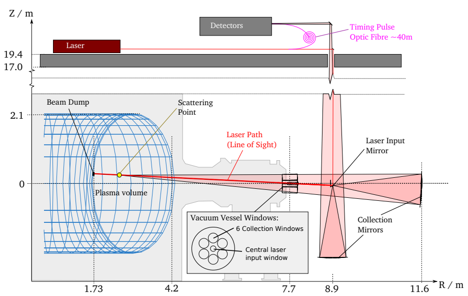

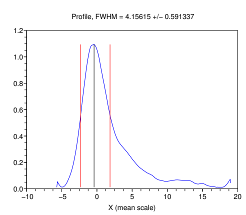

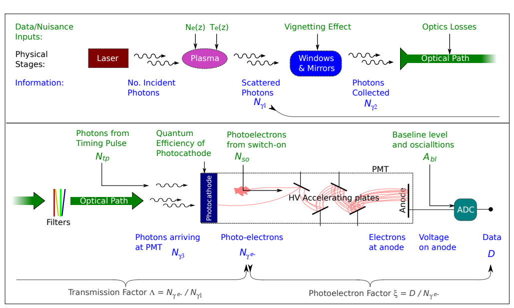

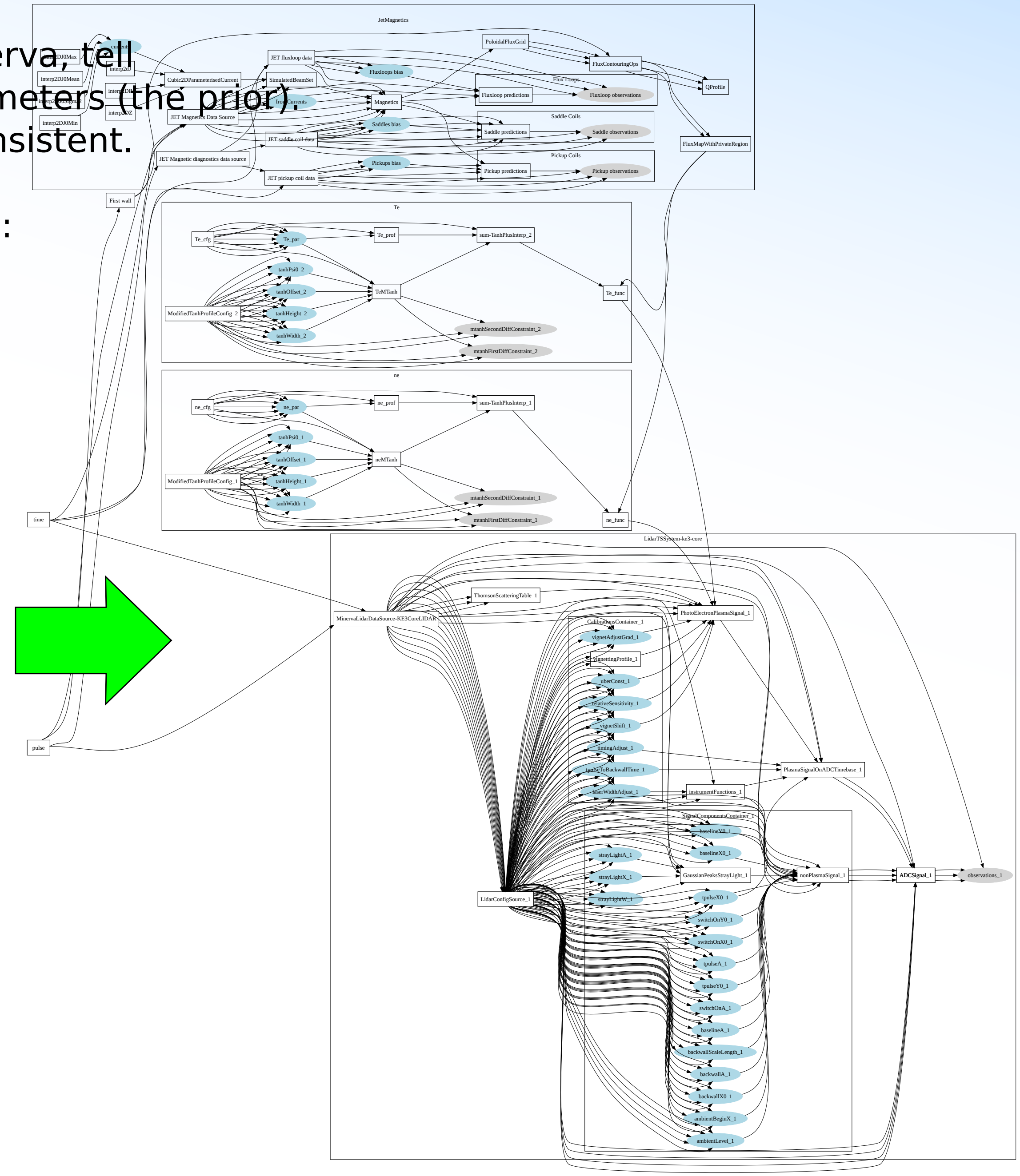

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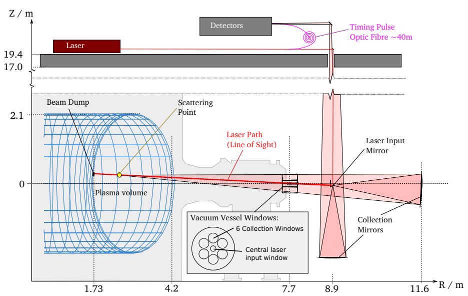

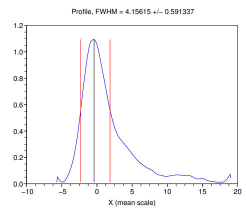

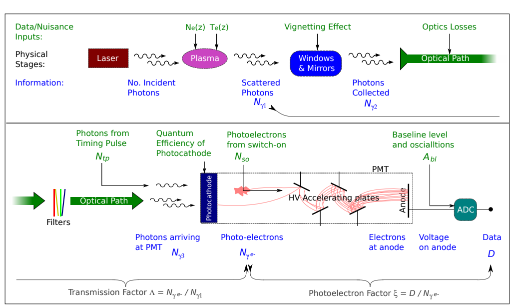

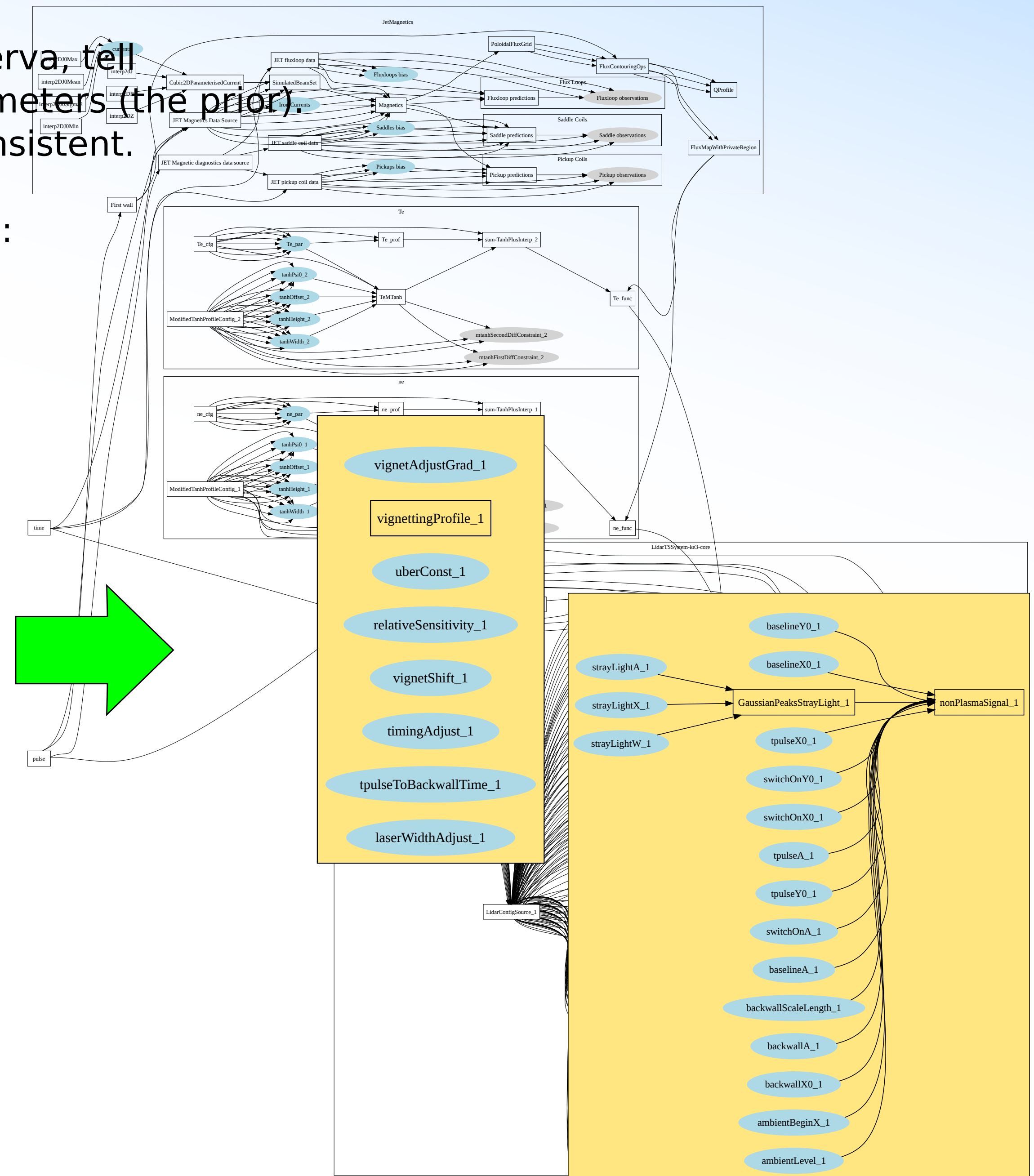

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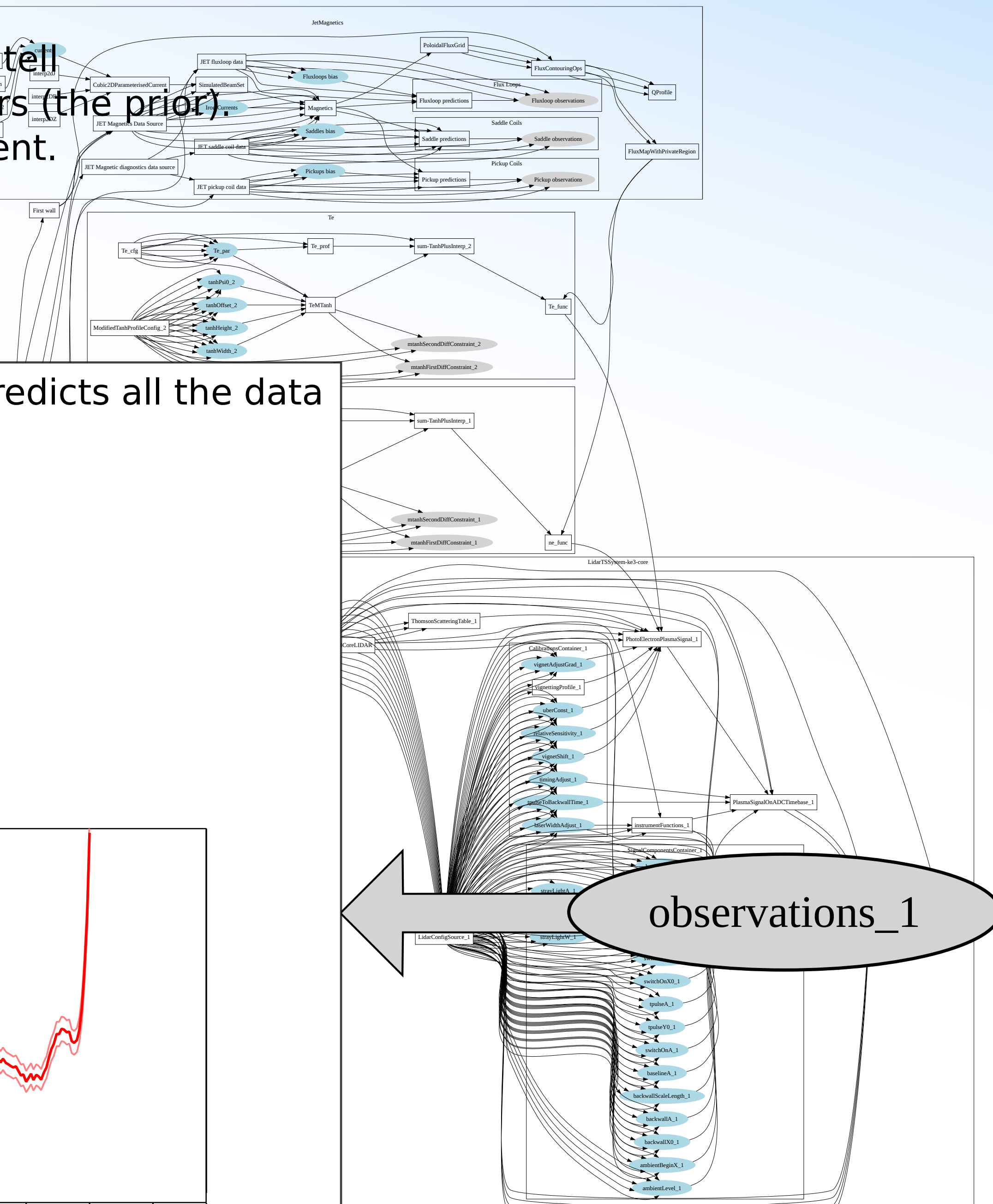
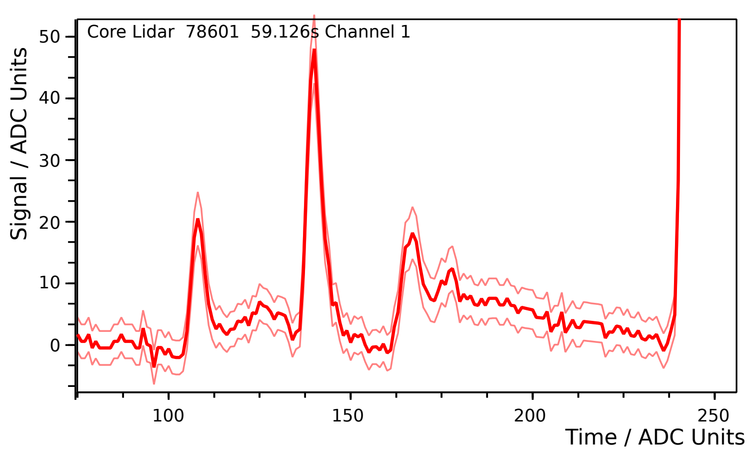
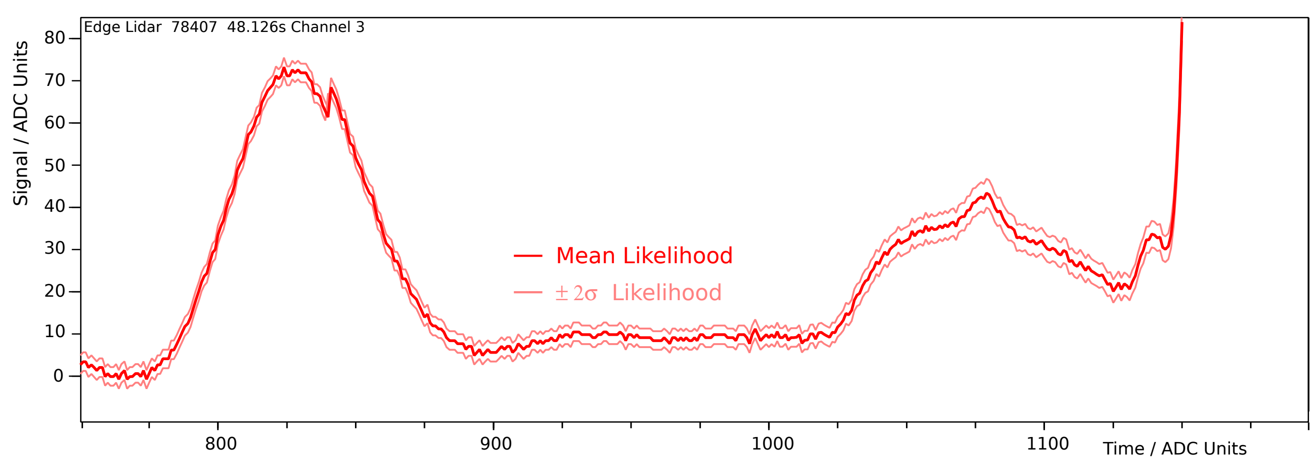


Model predicts all the data





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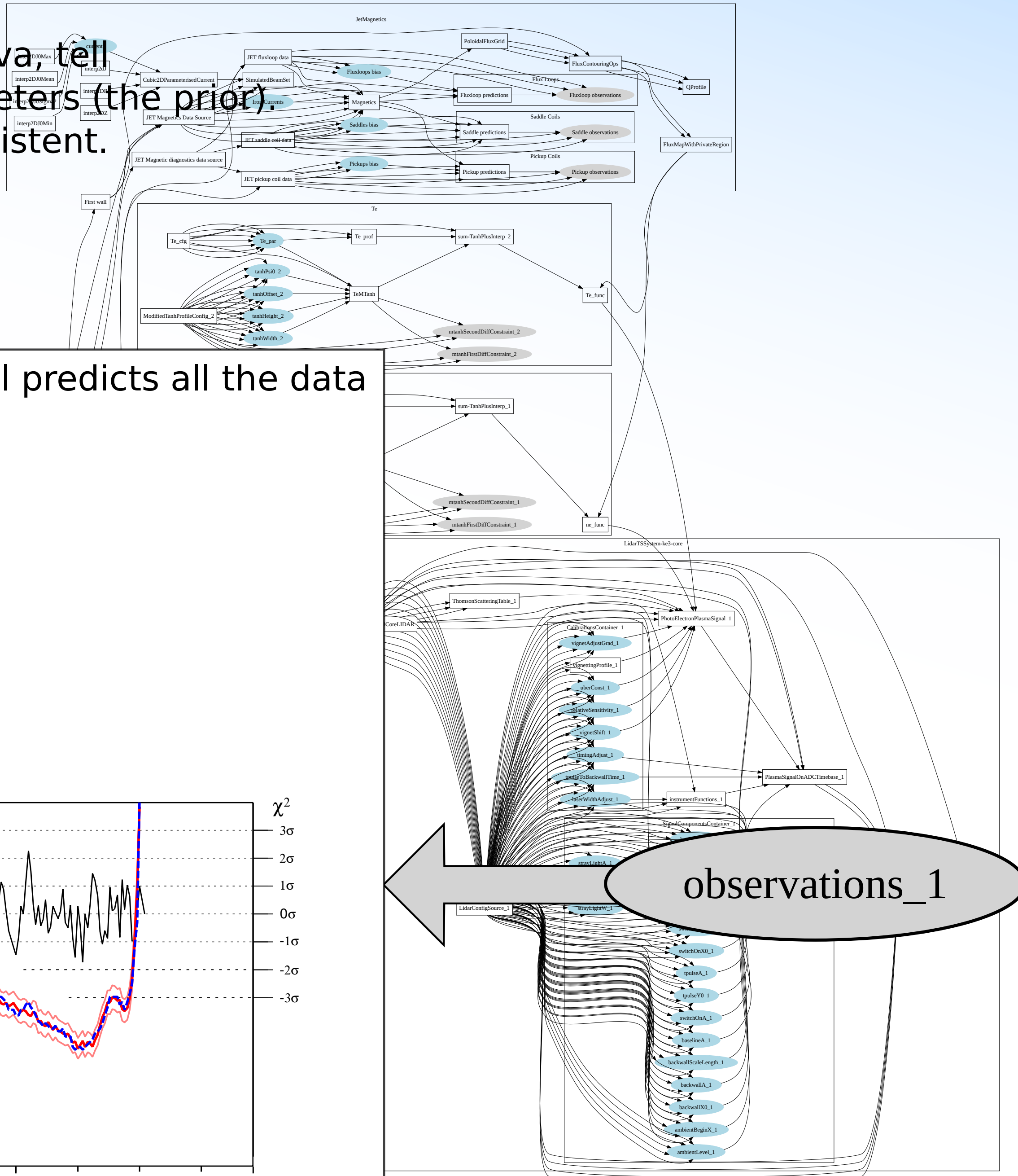

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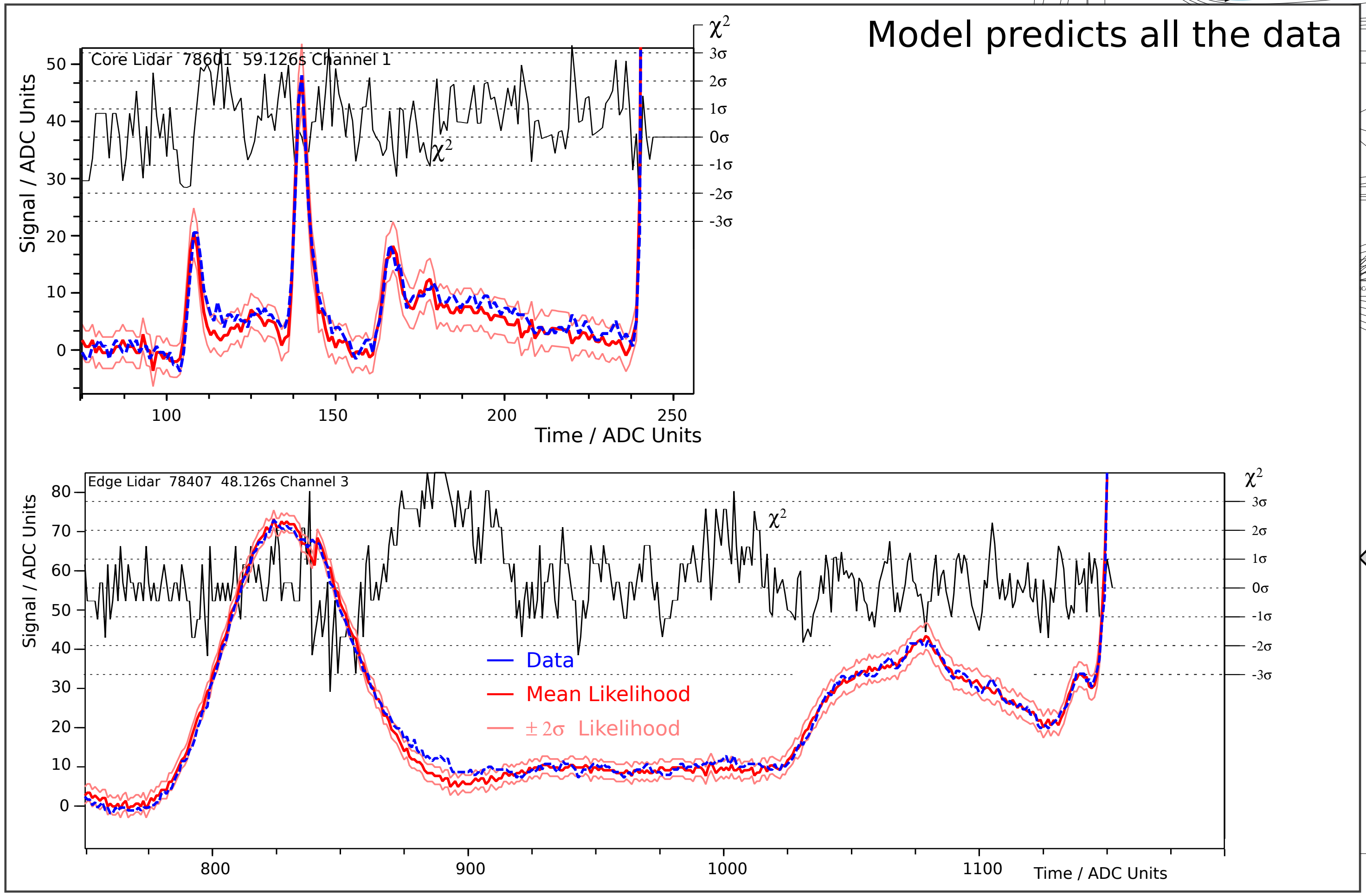

