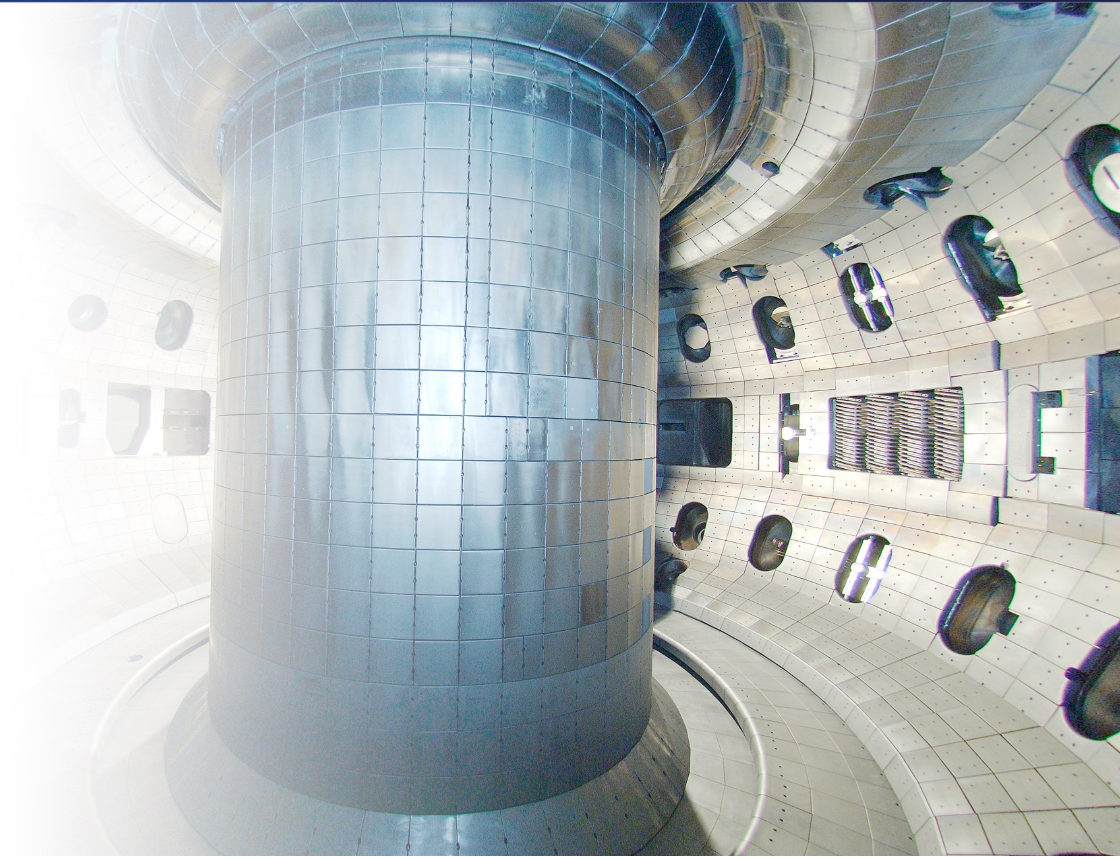
# Reduced transport model development informed by machine learning tools


