New insights on scrape-off layer plasma turbulence

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What are the properties of SOL plasma and how can we simulate it?

Mechanisms setting the SOL width? ES potential? Toroidal rotation?

How do our simulations compare with experiments?

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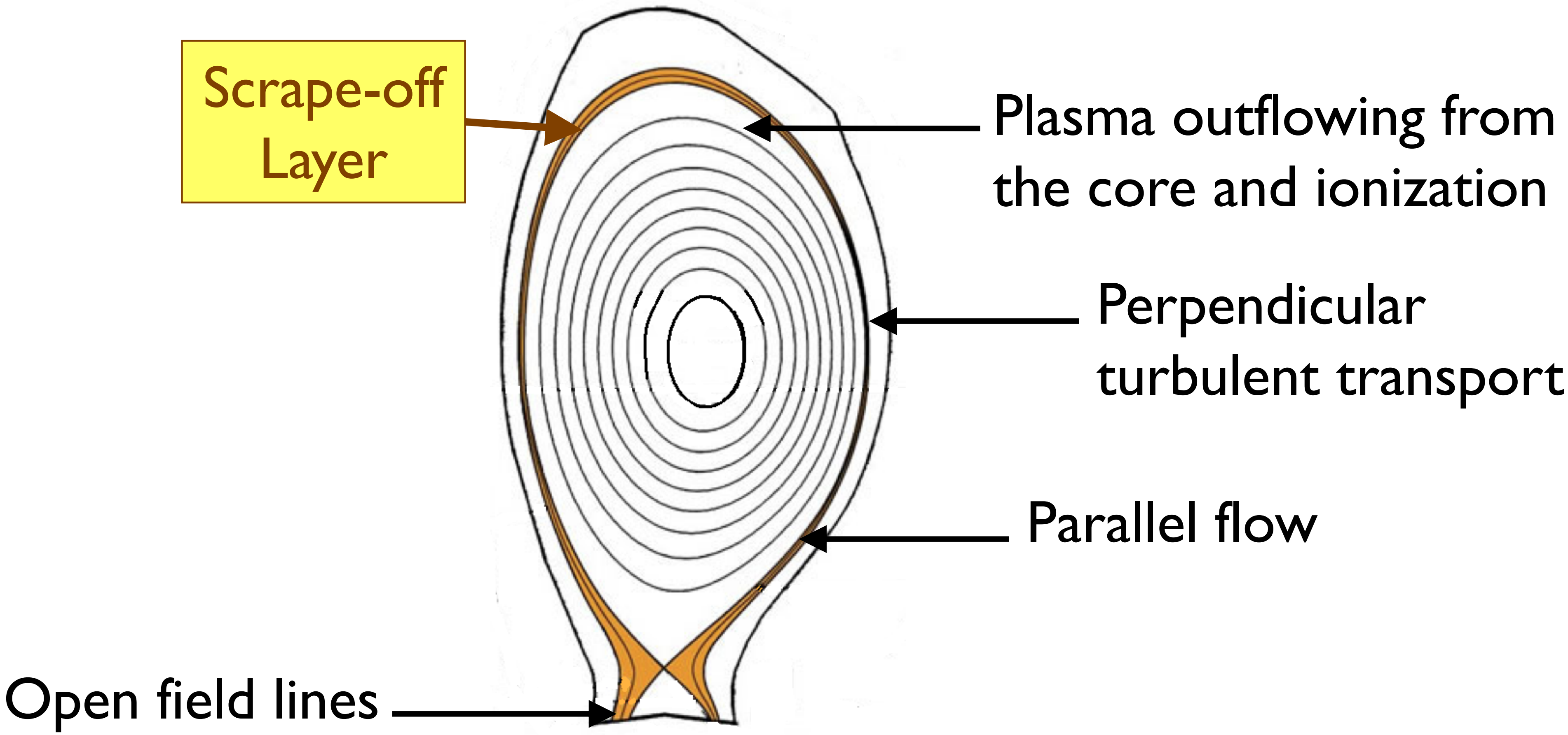
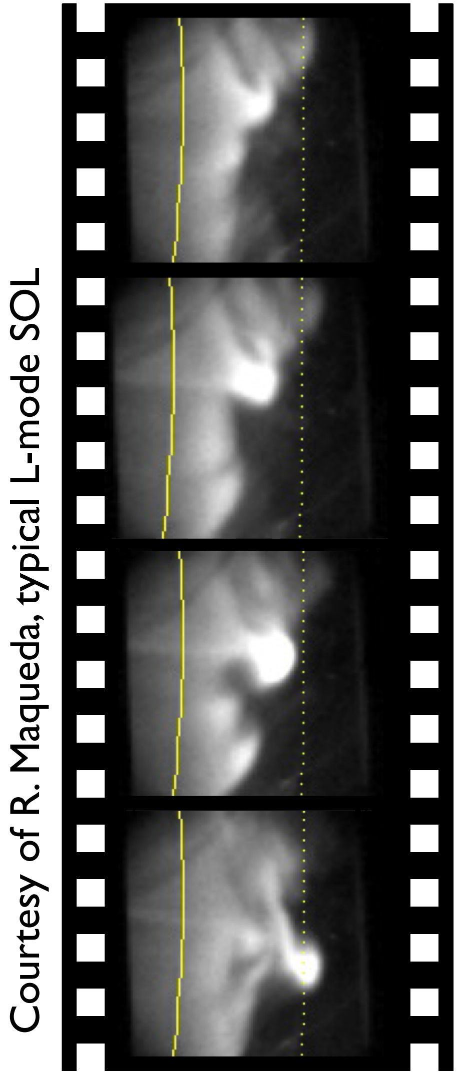
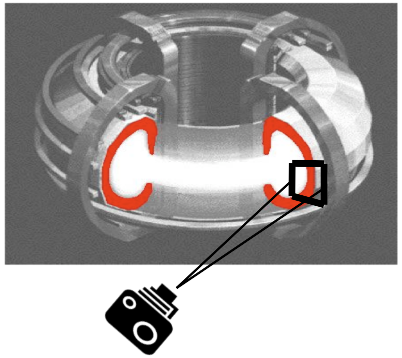
SOL channels particles and heat to the wall



SOL plasma properties





- $n_{fluc} \sim n_{eq}$
- $L_{fluc} \sim L_{eq}$
- Fairly cold (< 100 eV, $n_e \sim 10^{19}$ m^{-3}) magnetized plasma
- Role of neutrals
- Sheath physics

A model to evolve plasma turbulence in the SOL

Collisional Plasma → **Braginskii model** → ($\rho_i << L$, $\omega << \Omega_{ci}$) → **Drift-reduced Braginskii equations**

$$\frac{\partial n}{\partial t} + [\phi, n] = \hat{C}(nT_e) - n\hat{C}(\phi) - \nabla_{||}(nV_{||e}) + n_n \nu_{\text{ion}} - n\nu_{\text{rec}} + S_n$$

- $[\phi, n]$: E × B CONVECTION
- $\hat{C}(nT_e) - n\hat{C}(\phi)$: MAGNETIC CURVATURE
- $\nabla_{||}(nV_{||e})$: PARALLEL DYNAMICS
- $n_n \nu_{\text{ion}}$: IONIZATION
- $n\nu_{\text{rec}}$: RECOMBINATION
- S_n: OUTFLOW FROM CORE

T_e, T_i, Ω (vorticity) → similar equations

$V_{||e}$, $V_{||i}$ → parallel momentum balance

$$\nabla \cdot (n \nabla_\perp \phi) = \Omega - \tau \nabla_\perp^2 p_i$$

$$\nabla_\perp^2 \psi = j_{||}$$

A model to evolve plasma turbulence in the SOL

+ coupling with neutrals

$$\frac{\partial f_n}{\partial t} + \mathbf{v} \cdot \frac{\partial f_n}{\partial \mathbf{x}} = -\nu_{\text{ion}} f_n - \nu_{\text{CX}}(f_n - n_n f_i / n_i) + \nu_{\text{rec}} f_i$$

STREAMING

IONIZATION

$\nu_{\text{ion}} = n \langle v_e \sigma_{\text{ion}} \rangle$

CHARGE EXCHANGE

$\nu_{\text{CX}} = n \langle v_{\text{rel}} \sigma_{\text{CX}}(v_{\text{rel}}) \rangle$

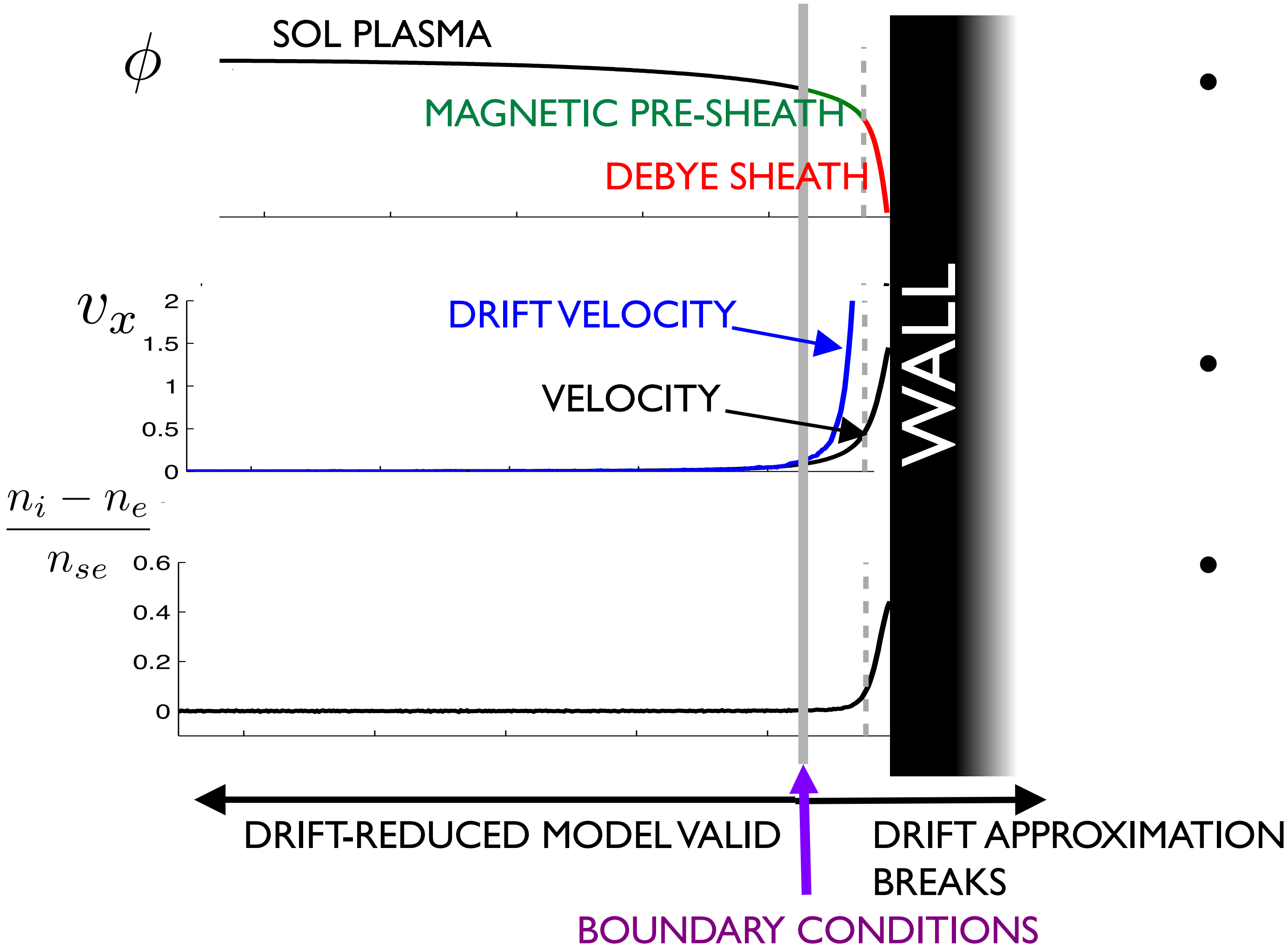
RECOMBINATION

$\nu_{\text{rec}} = n \langle v_e \sigma_{\text{rec}} \rangle$

Wersal & Ricci, NF 2015

We solve in 3D geometry, taking into account plasma outflow from the core, turbulent transport, ionization and charge exchange processes, and losses at the vessel

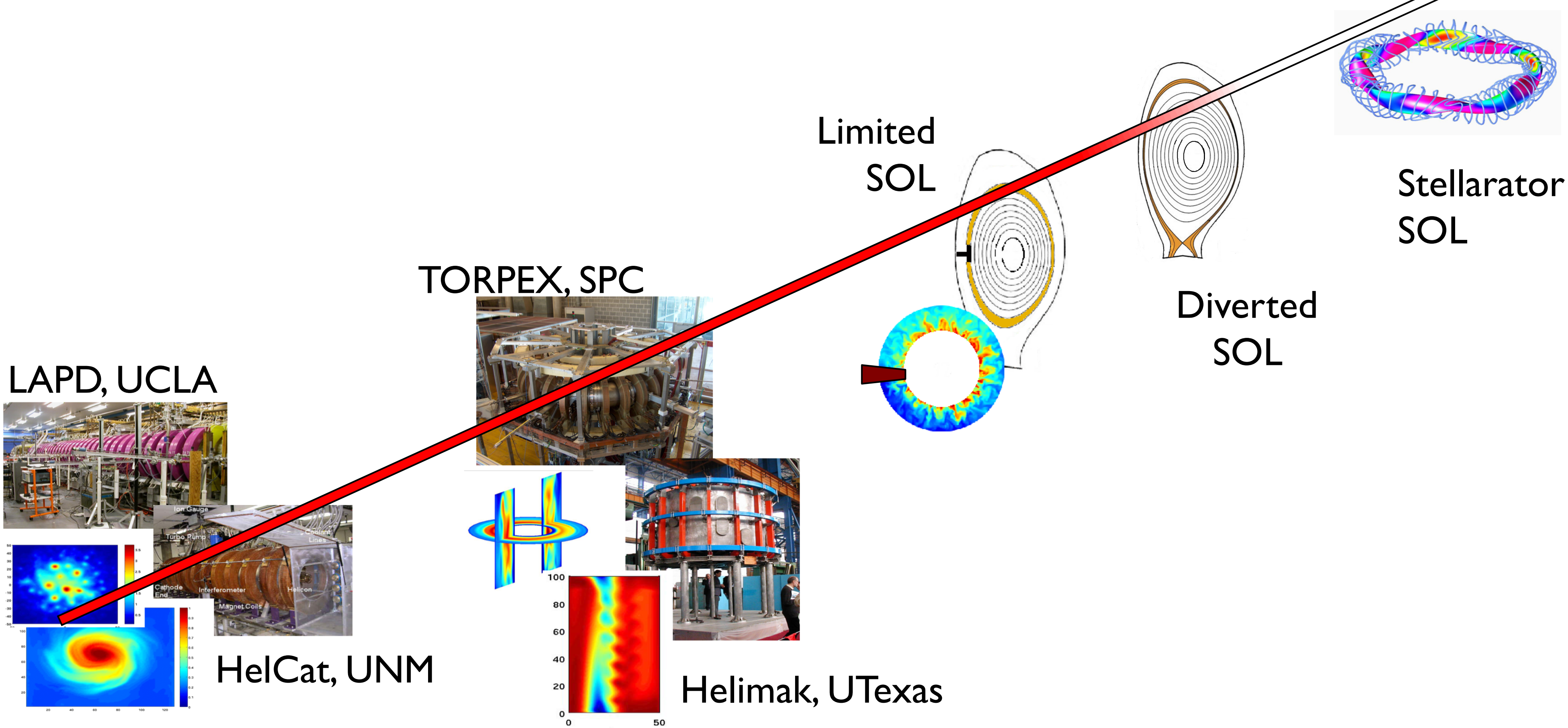
Boundary conditions at the plasma-wall interface



- Set of b.c. for all quantities, generalizing Bohm-Chodura
- Checked agreement with PIC kinetic simulations
- Neutrals: reflection and re-emission with cosine distribution

Loizu et al., PoP 2012

GBS: our simulation tool



Ricci et al., PPCF 2012; Halpern et al., JCP 2016

How do you make sure there are no bugs in your code?

