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TH/2-1

Gyrokinetic projection of the divertor heat-flux width from present tokamaks to ITER

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Outline

- **Introduction**
- **Validation on DIII-D, C-Mod and NSTX (US Milestone)**
  - **Attached divertor regime to study the minimal heat-flux width**
  - **Measure heat-flux footprint at entrance to Debye Sheath**
    - **Then, map to outboard midplane to obtain λ_q**
  - NSTX and DIII-D are in the drift-dominant λ_q regime
  - C-Mod at cross-over from drift to turbulent λ_q
- **Prediction for ITER: blobby turbulence dominated**
  - $\lambda_q \approx 5.6\text{mm} >> 0.63\ B_{pol}^{-1.19}$
- **A simple heuristic explanation**
- **Conclusion and discussion**

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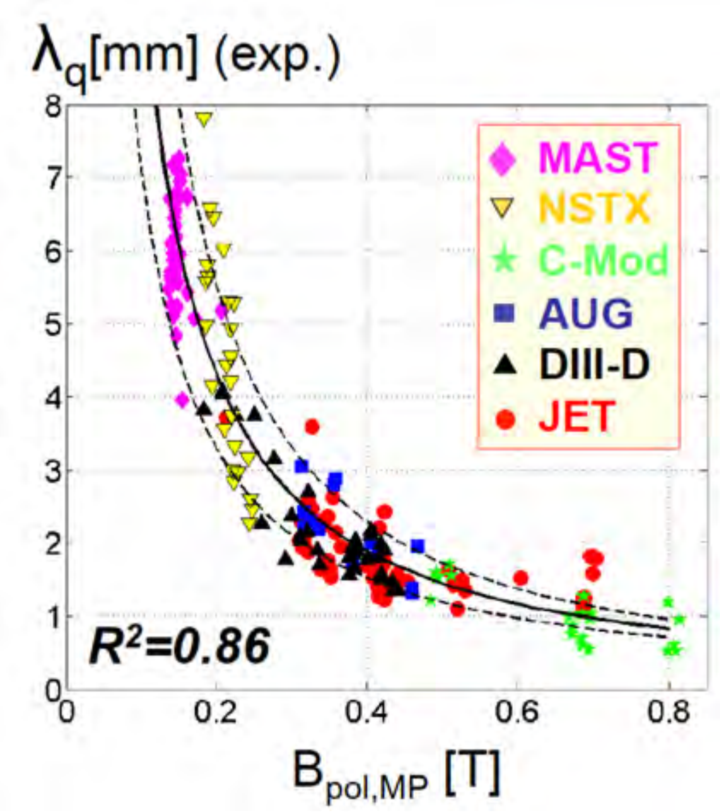
+ First Author acknowledges helpful discussions with R. Goldston.

Introduction

- Neoclassical, turbulence, and neutral particle physics are **all** important
- Neoclassical dominant models, by XGC0 [‘10 US JRT] and Goldston, gave

  $\lambda_q \propto 1/B_p^{\gamma}$, $\gamma \sim 1$

  - Appears to be working for the present-day tokamaks. But, high B_p cases?
- Will this be true in ITER? Predict using XGC1 with electrostatic blobby turbulence
- XGC1 validation?
- Edge plasma is in non-equilibrium kinetic state: non-Maxwellian, non-diffusive
  - Requires a full-f kinetic ion & electron simulation for high-fidelity predictability



T. Eich et al., NF 2013
PRL 107, 215001 (2011)

→ **Extreme scale computing**: We use 90% Titan (~300K cores + 19K GPUs, spending 10M core hours/day) for 3 days for 1 ITER case

5D Total-f XGC Family Codes

Code	GK, DK	Solver Dimension	3D	X-point	MC neutrals recycling
XGC1 hybrid (E&M)	GK ions hybrid electrons	3D (r, θ, ζ) Turbulence		Yes	Built-in
XGC1 kinetic (CAAR*, NESAP**)	GK ions, DK or GK electrons	3D (r, θ, ζ) Turbulence		Yes	Built-in
XGCa (NESAP**)	GK ions, DK electrons	2D (r, θ) GK Neoclassical & Kinegtic transport modeling	RMP	Yes	Built-in
XGC0	DK ions & electrons	1D (r) DK Neoclassical & Kinetic transport modeling	RMP	Yes	DEGAS2

Blobs from XGC1: S. Ku, TH/P6-16
Neutrals on turb.: Stotler, TH/P6-7

SOL phys: Churchill, TH/P6-10
Edge boostrap: Hager, TH/P2-27

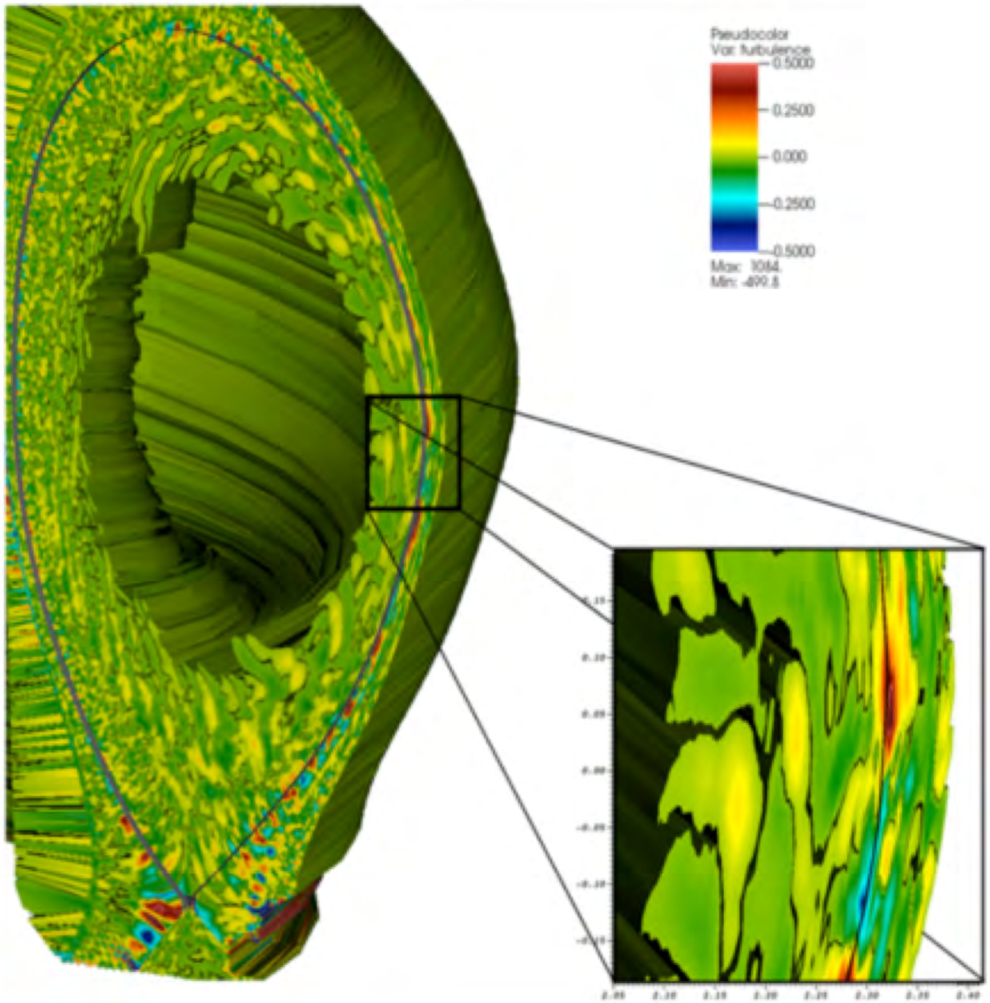
*CAAR program at OLCF gives one postdoc support to XGC for GPU optimization
*NESAP program at NERSC gives one postdoc support to XGC for Vectorization.