by

**Tom Neiser**

with

**Adam Eubanks,**
**Orso Meneghini,**
**Sterling Smith,**
**Gary Staebler,**
**Jeff Candy**

Presented at the

**IAEA FDPVA**

**Dec 1st, 2021**

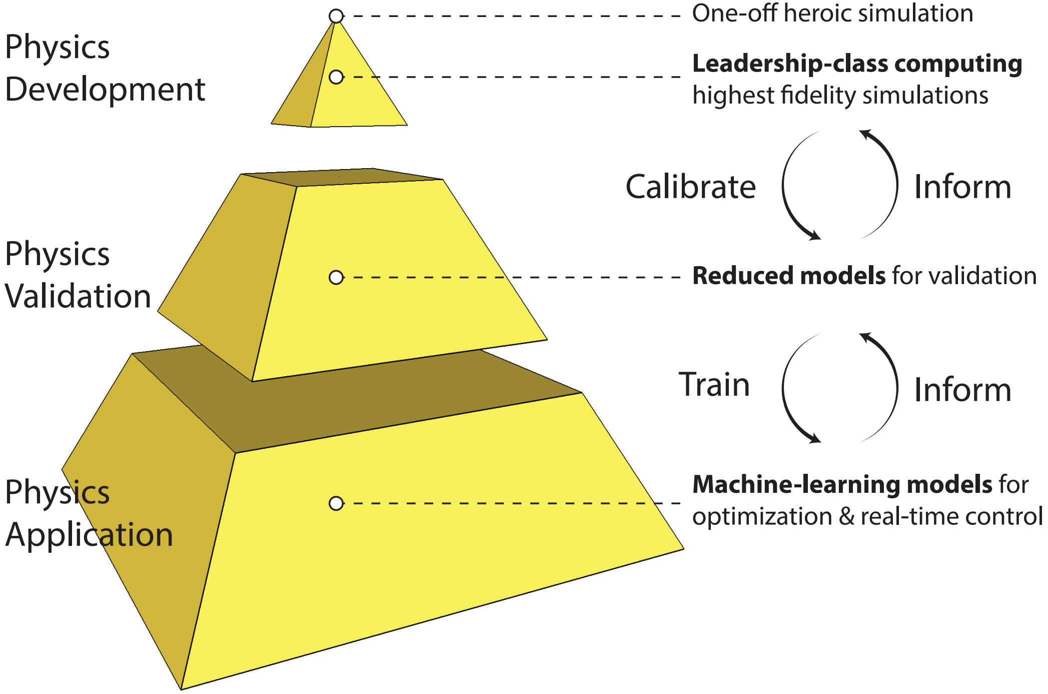
DIII-D NATIONAL FUSION FACILITY



GENERAL ATOMICS

# Reduced models are important for present and future devices

- TGLF is a quasi-linear model of transport driven by gyrokinetic turbulence
- TGLF is never fit to experiment so that it can be used to test gyrokinetic theory over large datasets and *predict* plasma profiles
- DIII-D has a large database (DB) of plasma discharges that can be used for **big data validation**







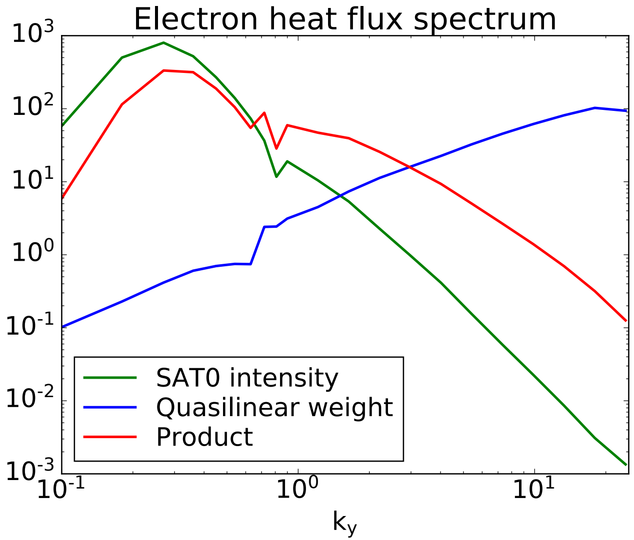

GENERAL ATOMICS

# TGLF employs three saturation rules: SAT0, SAT1 and SAT2

The **TGLF** [1] heat flux is given by

$$Q = \underbrace{\frac{3}{2}\sum_{\hat{k}_y} pc_s \left[\frac{\mathrm{Re}\left(i\hat{k}_y\tilde{\Phi}^*\tilde{p}_T\right)}{\sum_a \tilde{V}_a^*\tilde{V}_a}\right]}_{\text{quasilinear weight}} \underbrace{\bar{V}^2}_{\text{intensity}}$$

quasilinear weight intensity




**SAT0:**

The intensity for SAT0 is given by

$$\bar{V}^2 = C_{\mathrm{norm}}\left(\frac{\rho_s\hat{\omega}_{\mathrm{d},0}}{a\hat{k}_y^2}\right)^2\left(1+\frac{T_e}{T_i}\right)^2\left(\bar{\gamma}_{\mathrm{net}}^{C_1} + C_2\bar{\gamma}_{\mathrm{net}}\right)\frac{1}{\hat{k}_y^{C_3}}$$

where the free parameters are calibrated by first-principles gyrokinetic simulations using GYRO [2].