1) Simple tests
2) Code-to-code comparisons (benchmarking)
3) Discretization error quantification
4) Convergence tests
5) Order-of-accuracy tests

NOT SUFFICIENT

RIGOROUS, requires analytical solution

Only verification ensuring convergence and correct numerical implementation

Riva et al., PoP 2014; Ricci et al., PoP 2015; Riva et al., PoP 2017

Order-of-accuracy tests, method of manufactured solution

Our model: $A(f) = 0$, f unknown

We solve $A_n(f_n) = 0$, but $\epsilon_n = f_n - f = ?$

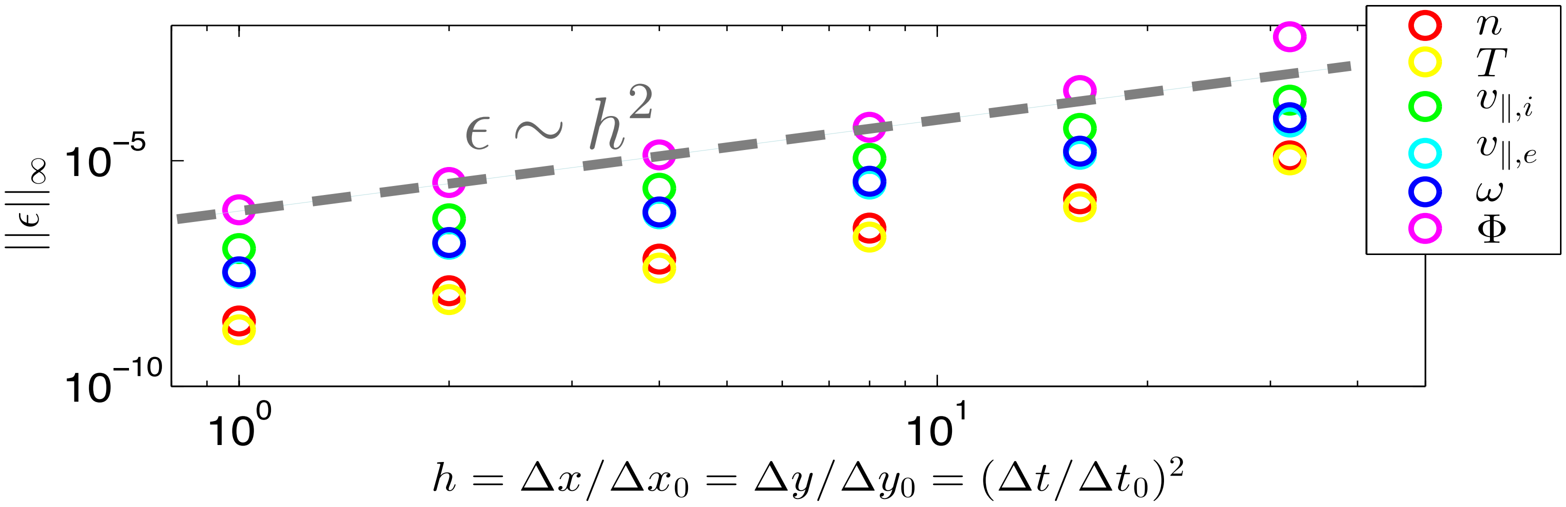
Method of manufactured solution:

1) we choose g, then $S = A(g)$

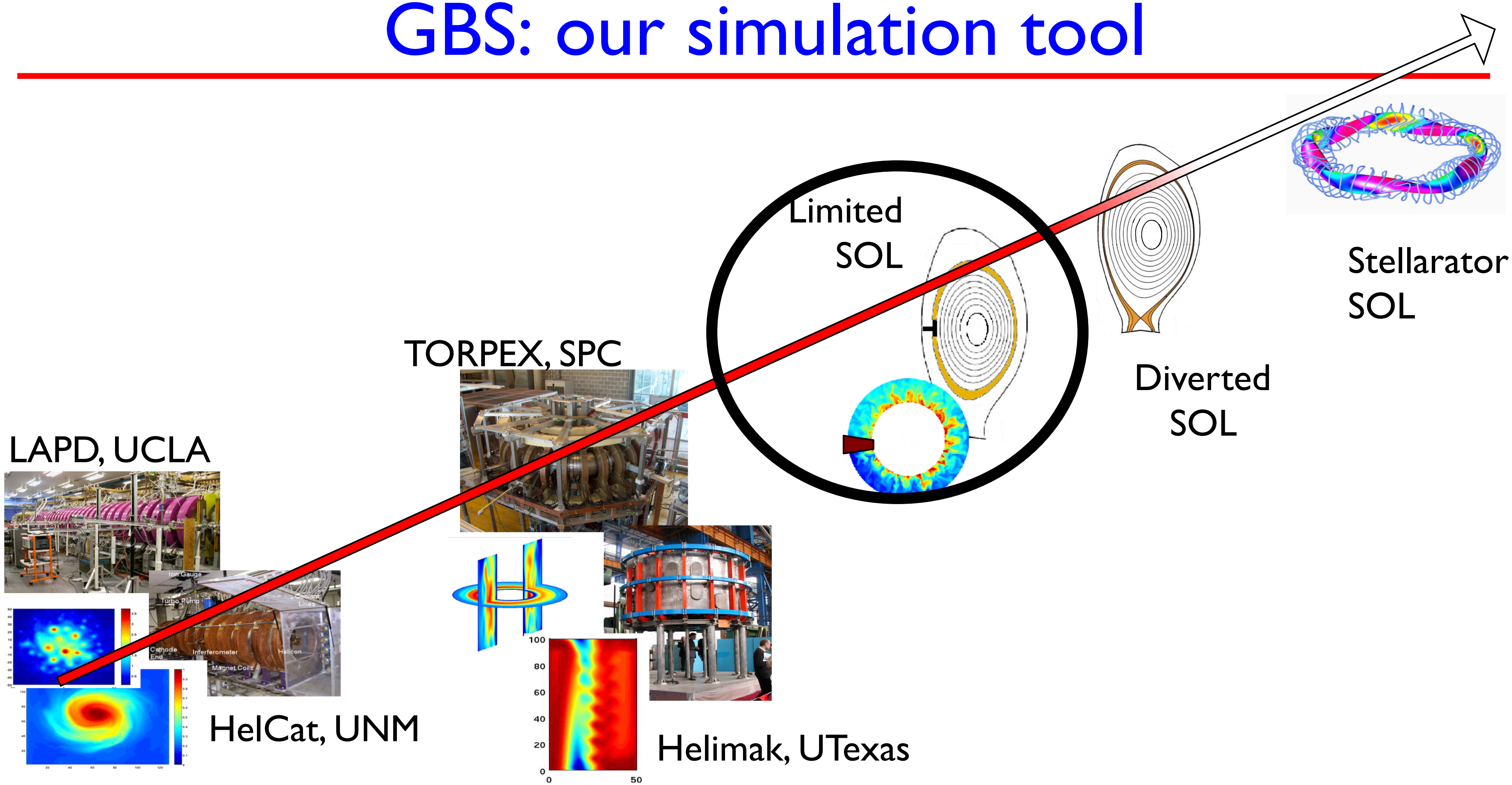
2) we solve: $A_n(g_n) - S = 0$

$\rightarrow$ $\epsilon_n = g_n - g$

For GBS:

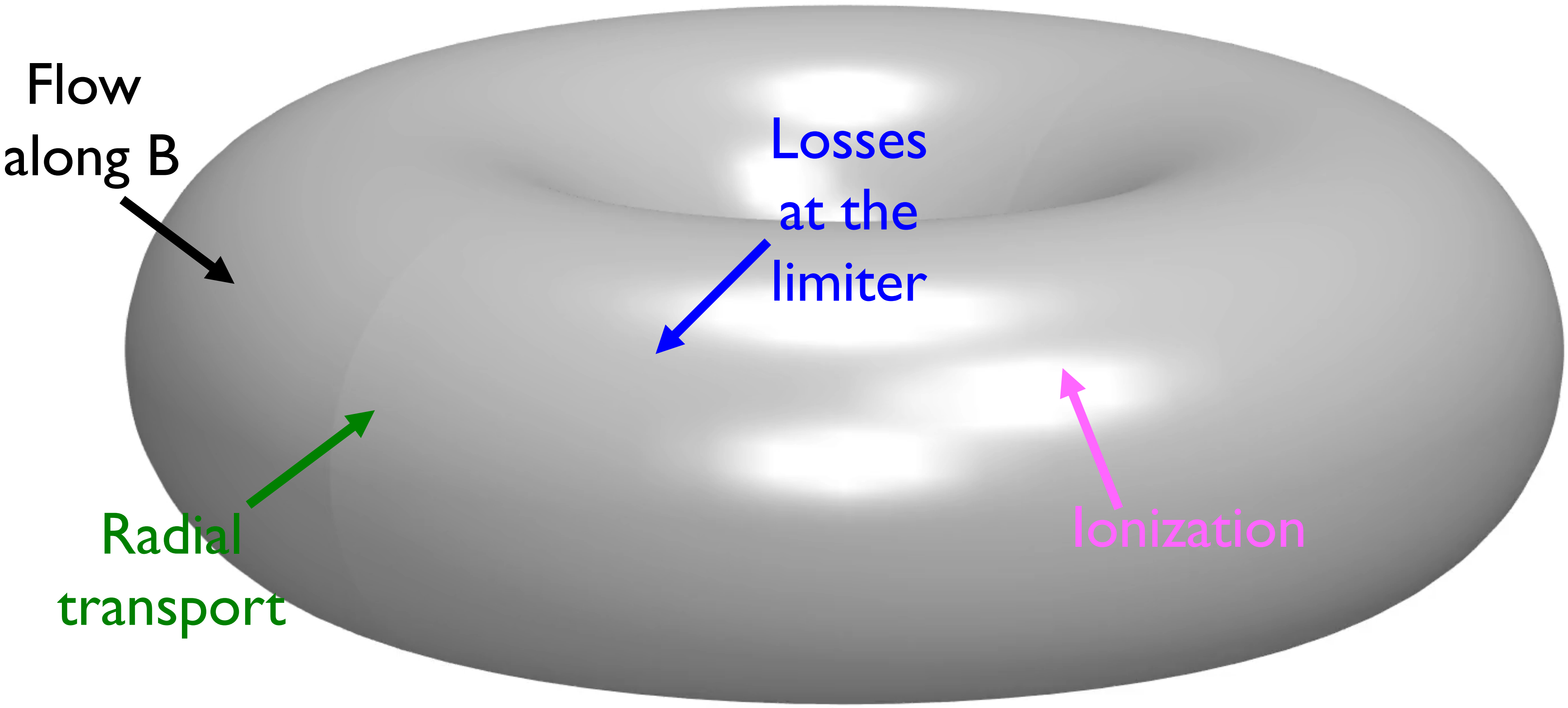


GBS: our simulation tool

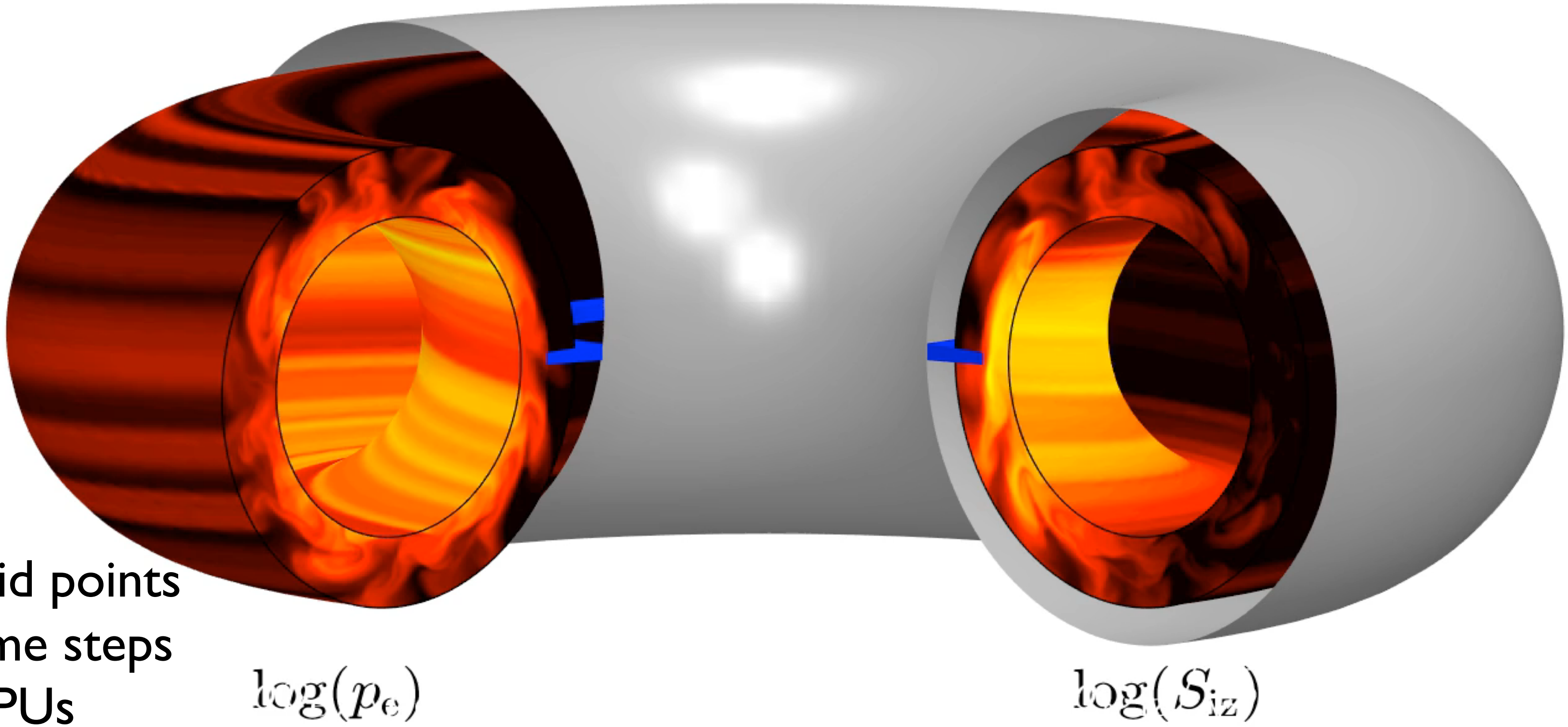


Ricci et al., PPCF 2012; Halpern et al., JCP 2016

GBS evolves plasma and neutrals self-consistently



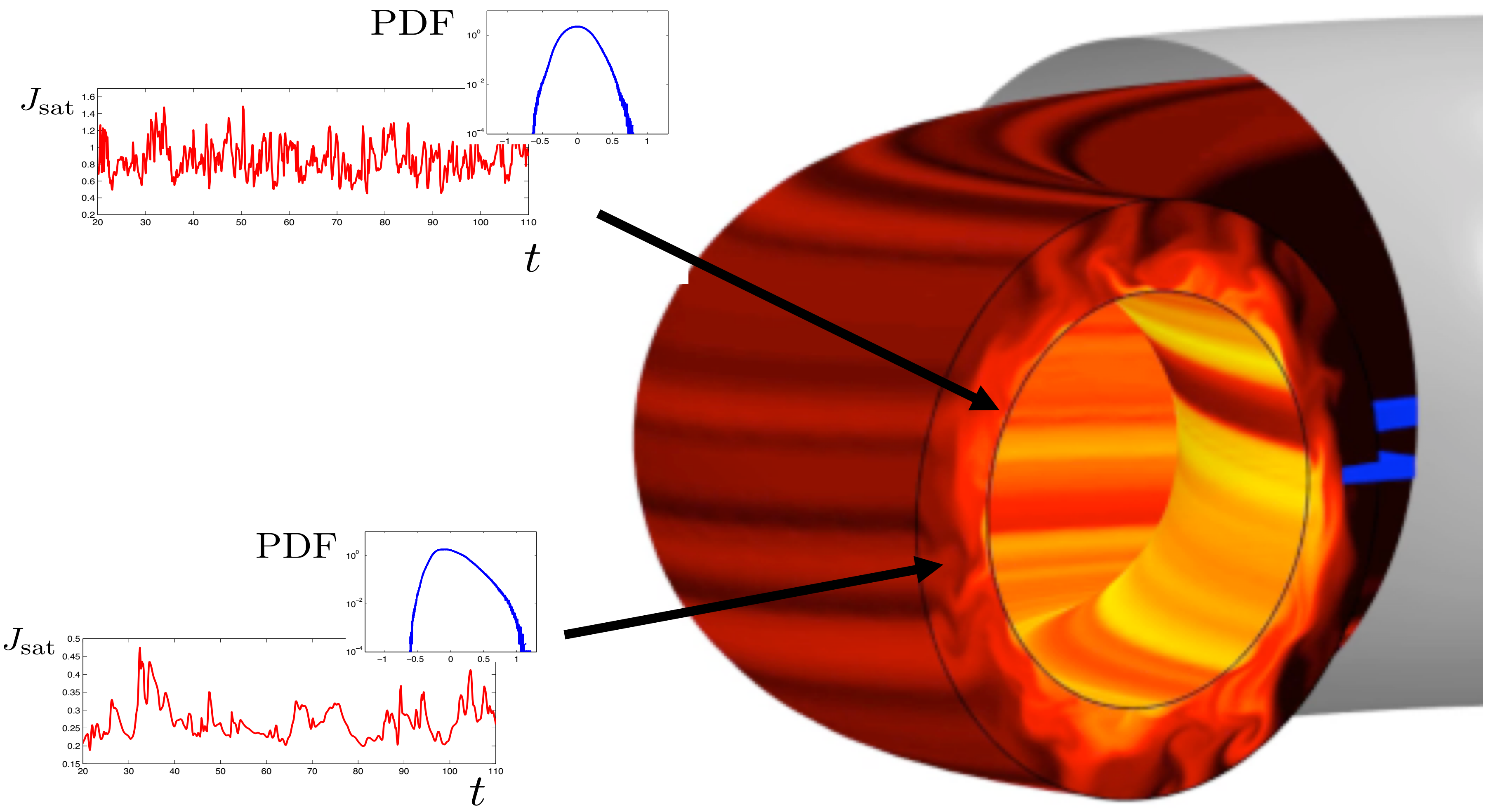
GBS evolves plasma and neutrals self-consistently



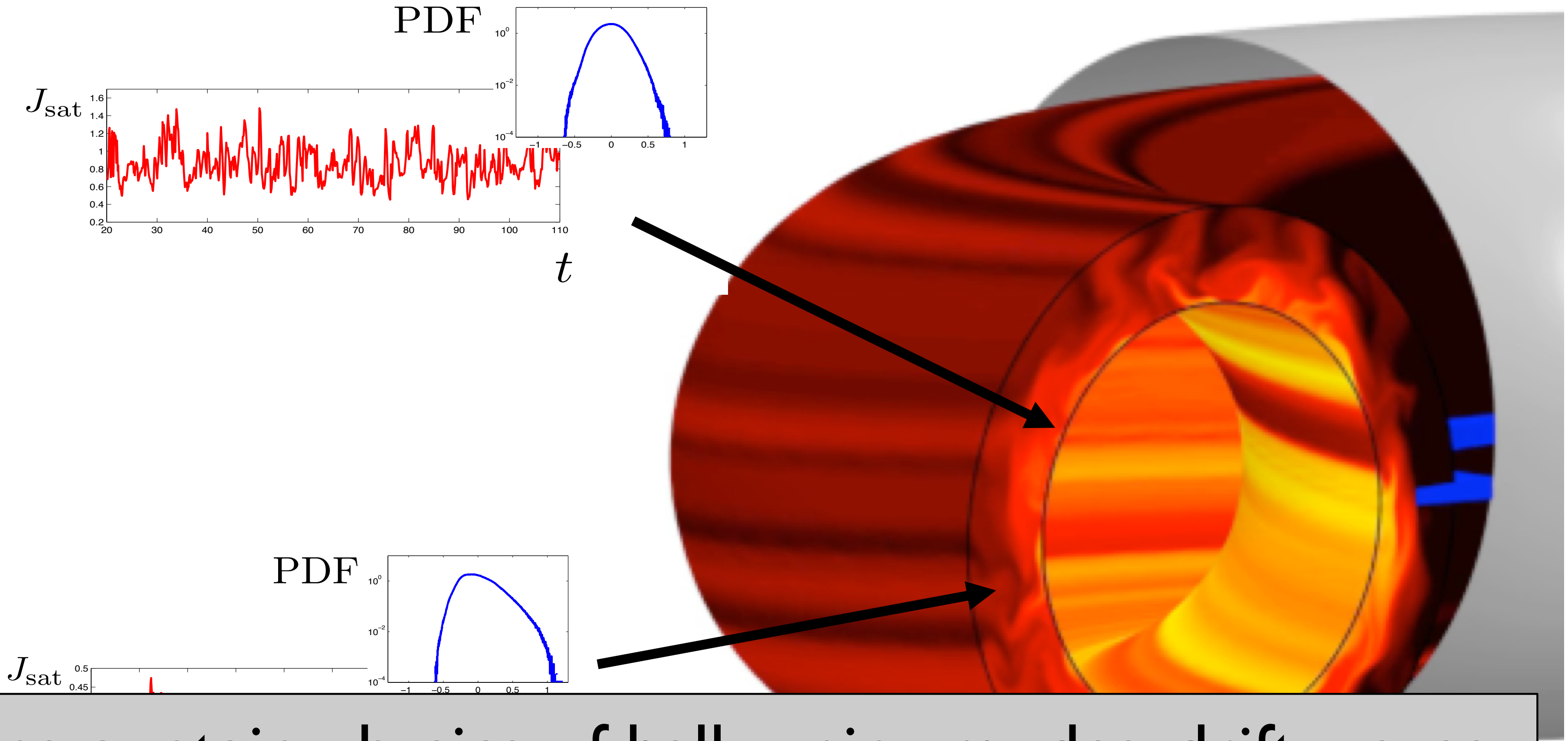
- 10^7 grid points
- 10^6 time steps
- 10^4 CPUs

→ 10^5 CPU hours

Main experimental features retrieved

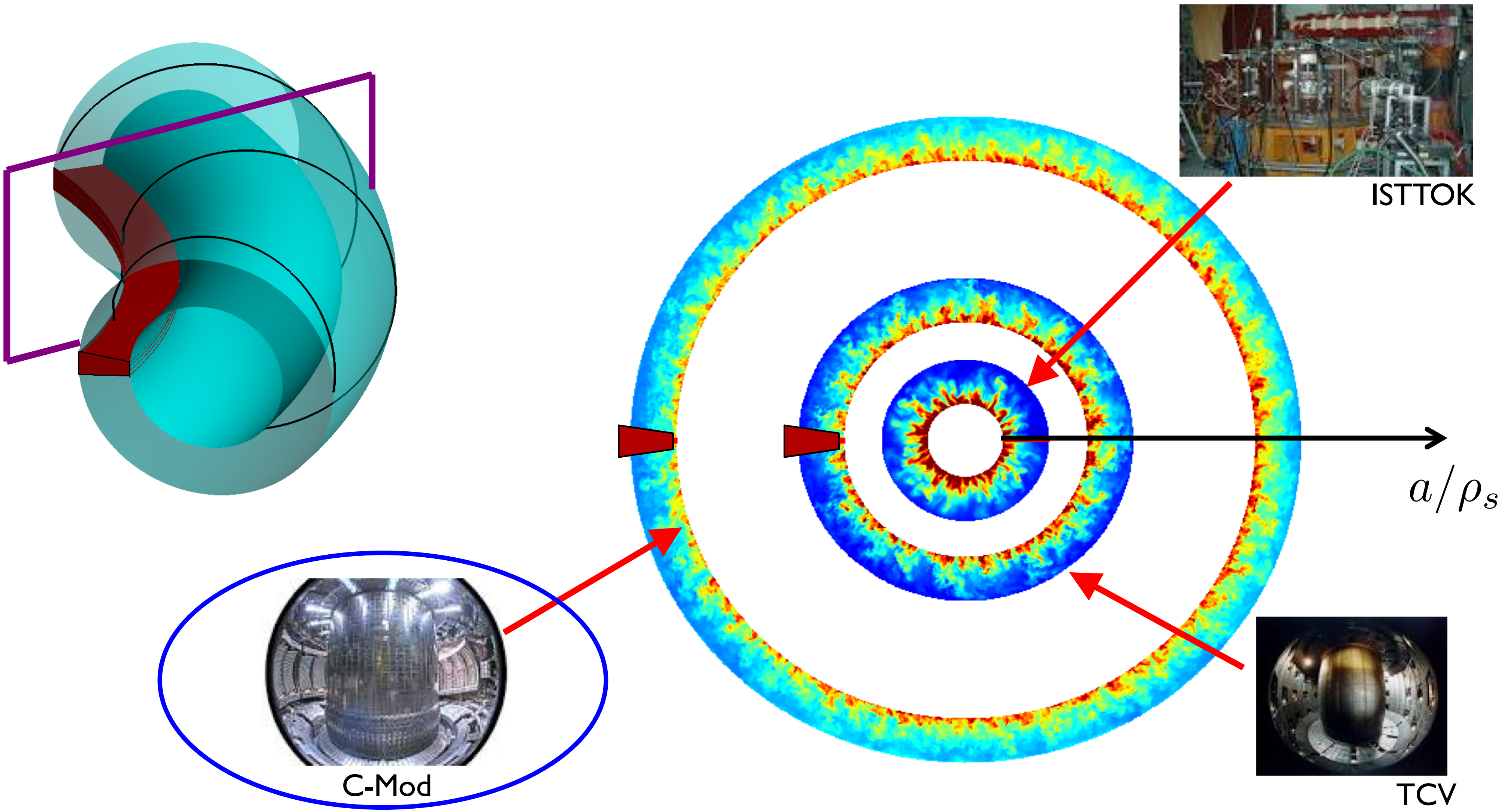


Main experimental features retrieved

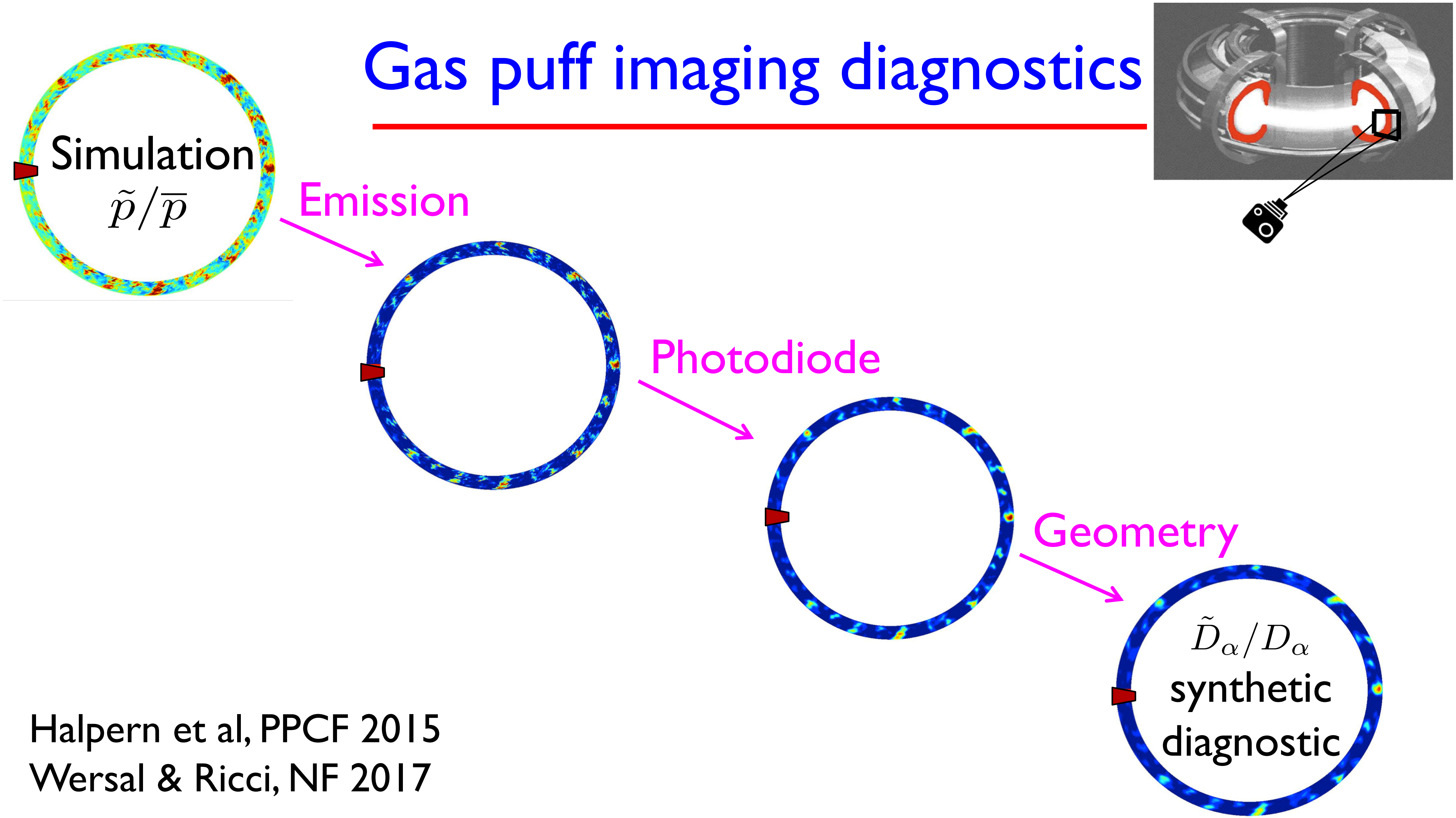


Simulations contain physics of ballooning modes, drift waves, Kelvin-Helmholtz, blobs, parallel flows, sheath losses…