Ability for "blobby" edge turbulence + orbit dynamics is a pre-requisite for heat-flux width study

2013-2014 INCITE, using 90% (16,384+ nodes~25pF) maximal heterogeneous Titan

- Relevant region for the λ_q study: $0.98 \lesssim \Psi_N \lesssim 1.02$
- Attached plasma
- For a minimal 1st-principles based study, a GK simulation should have
  - electrostatic blobs with kinetic electrons [D'Ippolito et al., (2011)]
  - neoclassical orbit dynamics
  - ExB dynamics
  - $E_{||}$ solution
  - neutral recycling
  - nonlinear e&I collisions

  across magnetic separatrix



Blobs from XGC1: S. Ku, THP-6/16

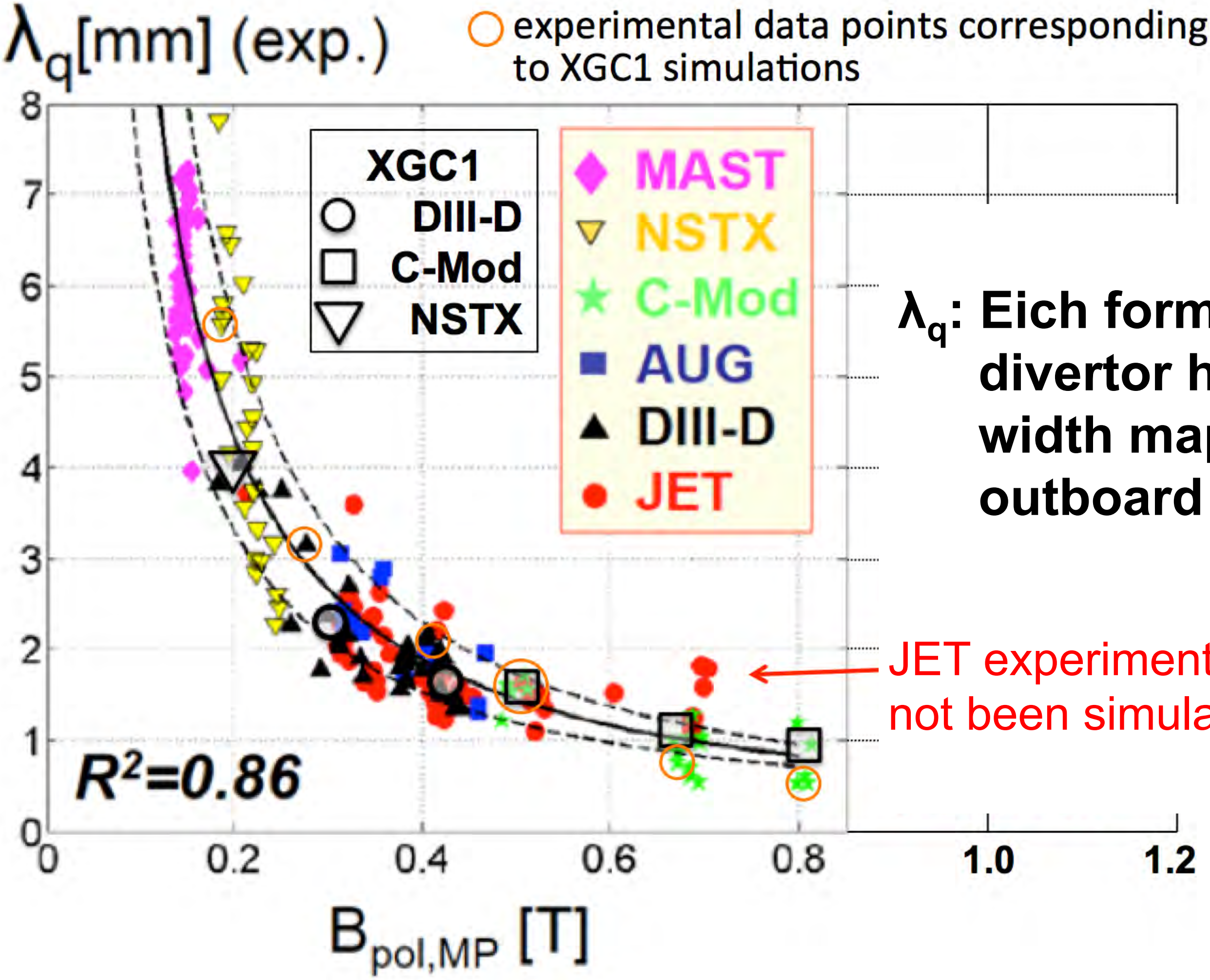
**Simulation by S. Ku,
Visualization by D. Pugmire**

Experimental validation cases studied by XGC1

B-field, first wall, plasma profiles and the heat source are imported from eqdsk files.

Shot	**Time (ms)**	**B_T (T)**	**I_P (MA)**	**$B_{pol,OM}$ (T)**
NSTX 132368	360	0.4	0.7	0.20
DIII-D 144977	3103	2.1	1.0	0.30
DIII-D 144981	3175	2.1	1.5	0.42
C-Mod 1100223026	1091	5.4	0.5	0.50
C-Mod 1100223012	1149	5.4	0.8	0.67
C-Mod 1100223023	1236	5.4	0.9	0.81

Successful validation of the XGC1 heat-flux widths λ_q against all three US tokamak data

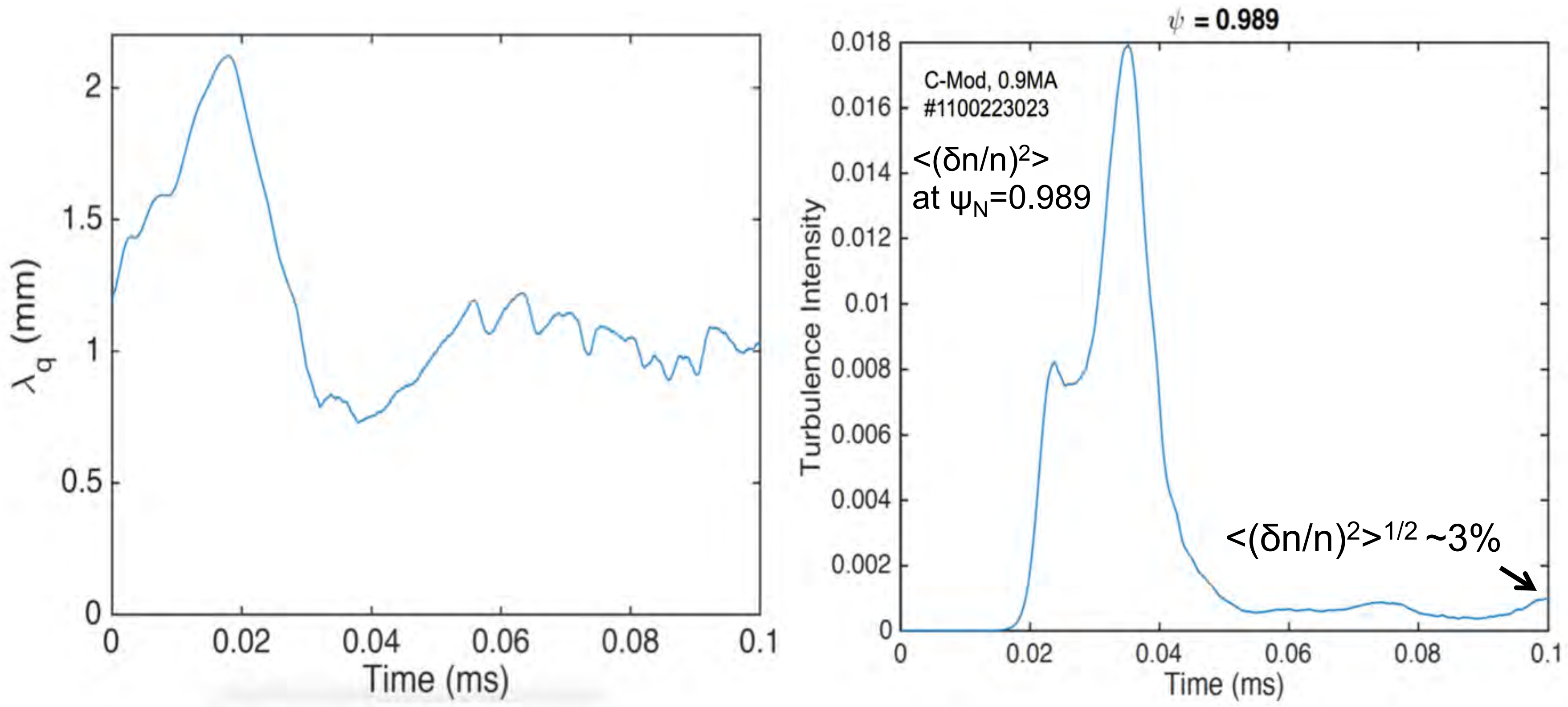


λ_q: Eich formula fit for divertor heat-flux width mapped to outboard midplane

JET experiments have not been simulated, yet.