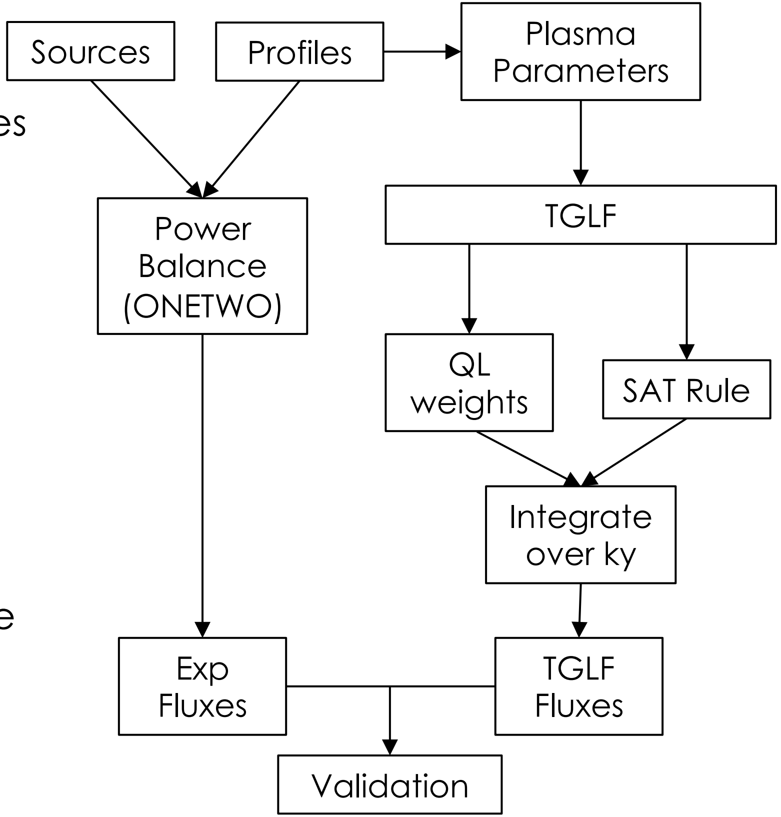

[1] G. M. Staebler, J. E. Kinsey, and R. E. Waltz, Phys. Plasmas **14**, 055909 (2007)
[2] J. Candy and R. W. Waltz, J. Comput. Phys. **186**, 545 (2003)

# Goal: Big data validation of TGLF saturation rules

- **Built large experimental database:**
  - 2500 randomly selected DIII-D plasma discharges
  - 9 radial locations: [0.1, 0.2, … , 0.9]
  - 9 time slices: [2000, 2100, … , 2800]
  - Leveraged automated workflows within OMFIT

- **Built large TGLF database:**
  - Used nominal experimental inputs
  - Translated SAT0, SAT1 and SAT2 to python and vectorized with Tensorflow to check for merit of recalibrating free parameters with GK database
  - Defined error:

$$\sigma_Q \equiv \sqrt{\frac{\sum_Q (\log_{10} Q_{\mathrm{model}} - \log_{10} Q_{\mathrm{exp}})^2}{\sum_Q (\log_{10} Q_{\mathrm{exp}})^2}}$$