A large validation effort

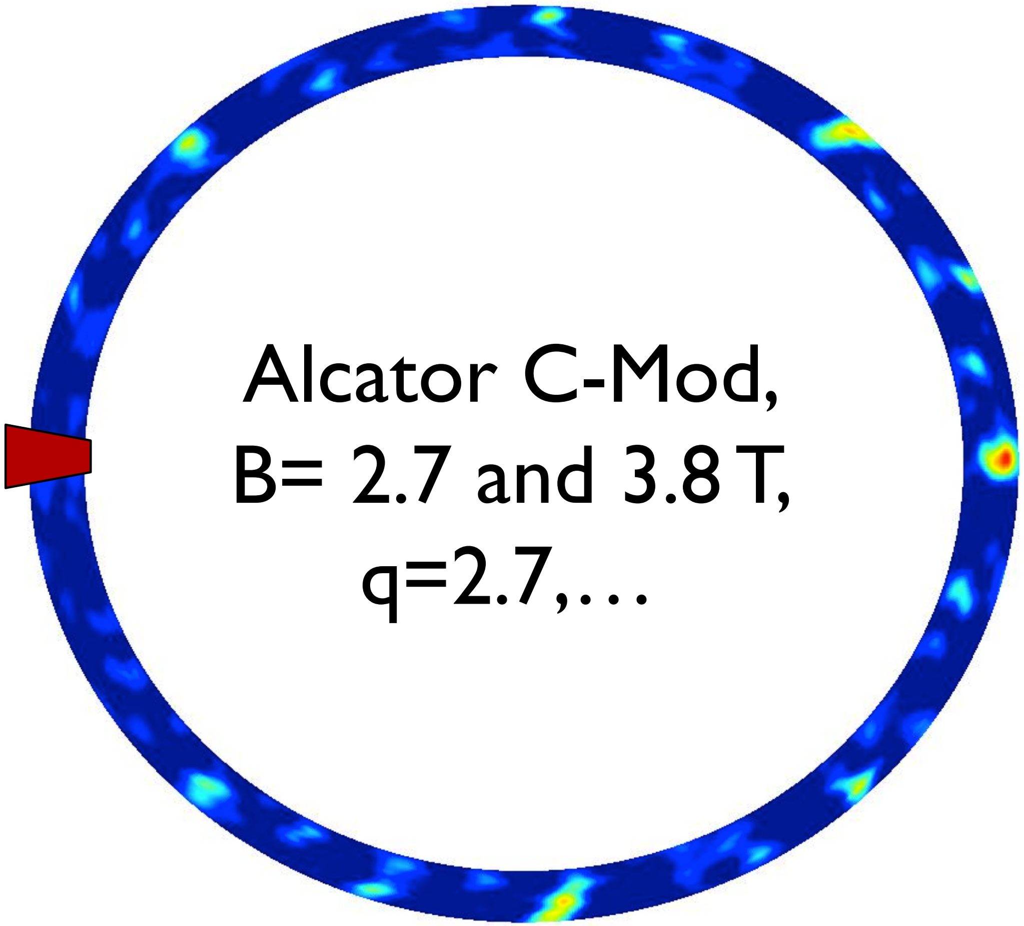


Gas puff imaging diagnostics

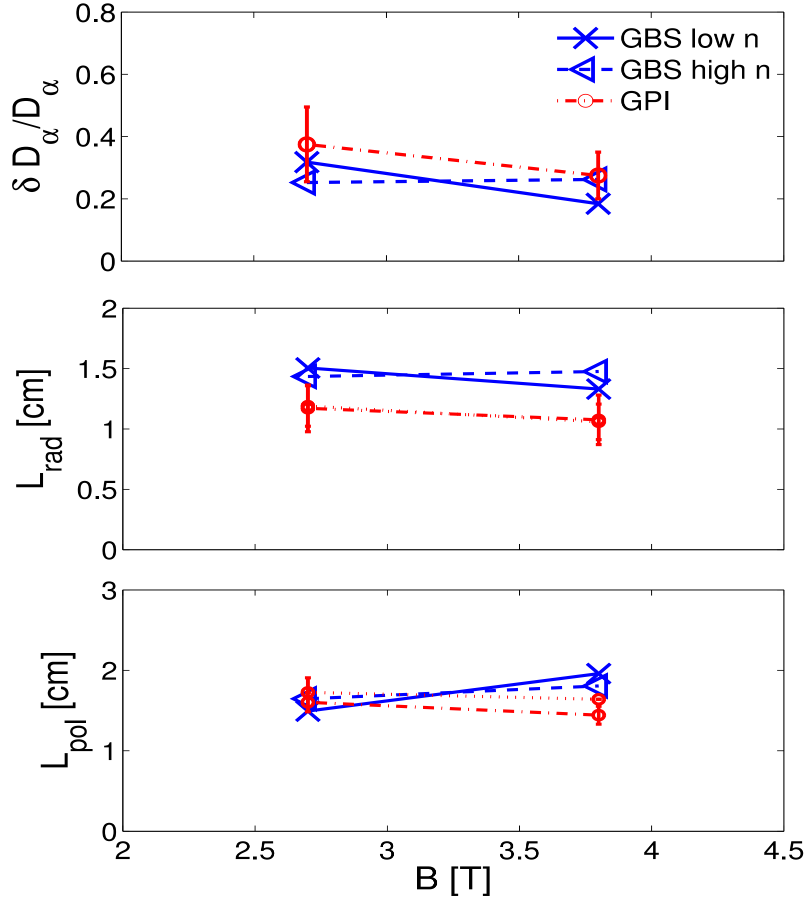


Halpern et al, PPCF 2015
Wersal & Ricci, NF 2017

C-Mod fluctuation properties well captured



Alcator C-Mod,
B= 2.7 and 3.8 T,
q=2.7,…



Halpern et al., PPCF 2015

A few of the key questions we addressed

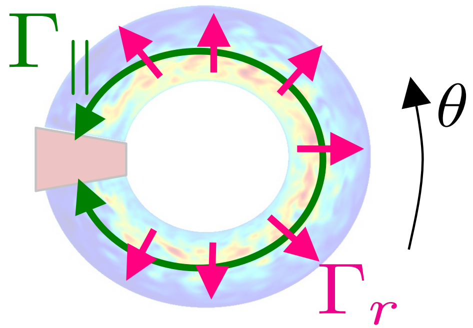
- How is the SOL width established?

- Why is there a difference between near and far SOL?

- What determines the SOL electrostatic potential?

- Are there mechanisms to generate toroidal rotation in the SOL?

SOL width – analytical estimate



$$\nabla_r \Gamma_r \sim \nabla_\parallel \Gamma_\parallel$$

$\nabla_\parallel \sim \frac{1}{qR}$

$\Gamma_\parallel \sim c_s p$ Bohm's

$\nabla_r \sim \frac{1}{L_p}$

$$\Gamma_r = \langle \tilde{p}\tilde{v}_{E\times B,r}\rangle_t = \frac{1}{B}\left\langle \tilde{p}\frac{\partial\tilde{\phi}}{\partial\theta}\right\rangle_t \sim \frac{\gamma\bar{p}}{L_p k_r^2} \sim \frac{\gamma\bar{p}}{k_\theta}$$

$$\frac{\partial p}{\partial t} + \nabla\cdot(p\mathbf{v}_{E\times B}) \simeq 0$$

Removal of driving gradient

Nonlocal

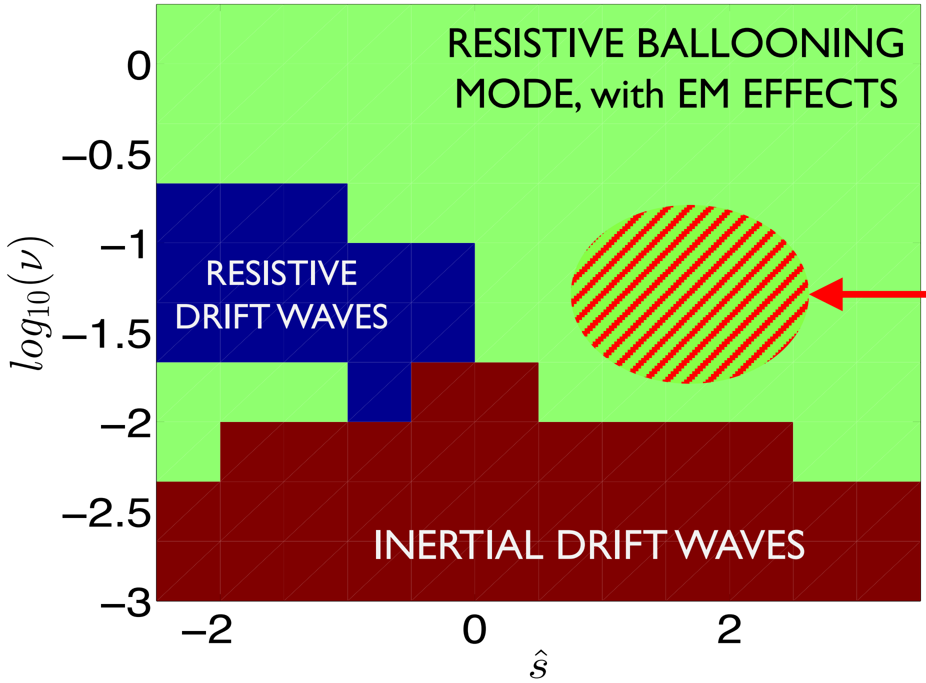
$$\frac{\partial\tilde{p}}{\partial r} \sim \frac{\partial\bar{p}}{\partial r}$$

$$L_p \simeq \frac{qR}{c_s}\left(\frac{\gamma}{k_\theta}\right)_{\max}$$

Ricci et al., PRL 2008; PoP 2013

SOL turbulent regimes

Instability driving turbulence depends mainly on $q, \nu, \hat{s}$.



TYPICAL LIMITED SOL OPERATIONAL PARAMETERS

$$L_p = \frac{qR}{c_s}\left(\frac{\gamma}{k_\theta}\right)_{\max}$$

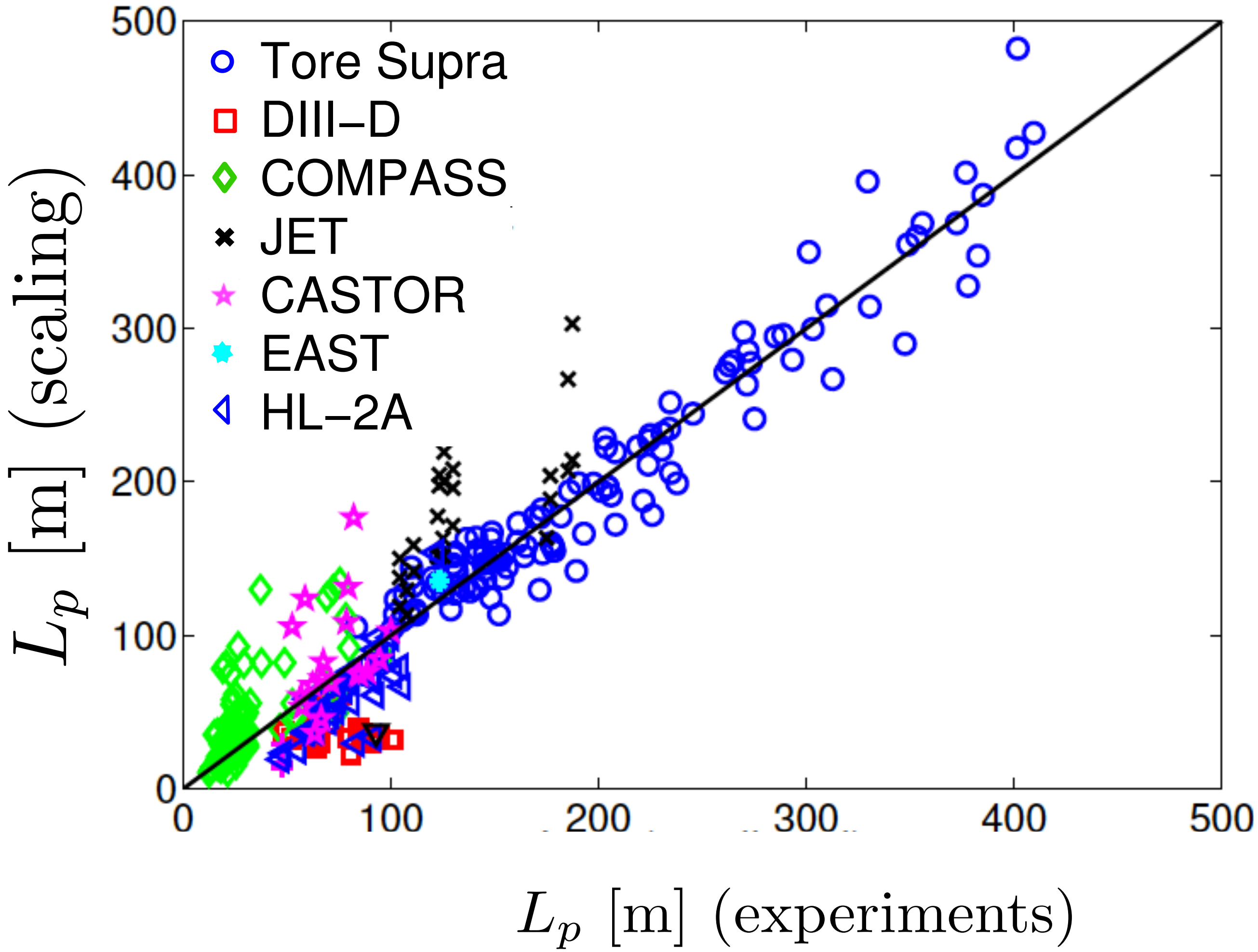
BM $\gamma \sim \gamma_b = c_s\sqrt{\frac{2}{RL_p}}$