Example time behavior: C-Mod, 0.9MA

We execute the simulation until λ_q ~saturates.



$<(\delta n/n)^2>$ at ψ_N=0.989

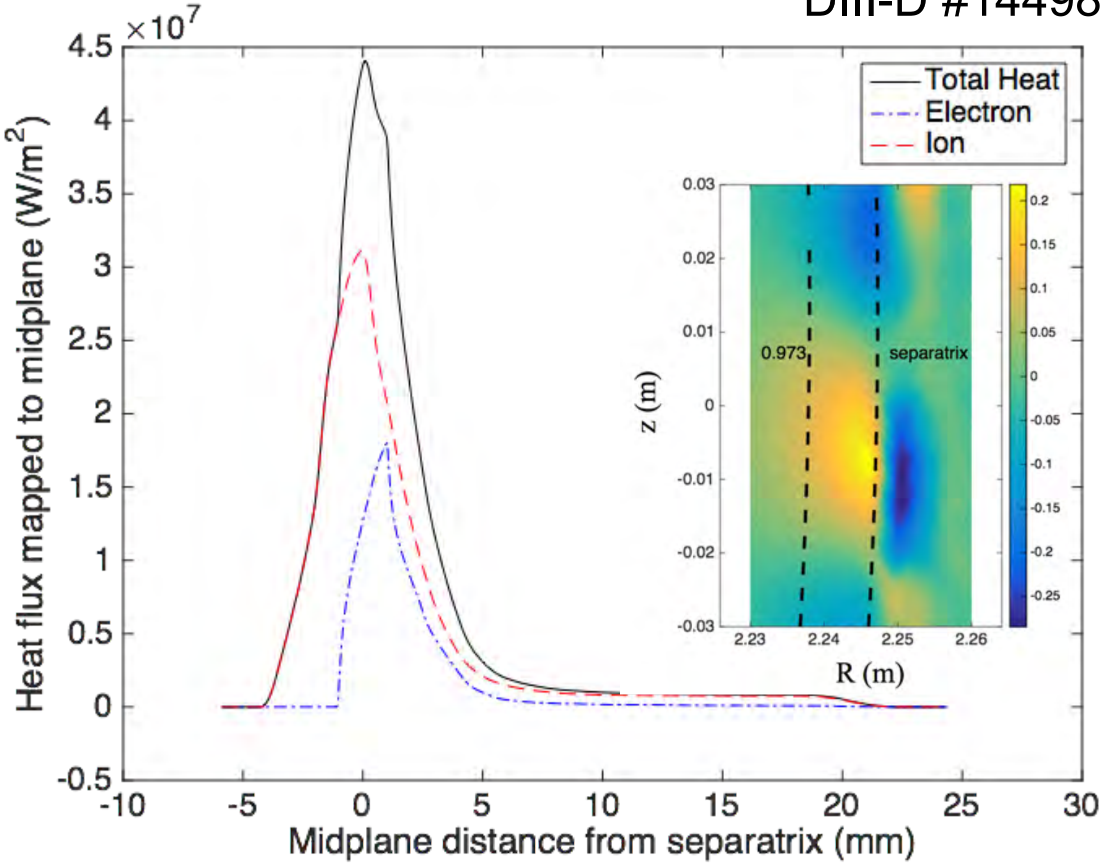
$<(\delta n/n)^2>^{1/2}$ ~3%

Saturation of λ_q (left) and turbulence intensity $(\delta n/n)^2$ (right). Turbulence intensity is plotted at $\Psi_N \approx 0.99$ where most of the blobs are born.

XGC1 prediction:

λ_q dominated by warm ions in DIII-D and NSTX plasmas.

DIII-D #144981, I_P=1.5MA



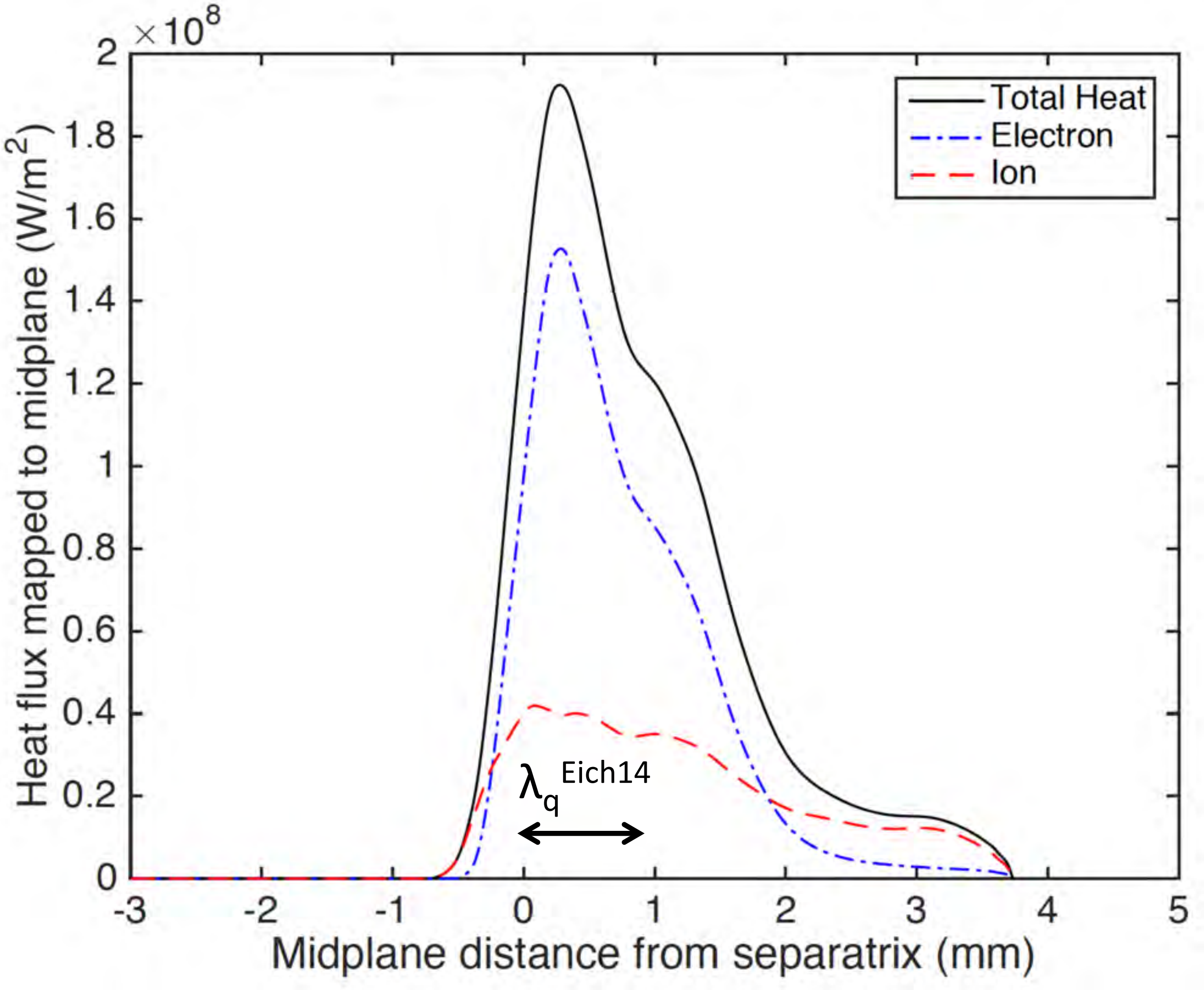
Breakdown of heat-flux footprint into ion and electron components on DIII-D, 1.5MA

- The heat-load spreading by electrons (blobby spread) is ~2X narrower than that by ions (neoclassical $V_{d,magnetic}$)
- Radial blob size ~5mm (see insert)
- T_i>T_e in scrape-off
- Ions (electrons) gain (lose) kinetic energy in the pre-sheath potential, elevating the ion effect.
- Neutral particle effect is only ~10%

XGC1: In high current (0.9MA) C-Mod, electrons dominate the heat-flux magnitude.