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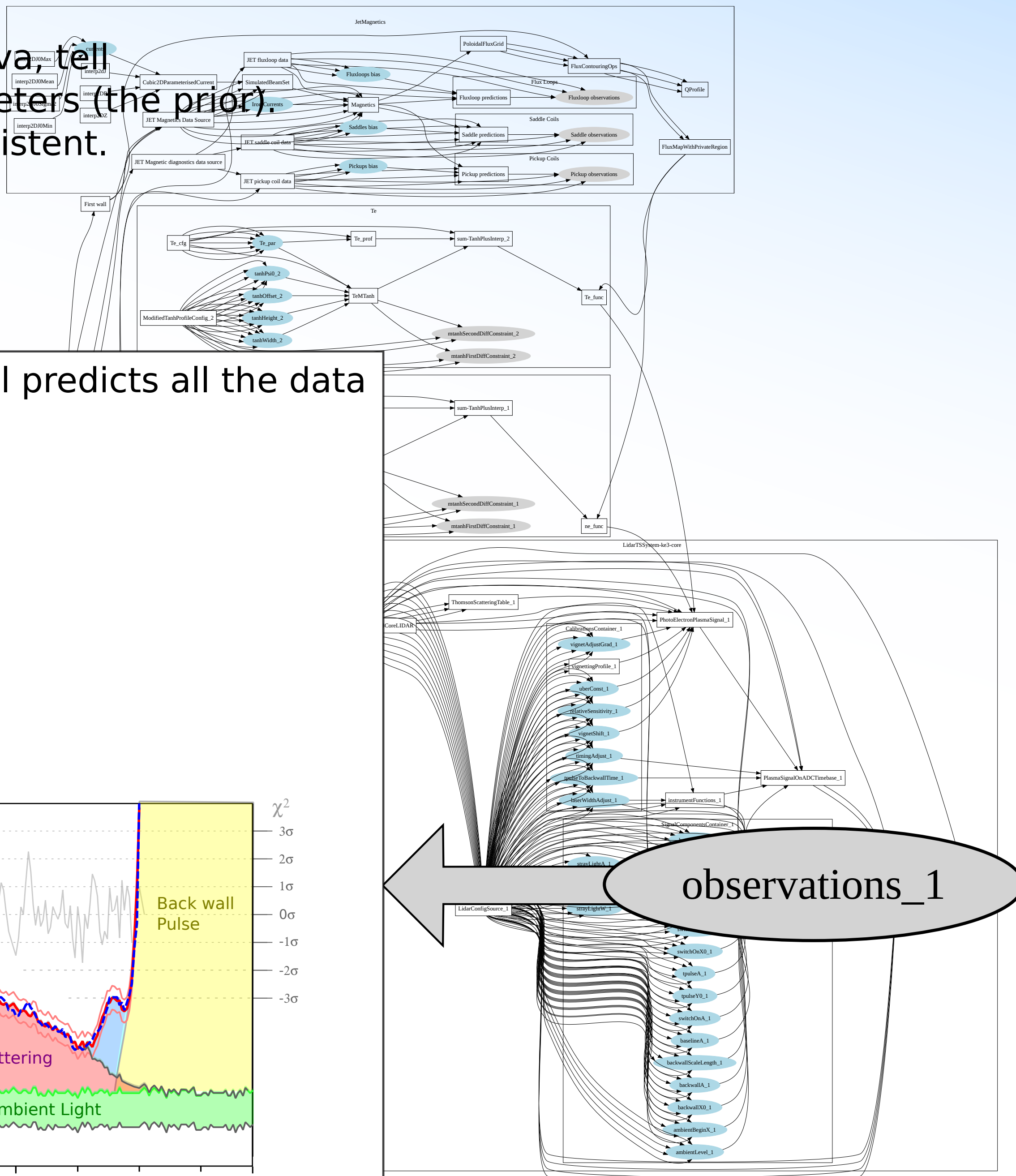
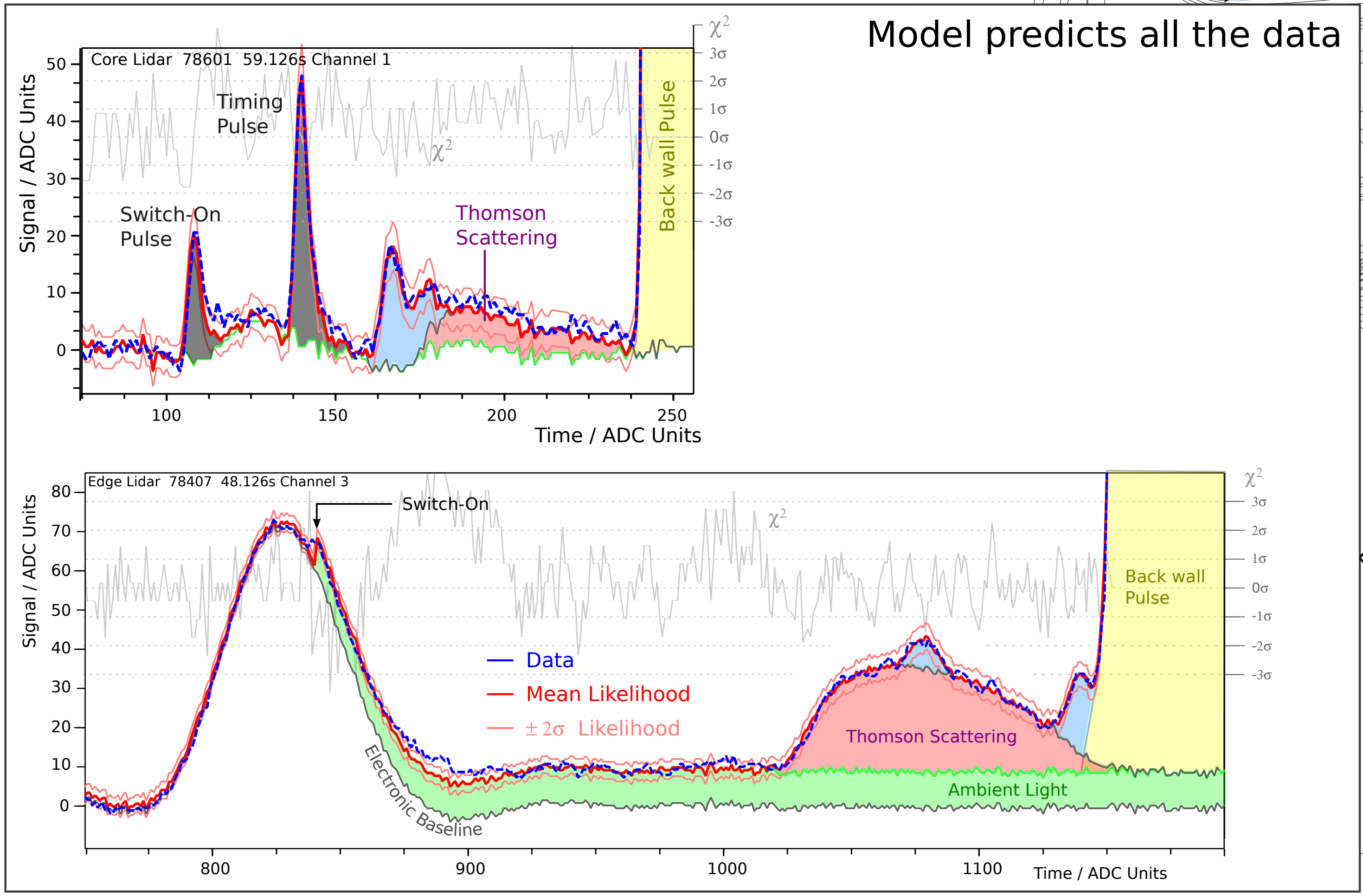


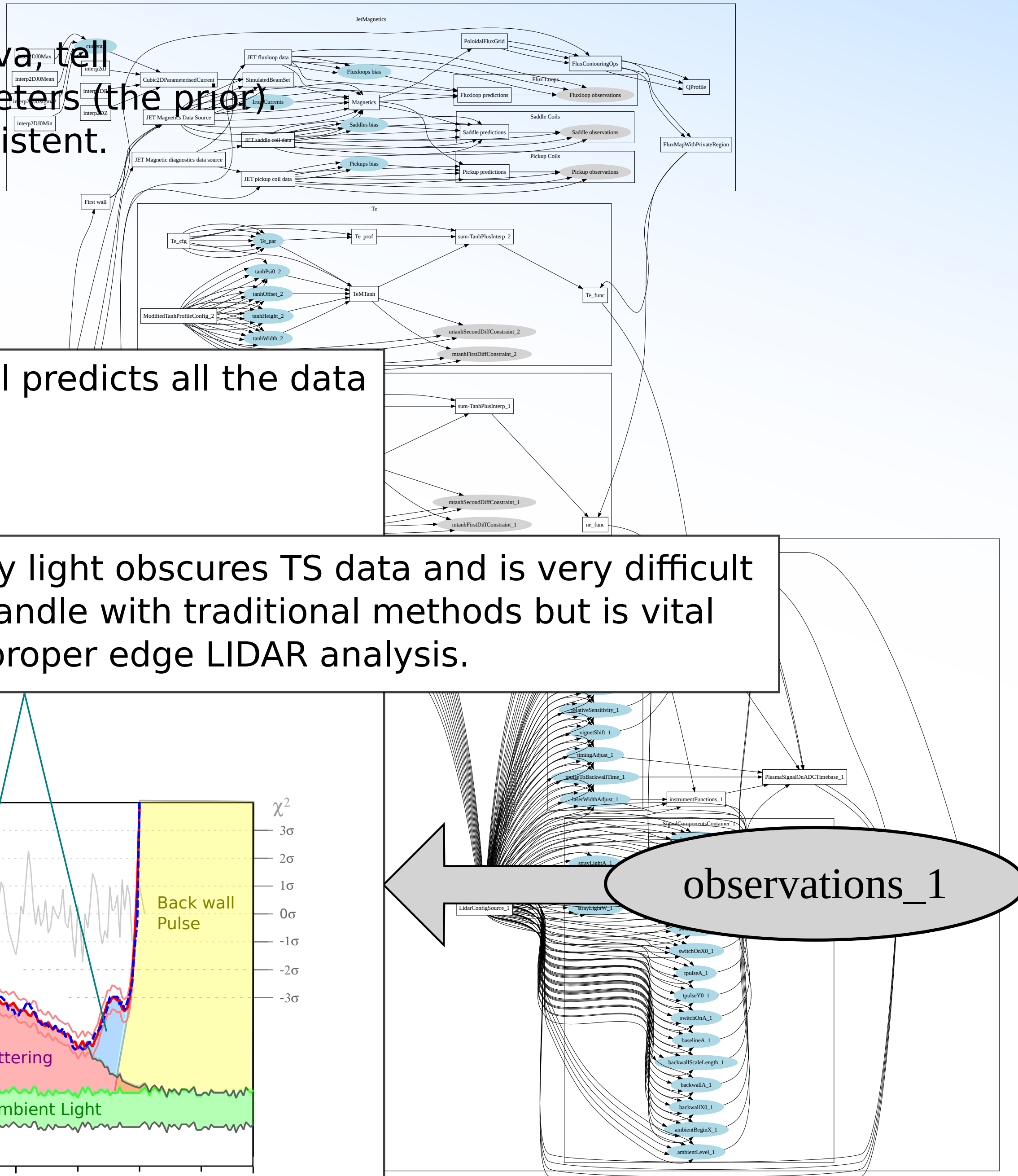
Model predicts all the data

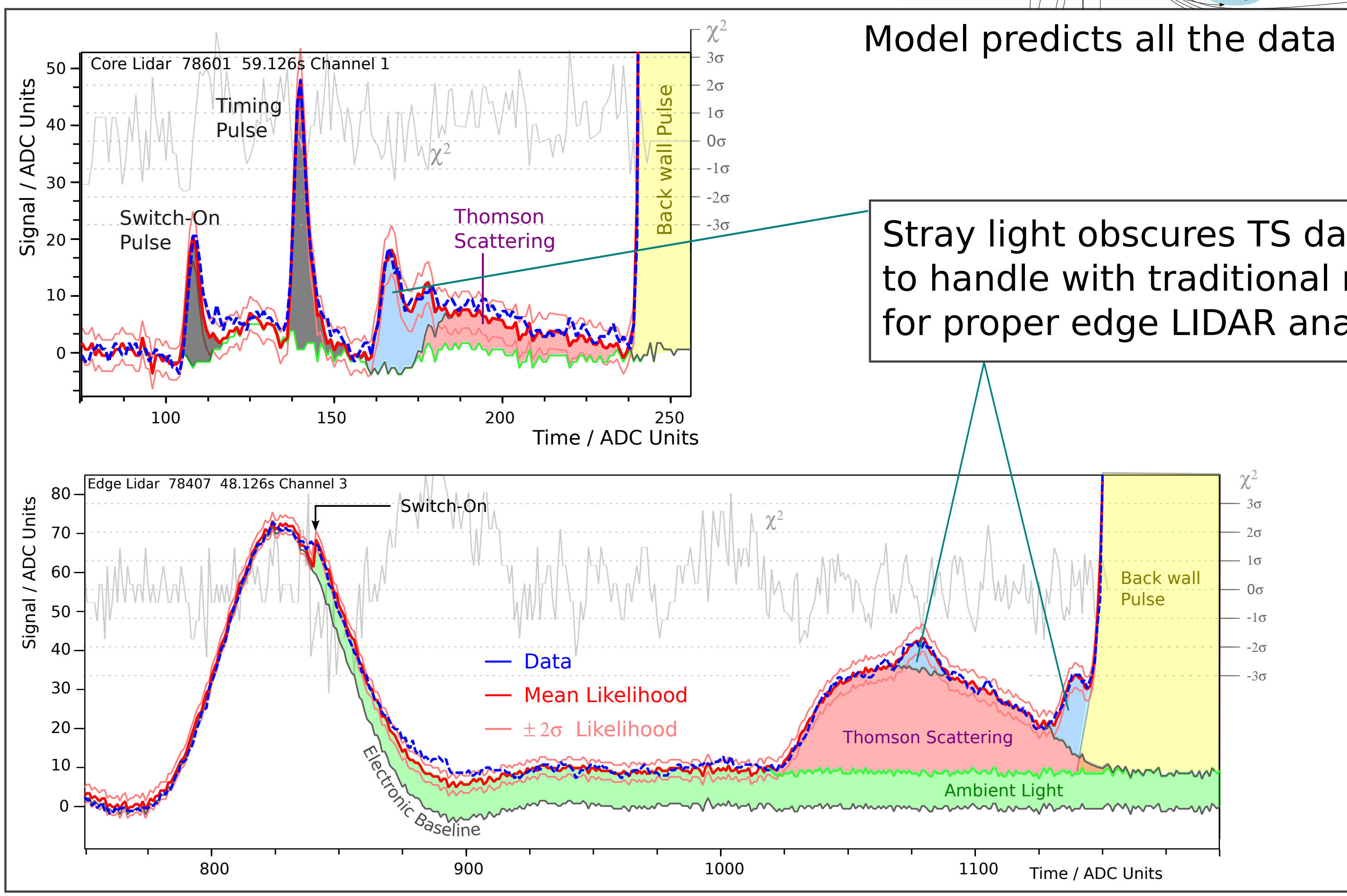


Core + Edge LIDAR: The model

So how do we deal with disagreement with other diagnostics?
 Shift and scale output profiles to match?
 No - Build the model for each and wire up to Minerva, tell
  it what we do know about the calibration parameters (the prior)
  and let it work out how to make everything consistent.

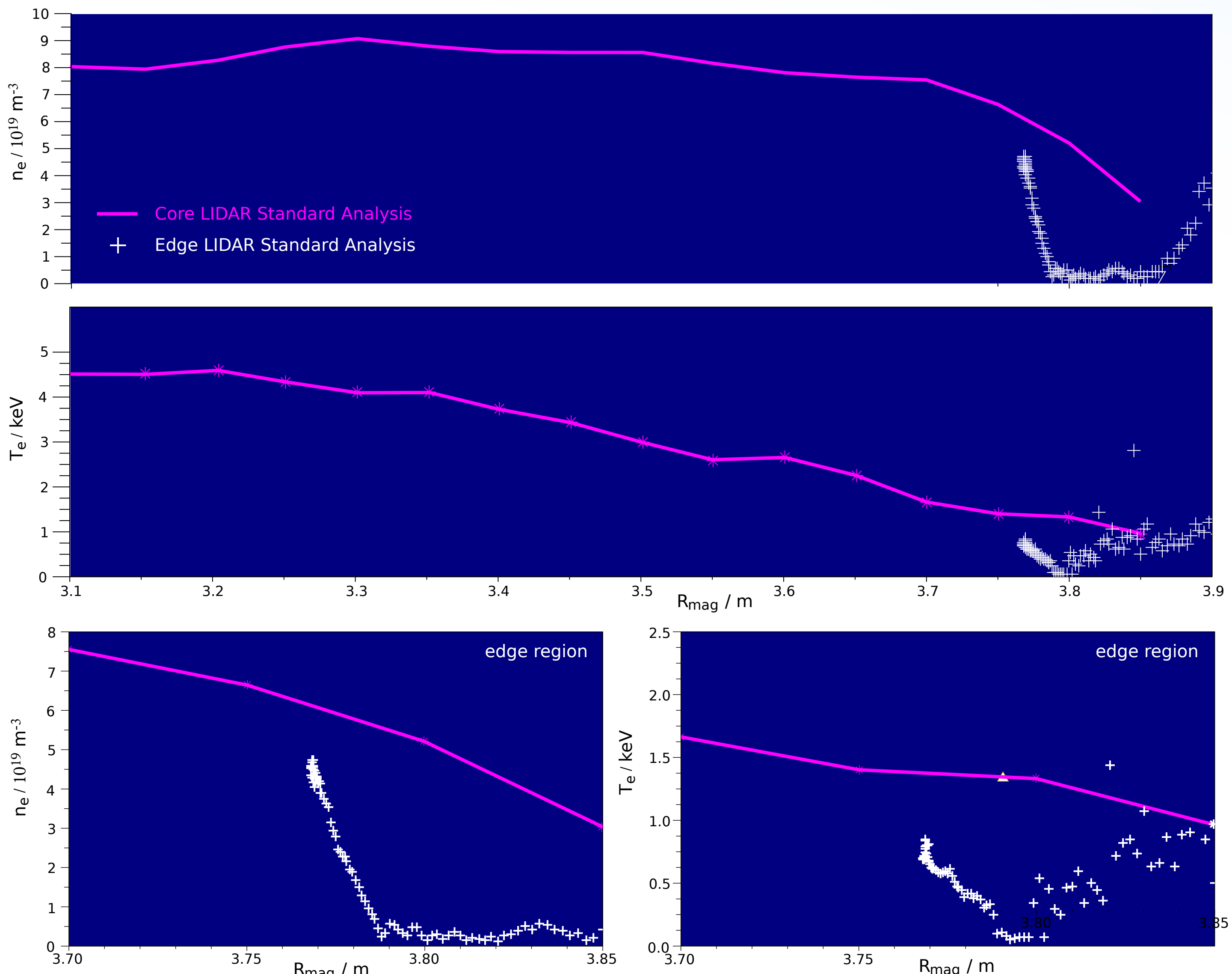
We must really understand each part of the system:
Laser Pulse, TS physics, Optics, Filters,
Photomultipliers, Counting Noise (PDFs), ADCs.





Core LIDAR + Edge LIDAR + Interferometry

A typical high density H-mode pulse:



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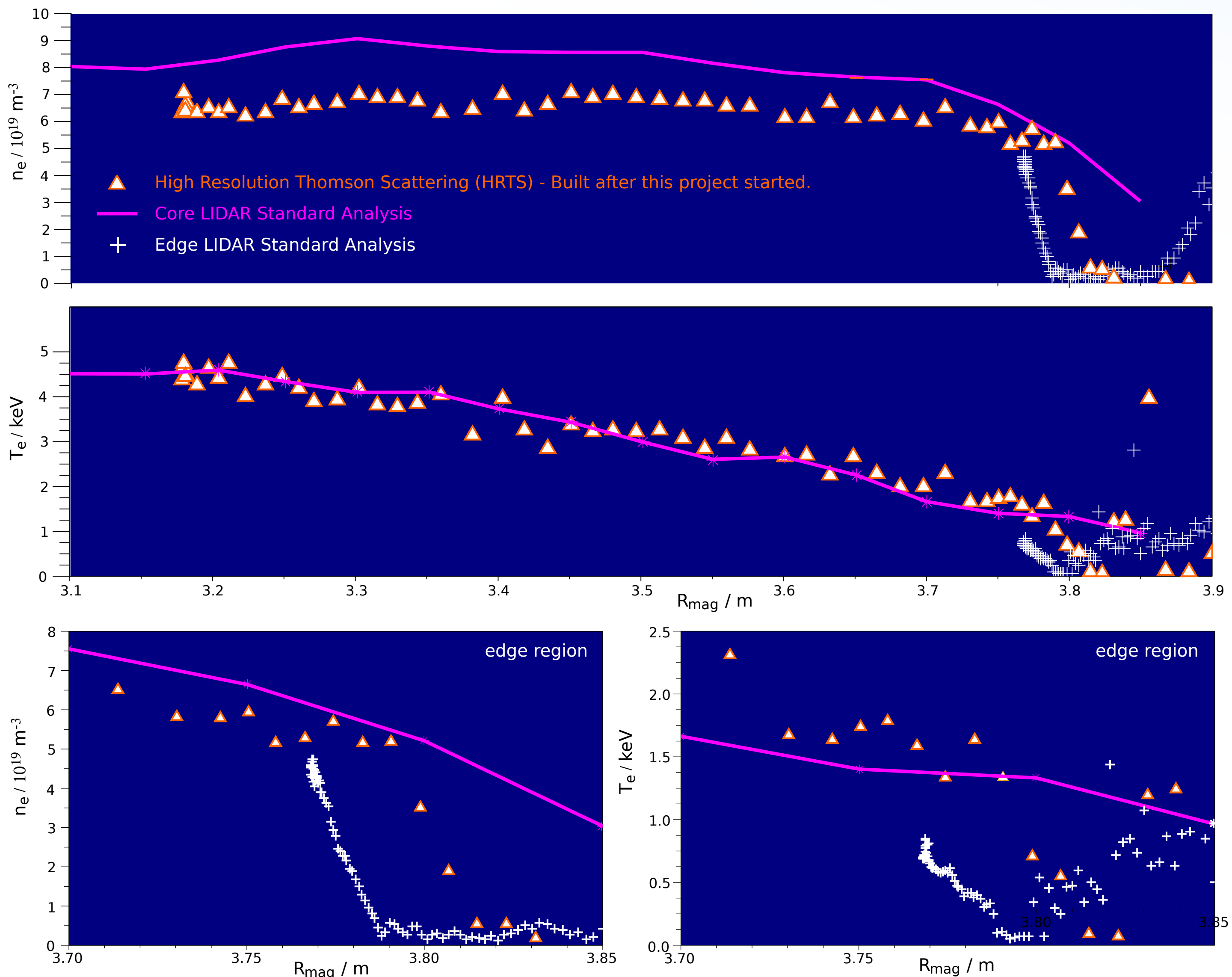
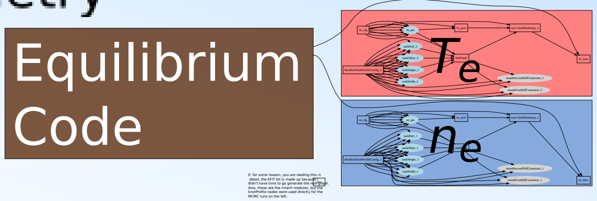
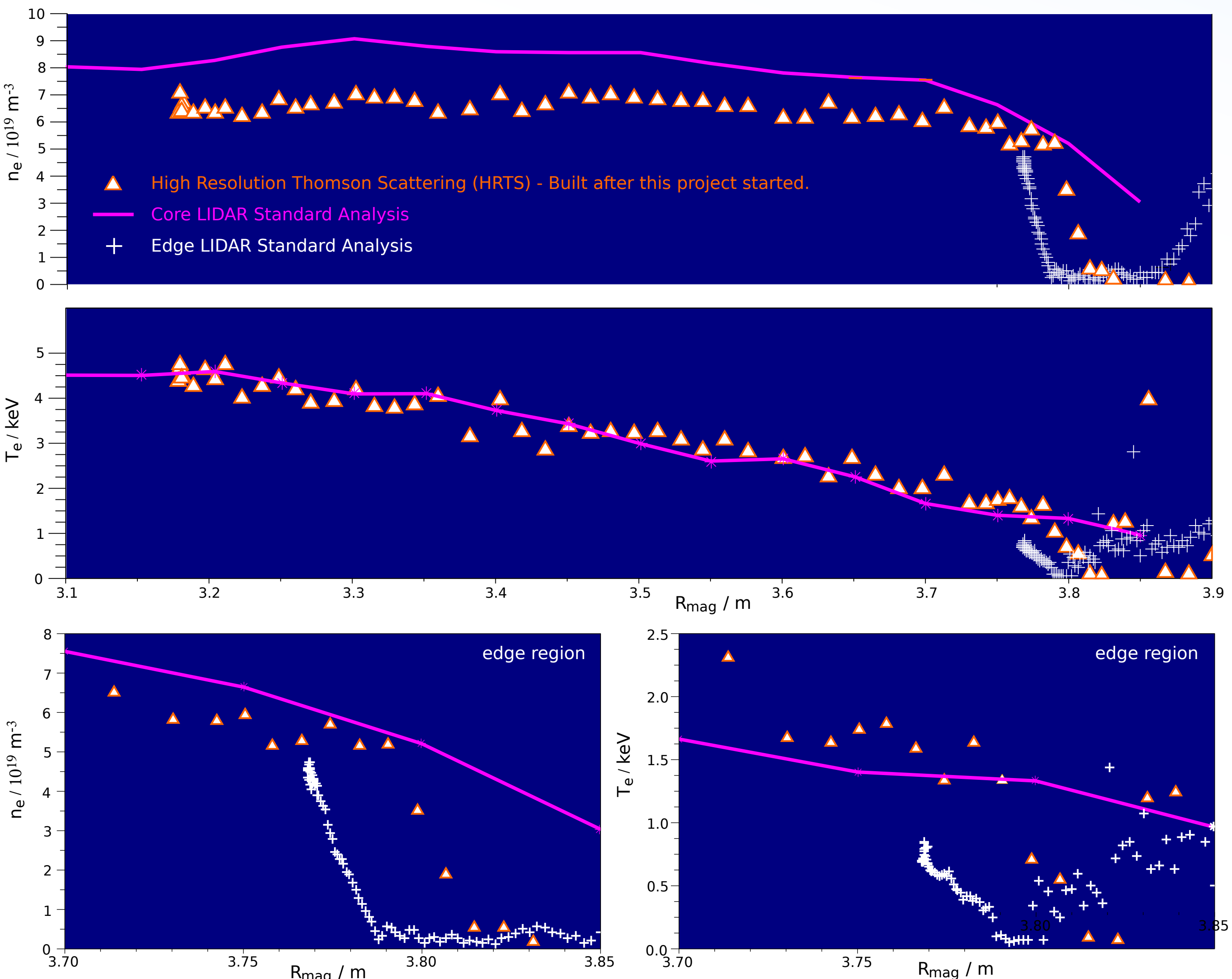


Core LIDAR + Edge LIDAR + Interferometry

A typical high density H-mode pulse:
- Connect up the model.