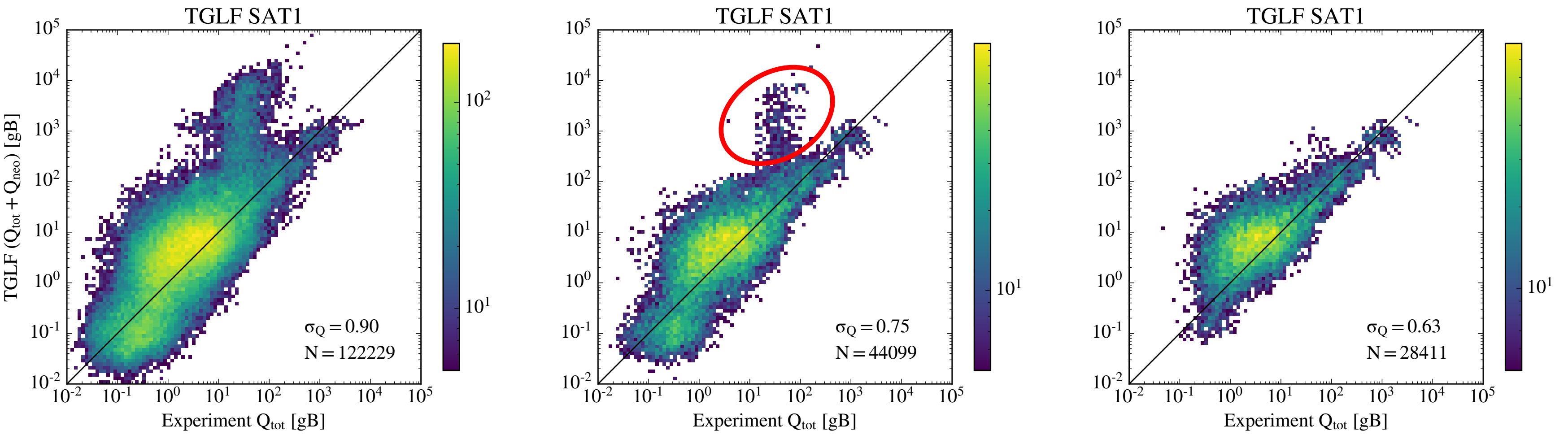



OMFIT



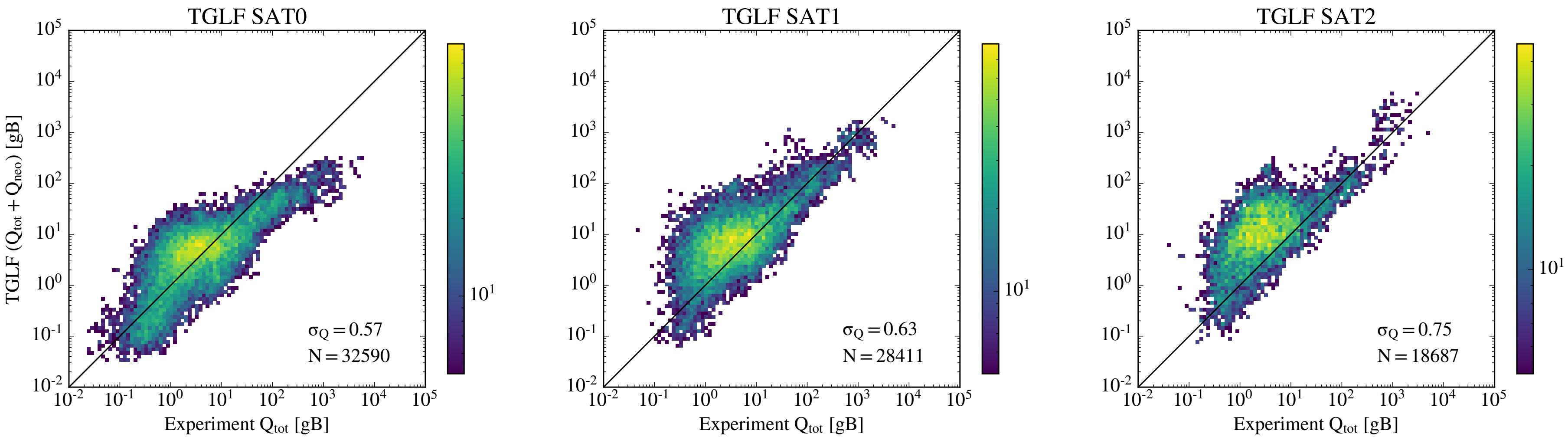
GENERAL ATOMICS

# Filter: Identify and remove cases where TGLF does not apply




- Removed cases with negative experimental or TGLF fluxes ($Q_{e,i} < 0$), and positive normalized temp. gradients ($a \frac{d \ln T_{e,i}}{dr} > 0$), and large positive density gradients ($a \frac{d \ln n_{e,i}}{dr} > 1$) (*left plot*)
- No cases with missing toroidal rotation data or MHD activity by NTMs (*middle plot*)
- No cases with KBMs ($\frac{Q_{EM}}{Q_{ES}} > 0.01$ at $\rho \geq 0.8$), marginally unstable ITG modes or more than 3 zeroes in the quasi-linear weight spectrum (*right plot*)