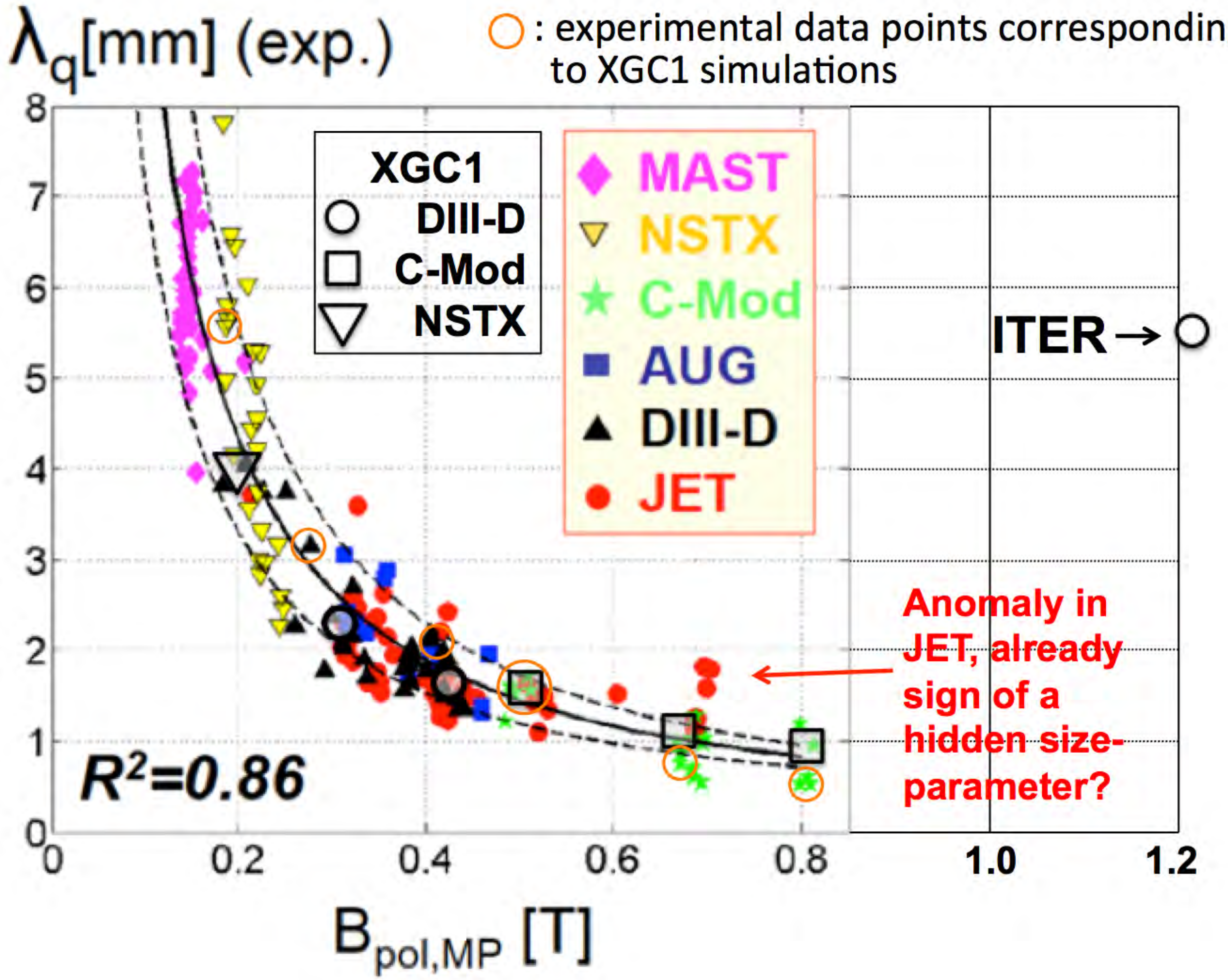
Electron width (blobby spread) ~ion width

Ions: Neoclasscial + Blobs, blobs able to spread warm ions.

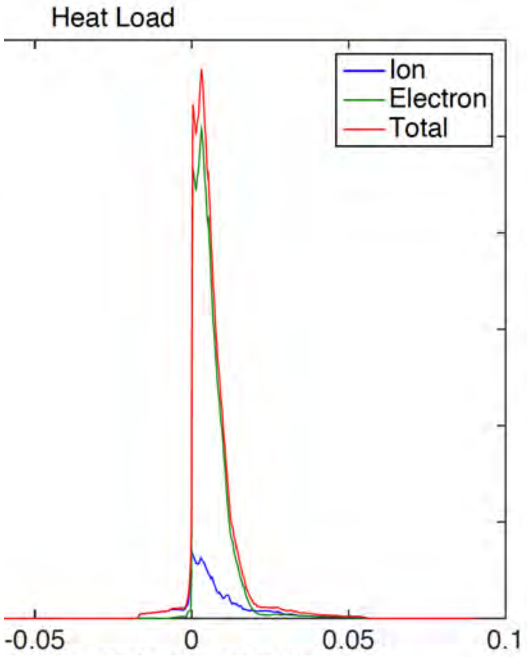


Prediction for ITER

- The same code that reproduces three US tokamak experimental results predicts $\lambda_q \approx 5.6$mm, instead of <1mm, using a model edge profile
  - But, λ_q is not very sensitive to details of the edge profile.
- ITER λ_q is blob-dominant → Indication of a hidden size parameter



Anomaly in JET, already sign of a hidden size-parameter?



ITER midplane distance from separatrix (m)

When will the blob effect be significant for λ_q?

A new heuristic argument, using ion magnetic drift and δExB mixing

[ρ_i and $\rho_{iPOL}$are at outboard midplane using $T_{i,sep}$]