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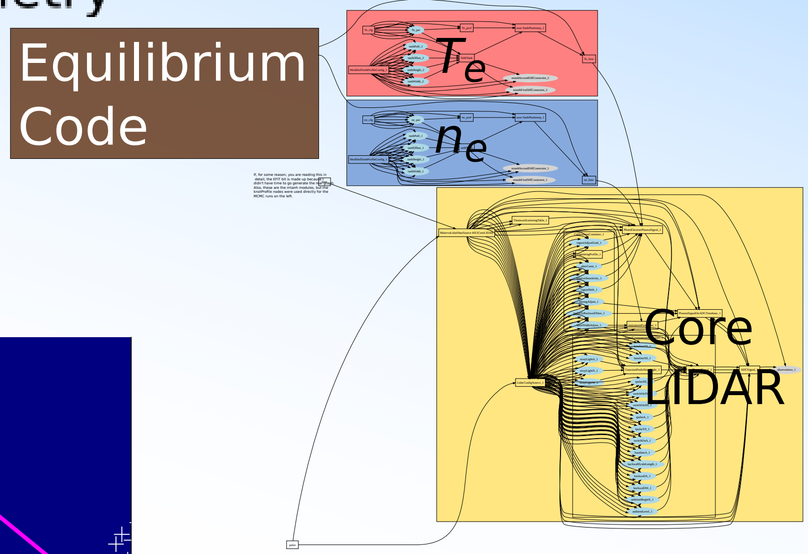

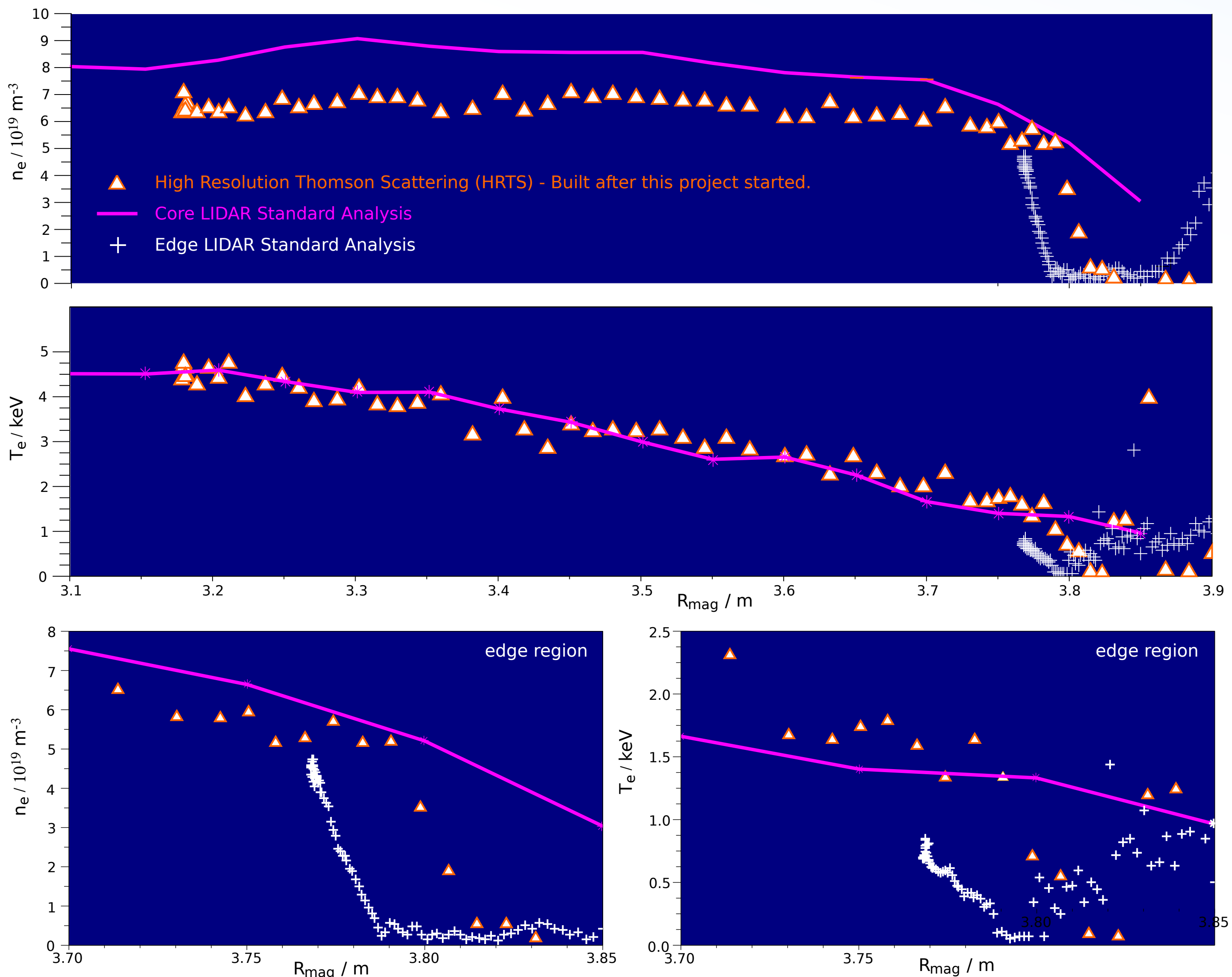

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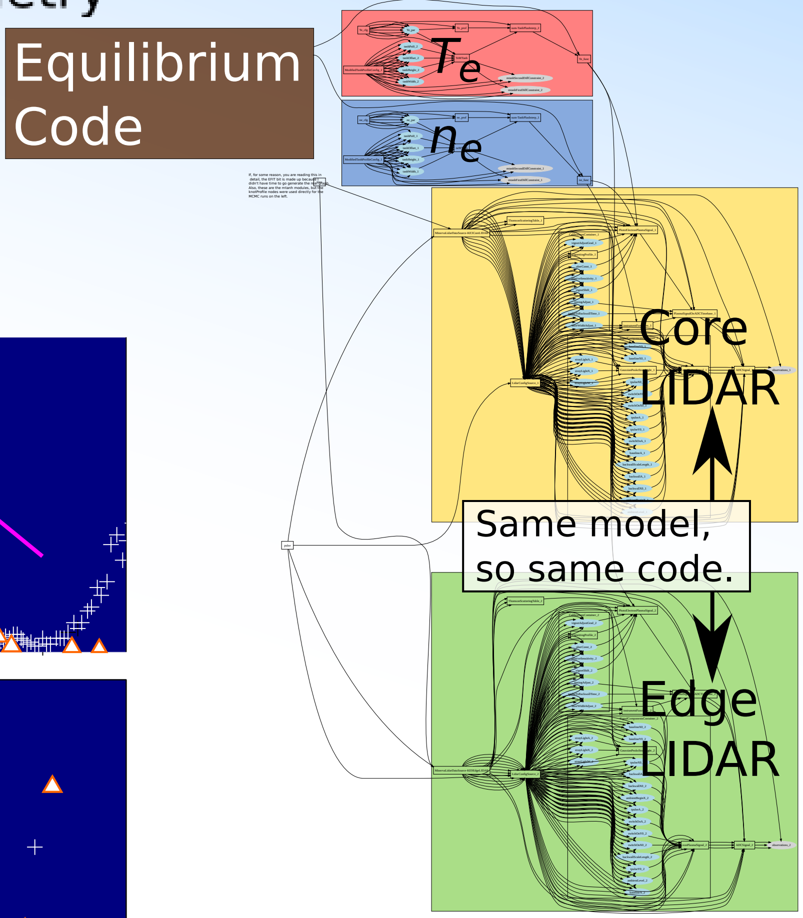

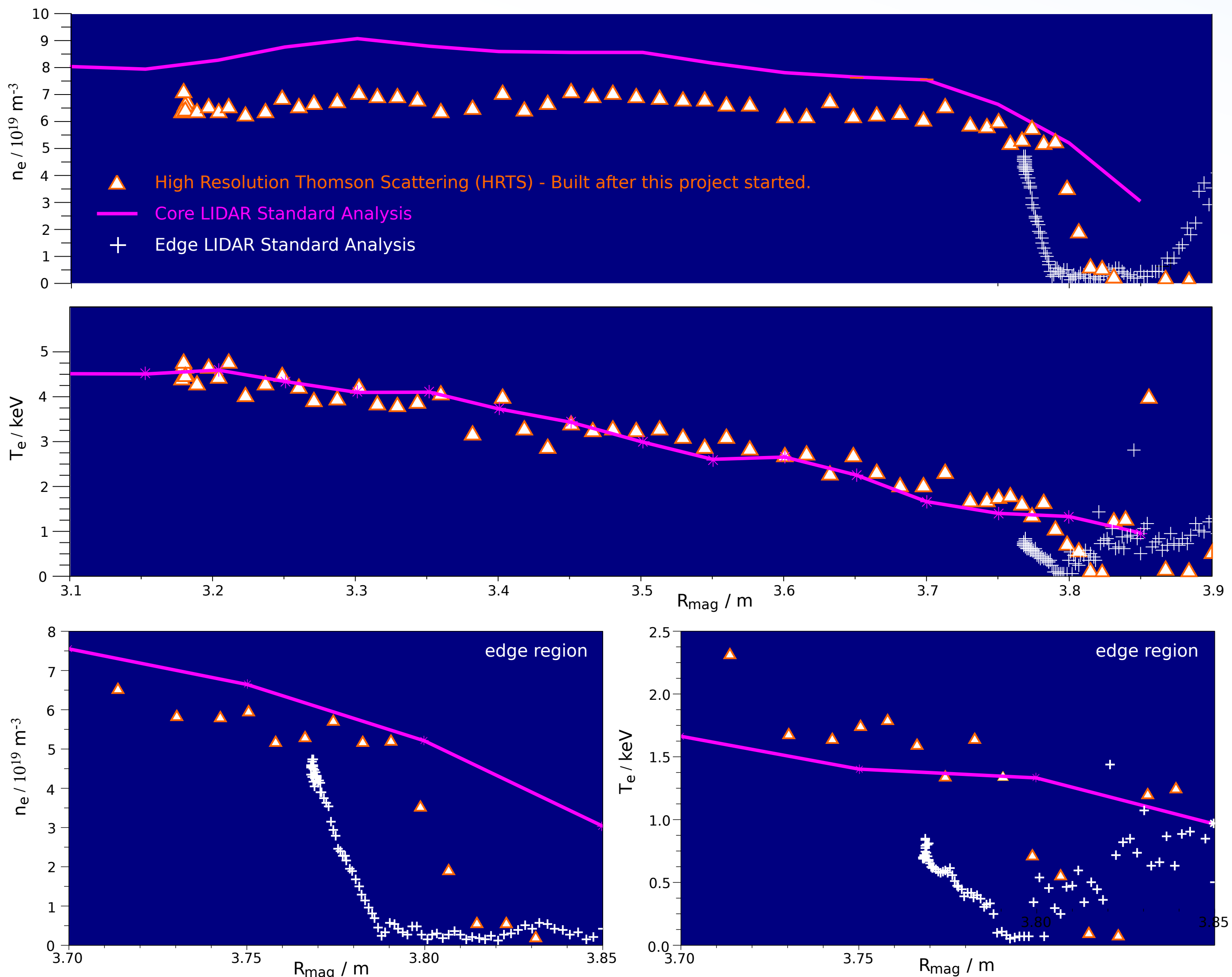

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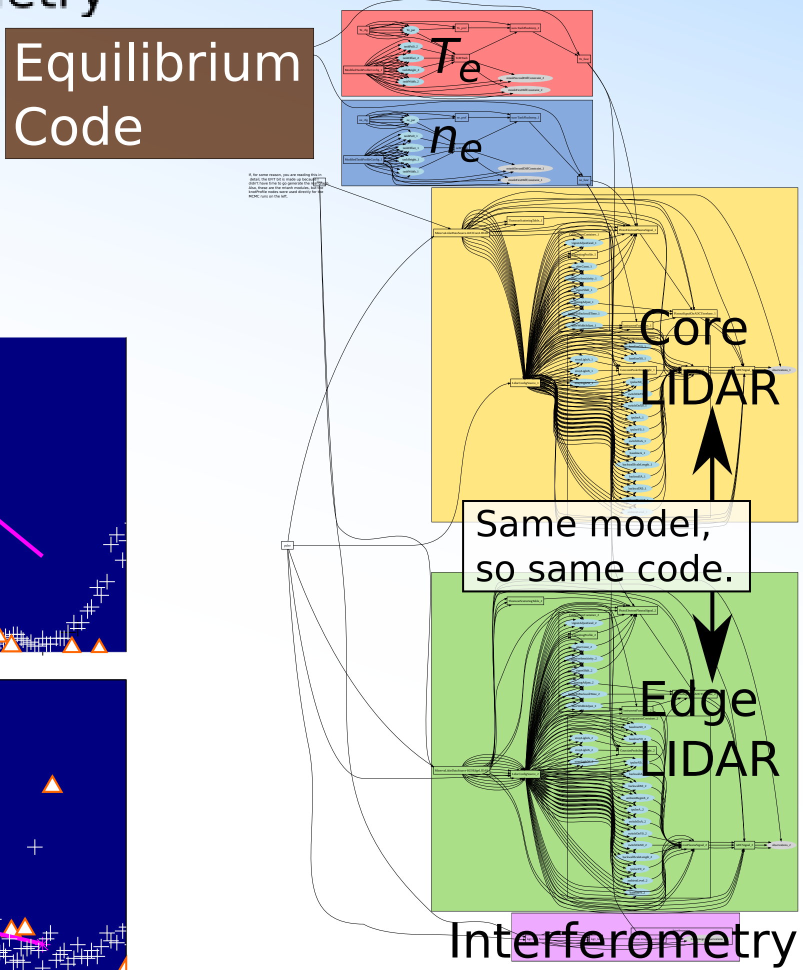

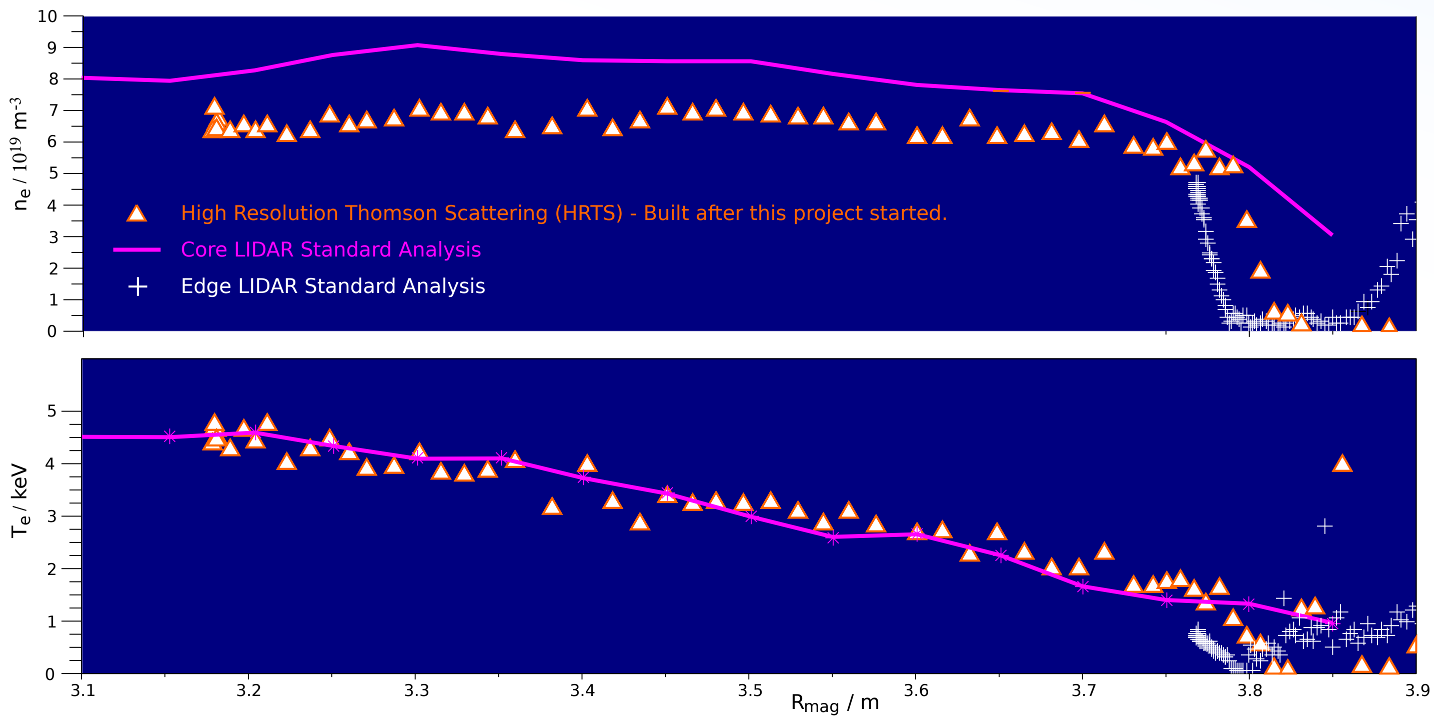

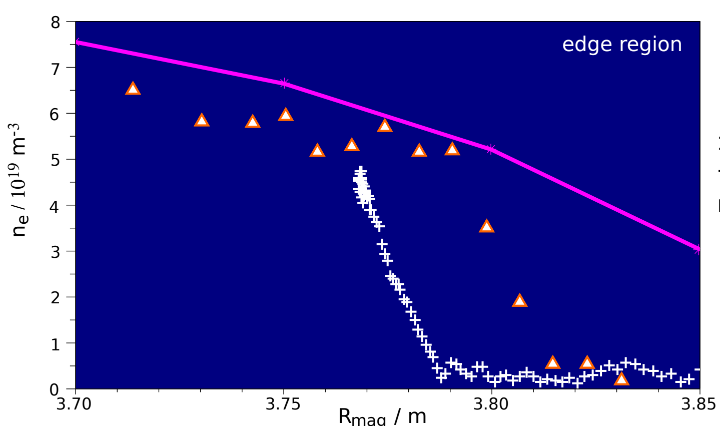

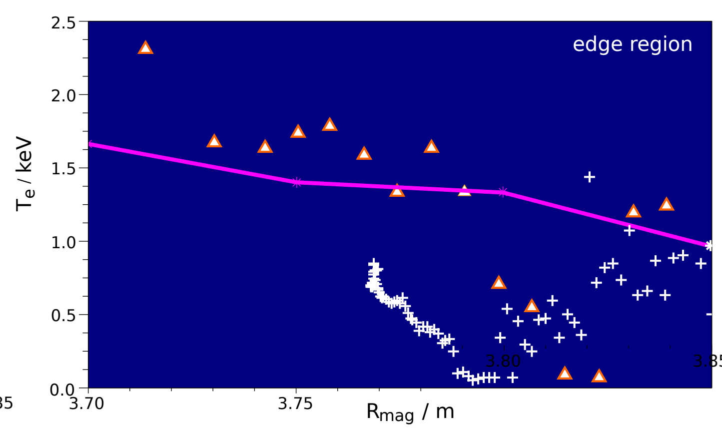

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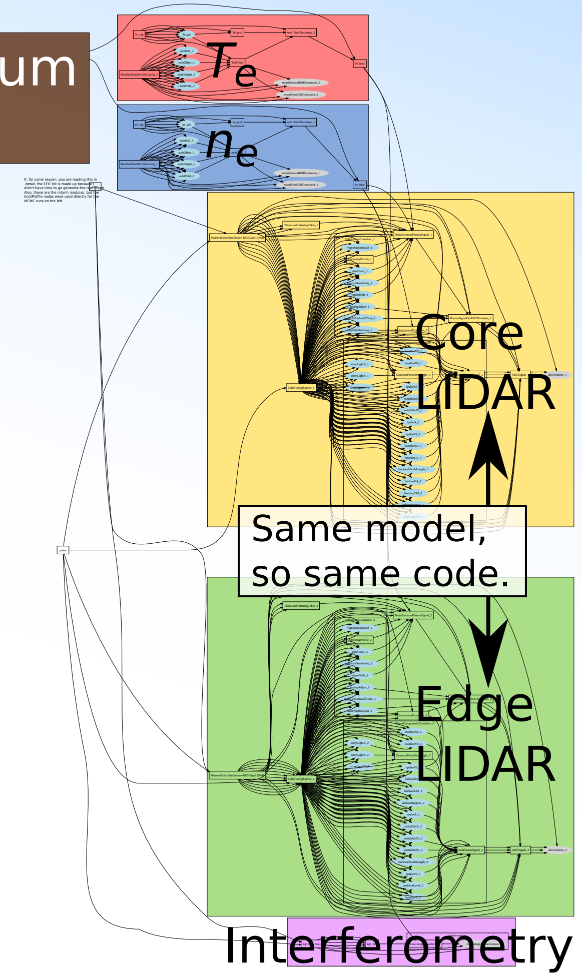

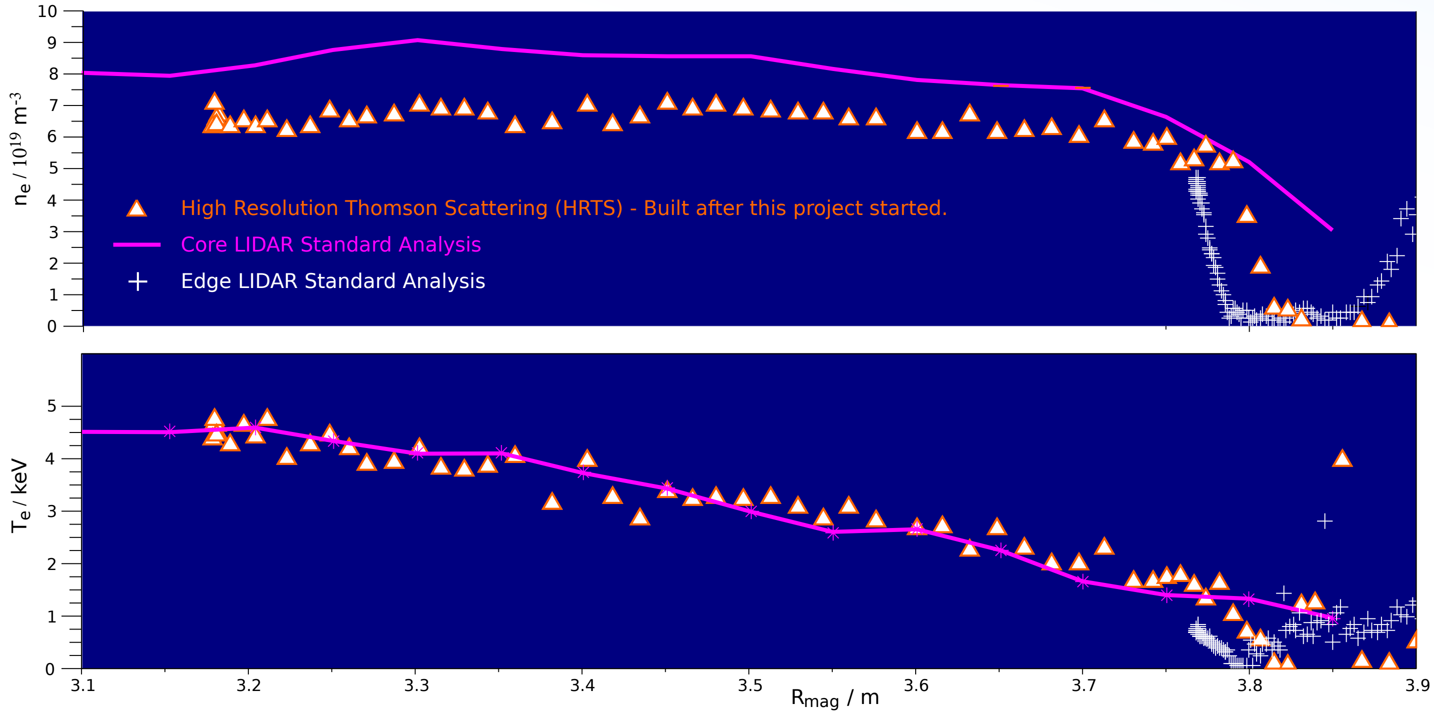

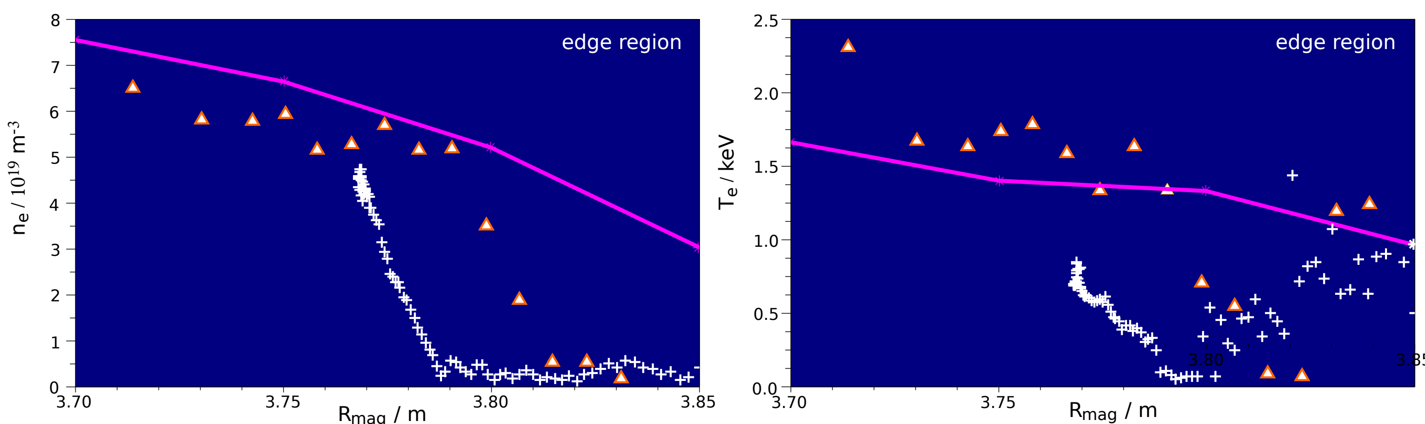

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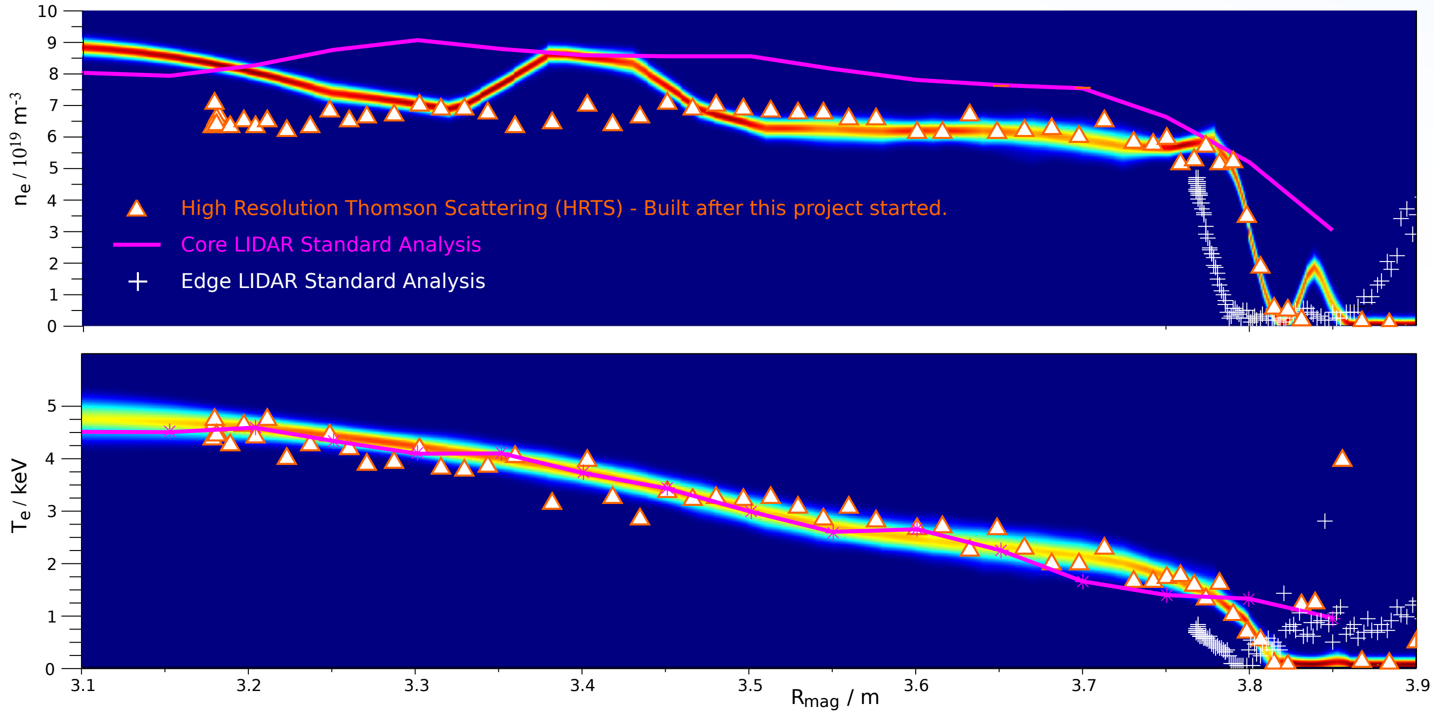