# Summary: SAT0, SAT1 and SAT2 were successfully validated




- SAT1 and SAT2 match experiment better than SAT0 at high fluxes (near-edge)
- SAT1 and SAT2 overpredict population of intermediate value fluxes (core)
- Could be due to too sensitive KBM threshold or profile uncertainty (see next slide)





GENERAL ATOMICS

# Highlight: SAT1 does well when $\frac{Q_{EM}}{Q_{ES}} < 0.01$

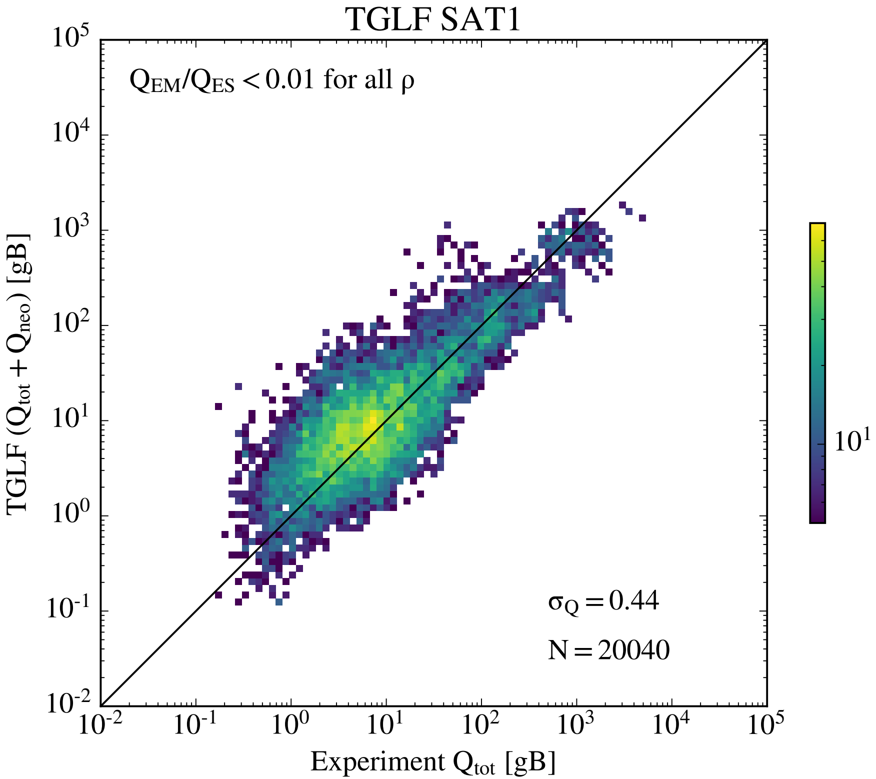
- KBMs were previously filtered out only in the near-edge region such that

$$\frac{Q_{EM}}{Q_{ES}} < 0.01 \text{ for } \rho \geq 0.8$$

- Remarkable agreement between SAT1 and experiment is found when KBM filter is extended such that

$$\frac{Q_{EM}}{Q_{ES}} < 0.01 \text{ for all } \rho$$

- Want to determine if this is due to profile uncertainties and/or too sensitive KBM threshold in TGLF, or some other missing physics (Dimits shift)