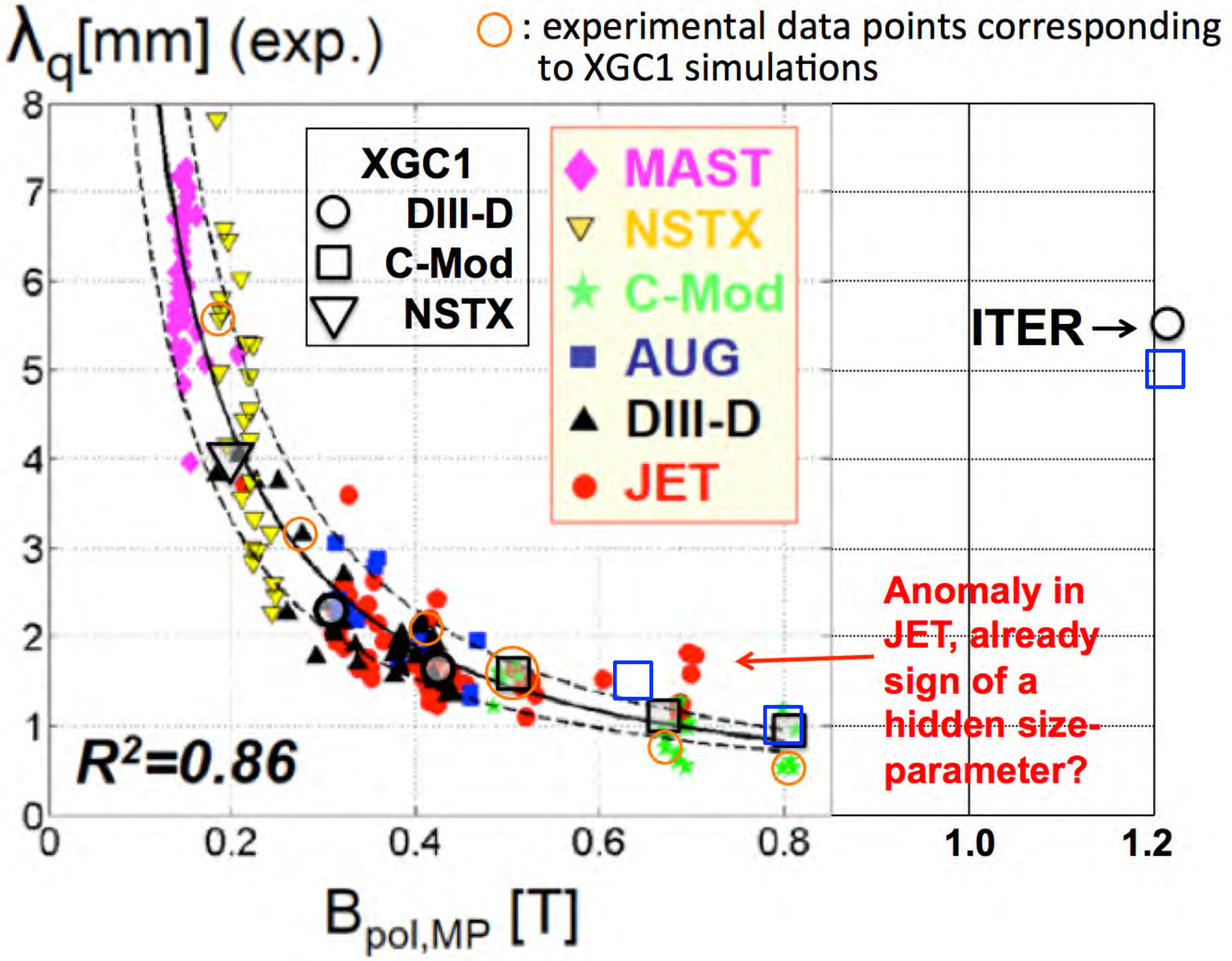
- Blob size $\Delta_{blob} \approx$ edge meso scale $\approx$ $(L_n \rho_i)^{1/2} \approx (0.05a\rho_i)^{1/2}$
- Radial ambipoar spread by blobs $\lambda_q^{Blob} \approx (\Delta_{blob}/2)(T_{e,sep}/T_{i,sep})$

  → Δ_{blob} ≈1.0 mm for 0.8-0.9MA C-Mod, $T_{i,\Psi=0.99}=T_{e,\Psi=0.99}$=75eV, and

  ≈ 5.0 mm for ITER, $T_{i,\Psi=0.99}=T_{e,\Psi=0.99}$=0.8keV
- Ion-drift spread $\lambda_{q,HD}$(Goldston)~(2a/R) ρ_{iPOL} ~$\lambda_q^{Eich14} = 0.63\, B_{pol}^{-1.19}$
- **λ_q=Max(λ_q^{Eich14}, λ_q^{Blob}) yields a good projection from C-Mod to ITER**
- JET is the closest tokamak to ITER and can be an excellent validation bed for a quantitative scaling formula if a higher Bp operation is possible.
- Small C-Mod at higher Bp and fixed $T_{i,sep}$ can also be helpful.

Different arguments on turbulent spreading of λ_q in [J. Myra et al., PoP 22, 042516 (2015)], and in references therein.

“□” from λ_q=Max(λ_q^{Eich14}, λ_q^{Blob}) recovers Eich14 (≈ Goldston), JET high B_p, and all the XGC1-predicted data points including ITER.



Anomaly in JET, already sign of a hidden size-parameter?

Conclusion and discussion

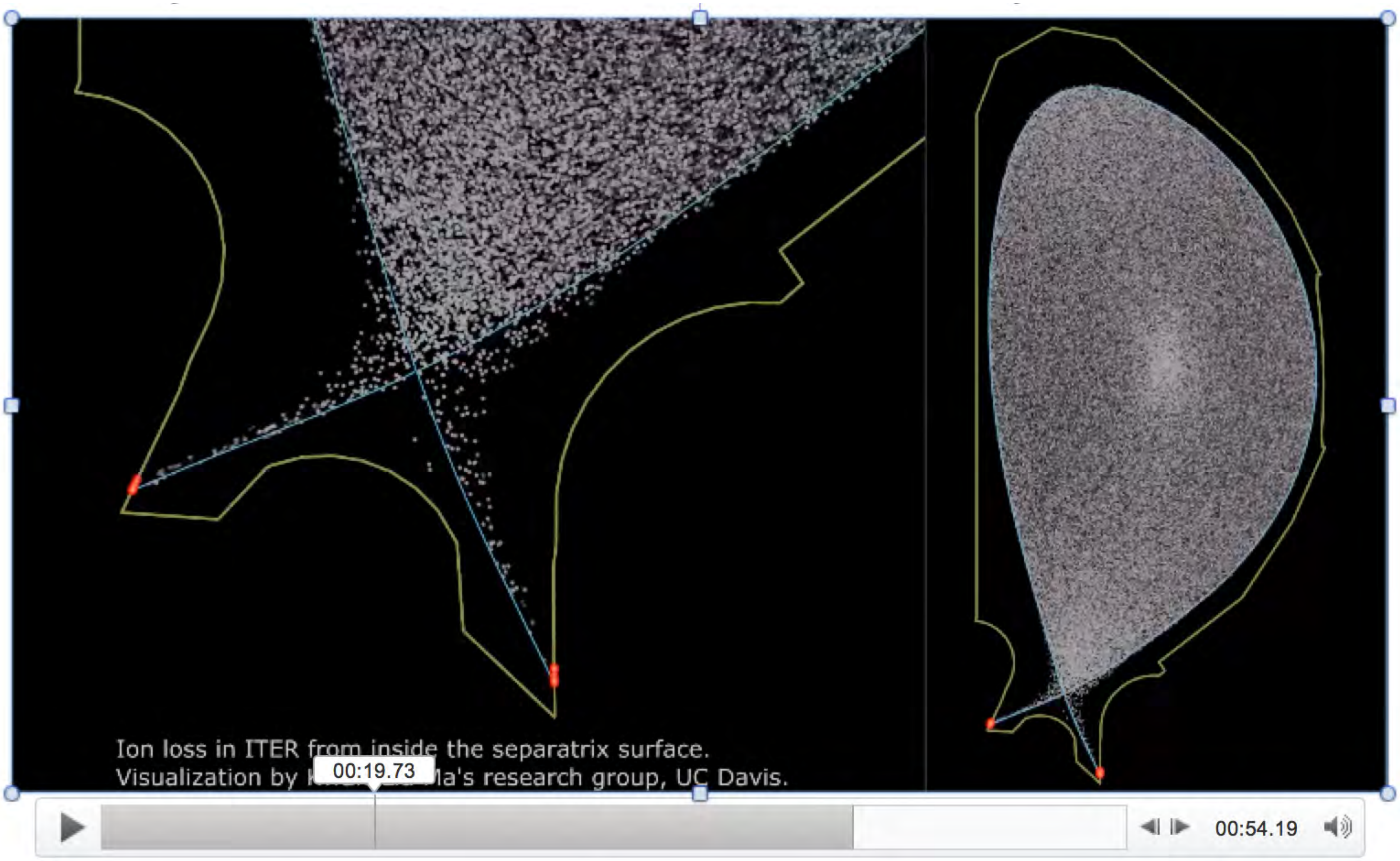
- Prediction from gyrokinetic XGC1 simulations on the 3 US tokamaks have been validated against the experimental scaling $\lambda_q \propto 1/B_P^{1.19}$.
- For DIII-D and NSTX, heat-flux width is dominated by the ion magnetic drift physics → Similar to Goldston scale, but by warm ions
- For C-Mod (small size) that has high B_p and small magnetic drift, λ_q is at cross-over between magnetic-drift and blobby spreads.
- The same code that reproduces the experimental results on three US tokamaks shows ~ $\lambda_q \approx 5.6$mm for ITER (large size): blob dominated

  → Much easier operation of ITER
- It appears that there is a size scaling missing in the existing formula.
  - $\lambda_q = \mathrm{Max}[\lambda_q^{Eich14}, \lambda_q^{Blob}]$ gives an adequate projection from C-Mod to ITER (and JET experiment)
- JET at higher B_P could shed brighter light on the hidden size scaling parameter.
- More computing time could nail this down.