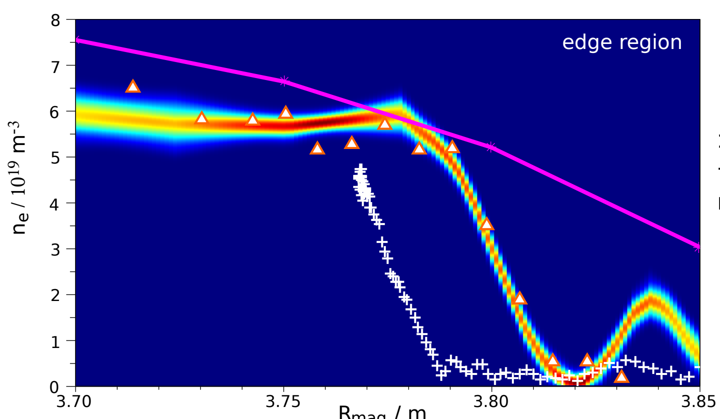

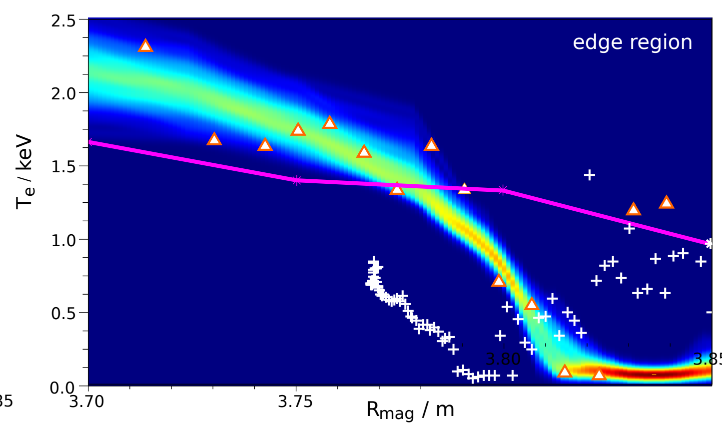

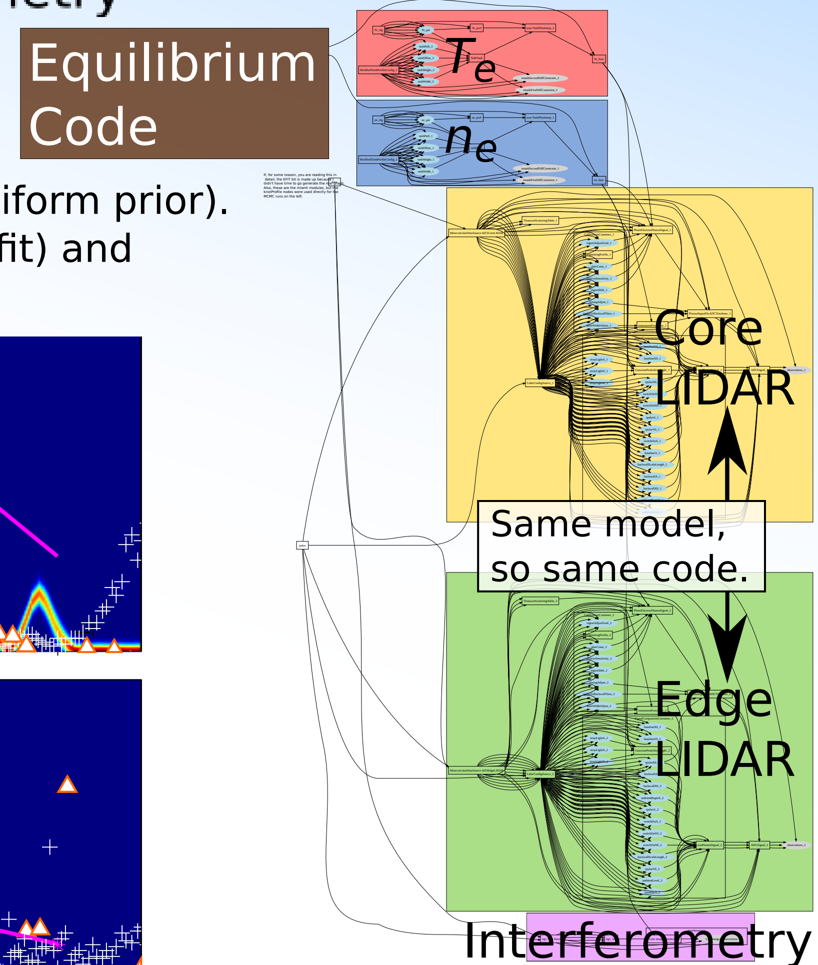

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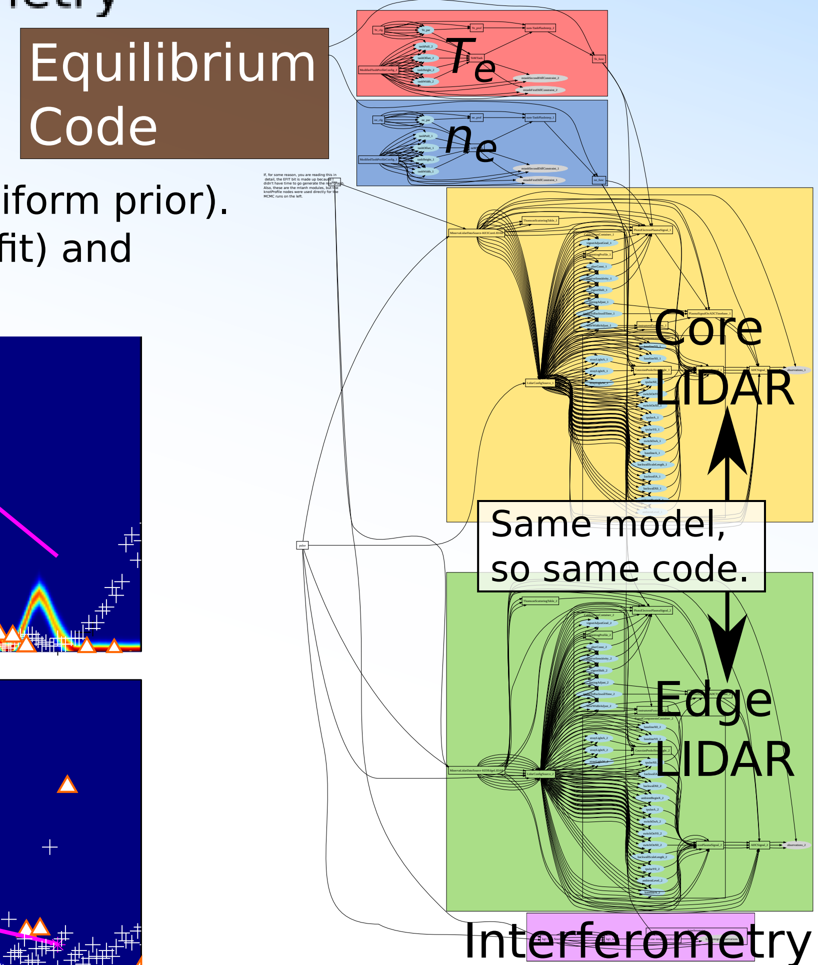
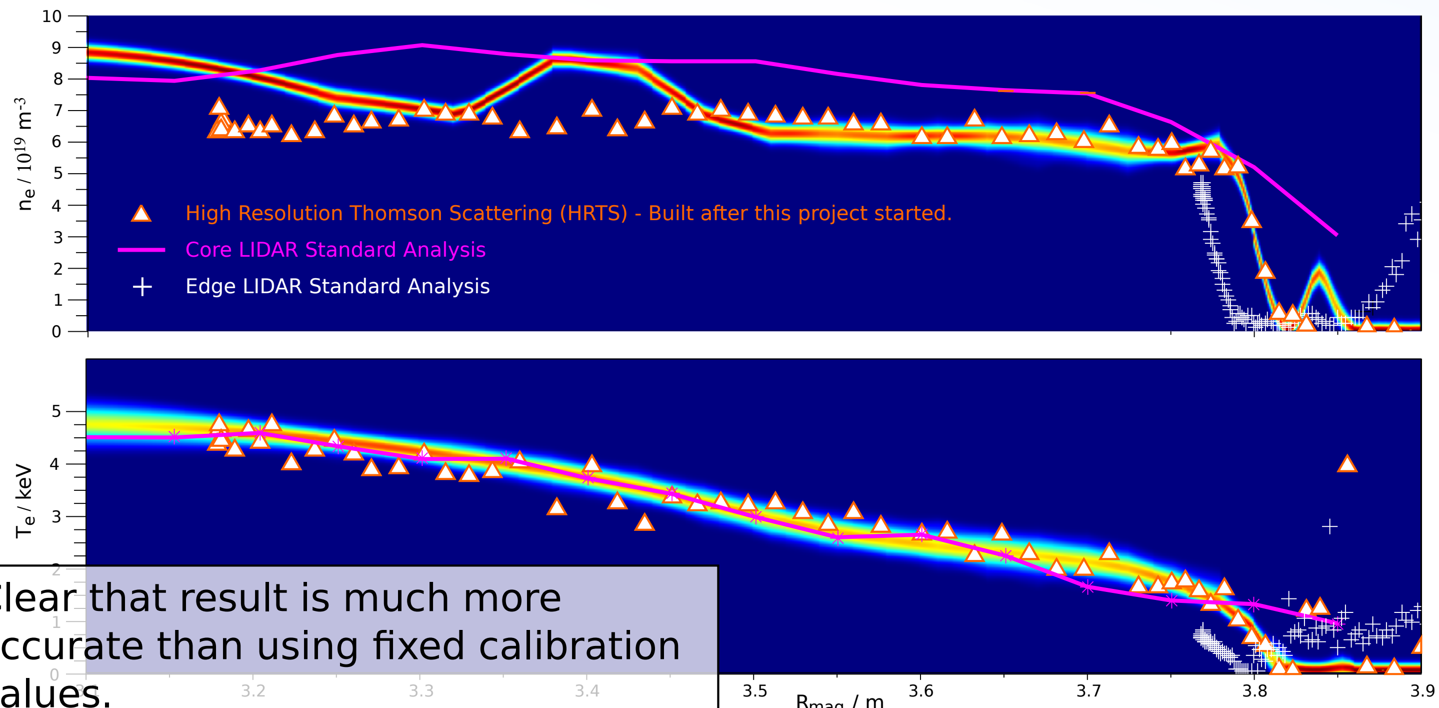
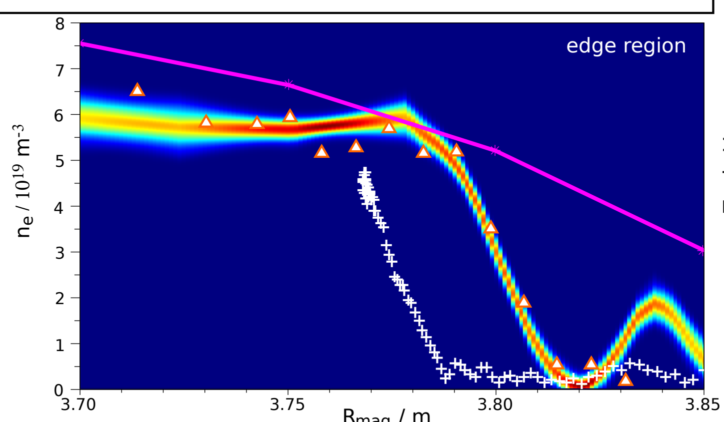
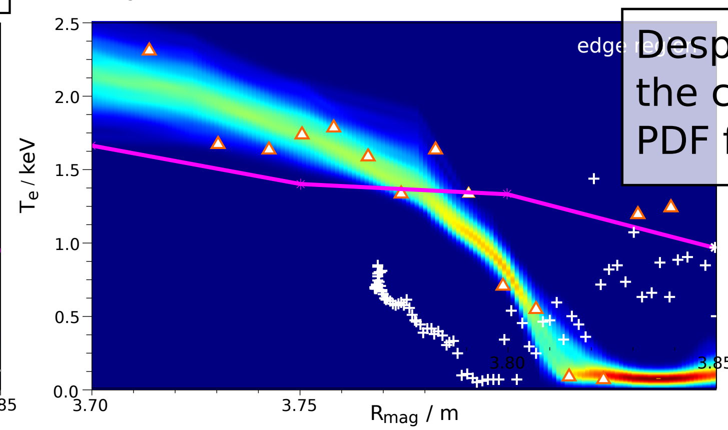




Clear that result is much more accurate than using fixed calibration values.





Despite completely free T_e calibration, the combination can fix Te and gives a PDF for the calibration values.

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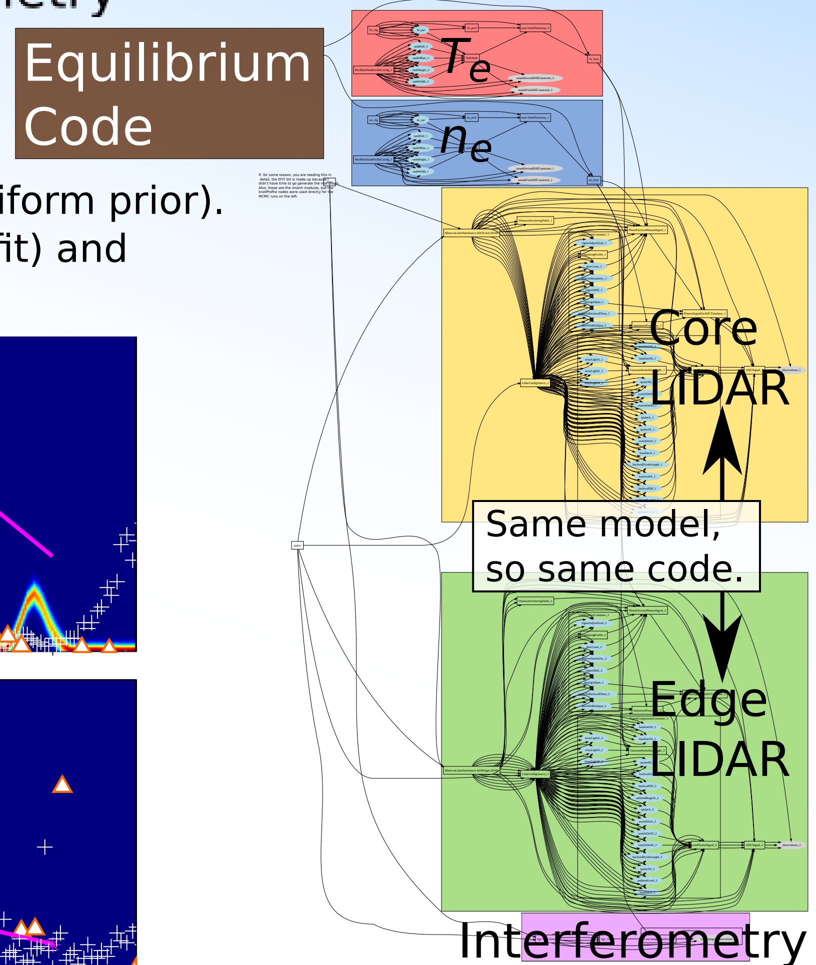

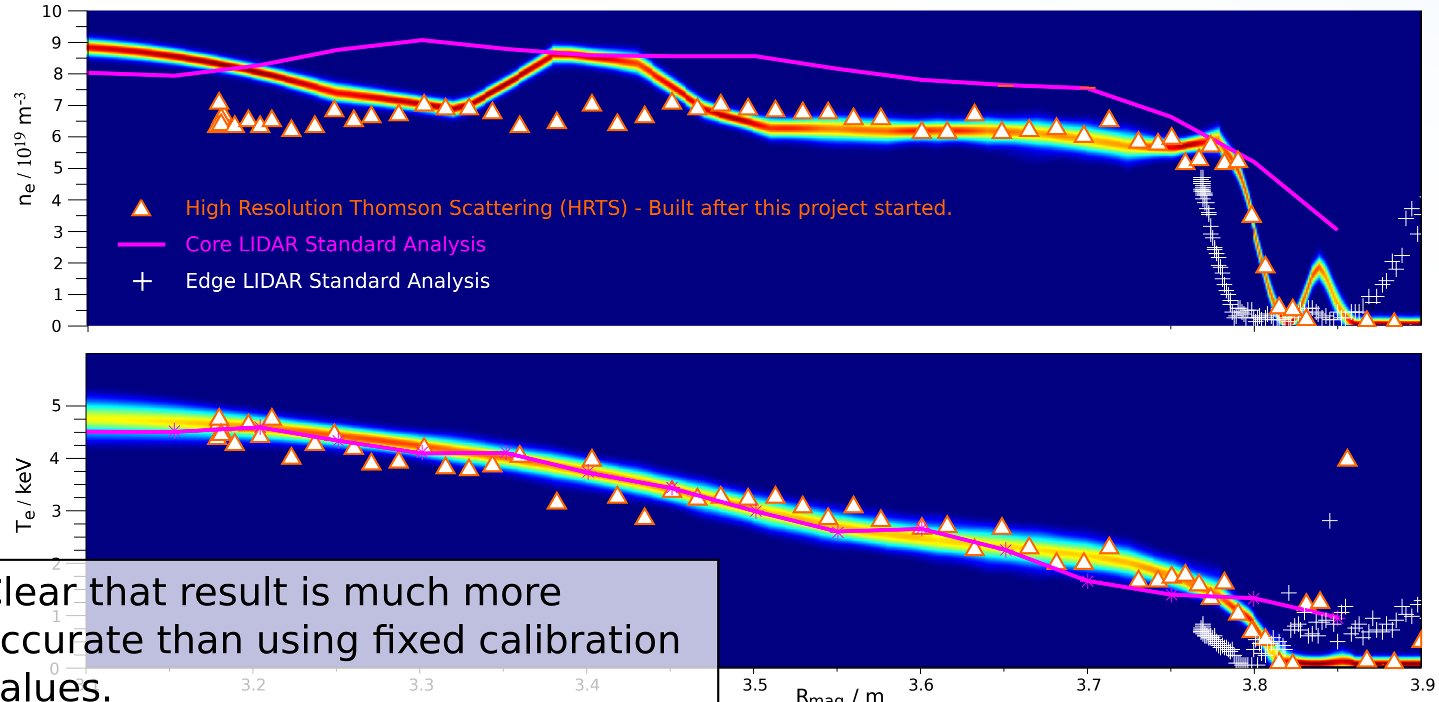

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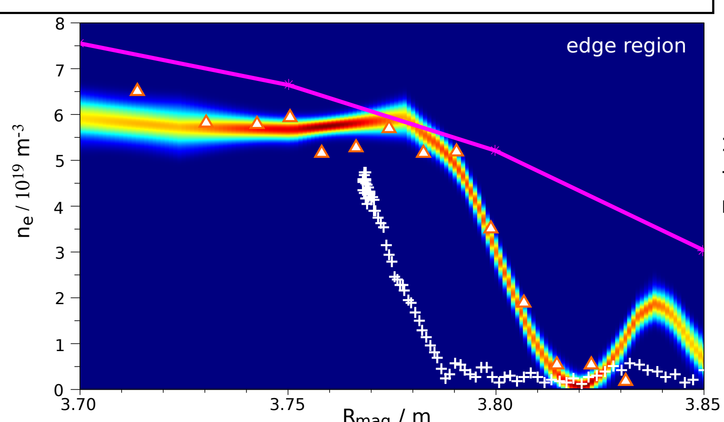
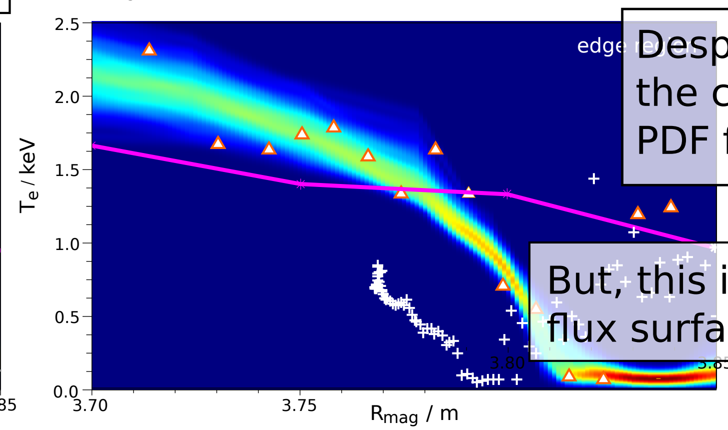


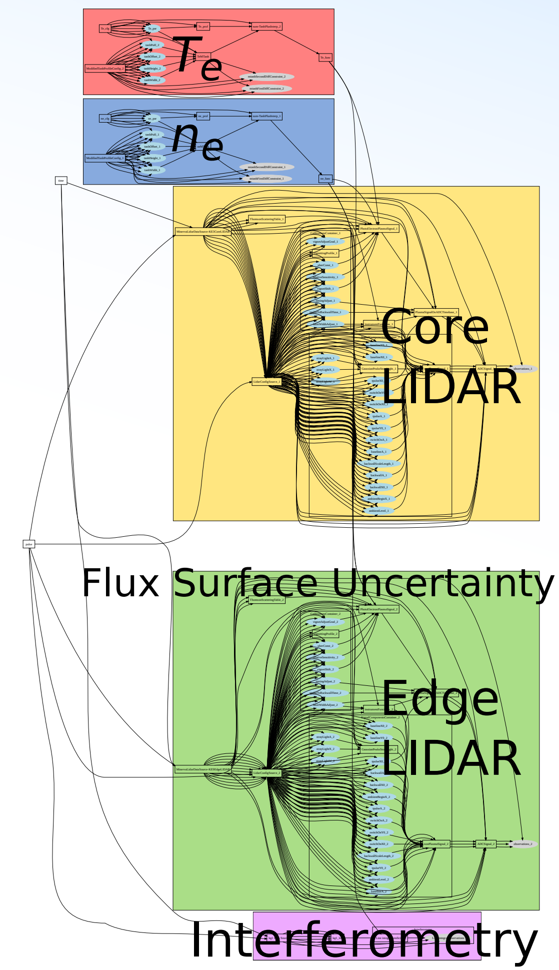


Despite completely free T_e calibration, the combination can fix Te and gives a PDF for the calibration values.

But, this isn't complete - we are still using flux surfaces fixed to the equilibrium code.

Core LIDAR + Edge LIDAR + Interferometry + Magnetics

Connect magnetics model and run inversion.