BM $k_\theta \sim \sqrt{\frac{\mu_0 \sigma_\parallel c_A^2}{q^2 R^2 \gamma_b}}$

Mosetto et al., PoP 2013; PoP 2015

Successful validation of ballooning scaling

Good agreement with simulation results and ITPA database



Halpern et al., NF 2013; NF 2014, PPCF 2016

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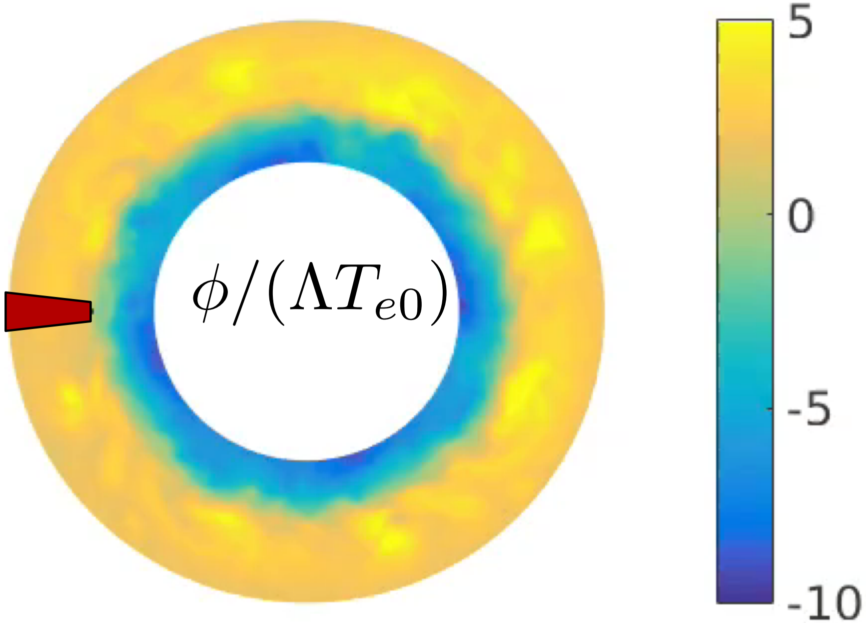
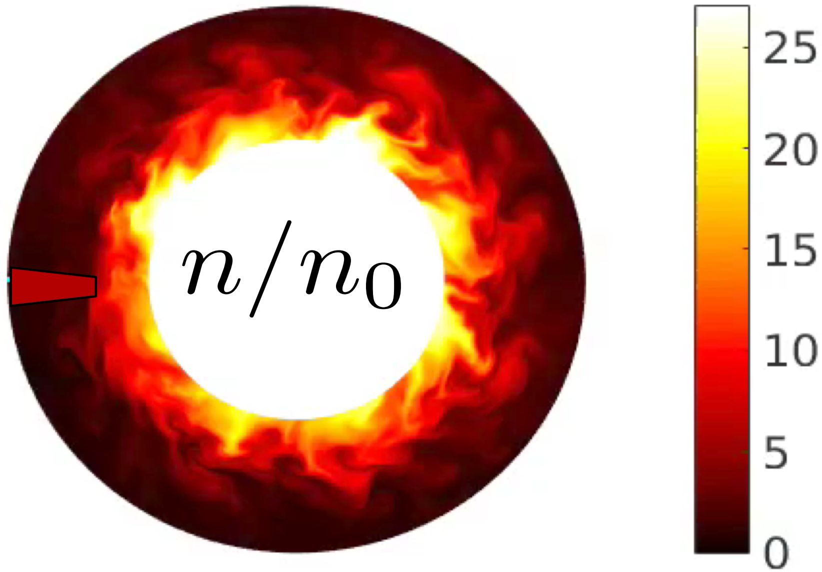
Different turbulent properties in near and far SOL



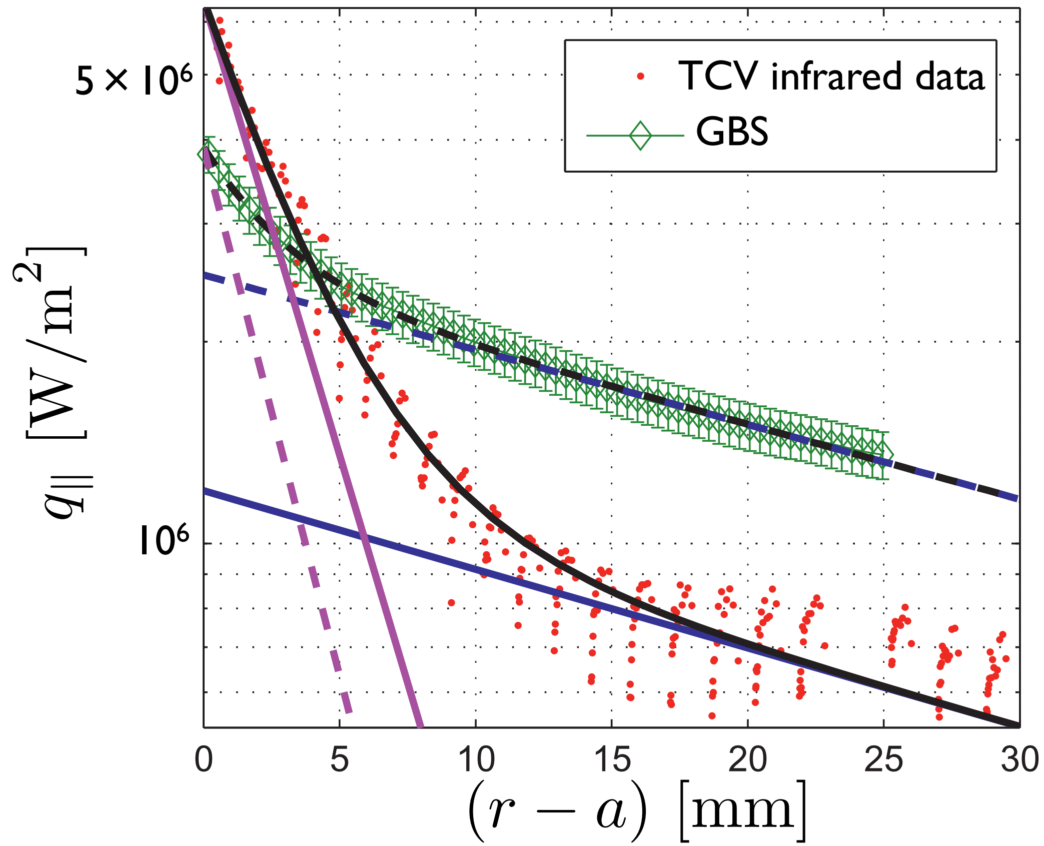
Strong shear flow at the LCFS…

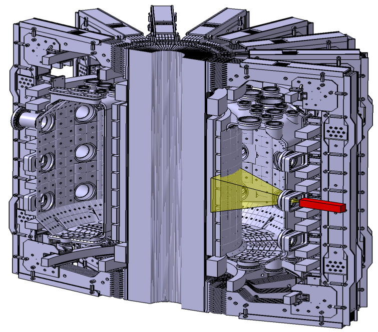
… resulting into a strong density gradient



Halpern & Ricci, NF 2017

Narrow feature at LCFS, long decay in far SOL





- TCV comparison: similar scale lengths, reduced heat flux in narrow feature
- Short scale: turbulence correlation length

Nespoli et al., JNM 2017
Halpern & Ricci, NF 2017

ITER inner wall was redesigned

A few of the key questions we addressed

- How is the SOL width established?
- Why is there a difference between near and far SOL?
- What determines the SOL electrostatic potential?
- Are there mechanisms to generate toroidal rotation in the SOL?

Potential in the SOL set by sheath and electron adiabaticity

Typical estimate: at the sheath

$$v_{\|i} = c_s \qquad v_{\|e} = c_s \exp(\Lambda - e\phi/T_e^{\mathrm{sh}})$$

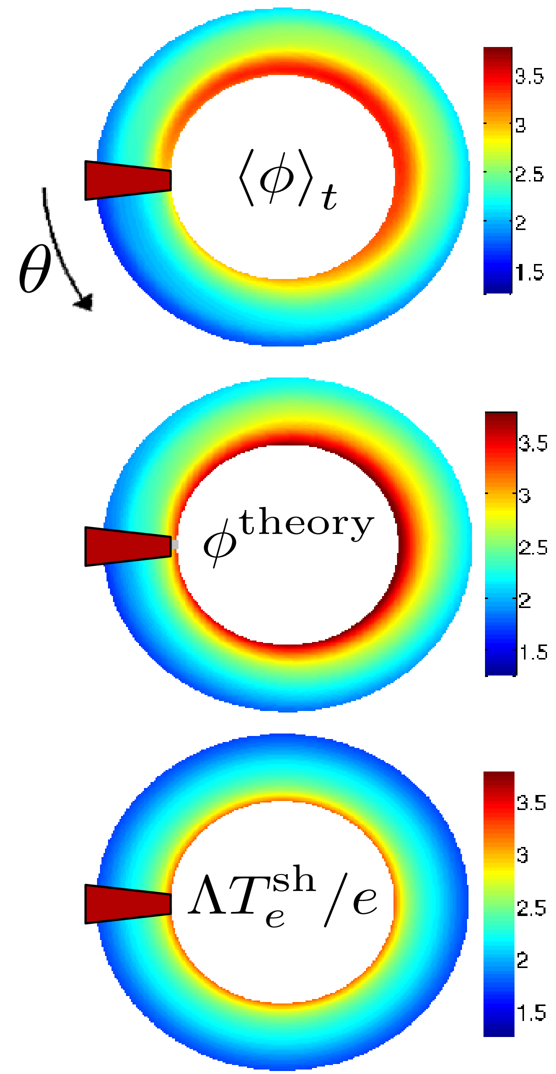
to have ambipolar flows, $v_{\|i} = v_{\|e}$

$$\phi = \Lambda T_e^{\mathrm{sh}}/e \simeq 3T_e^{\mathrm{sh}}/e$$

$$\phi = \underbrace{\Lambda T_e^{\mathrm{sh}}/e}_{\text{Sheath}} + \underbrace{2.71(T_e - T_e^{\mathrm{sh}})/e}_{\text{Adiabaticity}}$$

Our more rigorous treatment, from $v_{\|e}$ equation

Loizu et al., PPCF 2013



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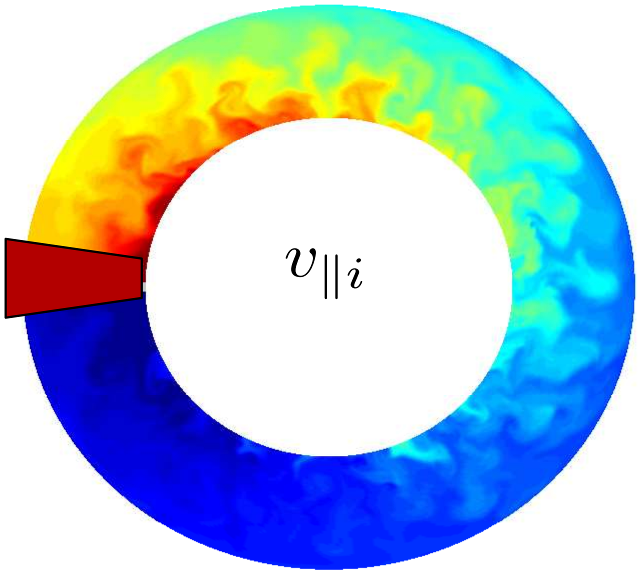
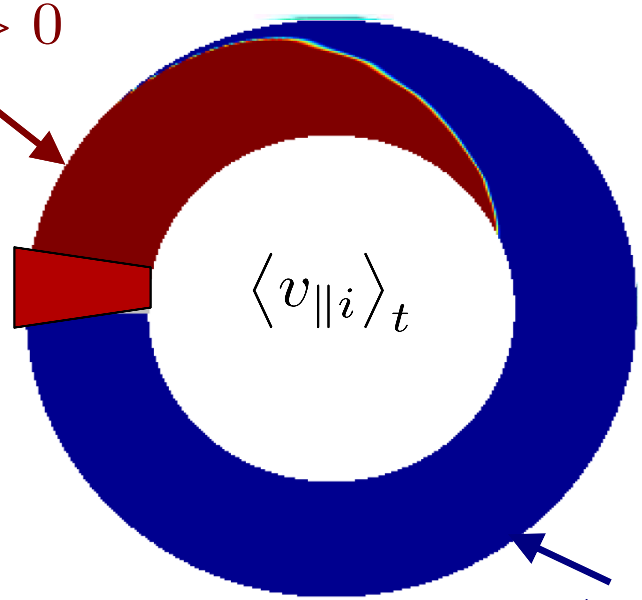
GBS simulations show intrinsic toroidal rotation





2D equation for the equilibrium flow

$$-\frac{\partial}{\partial r}\left(D_T \frac{\partial \overline{v}_{\parallel i}}{\partial r}\right) + \frac{\sigma_\varphi}{|B_\varphi|}\frac{\partial \overline{\phi}}{\partial r}\frac{\partial \overline{v}_{\parallel i}}{\partial \theta} + \alpha \sigma_\theta \overline{v}_{\parallel i}\frac{\partial \overline{v}_{\parallel i}}{\partial \theta} + \frac{\alpha \sigma_\theta}{m_i \overline{n}}\frac{\partial \overline{p}}{\partial \theta} = 0$$

Turbulent driven radial transport, gradient-removal estimate

Poloidal convection

Parallel convection

Pressure poloidal asymmetry

with boundary conditions:

$$\overline{v}_{\parallel i}\Big|_{se} = \pm c_s - \frac{q}{\epsilon}\frac{\partial \overline{\phi}}{\partial r}$$