Backup slides

XGC1 can study divertor heat-flux at unprecedented detail.

- Ion magnetic-drift loss from warm pedestal: $\lambda_{NEO} \approx 2(a/R)\ \rho^{w}_{iPOL}$(extruded part from separatrix) $\sim 2(a/R)\rho_{iPOL}$(at separatrix): Basis for Goldston model
- Blobby turbulent ion spread also comes into play: Checked by electrons.


Ion loss in ITER from inside the separatrix surface.
Visualization by K[illegible] Ma's research group, UC Davis.

ITER

In a core plasma, *f* evolves slowly, ≳100ms

For this argument, let's use the drift kinetic equation

$\partial f/\partial t+(\mathbf{v}_{||}+\mathbf{v}_d)\cdot \nabla f + (e/m)E_{||}\, v_{||}\, \partial f/\partial w = C(f,f) + Sources/Sinks$

where w is the particle kinetic energy.

In a near-thermal equilibrium, we can take the "transport ordering" (= diffusive ordering):

$\partial f/\partial t=O(\delta^2),\ S=O(\delta^2),\ \text{with}\ \delta<<1$

- Let $f=f_0+\delta f$, with $\delta f\,/\,f_o=O(\delta),\ \delta <<1,\ v_d/v_{||} = O(\delta),\ E_{||}/m = O(\delta \text{ or } \delta^2)$

$O(\delta^0)$: $v_{||}\cdot \nabla f_0 = C(f_0,f_0) \rightarrow f_0=f_M$: H-theorem → fluid background

$O(\delta^1)$: $\partial \delta f/\partial t + v_{||}\cdot \nabla \delta f + v_d\cdot \nabla f_0 + (e/m)\, E_{||} v_{||}\, \partial f_o/\partial w = C(\delta f)$

- ✧ Perturbative kinetic theories then yield transport coefficients $=O(\delta^2)$
- ✧ In this case, fluid transport equations ($f_o \rightarrow n,T$) can be used with the kinetically evaluated or ad hoc closures

→ **GK simulation is cheaper per physics time, but *δf* equilbrates on a slow time scale** $O(\delta^1\omega_{bi})$ ~ *ms.* **And, a meaningful time evolution of** f_0 **in** V_T **frame can only be obtained in a long "transport-time" scale** $O(\delta^2\omega_{bi})$. V_T **evolves on an even slower time scale.**

In edge plasma, *f* evolves fast, ~0.1ms

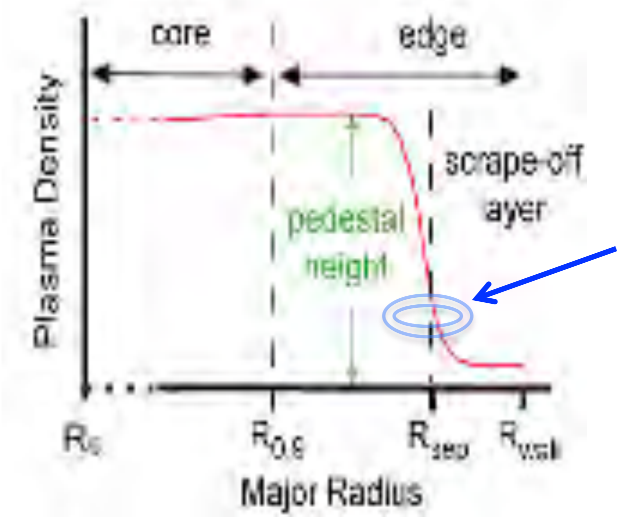
- Ion radial orbit excursion width ~ pedestal width & scrape-off layer width
- Orbit loss from $\psi_N<1$ and parallel particle loss to divertor

All terms can be large: ~ either $O(\omega_{bi})$ or $O(\nu_C)$

- $\mathbf{v}_{||}\cdot\nabla f \sim \mathbf{v}_d\cdot\nabla f \sim C(f,f) \sim eE_{||}v_{||}/m\,\partial f/\partial w \sim O(\omega_{bi})$ ~ 0.05 ms in DIII-D edge
- *f* equilibrates very fast: $\partial f/\partial t + (\mathbf{v}_{||}+\mathbf{v}_d)\cdot\nabla f\,(e/m) + E_{||}v_{||}\partial f/\partial w = C(f,f)+S.$

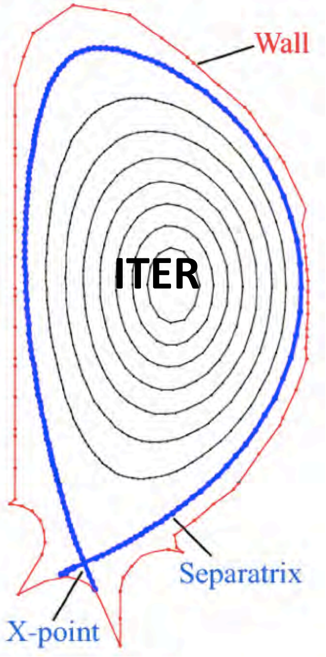
Fast-evolving nonthermal, non-diffusive kinetic system:

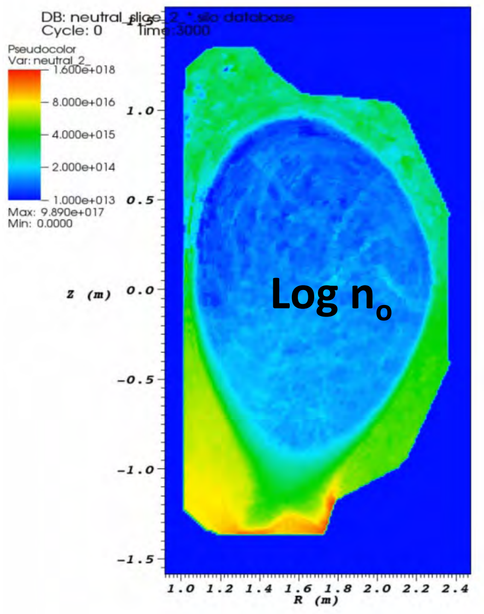
- Expensive per physics time → ideal for extreme scale computing.
- However, a short time simulation (~0.1ms) can yield equilibrium physics.