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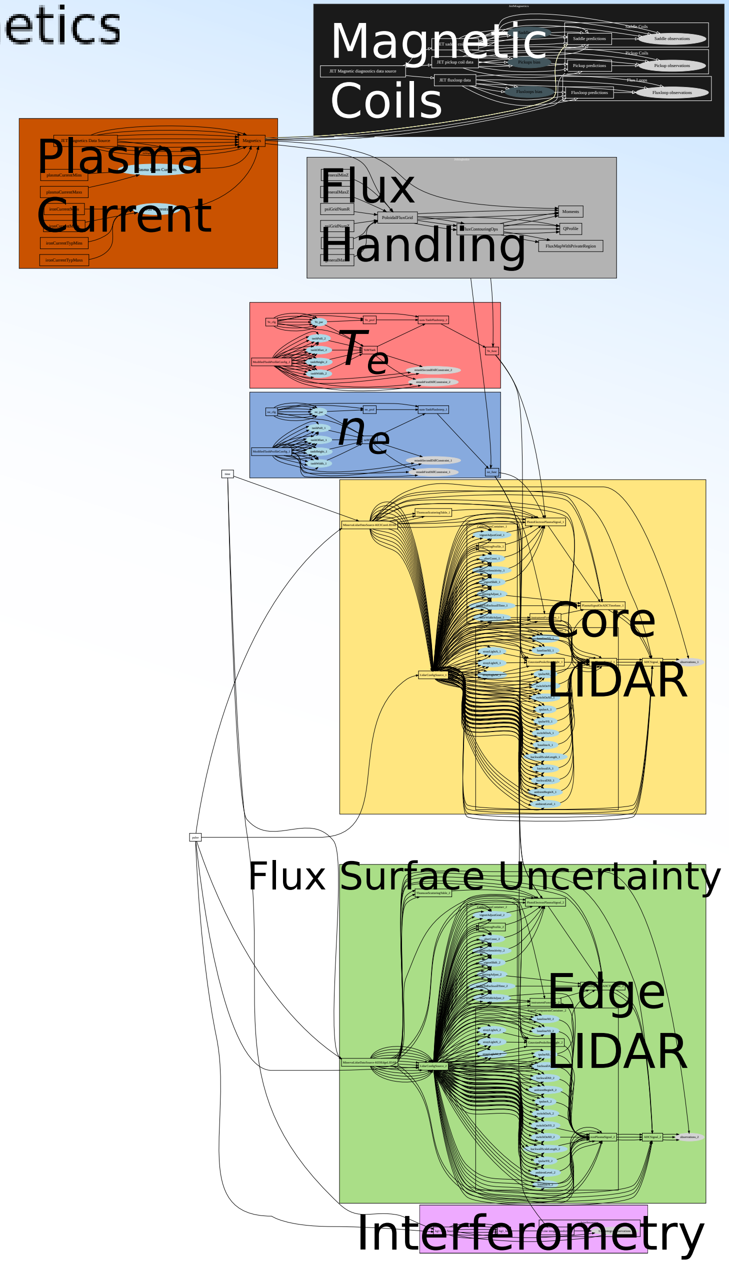

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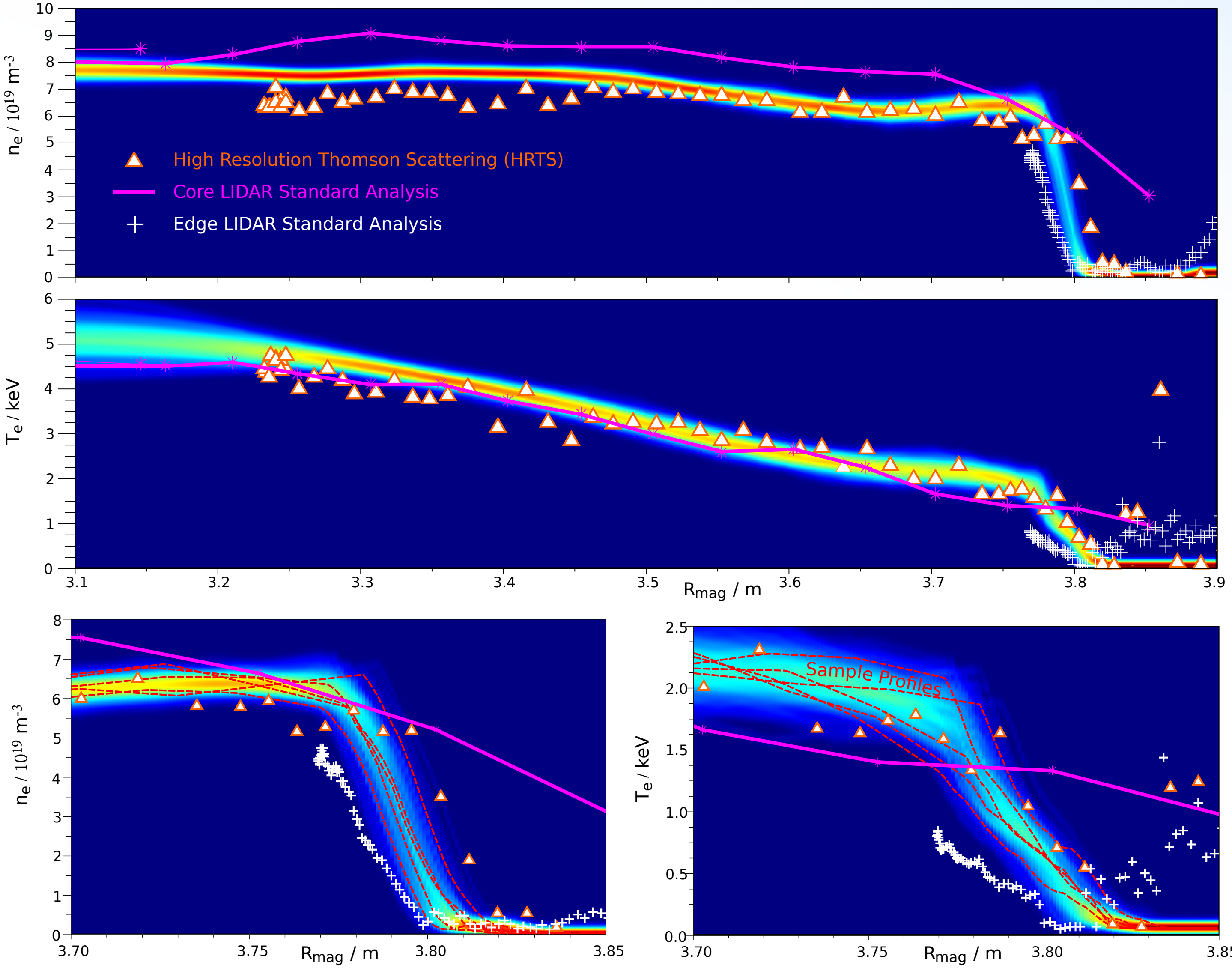

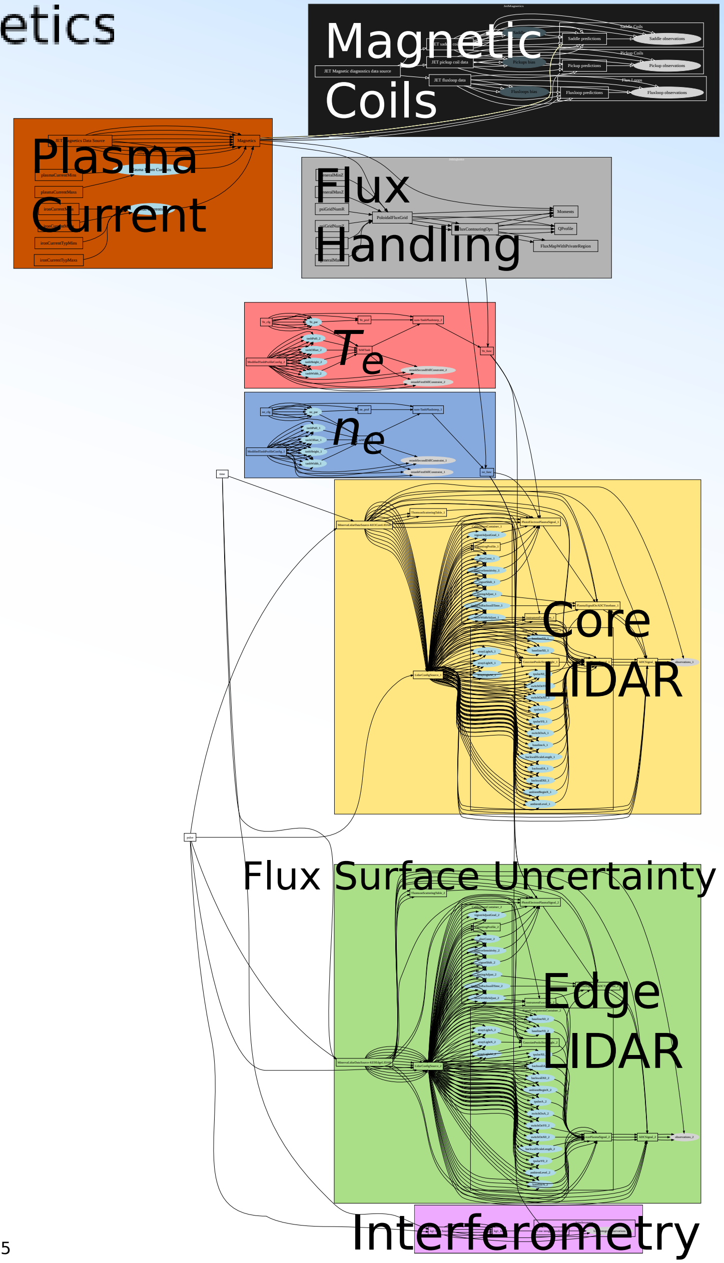

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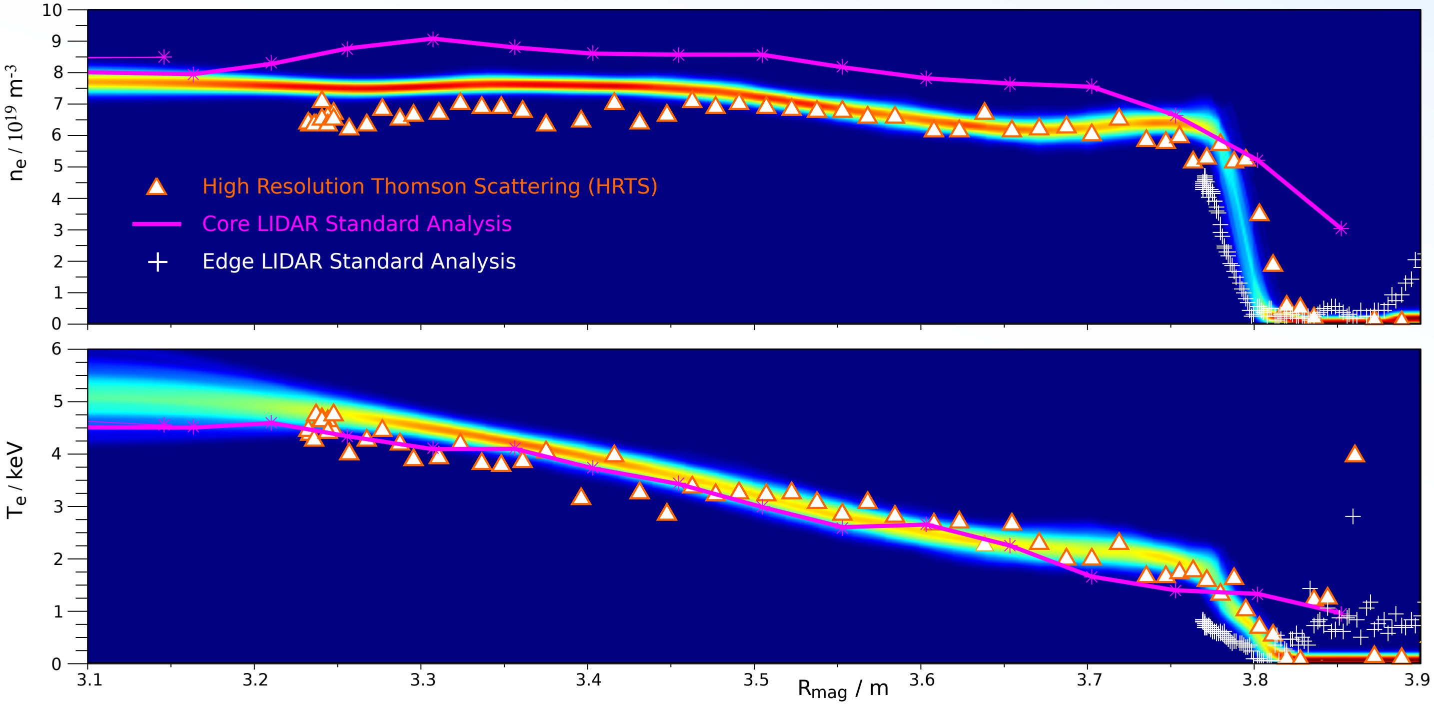

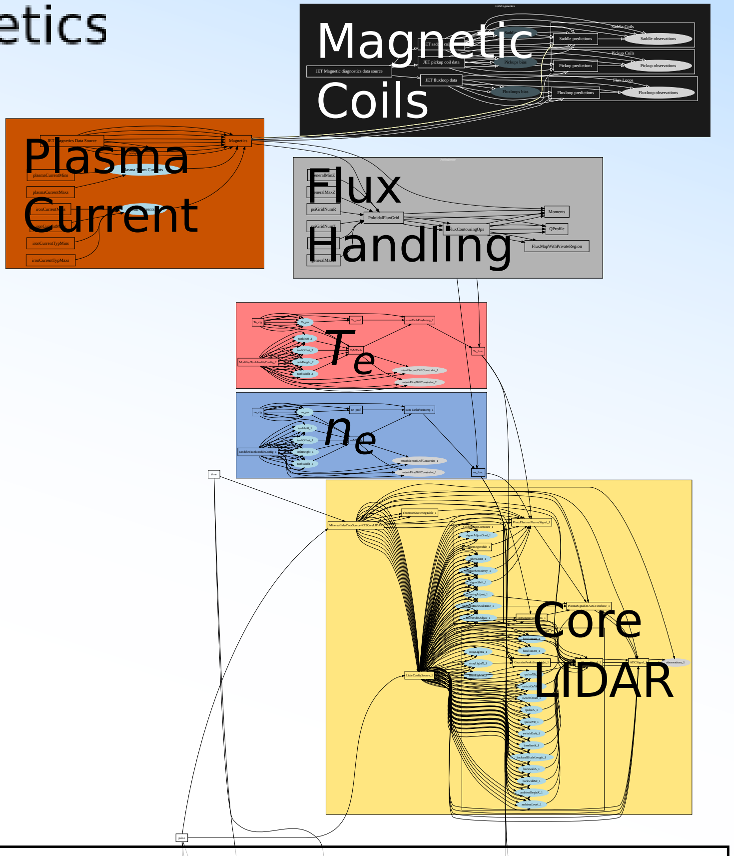

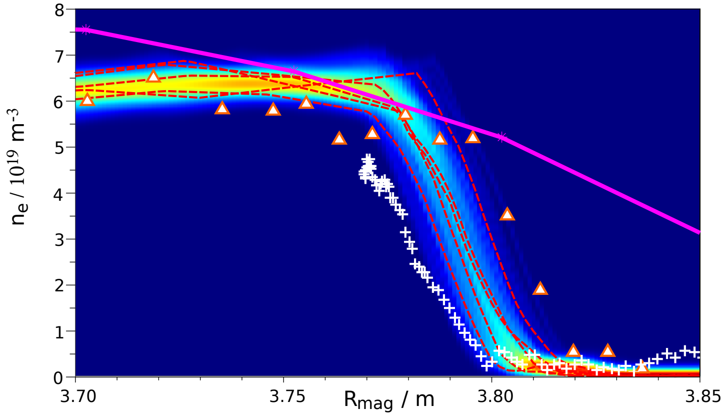

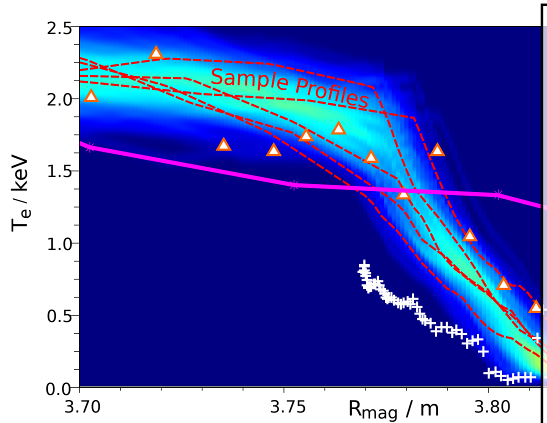

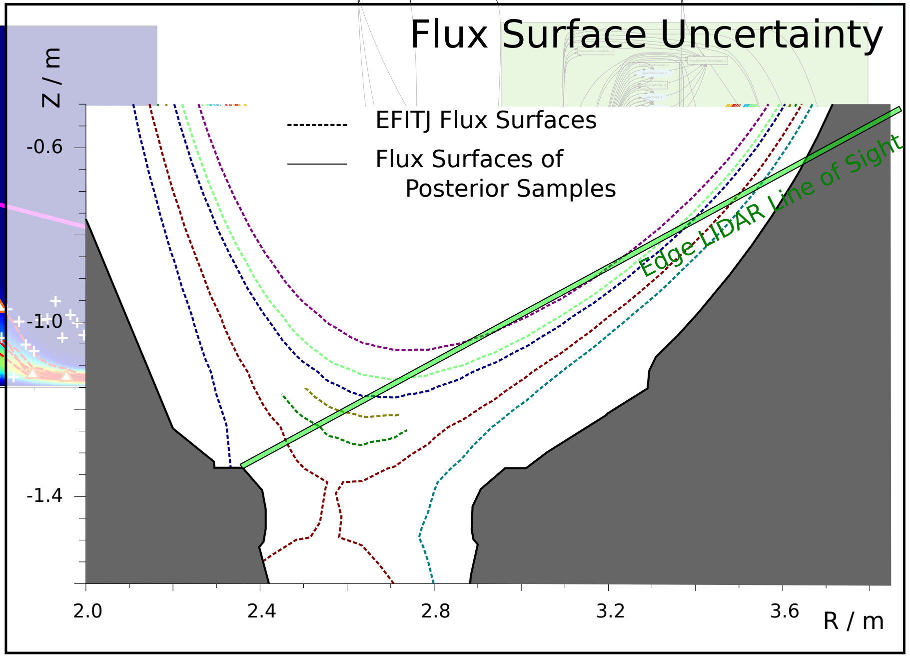

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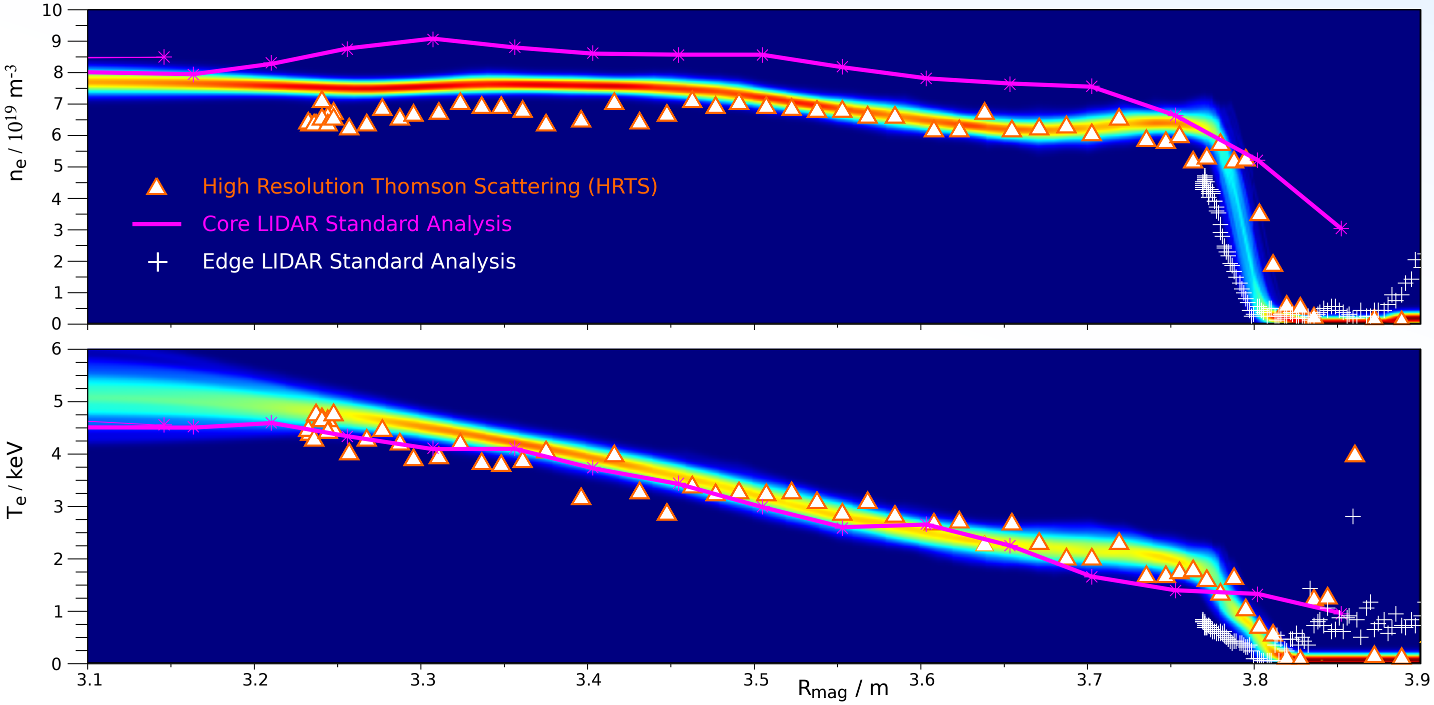

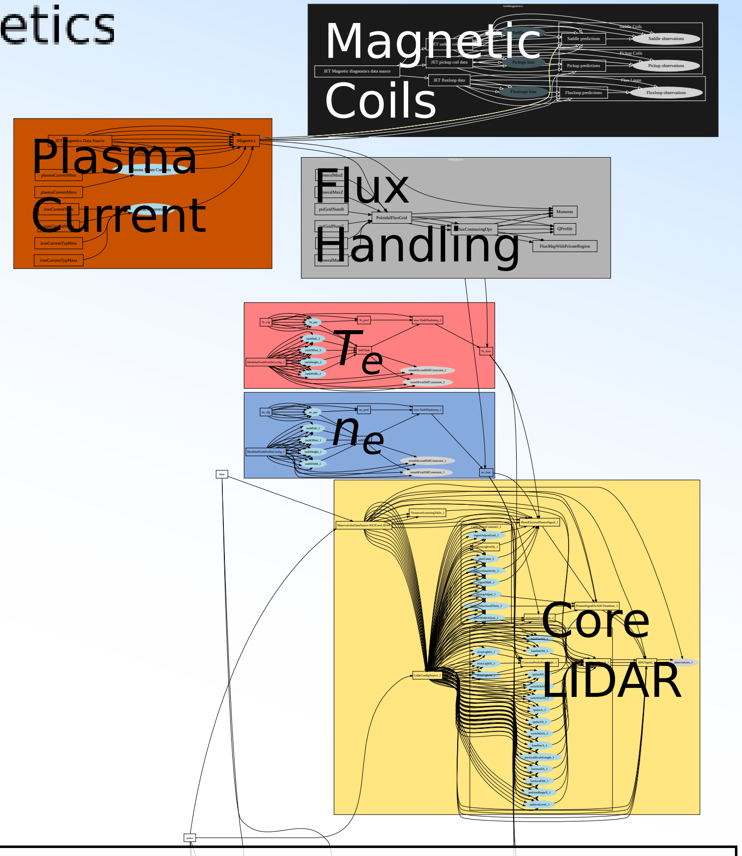

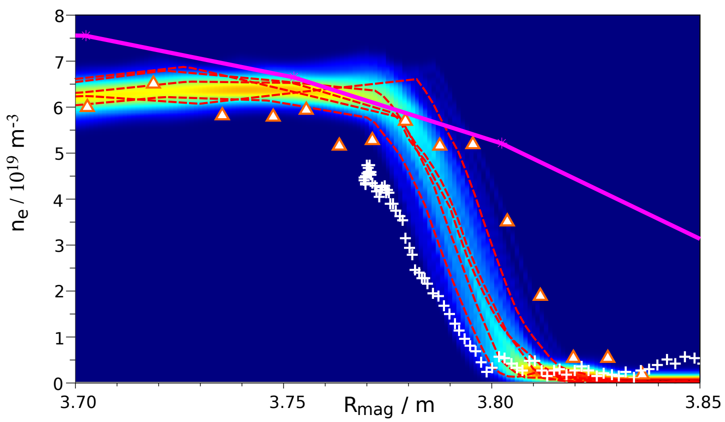

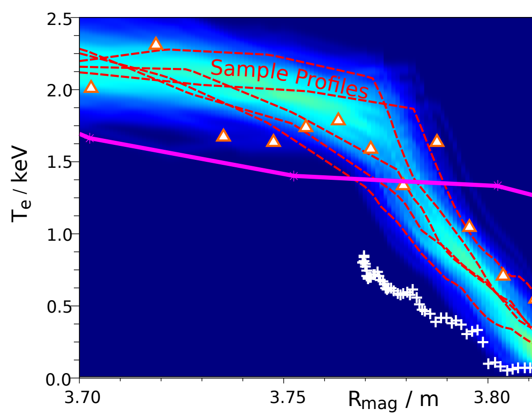

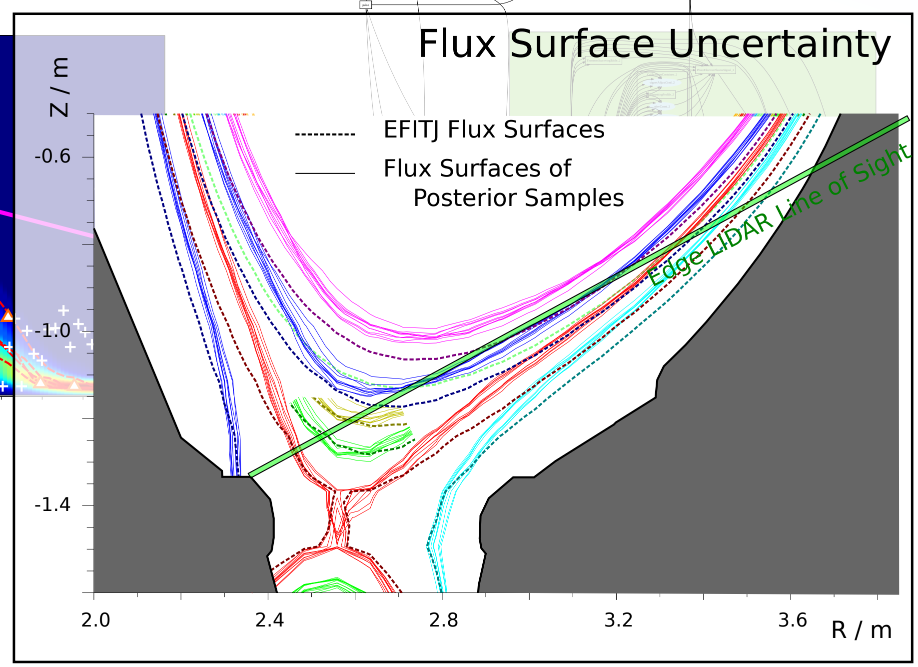

The TS diagnostics provide information on plasma current near line of sight.
Plasma current one of the most important and least diagnosed parameters in Tokamaks.