Bohm's criterion

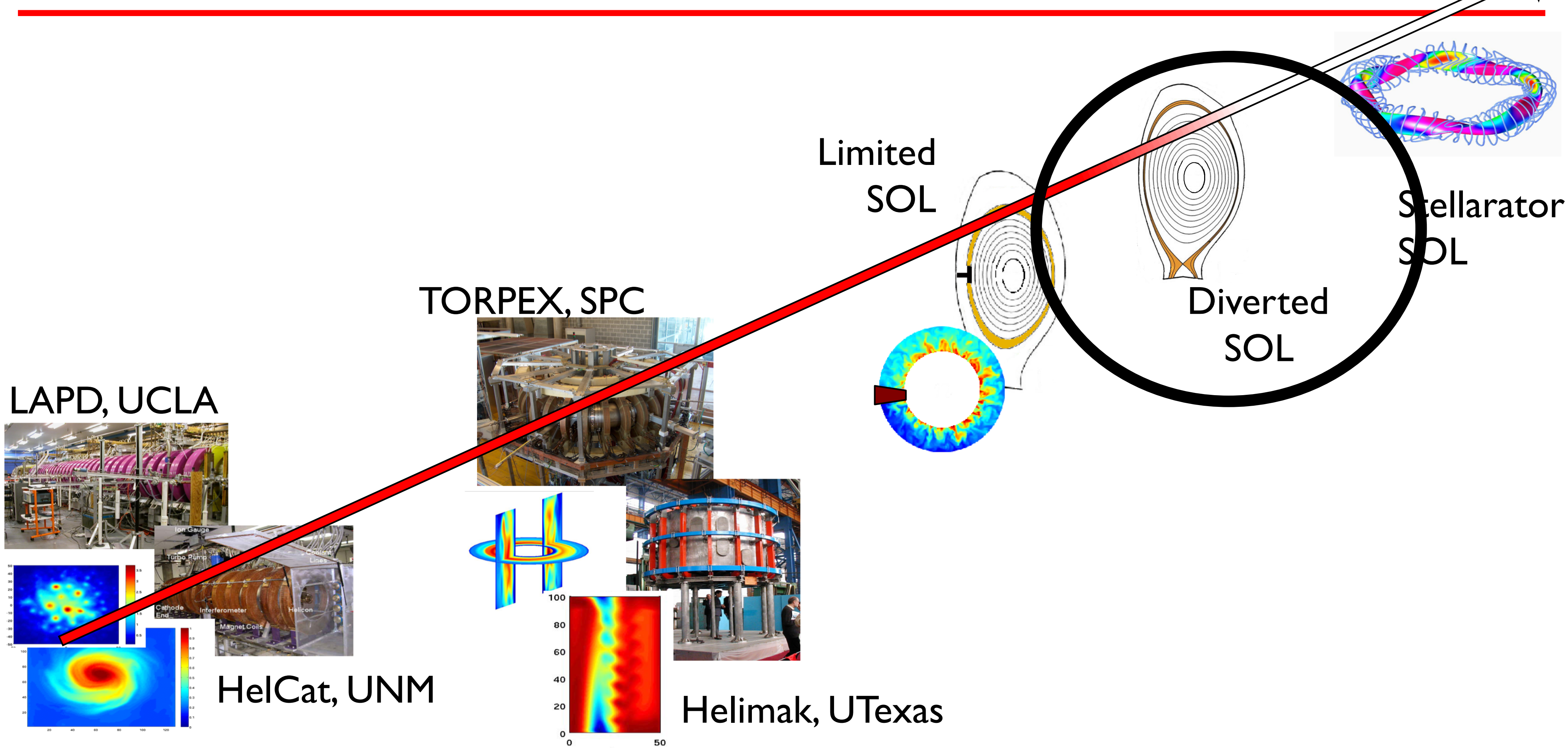
ExB correction

Sources of toroidal rotation

Agreement with C-Mod observations

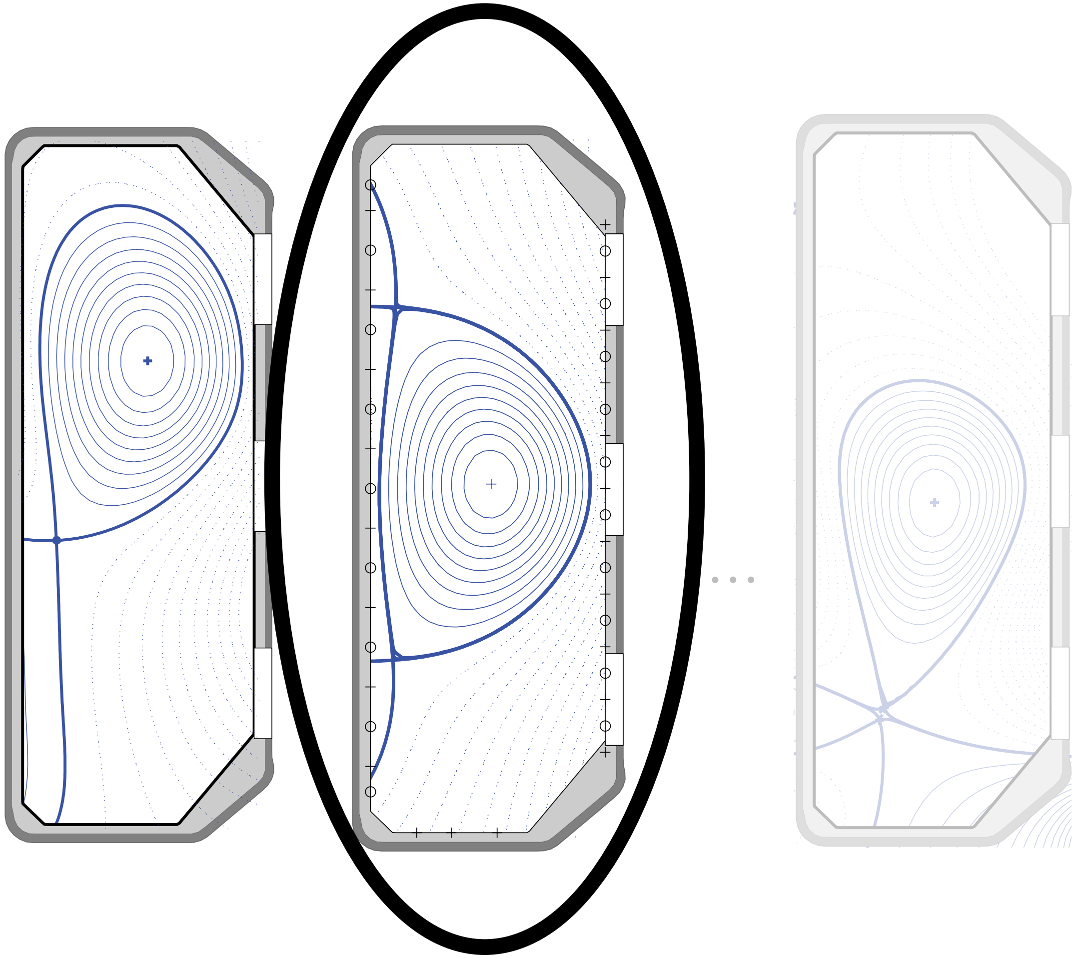
Loizu et al., PoP 2014

GBS: our simulation tool



Ricci et al., PPCF 2012; Halpern et al., JCP 2016

Flexible non-field aligned algorithm for diverted geometries

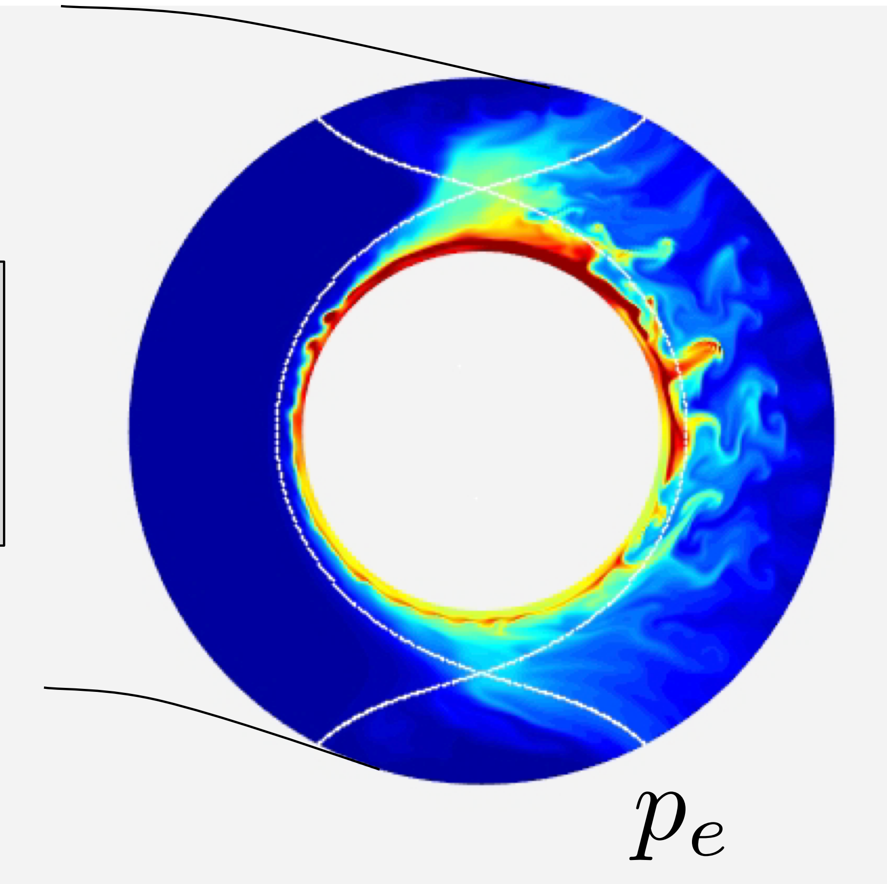


Double null:

- Possible heat exhaust solution
- High and low field sides separated

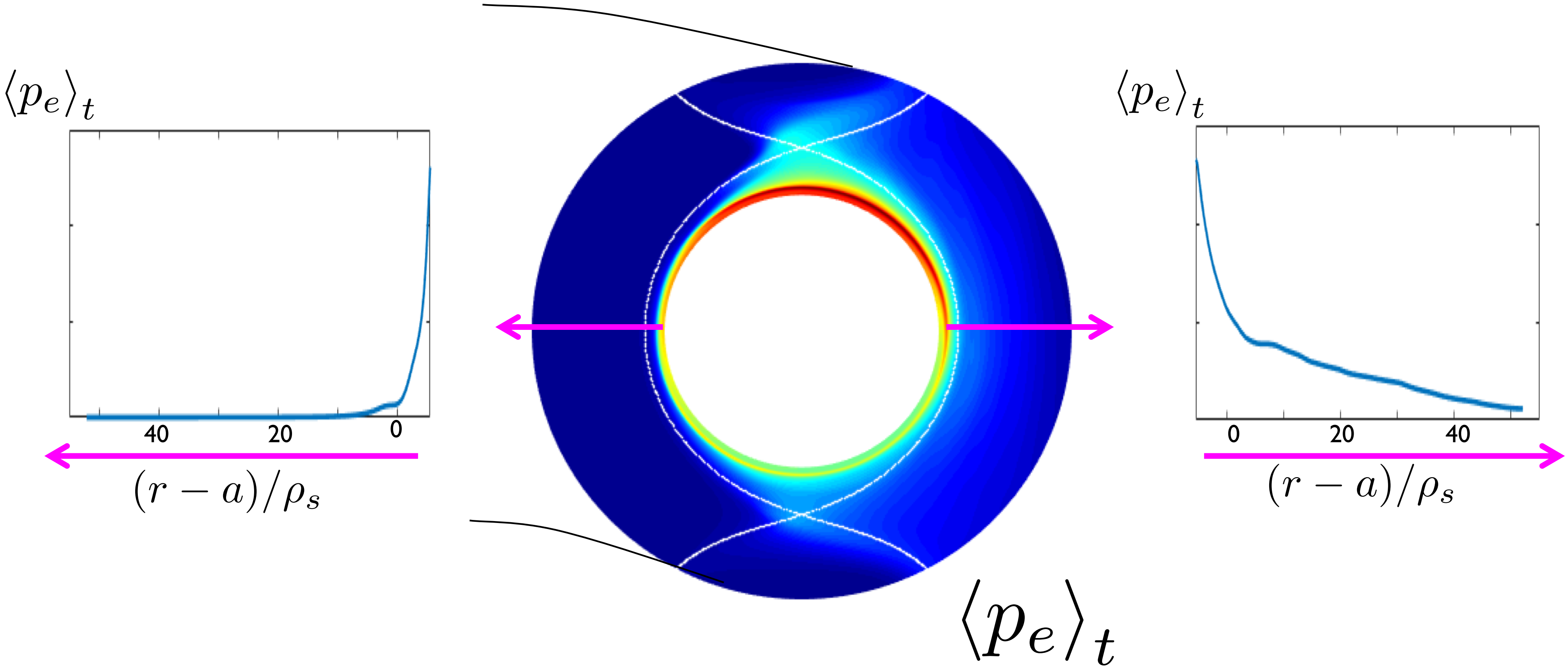
GBS simulations of double-null configurations

HFS: quiescent, almost empty, K-H turbulence

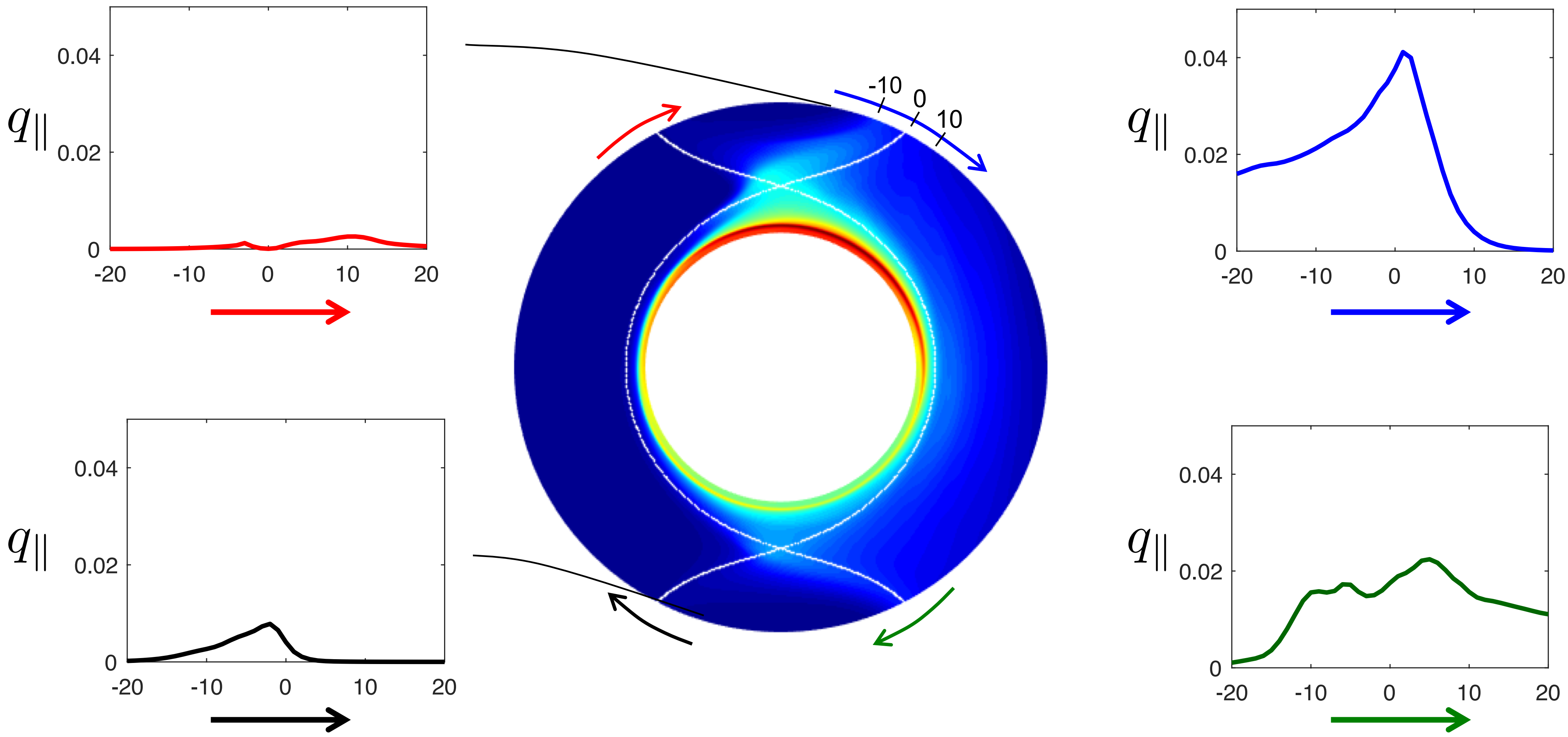


LFS: blobs, strong turbulence, ballooning drive...