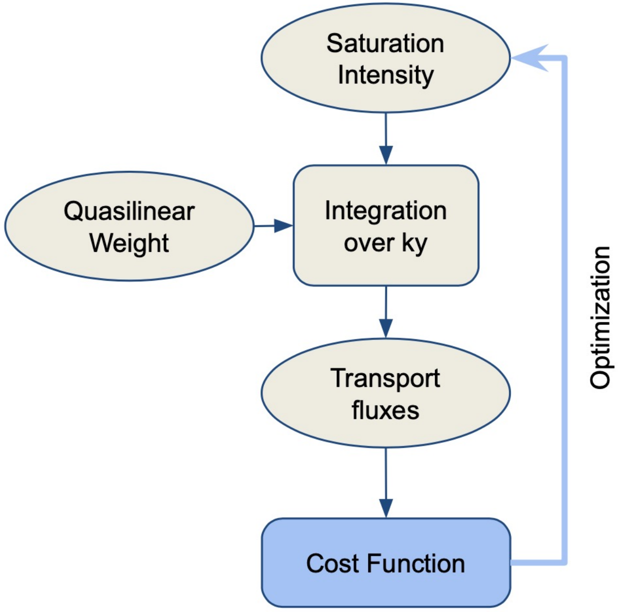





GENERAL ATOMICS

# Goal: Help direct model development with ML tools

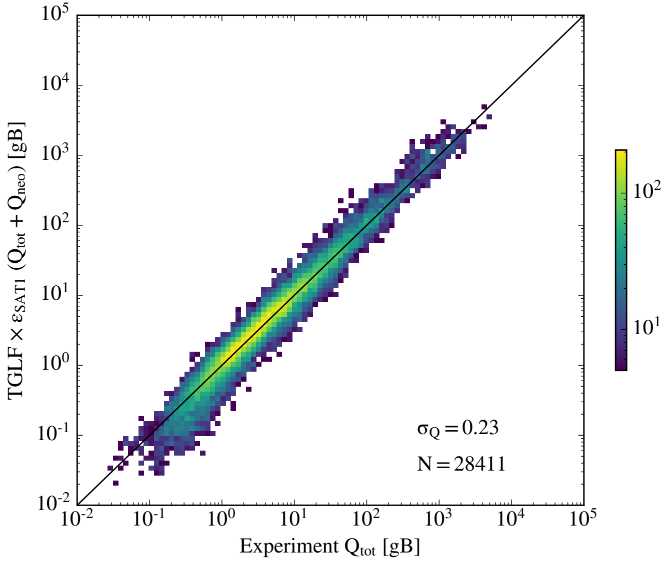
- Multiply SAT1 with an "error factor" $\epsilon_{SAT1}$ that can be expressed as a function of plasma parameters
- A suitable functional form for $\epsilon_{SAT1}$ is a power law
- We calculate $\epsilon_{SAT1}$ with Tensorflow:
  a. Start from random $\epsilon_{SAT1}$ values
  b. Compute NN fluxes
  c. Compare NN fluxes to experimental fluxes
  d. Update $\epsilon_{SAT1}$ to reduce error




[A. Eubanks et al., APS DPP, 2020]

# Goal: Help direct model development with ML tools

- Multiply SAT1 with an "error factor" $\epsilon_{SAT1}$ that can be expressed as a function of plasma parameters
- A suitable functional form for $\epsilon_{SAT1}$ is a power law
- We calculate $\epsilon_{SAT1}$ with Tensorflow:
    a. Start from random $\epsilon_{SAT1}$ values
    b. Compute NN fluxes
    c. Compare NN fluxes to experimental fluxes
    d. Update $\epsilon_{SAT1}$ to reduce error



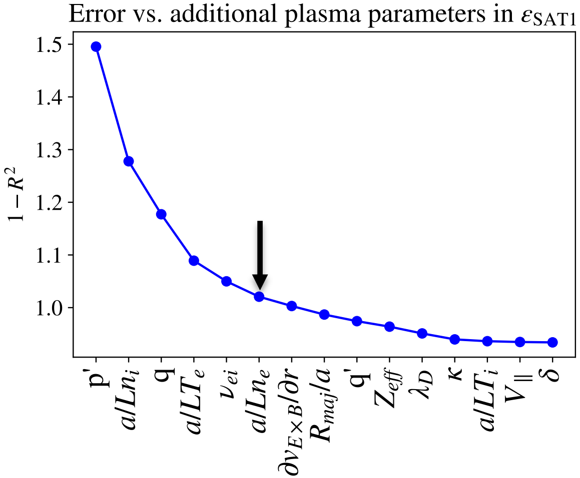





GENERAL ATOMICS

# Analytic expression for error factor in terms of plasma parameters is found with symbolic regression

- Want to balance accuracy with complexity:

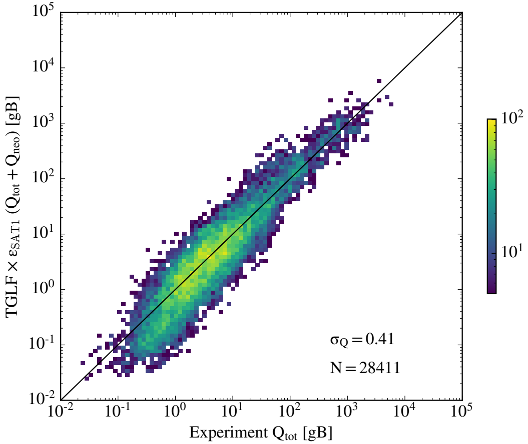



$$\epsilon_{\mathrm{SAT1}} \propto \frac{(1-a/L_{n_e})^{0.70} q^{0.94} (\nu_{ei}+\epsilon_0)^{0.51}}{\left(1-a/L_{n_i}\right)^{1.70} (-a/L_{T_e})^{0.56} (p'+\epsilon_0)^{1.14}}$$

$$\epsilon_0 = 10^{-3}$$

# Analytic expression for error factor in terms of plasma parameters is found with symbolic regression

- Want to balance accuracy with complexity:

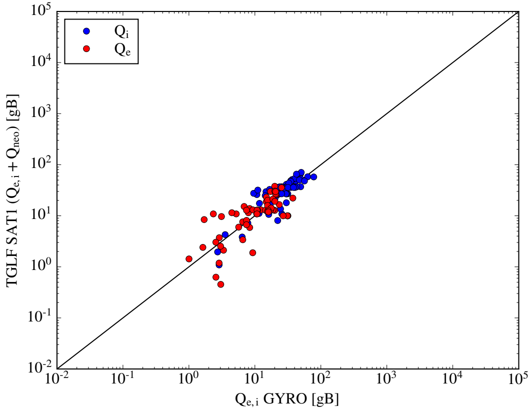


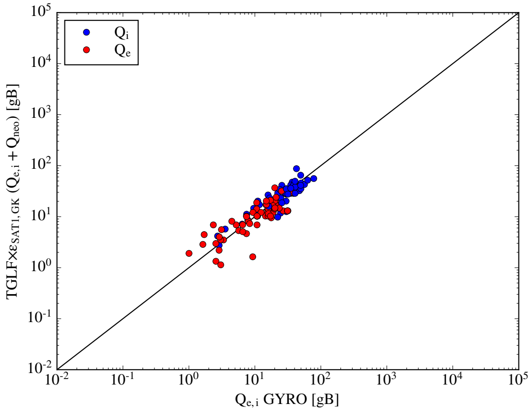

$$\epsilon_{\mathrm{SAT1}} \propto \frac{(1-a/L_{n_e})^{0.70} q^{0.94} (\nu_{ei}+\epsilon_0)^{0.51}}{\left(1-a/L_{n_i}\right)^{1.70} (-a/L_{T_e})^{0.56} (p'+\epsilon_0)^{1.14}}$$

$$\epsilon_0 = 10^{-3}$$

- **Next:** Want to identify theoretical mechanism explaining $\epsilon_{SAT1}$ parameter dependence (e.g. thresholds of KBM/ITG/TEM turbulence)
- Recommend scans in $p'$, $\nu_{ei}$, $dv_{ExB}/dr$ to add to CGRYO database