Core LIDAR + Edge LIDAR + Interferometry: Pedestal Evolution Study

Looked in detail at evolution of ne/Te pedestals through the ELM cycle. 28 time points over 6 almost identicle pulses.

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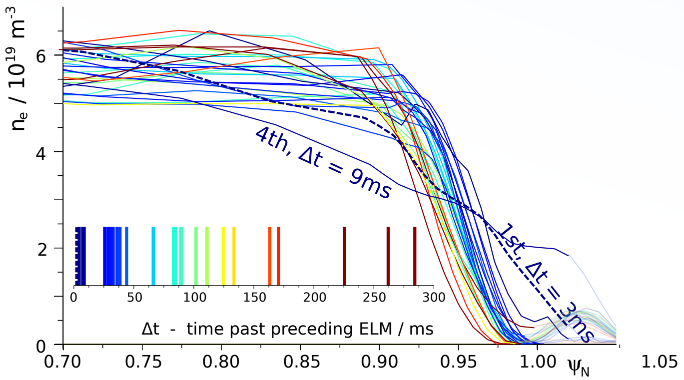

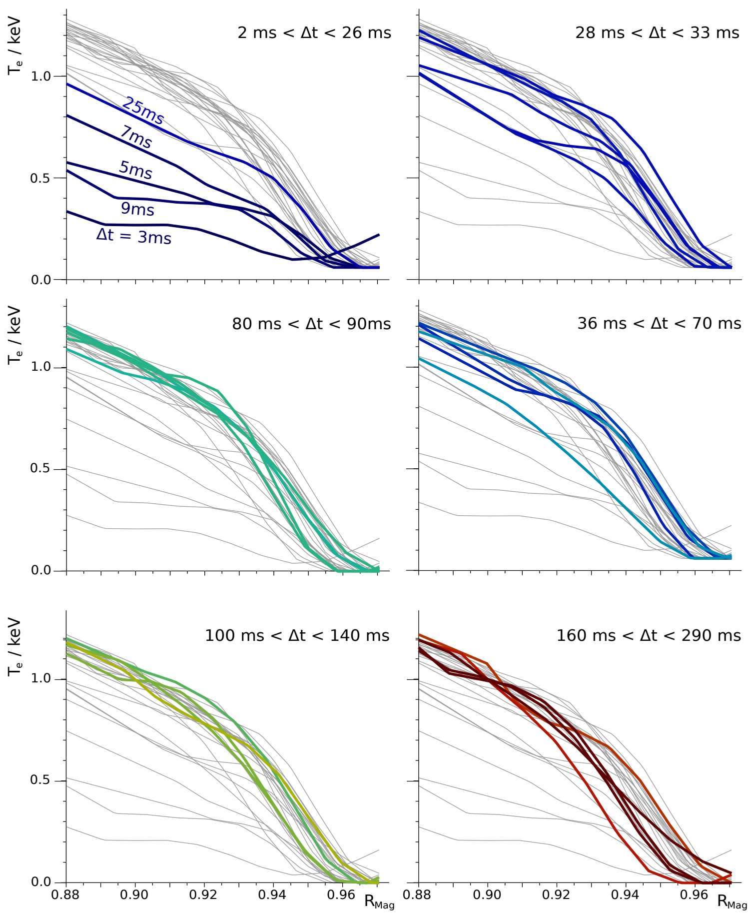

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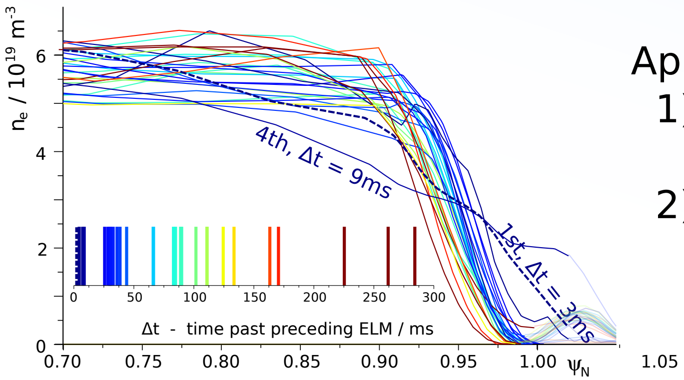
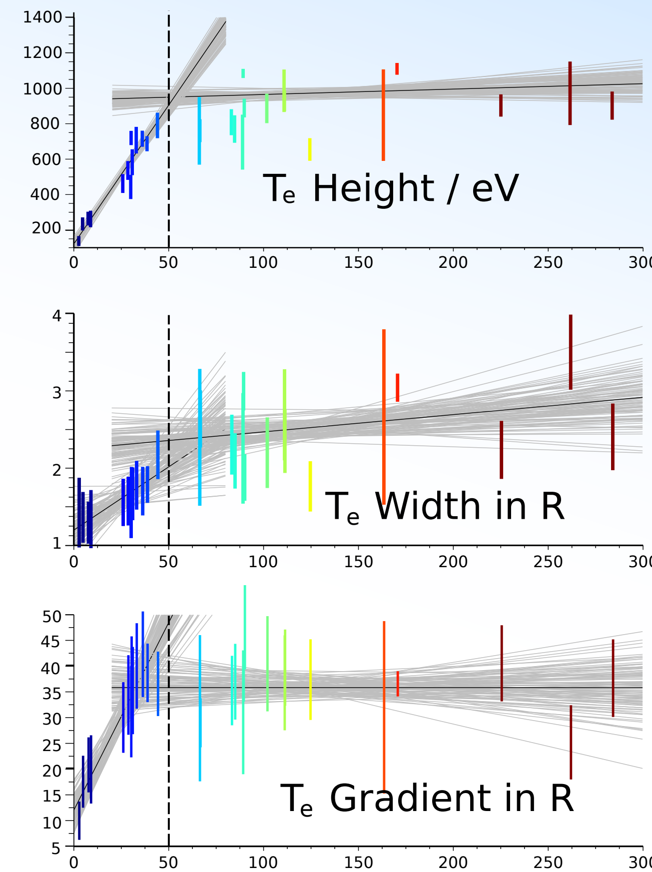
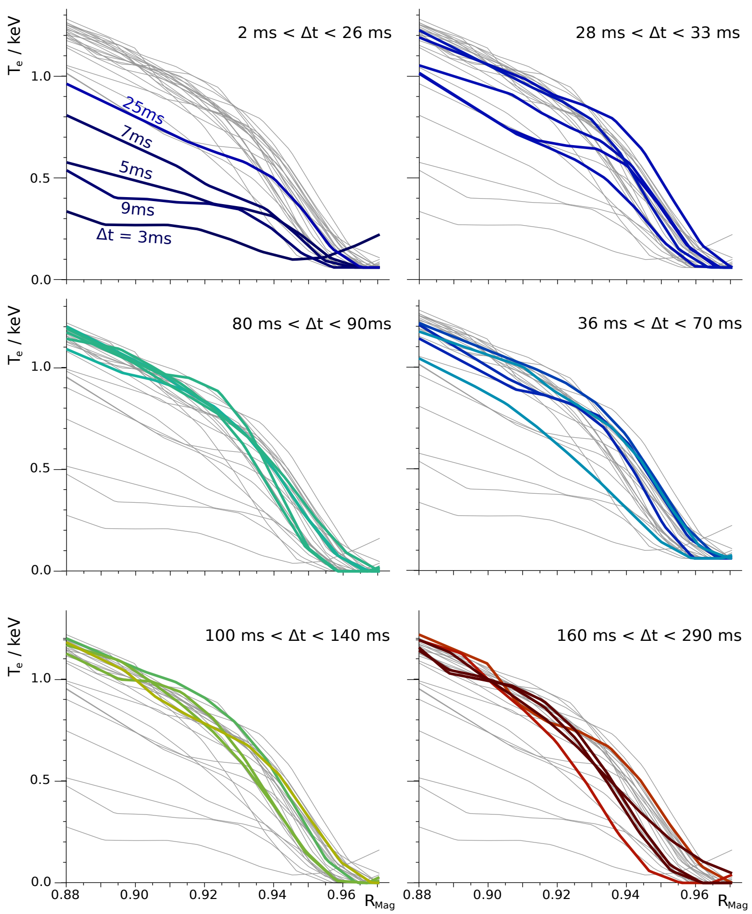


Appears to be two distinct phases for *Te*:

1) Rapid rise in height and gradient during first 50ms.
2) Slow rise in height and width at fixed gradient until next ELM.





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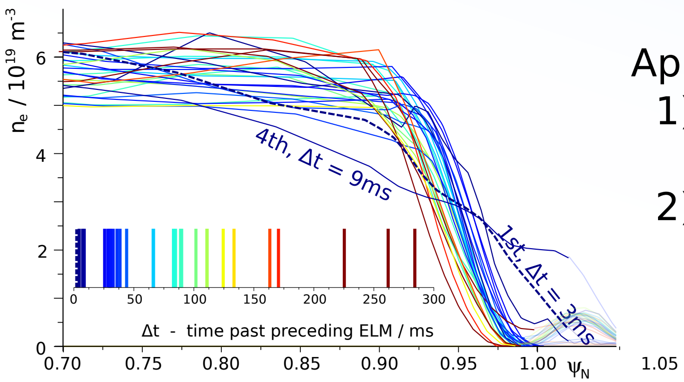

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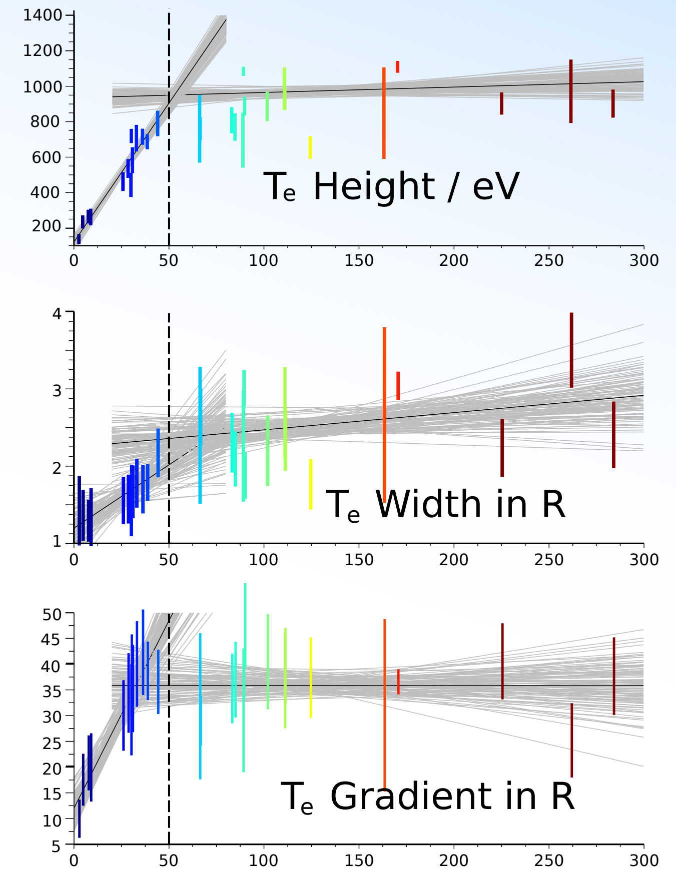
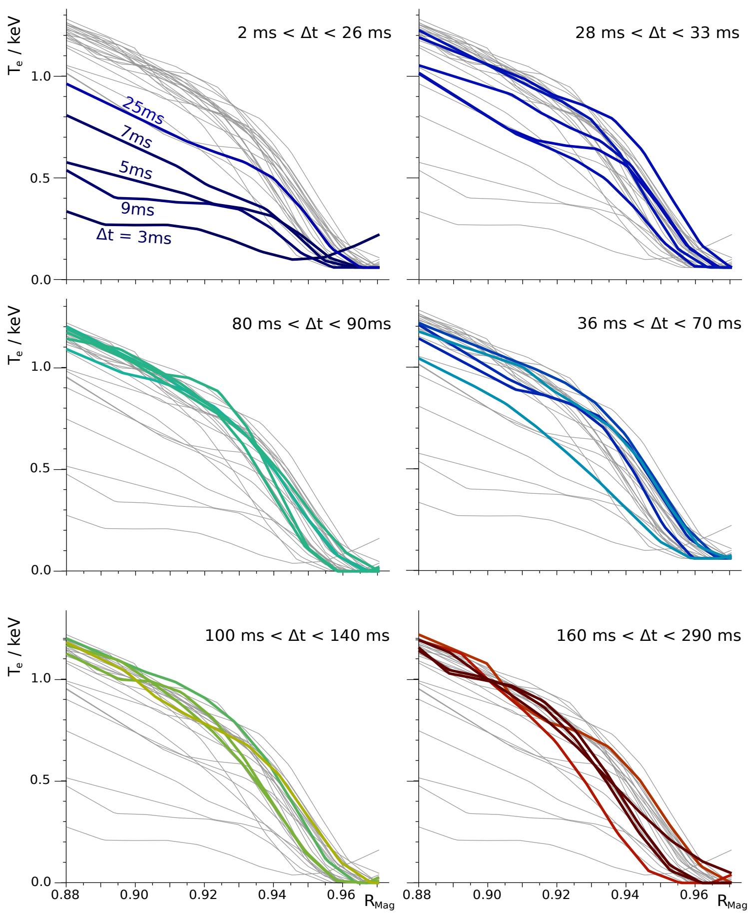
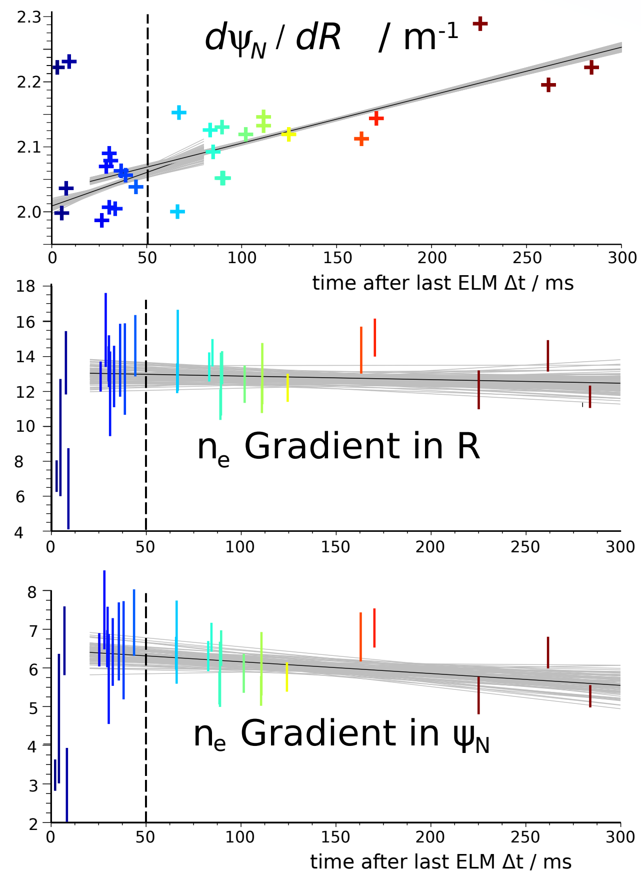




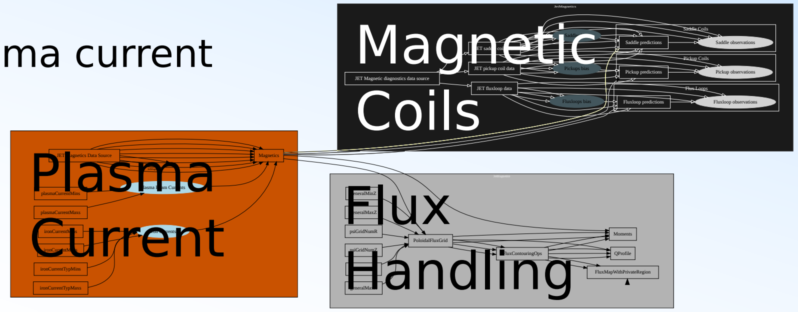


Some indication that *ne* pedestal has a fixed gradient in real space despite compression of flux surfaces.

Equilbrium I

Inference of plasma current and flux surfaces P(ψ_N | ...) is the big problem.

With enough extra diagnostics, it might be possible to infer plasma current accurately, entirely from data.



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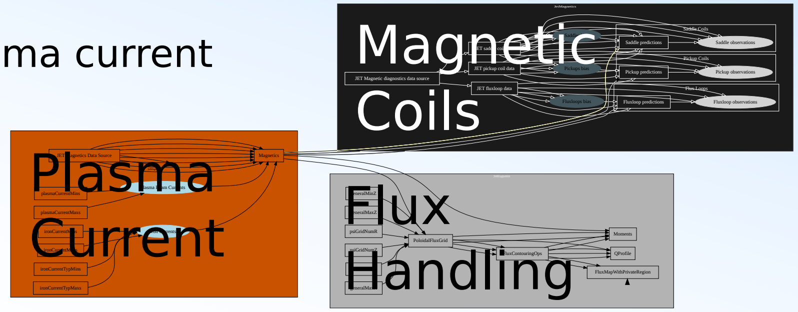

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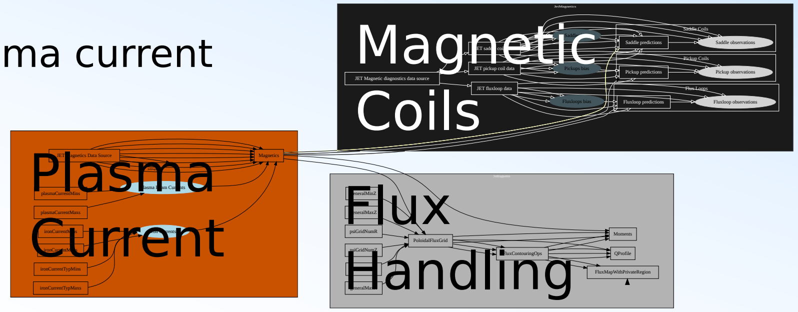

For now, we can add the prior assumption of Equilibrium.
(Isotropic and no flow)

$$J_\phi = Rp' + \frac{\mu_0}{R} f f'$$

NB: It's not immediately clear how restrictive force balance (GS equation) actually is, since it is almost always used with strong prior constraints on *p*' (or *p* - the equilibirum pressure) and *ff*' (or *f* - the poloidal current flux). With weak contraints on *p*' and *ff*', the space of possible solutions is still very large.

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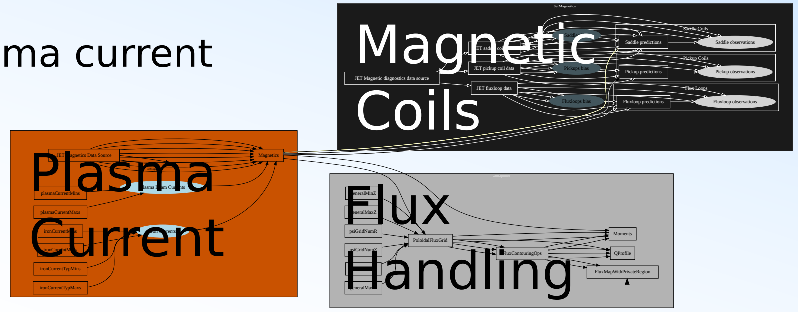

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Assume GS equality is almost correct: assign a PDF on difference:

P(*J*, *p*', *ff*') = G(*J* - *Rp*' - *ff*'/*R*;   0, σ_{GS}) with small σ_{GS}.

The posterior P(*J*, *p*', *ff*' | D_{diags} + ~Equilibrium) will include all possible combinations of *J*, *p*' and *ff*' that are consistent with the diagnostics, the priors and describe a plasma very close to equilbrium.

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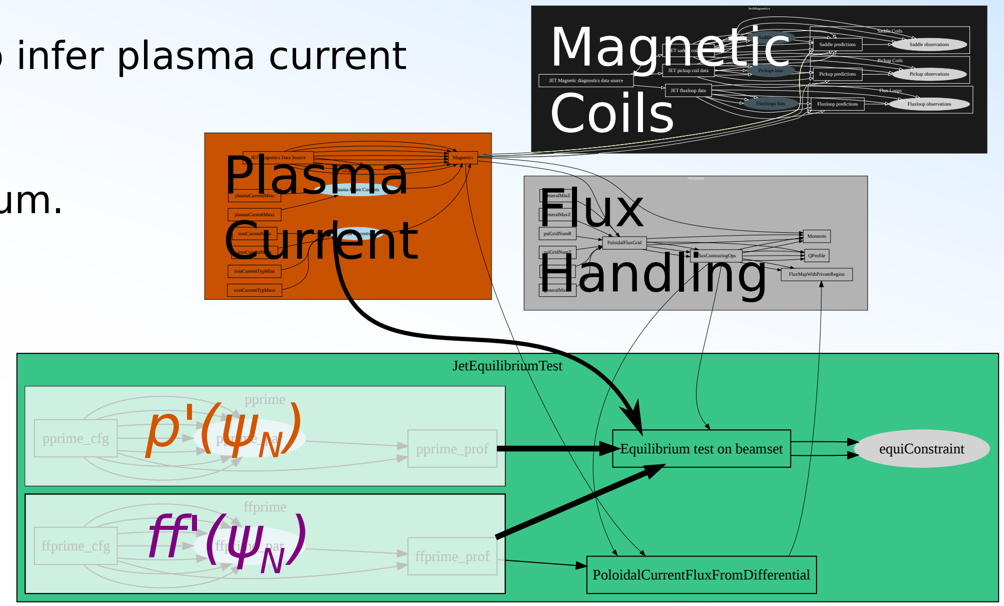

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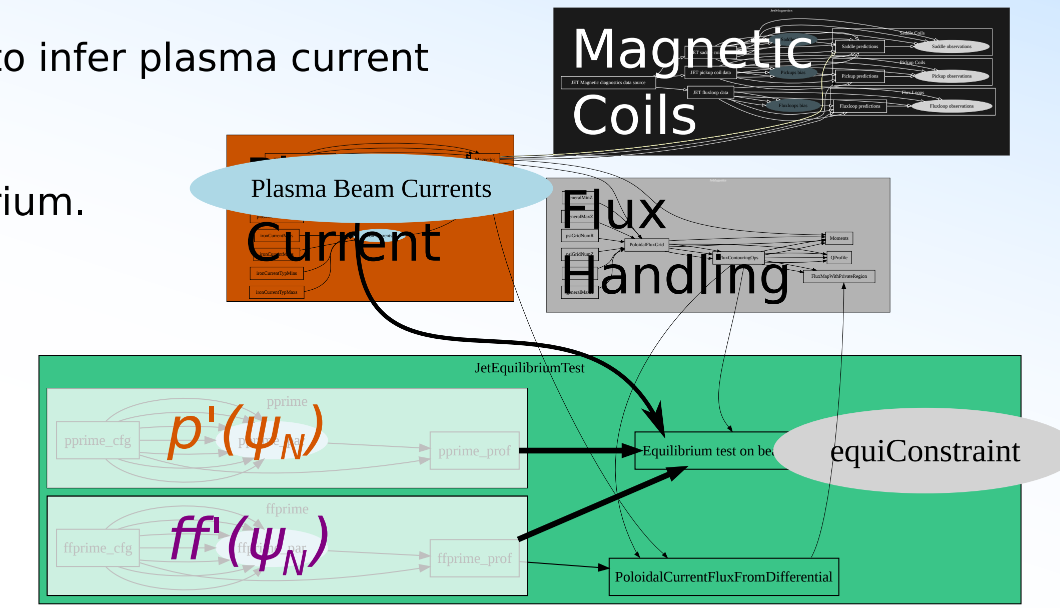

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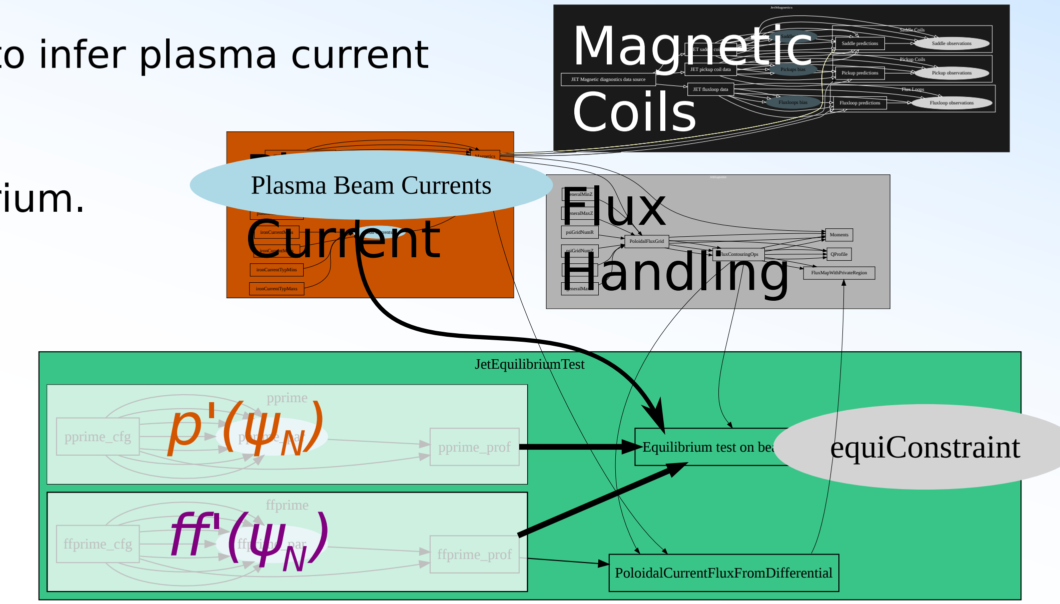

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Adding to model (and the code) is fairly trivial, but, the problem is now very hard for the external algorithms to handle due to non-linear 1000D+ posterior.