Steep gradient at HFS, 2 scale lengths at LFS

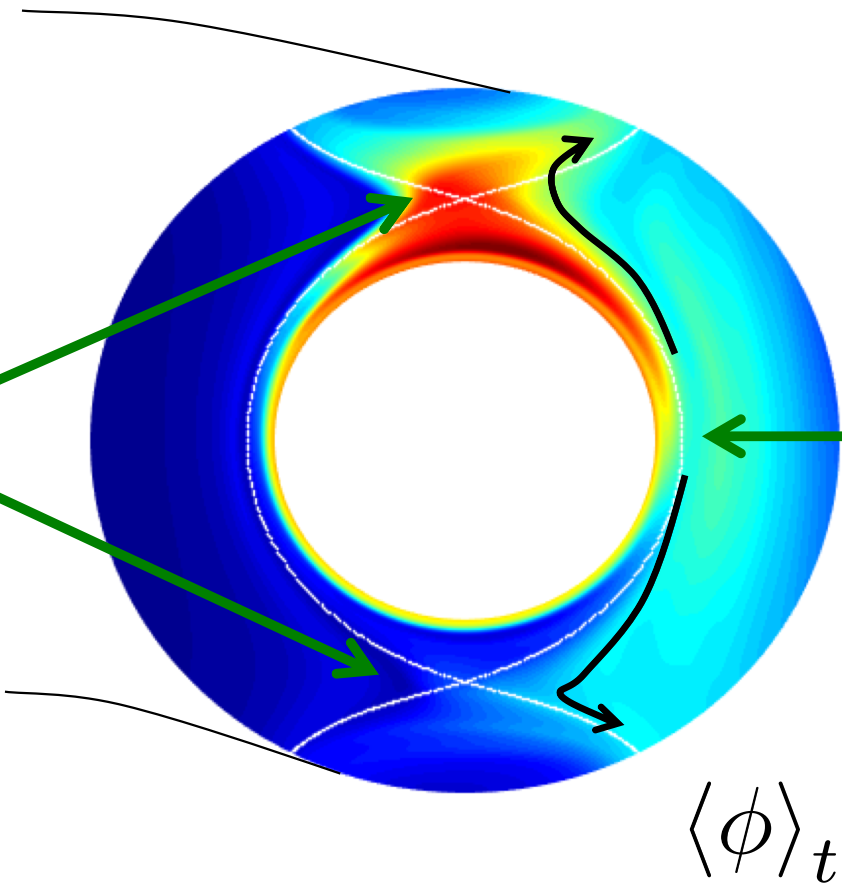


Very different heat fluxes along 4 legs



Complex circulation pattern

Up-down asymmetry due to curvature and $\mathbf{E} \times \mathbf{B}$ drift



Shear flow channeling particles to divertor legs

What are we learning on SOL dynamics?

- The use first-principles simulations and analysis to investigate SOL plasma dynamics
- Progressive approach to complexity
- Results in limited configuration:
  - SOL width set by resistive ballooning-driven turbulence saturated by the gradient removal mechanism in good agreement with multi-machine database
  - Presence of strong shear flow at the LCFS, resulting into 2 scale lengths
  - Mechanisms setting electrostatic potential and toroidal rotation
- Diverted configurations, complex flow patterns

http://people.epfl.ch/paolo.ricci

Extra slides

The complete set of equations

$$\frac{\partial n}{\partial t} = -\rho_\star^{-1}[\phi, n] + \frac{2}{B}[C(p_e) - nC(\phi)] - \nabla_\parallel(n v_{\parallel e}) + \mathscr{D}_n(n) + S_n + n_n n r_{iz} - n^2 r_{rec} \quad (1)$$

$$\frac{\partial \tilde{\omega}}{\partial t} = -\rho_\star^{-1}[\phi, \tilde{\omega}] - v_{\parallel i}\nabla_\parallel \tilde{\omega} + \frac{B^2}{n}\nabla_\parallel j_\parallel + \frac{2B}{n}C(p) + \mathscr{D}_{\tilde{\omega}}(\tilde{\omega}) \quad (2)$$

$$\frac{\partial v_{\parallel e}}{\partial t} + \frac{m_i}{m_e}\frac{\beta_e}{2}\frac{\partial \Psi}{\partial t} = -\rho_\star^{-1}[\phi, v_{\parallel e}] - v_{\parallel e}\nabla_\parallel v_{\parallel e} + \frac{m_i}{m_e}\left(\nu\frac{j_\parallel}{n} + \nabla_\parallel \phi - \frac{1}{n}\nabla_\parallel p_e - 0.71\nabla_\parallel T_e\right) + \mathscr{D}_{v_{\parallel e}}(v_{\parallel e}) \quad (3)$$

$$\frac{\partial v_{\parallel i}}{\partial t} = -\rho_\star^{-1}[\phi, v_{\parallel i}] - v_{\parallel i}\nabla_\parallel v_{\parallel i} - \frac{1}{n}\nabla_\parallel p + \mathscr{D}_{v_{\parallel i}}(v_{\parallel i}) + n_n(r_{iz} + r_{cx})(v_{\parallel n} - v_{\parallel i}) \quad (4)$$

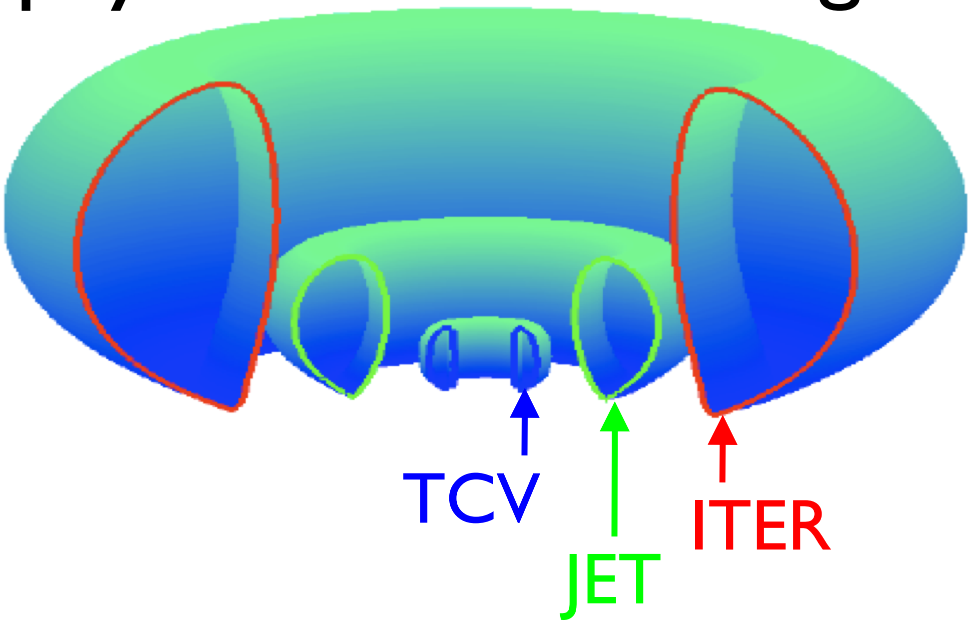
$$\frac{\partial T_e}{\partial t} = -\rho_\star^{-1}[\phi, T_e] - v_{\parallel e}\nabla_\parallel T_e + \frac{4T_e}{3B}\left[\frac{1}{n}C(p_e) + \frac{5}{2}C(T_e) - C(\phi)\right] + \frac{2T_e}{3}\left[\frac{0.71}{n}\nabla_\parallel j_\parallel - \nabla_\parallel v_{\parallel e}\right]$$
$$+ \mathscr{D}_{T_e}(T_e) + \mathscr{D}^\parallel_{T_e}(T_e) + S_{T_e} - n_n r_{iz} E_{iz} \quad (5)$$

$$\frac{\partial T_i}{\partial t} = -\rho_\star^{-1}[\phi, T_i] - v_{\parallel i}\nabla_\parallel T_i + \frac{4T_i}{3B}\left[\frac{1}{n}C(p_e) - \tau\frac{5}{2}C(T_i) - C(\phi)\right] + \frac{2T_i}{3}\left[(v_{\parallel i} - v_{\parallel e})\frac{\nabla_\parallel n}{n} - \nabla_\parallel v_{\parallel e}\right]$$
$$+ \mathscr{D}_{T_i}(T_i) + \mathscr{D}^\parallel_{T_i}(T_i) + S_{T_i} + n_n(r_{iz} + r_{cx})(T_n - T_i + (v_{\parallel n} - v_{\parallel i})^2) \quad (6)$$

$$\nabla_\perp^2 \phi = \omega,\ \nabla_\perp^2 \Psi = j_\parallel,\ \rho_\star = \rho_s/R,\ \nabla_\parallel f = \mathbf{b}_0 \cdot \nabla f + \frac{\beta_e}{2}\rho_\star^{-1}[\Psi, f],\ \tilde{\omega} = \omega + \tau\nabla_\perp^2 T_i,\ p = n(T_e + \tau T_i)$$

ITER design based on scaling law

SOL basic physics understanding is still missing



Simulations of SOL turbulence are crucial

The full set of GBS equations

$$\partial_t n = -\frac{R}{B}[\phi, n] + \frac{2}{B}\left[\hat{C}(p_e) - n\hat{C}(\phi)\right] - \nabla_{\|}(n v_{\|e}) + S_n$$

$$\partial_t \nabla_\perp^2 \phi = -\frac{R}{B}[\phi, \nabla_\perp^2 \phi] + \frac{2B}{n}\hat{C}(p_e) - v_{\|i}\nabla_{\|}\nabla_\perp^2\phi + \frac{B^2}{n}\nabla_{\|} j_{\|}$$

$$\partial_t\left(v_{\|e} + \frac{m_i \beta_e}{m_e 2}\psi\right) = -\frac{R}{B}[\phi, v_{\|e}] - v_{\|e}\nabla_{\|} v_{\|e}$$

$$+ \frac{m_i}{m_e}\left\{-\nu\frac{j_{\|}}{n} + \nabla_{\|}\phi - \frac{1}{n}\nabla_{\|} p_e - 0.71\nabla_{\|} T_e - \frac{2}{3n}\nabla_{\|} G_e\right\}$$

$$\partial_t v_{\|i} = -\frac{R}{B}[\phi, v_{\|i}] - v_{\|i}\nabla_{\|} v_{\|i} - \frac{1}{n}\nabla_{\|} p_e$$

$$\partial_t T_e = -\frac{R}{B}[\phi, T_e] - v_{\|e}\nabla_{\|} T_e + \frac{4}{3}\frac{T_e}{B}\left[\frac{7}{2}\hat{C}(T_e) + \frac{T_e}{n}\hat{C}(n) - \hat{C}(\phi)\right] + S_{T_e}$$

$$+ \frac{2}{3}T_e\left[0.71\nabla_{\|} v_{\|i} - 1.71\nabla_{\|} v_{\|e} + 0.71\left(\frac{v_{\|i} - v_{\|e}}{n}\right)\nabla_{\|} n\right]$$

Need boundary conditions for:

$n, v_{\|e}, v_{\|i}, T_e, \nabla_\perp^2\phi, \psi, \phi$

Gradient-removal estimate of ExB velocity transport

$$\Gamma_{v,r} \sim \left\langle \tilde{v}_{\parallel i} \frac{\partial \tilde{\phi}}{\partial \theta} \right\rangle_t \sim \left\langle \left(\frac{\partial \tilde{\phi}}{\partial \theta} \right)^2 \right\rangle_t \frac{\partial \overline{v}_{\parallel i}}{\partial r}$$

Parallel momentum
$\gamma \tilde{v}_{\parallel i} \sim \partial_r \overline{v}_{\parallel i} \partial_\theta \tilde{\phi}$

$$\sim \langle \tilde{p}^2 \rangle_t \frac{\partial \overline{v}_{\parallel i}}{\partial r} \sim -\frac{\gamma}{k_\theta} L_p \frac{\partial \overline{v}_{\parallel i}}{\partial r}$$

Continuity
$\gamma \tilde{p} \sim \partial_r \overline{p} \partial_\theta \tilde{\phi}$

Grad removal
$\partial_r \tilde{p} \sim \partial_r \overline{p}$

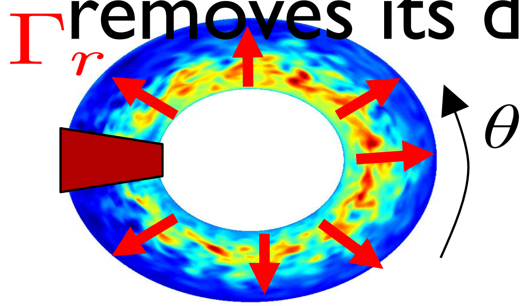
$$\sim -\frac{L_p^2 c_s}{qR} \frac{\partial \overline{v}_{\parallel i}}{\partial r}$$

Lp estimate
$L_p \sim qR\gamma/(c_s k_\theta)$

$$\Rightarrow \quad \Gamma_{v,r} = -D_{\mathrm{T}} \frac{\partial \overline{v}_{\parallel i}}{\partial r}, \quad D_{\mathrm{T}} = \frac{L_p^2 c_s}{qR}$$

Turbulent transport with gradient removal (GR) saturation

Turbulence saturates when it removes its drive $\rightarrow \frac{\partial \tilde{p}}{\partial r} \sim \frac{\partial \overline{p}}{\partial r} \rightarrow k_r \tilde{p} \sim \overline{p}/L_p$



$$\frac{\partial p}{\partial t} \simeq [p, \phi]$$

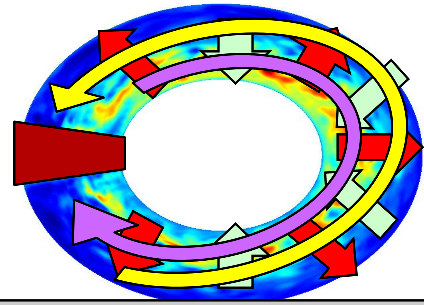
$$\Gamma_r = \left\langle \tilde{p} \frac{\partial \tilde{\phi}}{\partial \theta} \right\rangle_t$$

GR hypothesis

Nonlocal linear theory, $k_r \sim \sqrt{k_\theta / L_p}$

$$D_{GR} = \frac{\Gamma_r}{\overline{p}/L_p} \sim \frac{\gamma L_p}{k_\theta}$$

Turbulence saturation due to ~~Kelvin-Helmholtz instability (KH)~~



Primary instability grows until it causes KH unstable shear flow → $\frac{\partial \Omega}{\partial t} \sim [\phi, \Omega]$ → $\tilde{\phi} \sim \frac{\gamma}{k_\theta^2}$