“banana” excursion

Large banana mixing in Edge pedestal

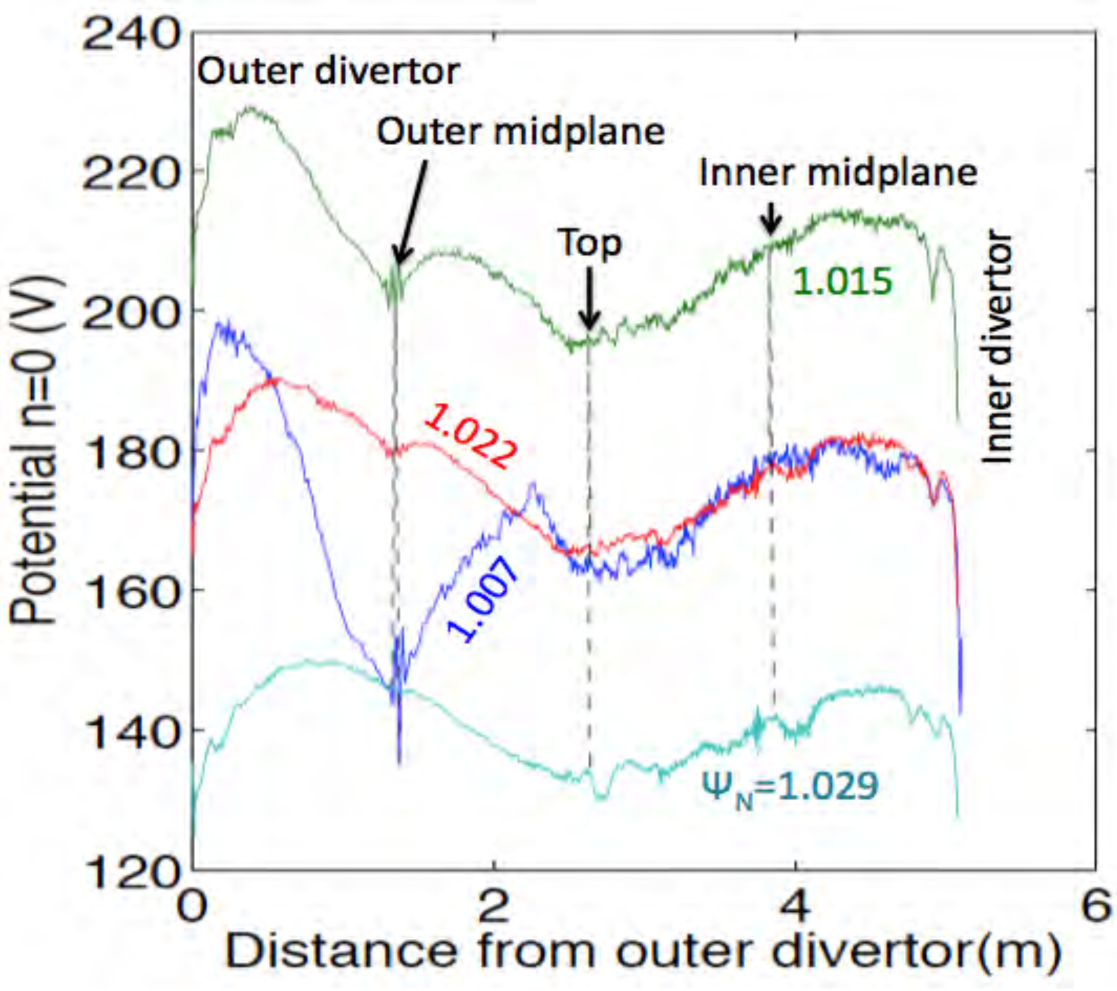




Poloidal potential variation in the scrape-off layer is also calculated in XGC1 for self-consistent heat-flux physics.

Notice strong pre-sheath in front of the divertor plates, which plays an important role in energy exchange between ions and electrons.

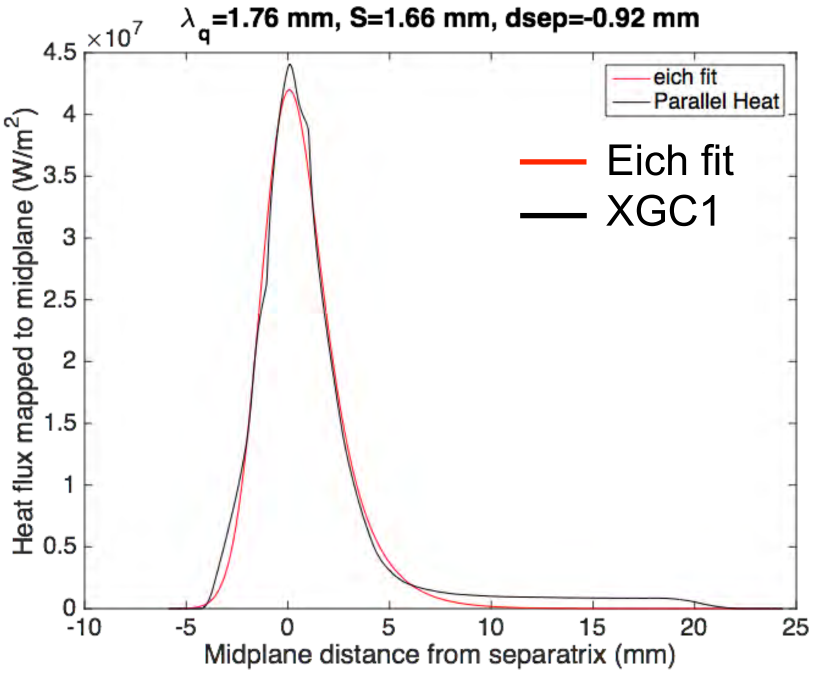
With nonlinear collisions and neutral recycling



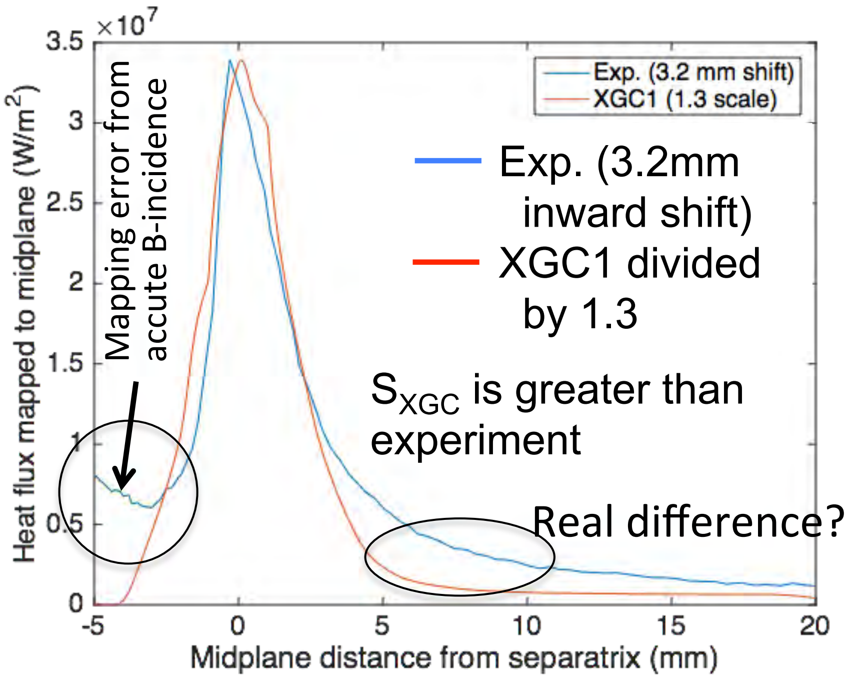
A model DIII-D H-mode plasma

Example heat flux footprint: DIII-D 144981, 1.5MA:

Some have better and some (e.g., NSTX data) have worse agreement with experimental data than shown.



Heat-flux footprint mapped back to outside midplane for DIII-D #144981. The Eich formula yields an excellent fit, with $\lambda_q^{XGC1} \approx 1.8$mm.



Mapping error from accute B-incidence

S_{XGC} is greater than experiment

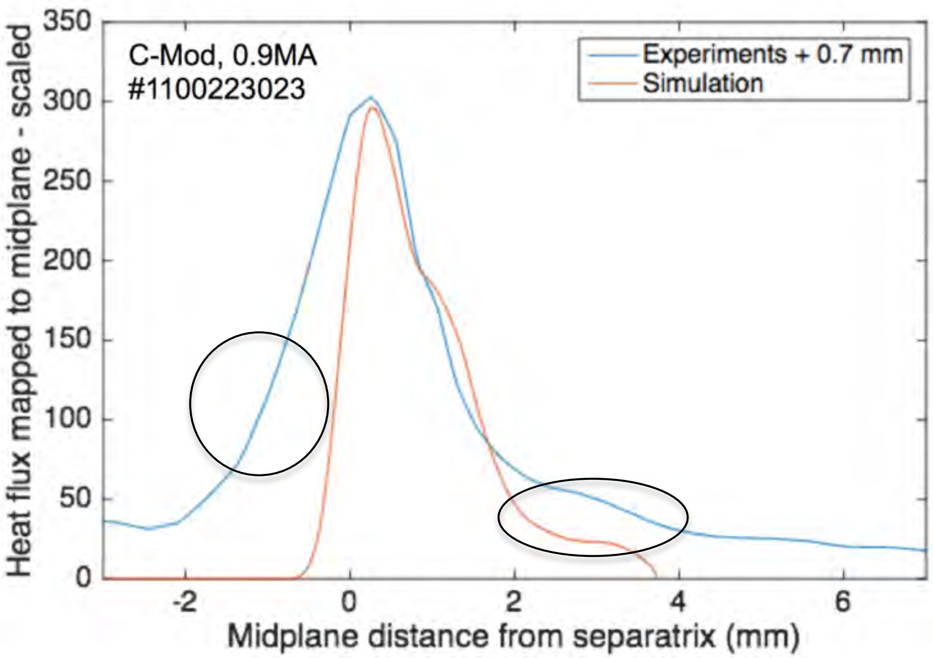
Real difference?