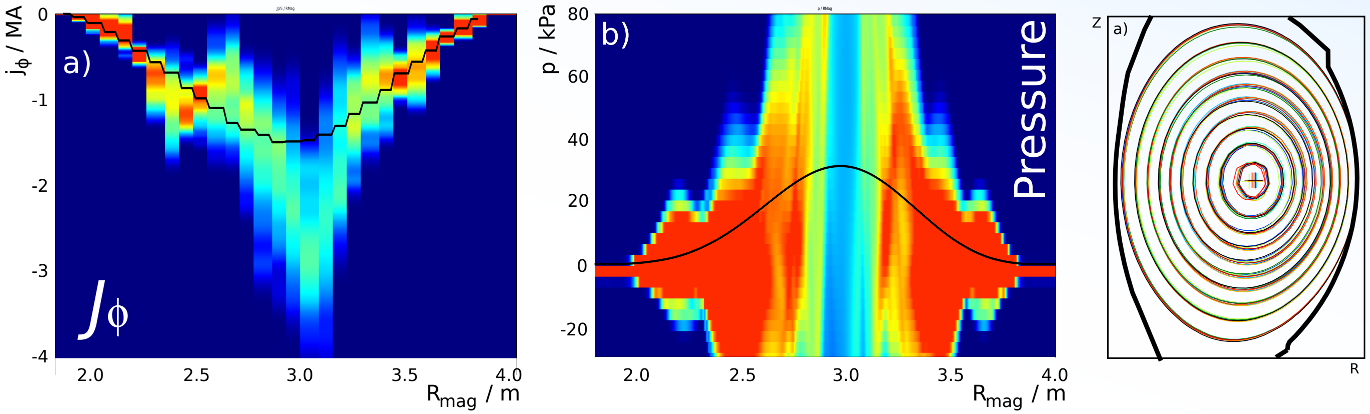
1) Parallelise the linear solver and iterate to find MAP
(slower but more stable than EFIT).

2) Exploring the PDF only just possible for simpler current profile shapes.

Equilbrium II: Posterior Exploratiand MAP estimates.

78601 High ne
H-Mode (pellets)

For simpler L-mode plasmas, we can explore the PDF,



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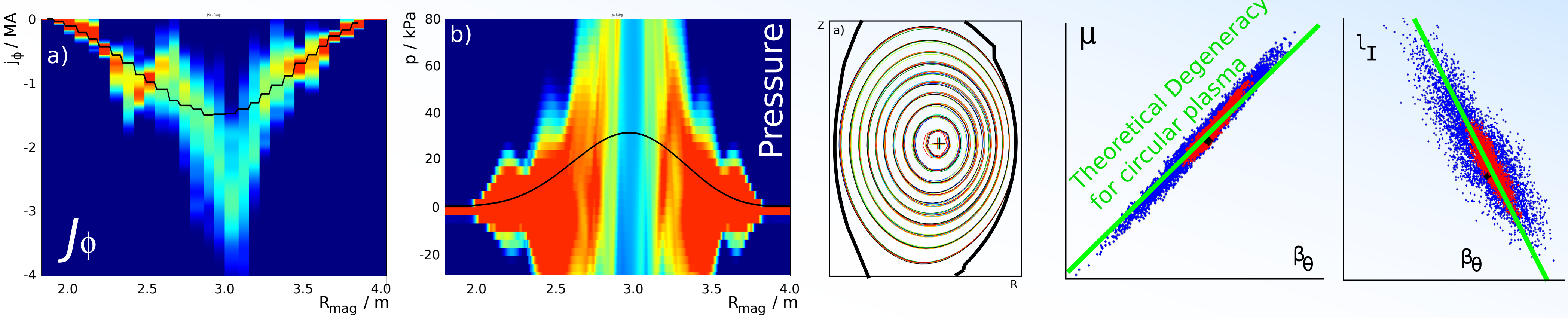

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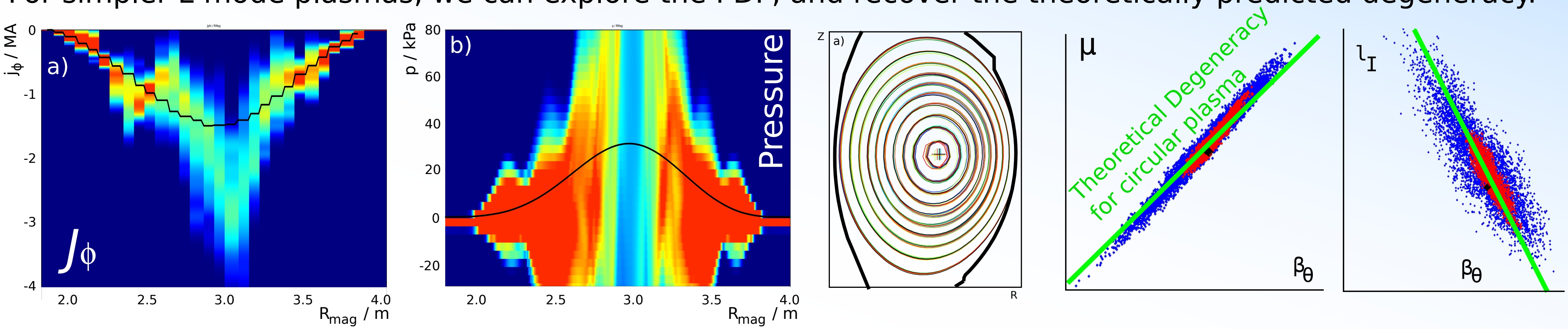

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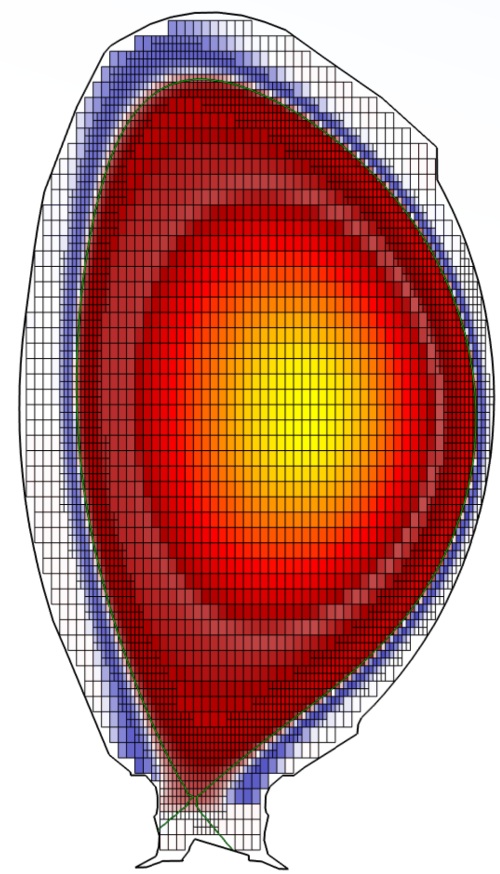

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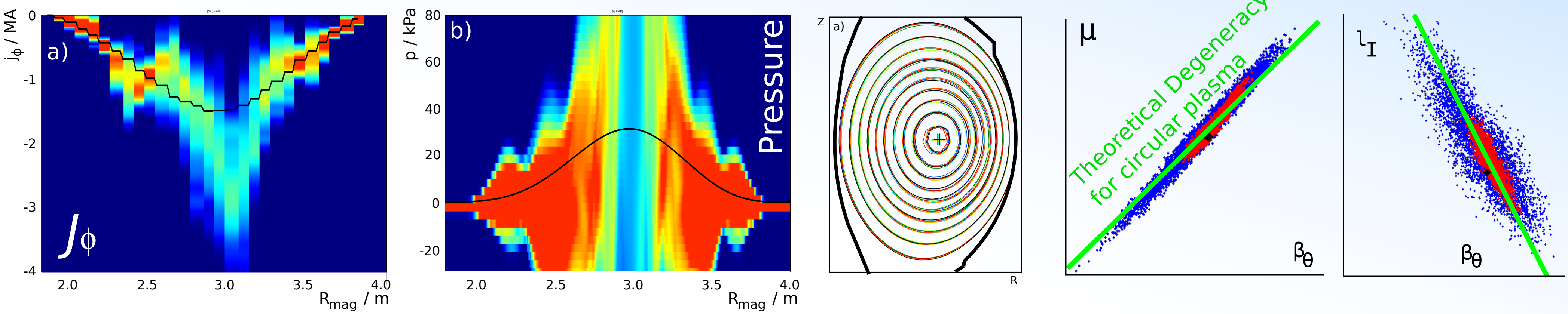

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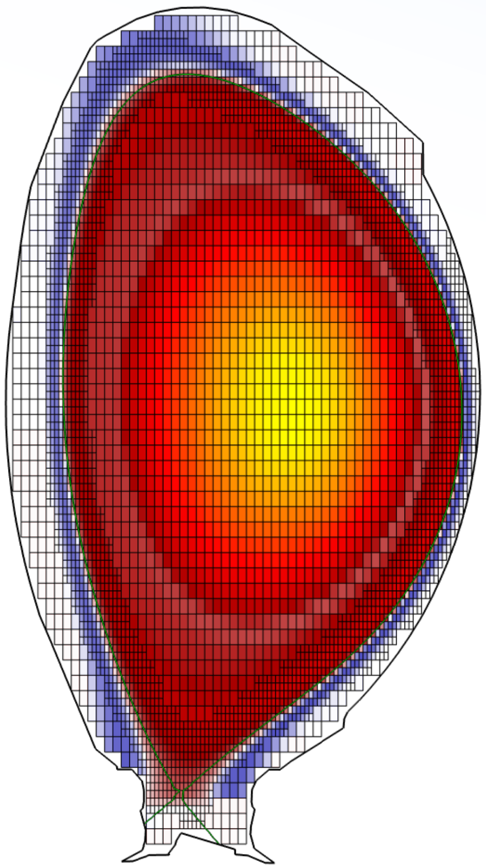

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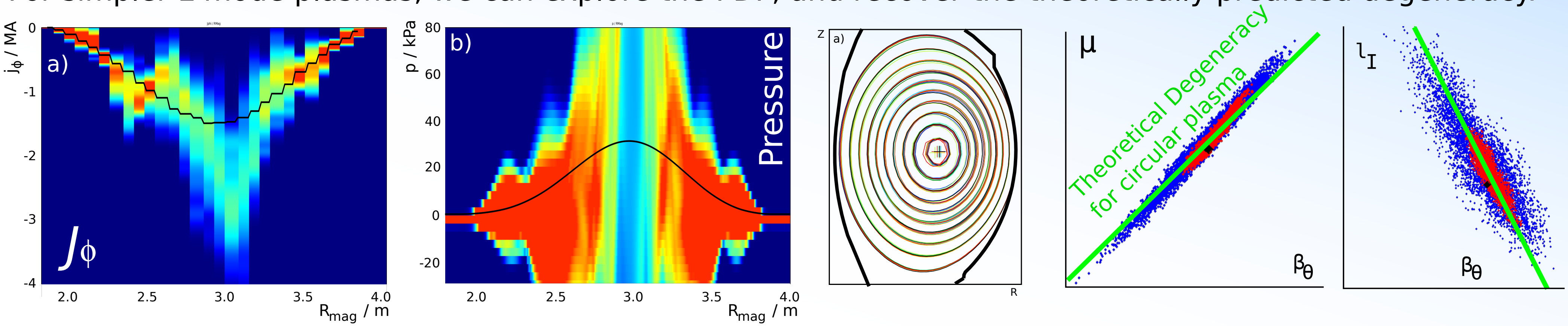

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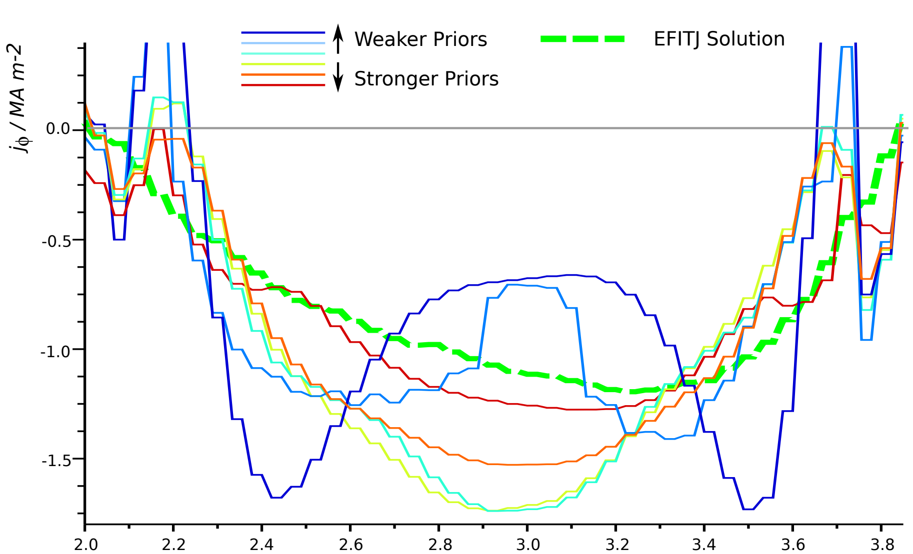

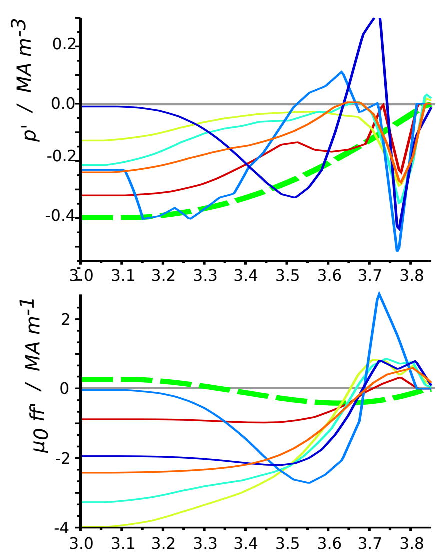

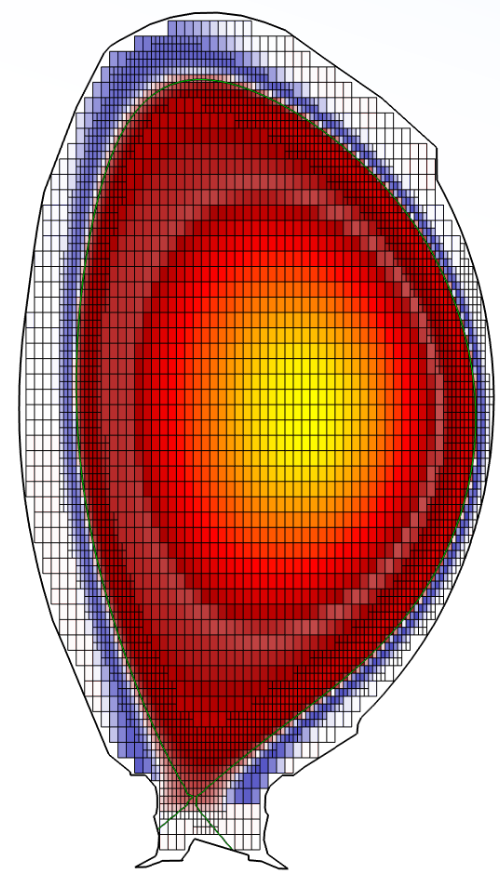

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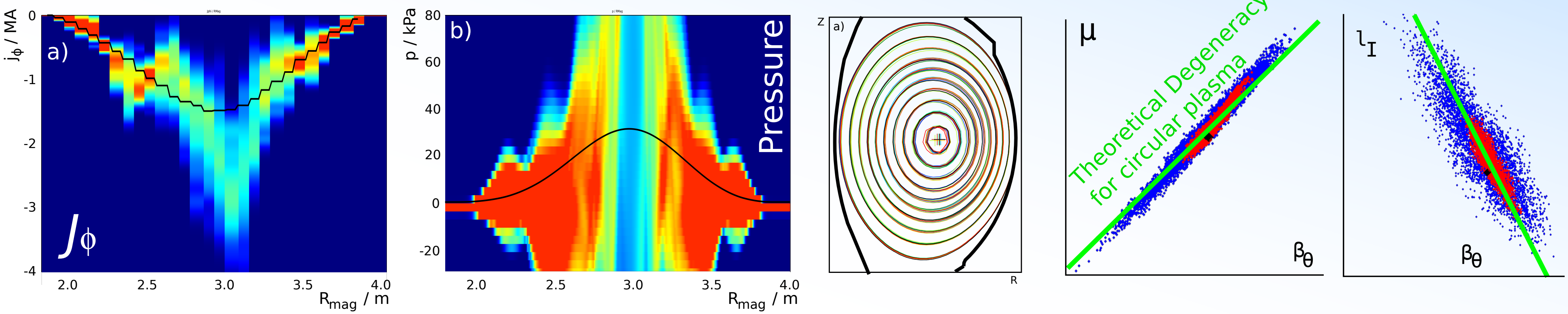

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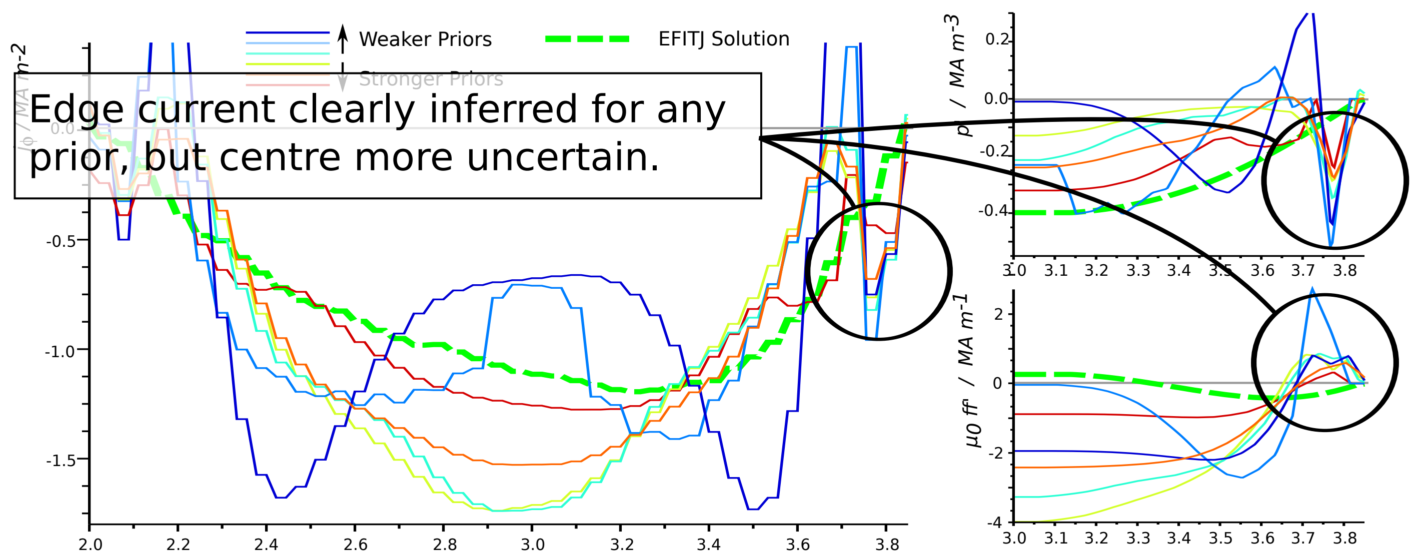

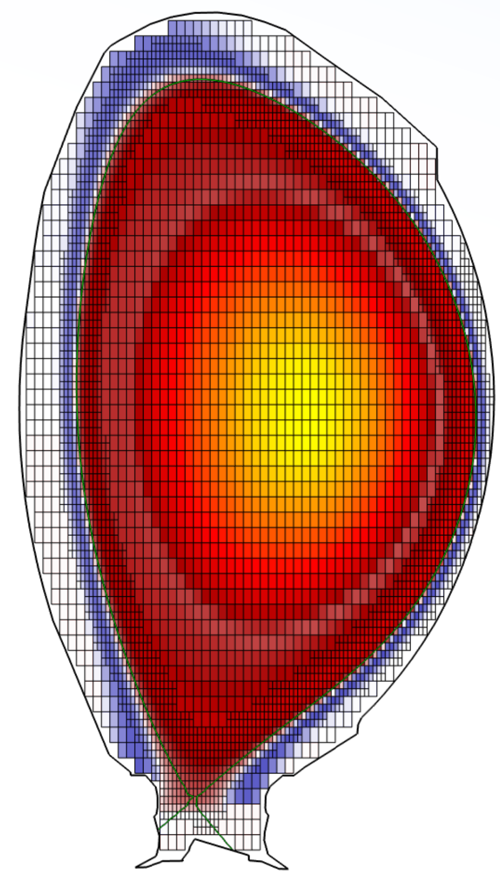

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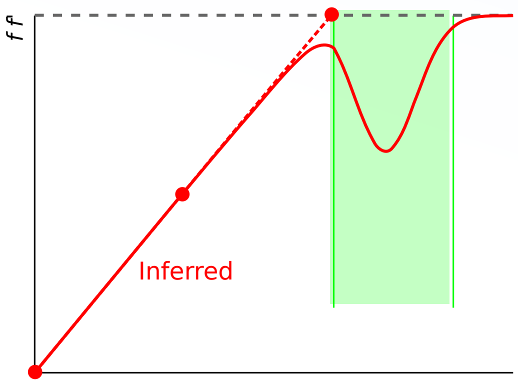

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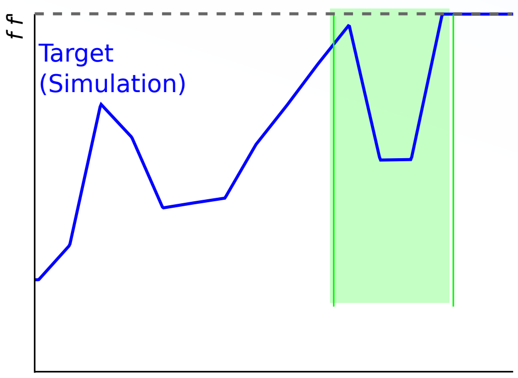

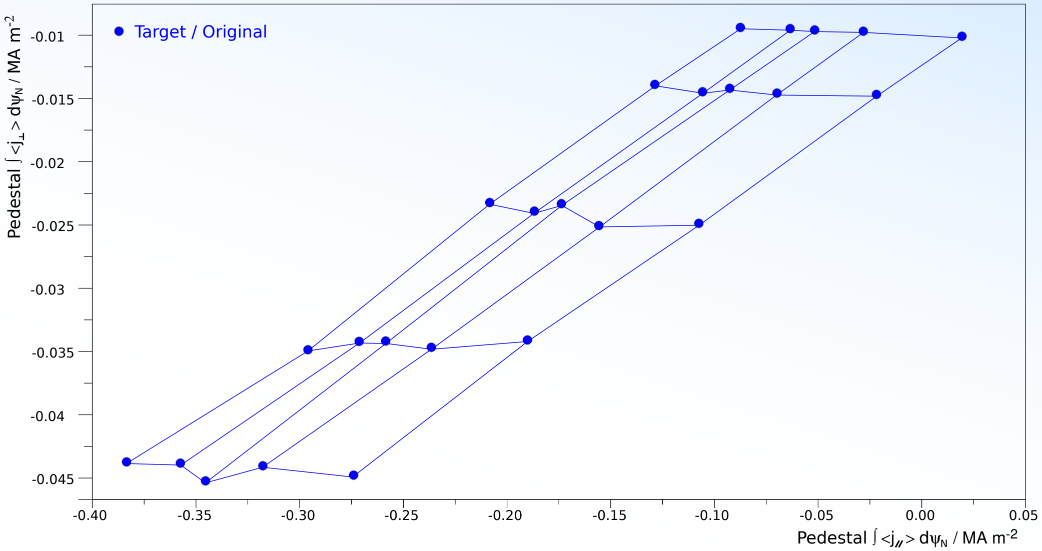

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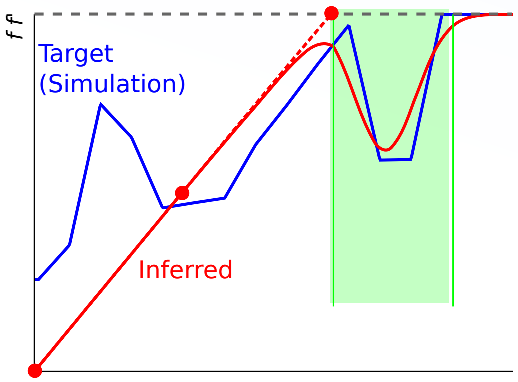

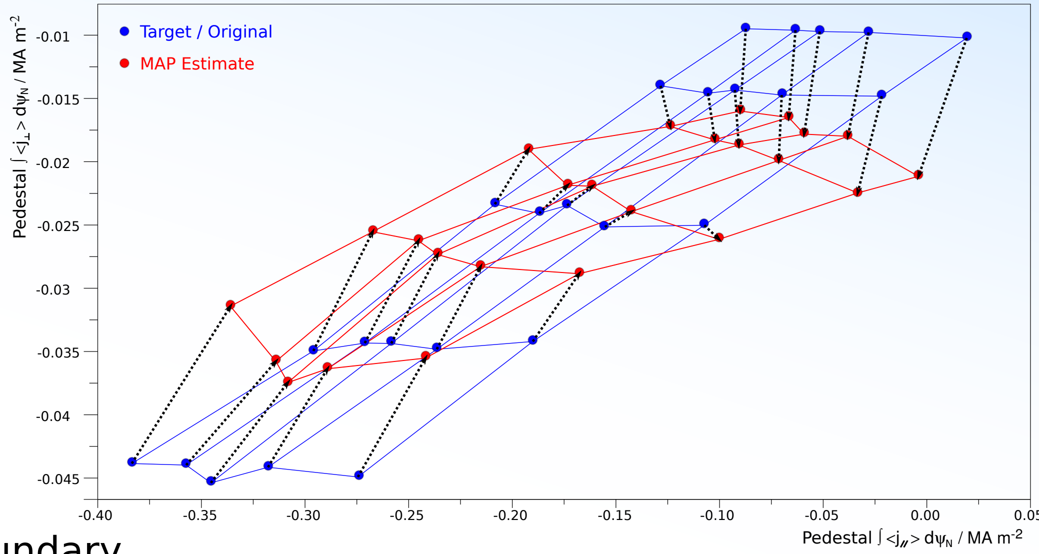

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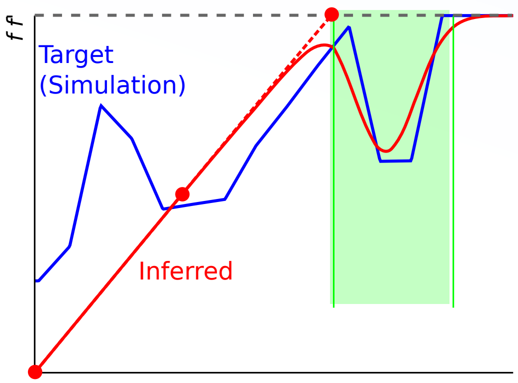