# Using plasma params scanned in existing GYRO DB, an error factor can also be found for TGLF vs GK DB



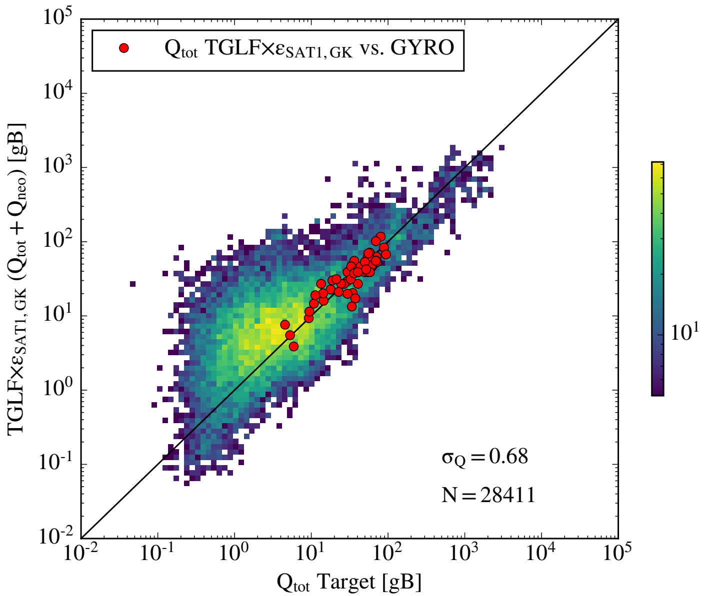



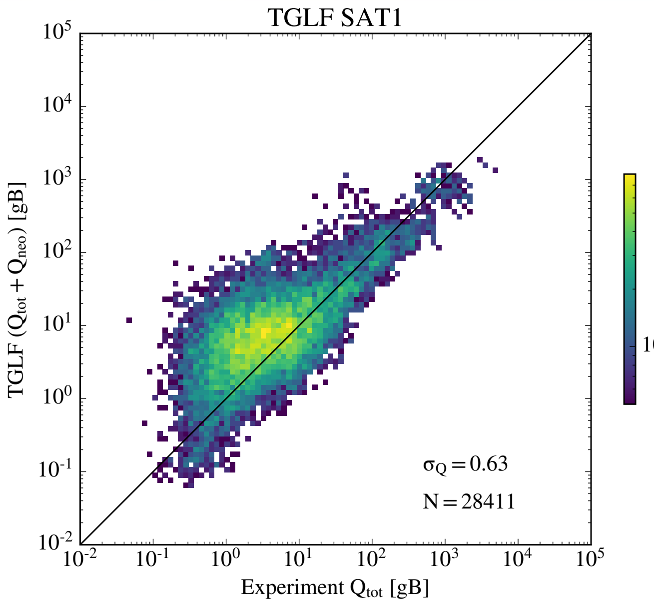

$$\epsilon_{\mathrm{SAT1}} \propto \frac{(1-a/L_{n_e})^{0.70} q^{0.94} (\nu_{ei}+\epsilon_0)^{0.51}}{\left(1-a/L_{n_i}\right)^{1.70} (-a/L_{T_e})^{0.56} (p'+\epsilon_0)^{1.14}}$$

$$\epsilon_{\mathrm{SAT1,GK}} \propto \frac{(1-a/L_{n_e})^{0.45} (T_i/T_e)^{0.31}}{(-a/L_{T_e})^{0.18} \left(-a/L_{T_i}\right)^{0.56} \kappa^{0.82} \delta^{0.01} q^{0.30} q'^{0.25}}$$

- Error factor $\epsilon_{SAT1,GK}$ gives better fit of SAT1 to GK database
- Confirms need for extension of GK DB with scans in temperature and density gradients
- Recommends extension in GK DB with scans in temperature ratio, elongation and safety factor

# Using plasma params scanned in existing GYRO DB, an error factor can also be found for TGLF vs GK DB




- TGLF×$\epsilon_{SAT1,GK}$ shows only minor difference to TGLF SAT1 validation
- Therefore, difference between SAT1 and experiment could also be due to limited GK coverage at lower fluxes

# Summary: Validated TGLF SAT rules and found avenues for further saturation rule development

- SAT1 and SAT2 match experiment better than SAT0 at high fluxes (near-edge), and overpredict population of fluxes deeper in core (correlated with $Q_{EM}/Q_{ES} > 0.01$)
- This could be due to profile uncertainty in experiments, too sensitive thresholds for turbulent heat flux in TGLF, and limited GK DB coverage

**Next steps:**

- Quantify sensitivity of TGLF to profile uncertainties (run TGLF with varied input parameters)
- Study thresholds for turbulent fluxes (run TGLF with varied $a/L_{T_{e,i}}$, $a/L_{n_{e,i}}$)
- Want to validate quasi-linear weights, namely the other factor in the heat flux calculation (run linear CGYRO simulations over sample of DB)

# Epilogue

This work is supported by the U.S. DOE under DE-FC02-04ER54698, DE-SC0017992, DE-FG02-95ER54309, and DE-AC02-09CH11466.

**Disclaimer:**