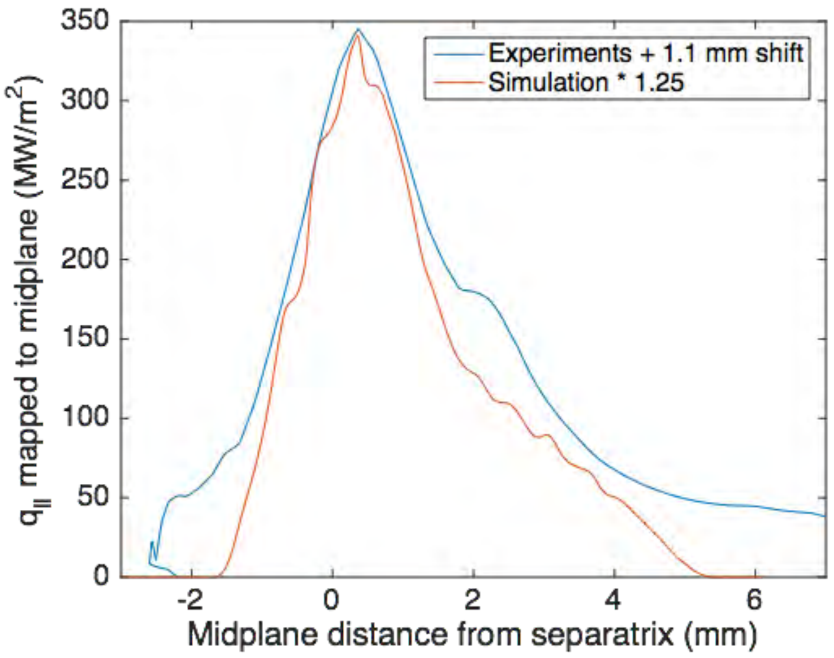
Heat-flux footprint comparison between XGC1 (divided by 1.3) and experiment (moved inward by 3mm) on DIII-D discharge #144981.

Disagreement in the private flux region with experiments exists on C-Mod, too, at high B_P, but not at lower B_P.

However, the C-Mod IR data in private flux region was not reliable (LaBombard).

Even with these disagreements with experiments in some cases, λ_q(XGC1) fits the overall scaling curve better than the experimental IR results do.

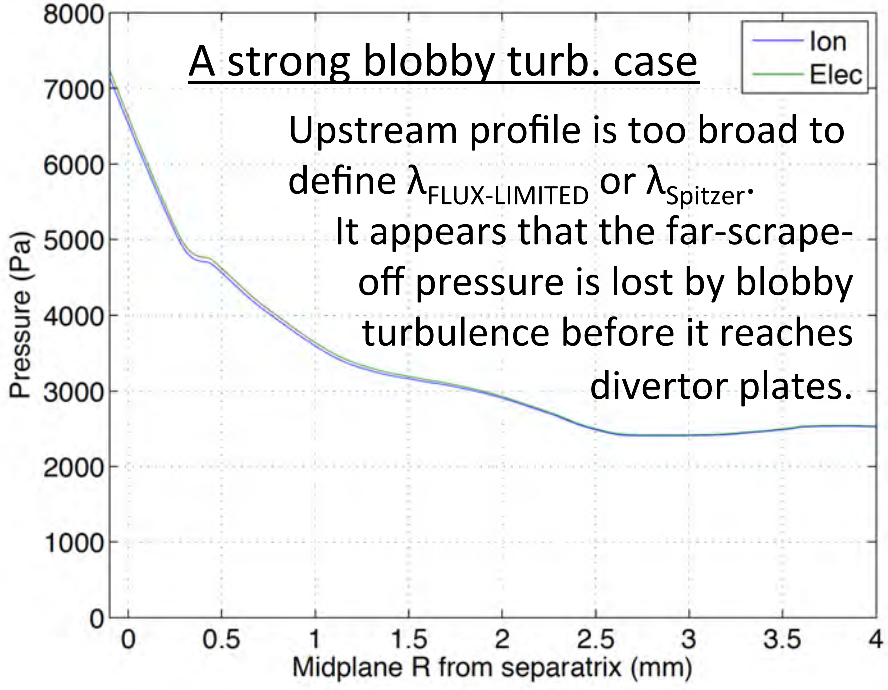




C-Mod, 1100223023, 0.9MA, showing a bigger spread of midplane IR footprint into the private flux region. Lower B_p C-Mod cases do not show this.

C-Mod, 1100223026, 0.5MA, does not show a wider spread of midplane IR footprint into the private flux region than what XGC1 shows.

2-point model check in XGC1: Not conclusive yet.

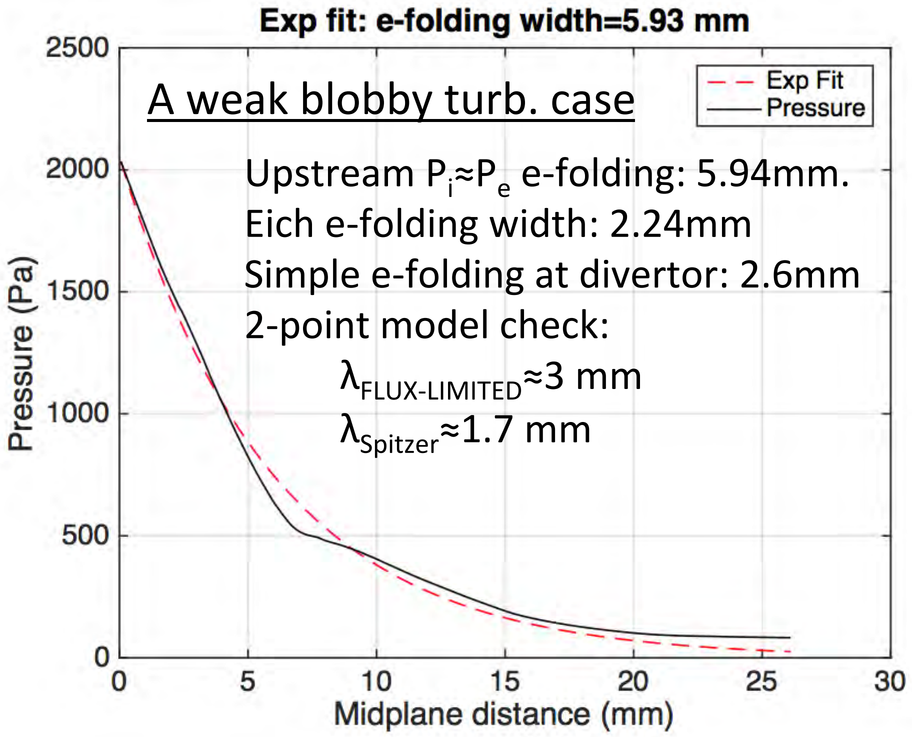


A strong blobby turb. case

Upstream profile is too broad to define $\lambda_{FLUX\text{-}LIMITED}$ or $\lambda_{Spitzer}$.

It appears that the far-scrape-off pressure is lost by blobby turbulence before it reaches divertor plates.

Upstream electron and ion pressure profile at outboard midplane from the 0.9MA C-Mode simulation using XGC1.



A weak blobby turb. case

Upstream $P_i \approx P_e$ e-folding: 5.94mm.

Eich e-folding width: 2.24mm

Simple e-folding at divertor: 2.6mm

2-point model check:

$\lambda_{FLUX\text{-}LIMITED} \approx 3$ mm

$\lambda_{Spitzer} \approx 1.7$ mm

Upstream pressure profile at outboard midplane from the 1MA DIII-D simulation using XGC1.

For those who are interested in Eich’s S-value

- The Eich spread parameter from XGC1 varies widely
  - $0.35 \leq S/\lambda_q \leq 0.94$ for DIII-D and C-Mod
  - Why does λ_q agree so well with experiments while S does not?
- For ITER, $S/\lambda_q = 0.375$