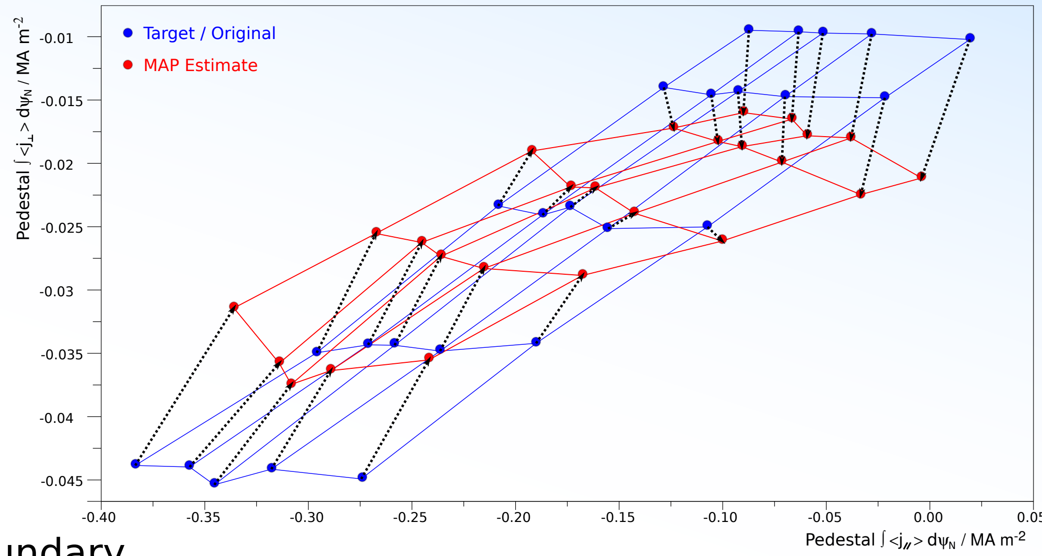

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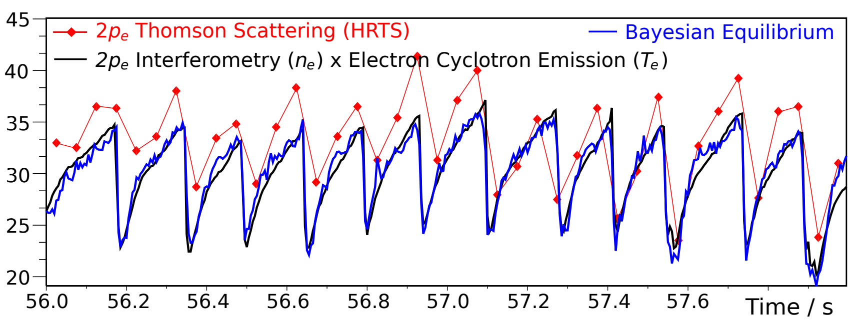

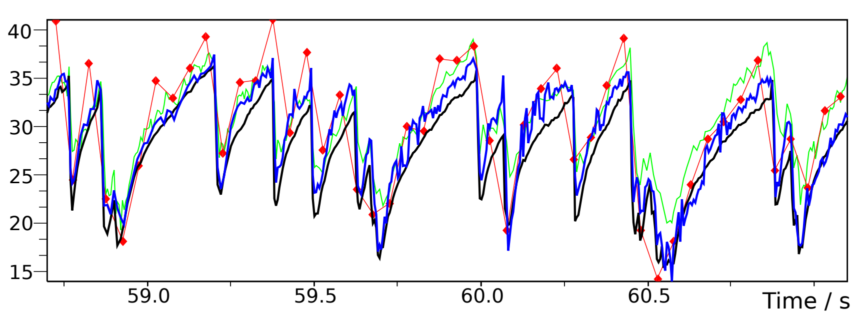

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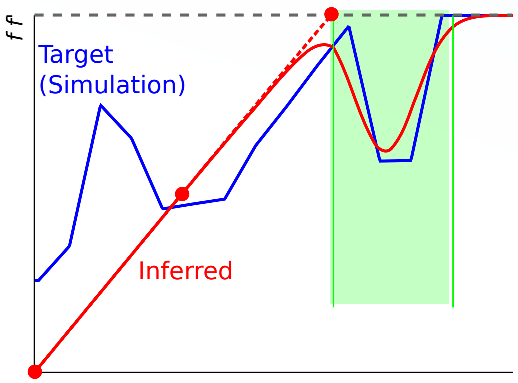

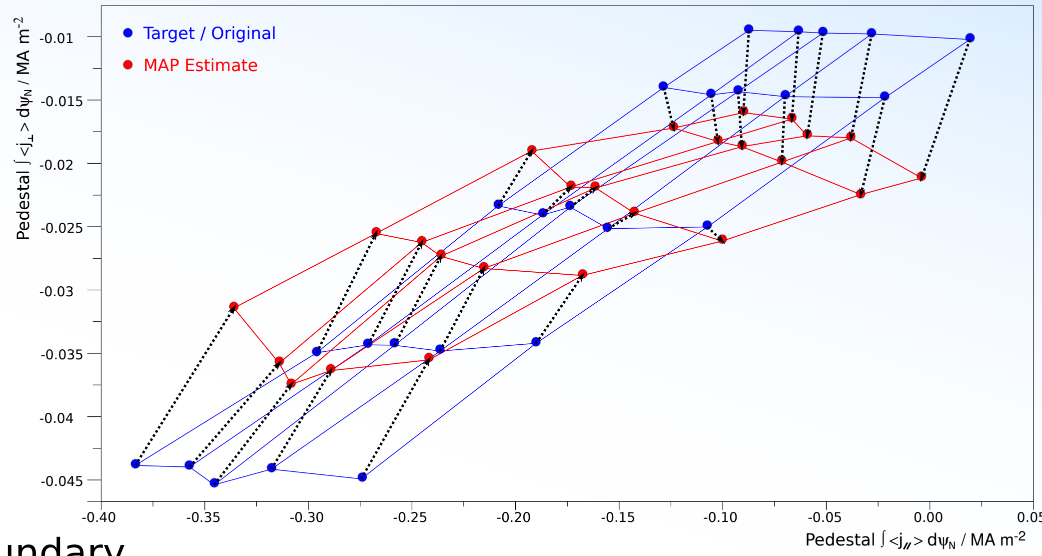

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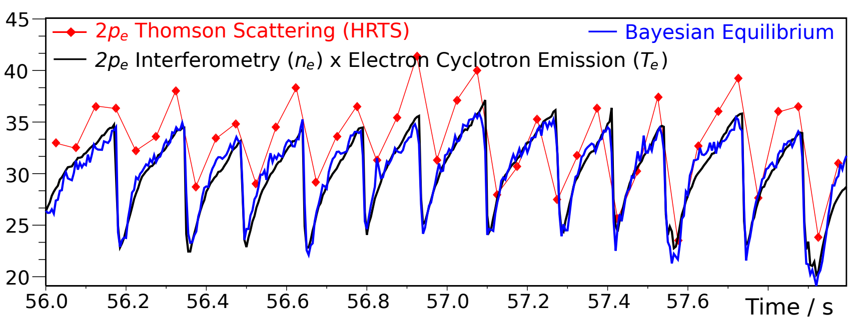

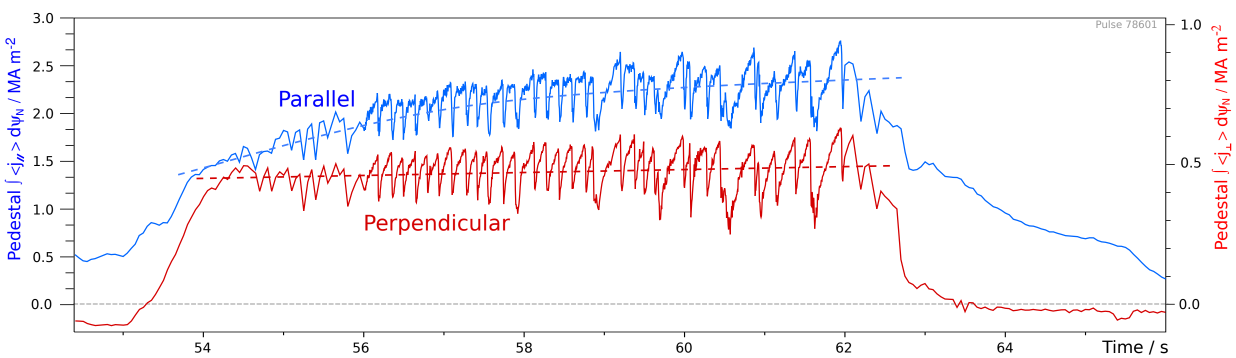

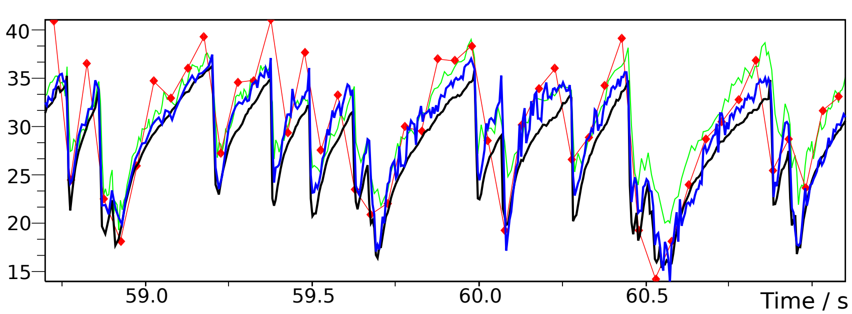

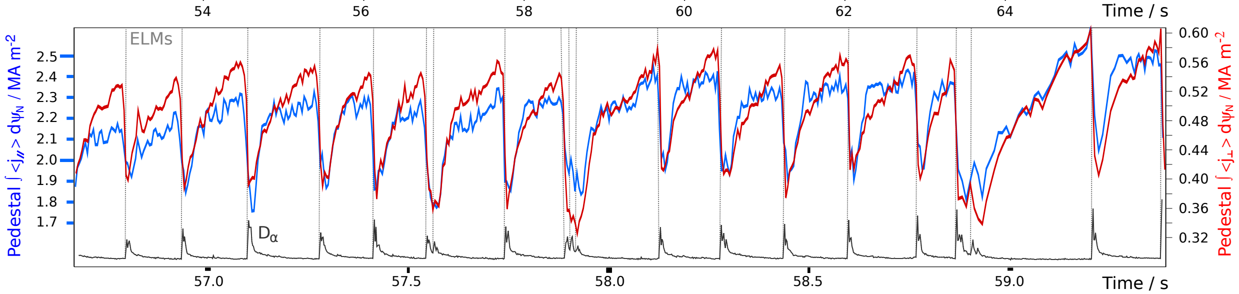

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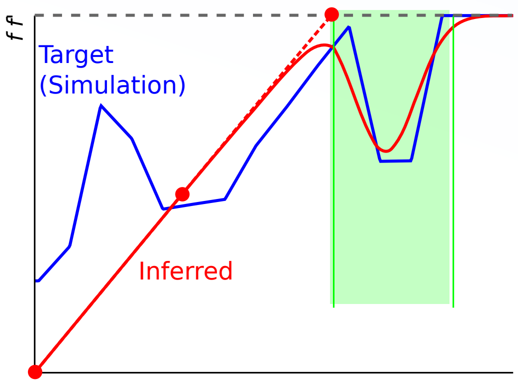

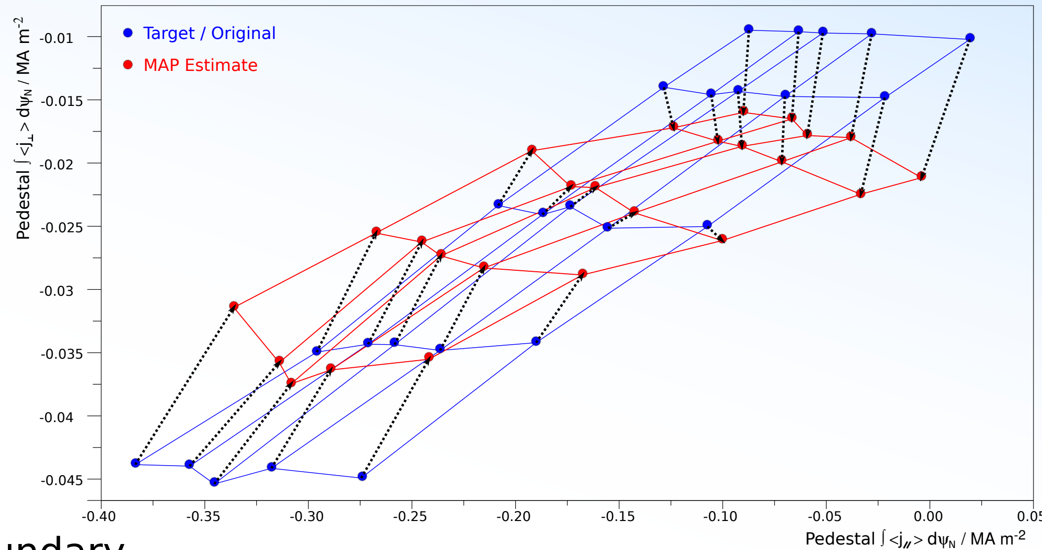

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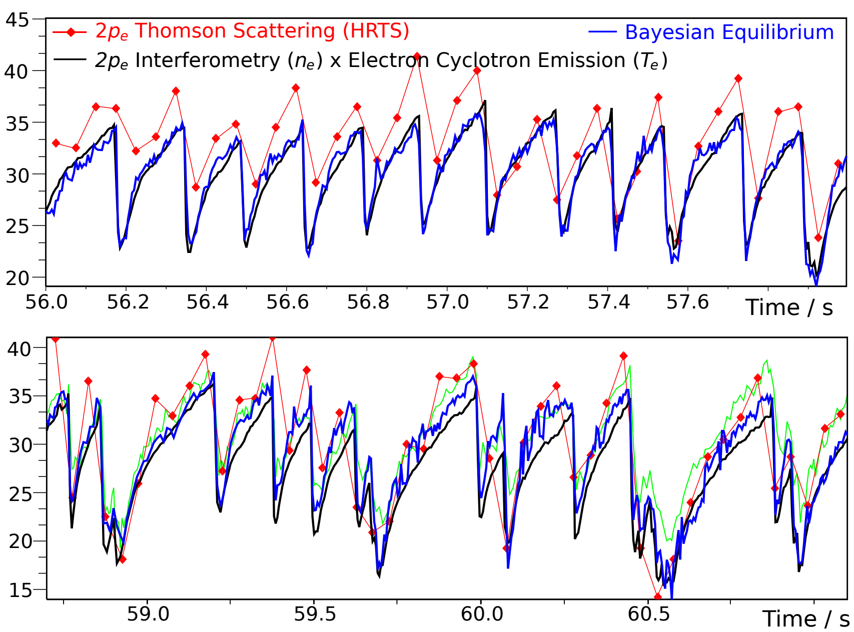

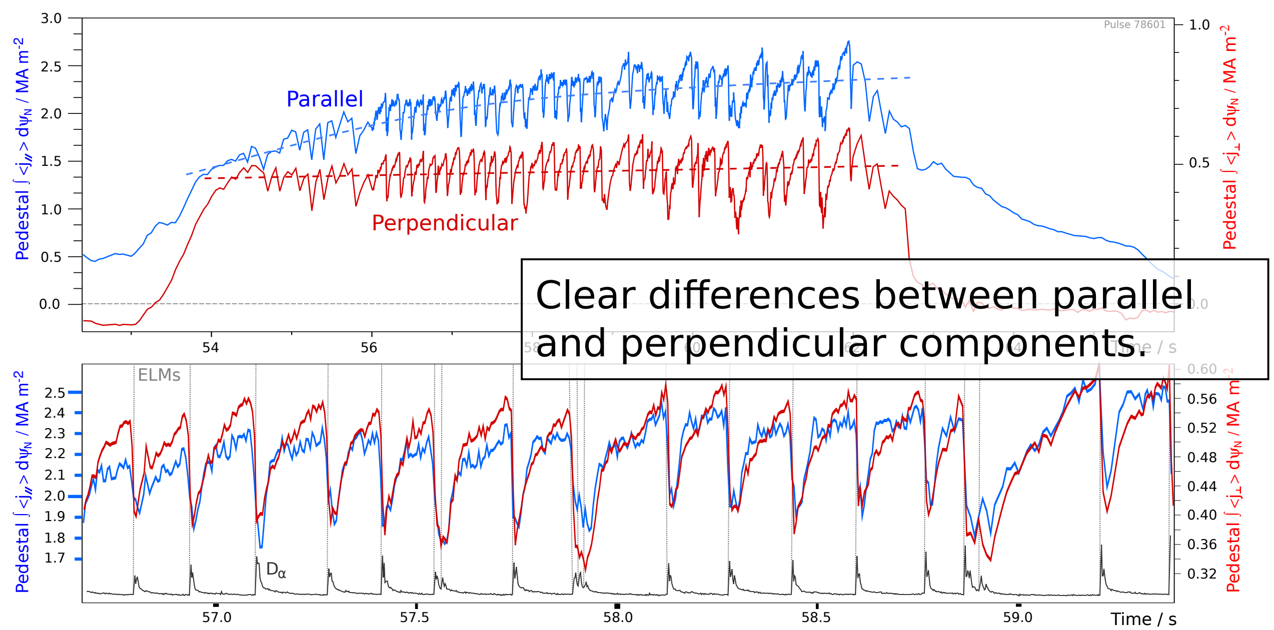

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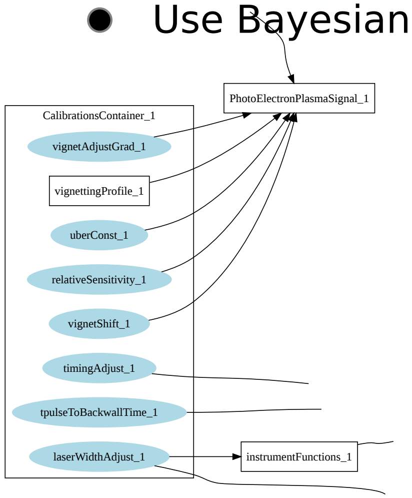

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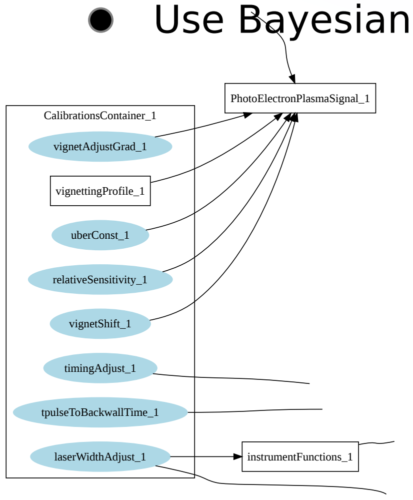

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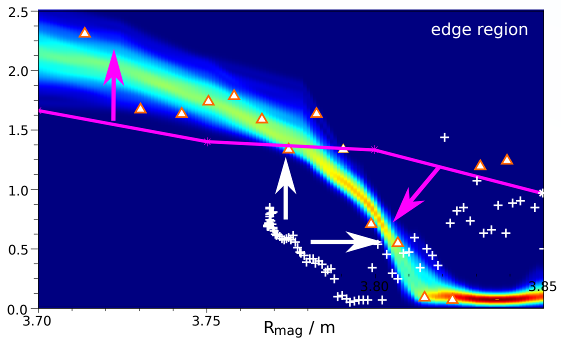

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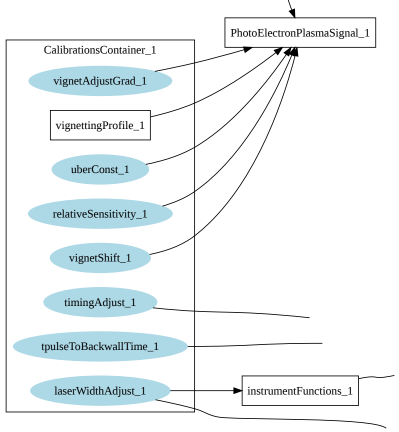

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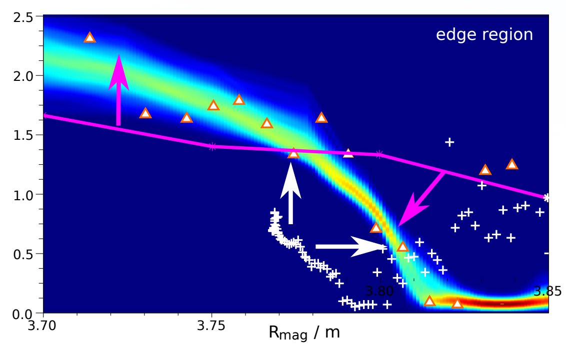

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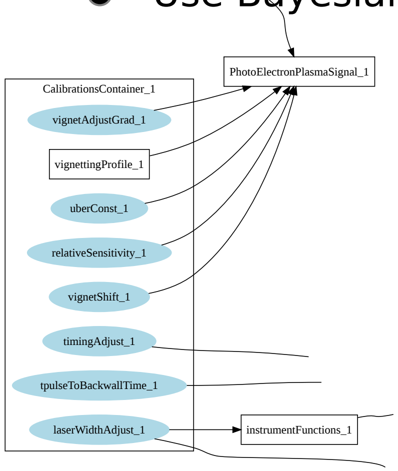

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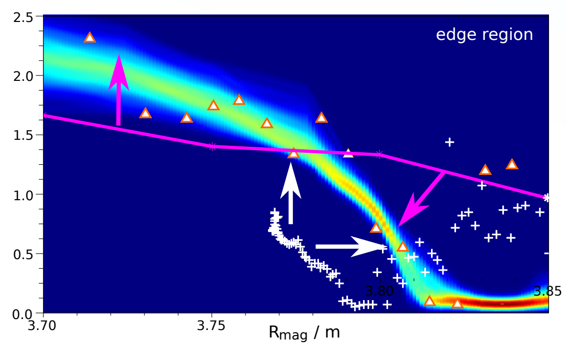

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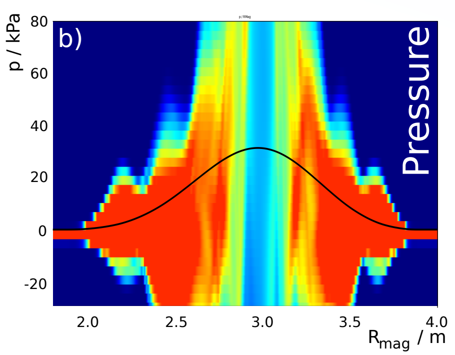

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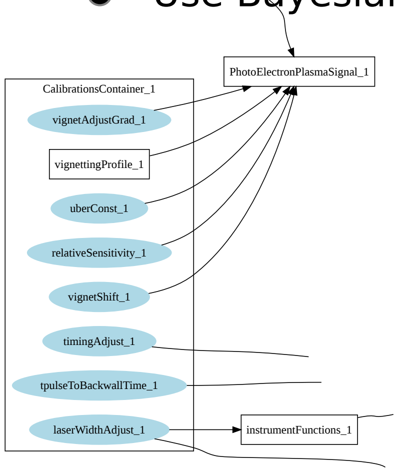

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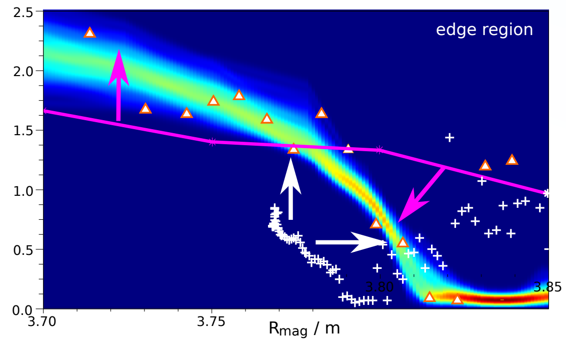

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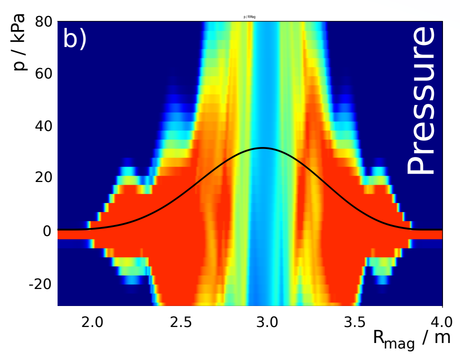

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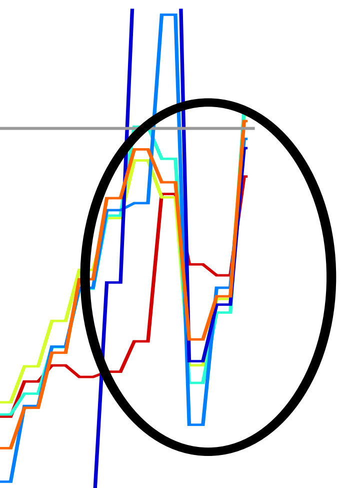

- Surprising amount of detail recoverable from magnetics alone (no internal measurement) when these strong assumptions are not included.