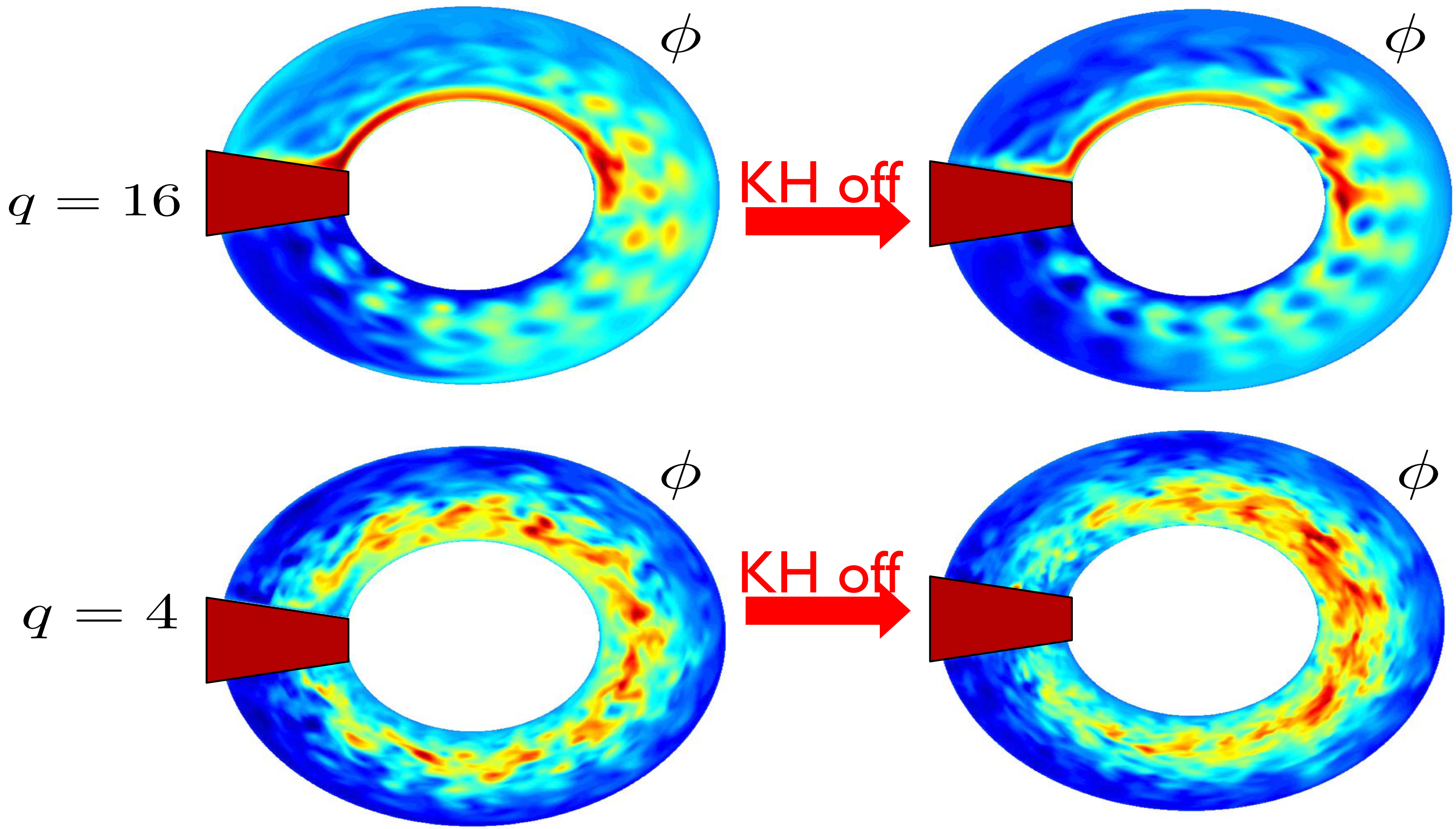
$$\Gamma_r = \left\langle \tilde{p} \frac{\partial \tilde{\phi}}{\partial \theta} \right\rangle_t \sim \frac{\gamma \bar{p}}{L_p k_\theta^2} \quad \Rightarrow \quad D_{KH} \sim \frac{\gamma}{k_\theta^2}$$

KH vs GR mechanism:

$$\frac{D_{KH}}{D_{GR}} \sim \frac{1}{k_\theta L_p} < 1$$

We expect KH to limit the transport, provided that KH is unstable!

Is KH really setting transport?

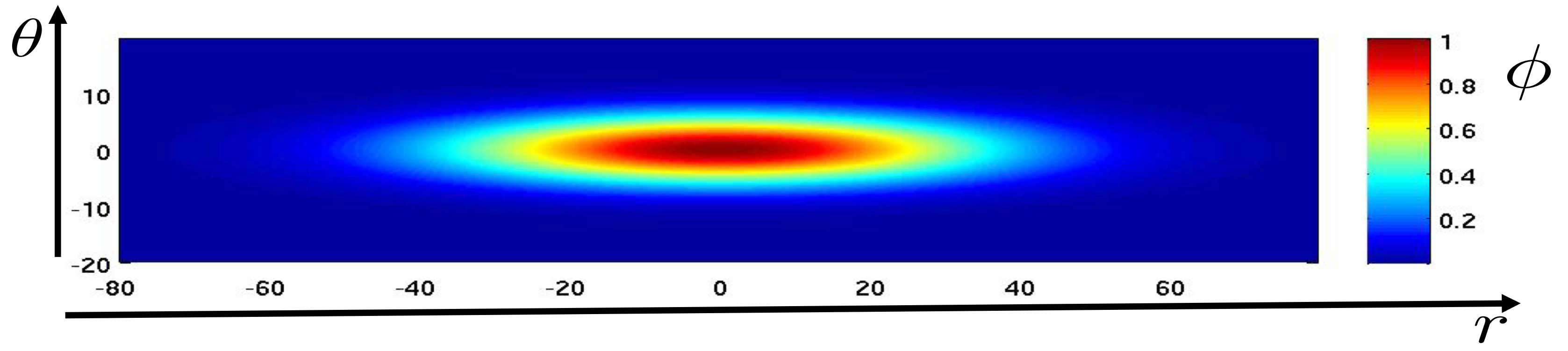


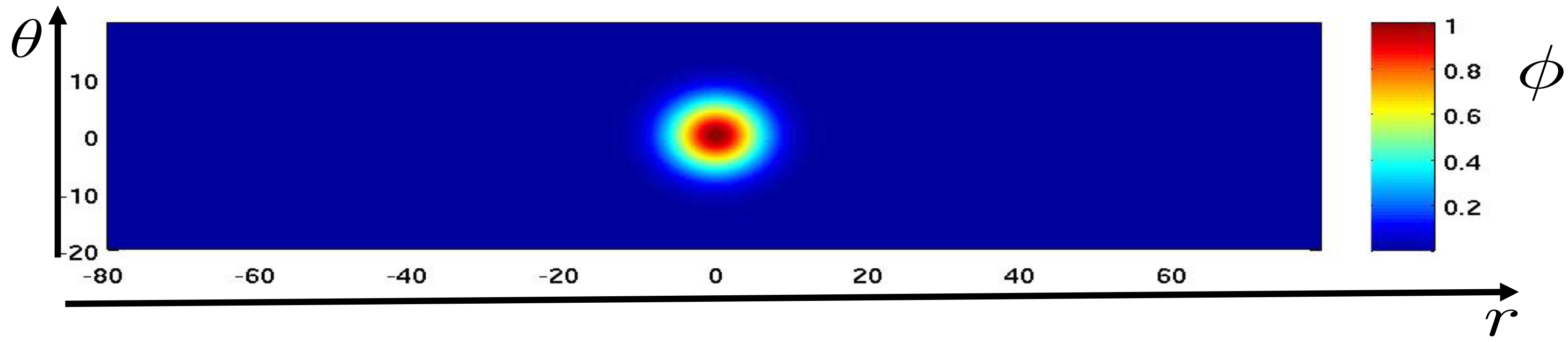
KH saturates turbulence

KH plays a minor role: GR!

Why is KH stable at low q but not higher q?

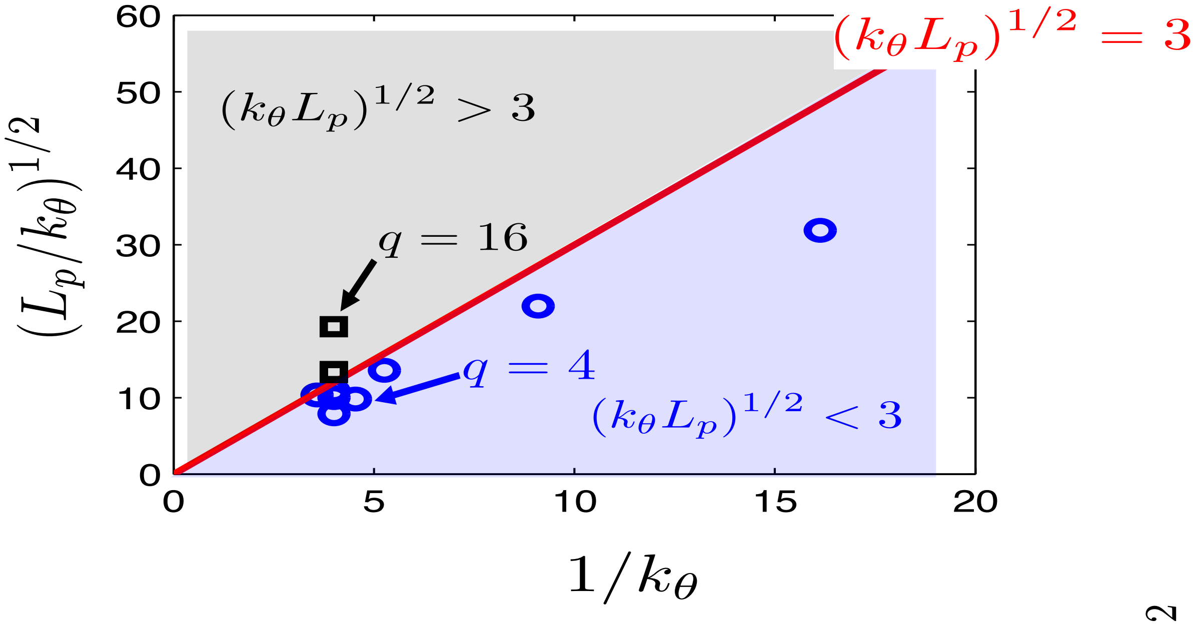
Only elongated eddies are KH unstable





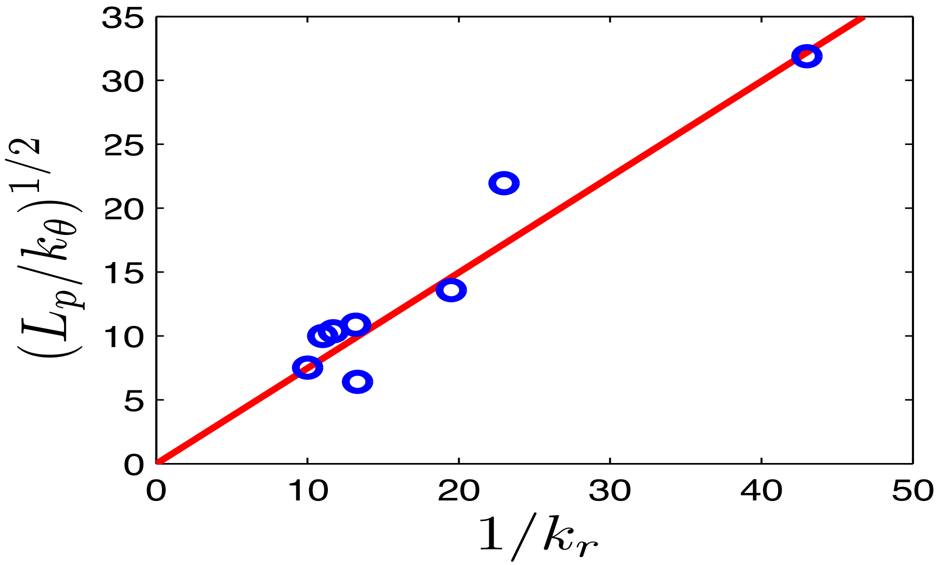
By comparing eddy turn over time and KH growth rate, KH unstable if: $\sqrt{k_\theta L_p} > 3$

Why is KH stable at low q but not higher q?



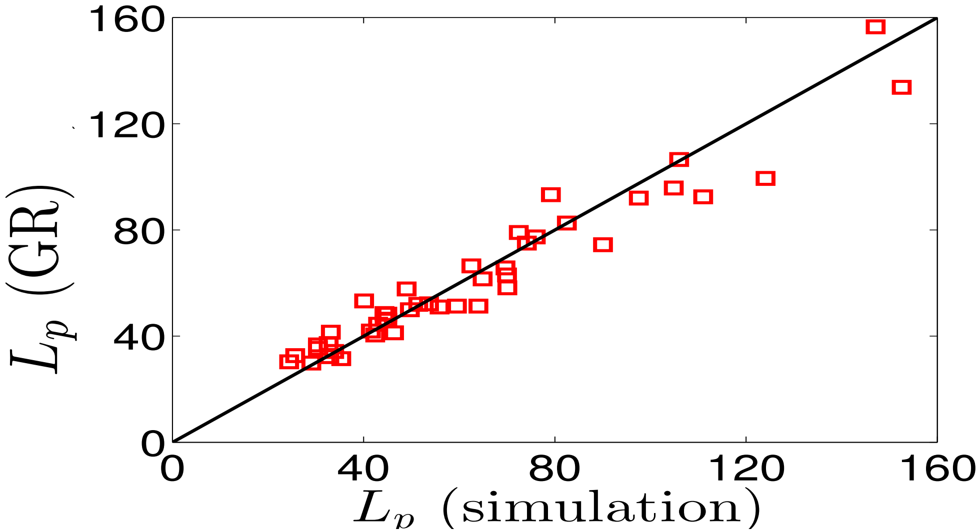
q=4 simulations are in the KH stable region

The eddies show the GR scaling properties

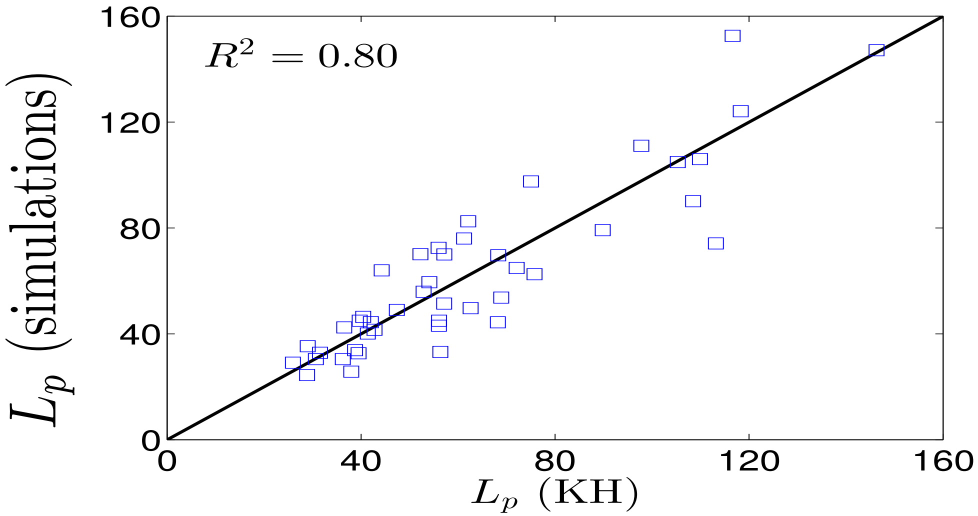


KH vs GR scaling?

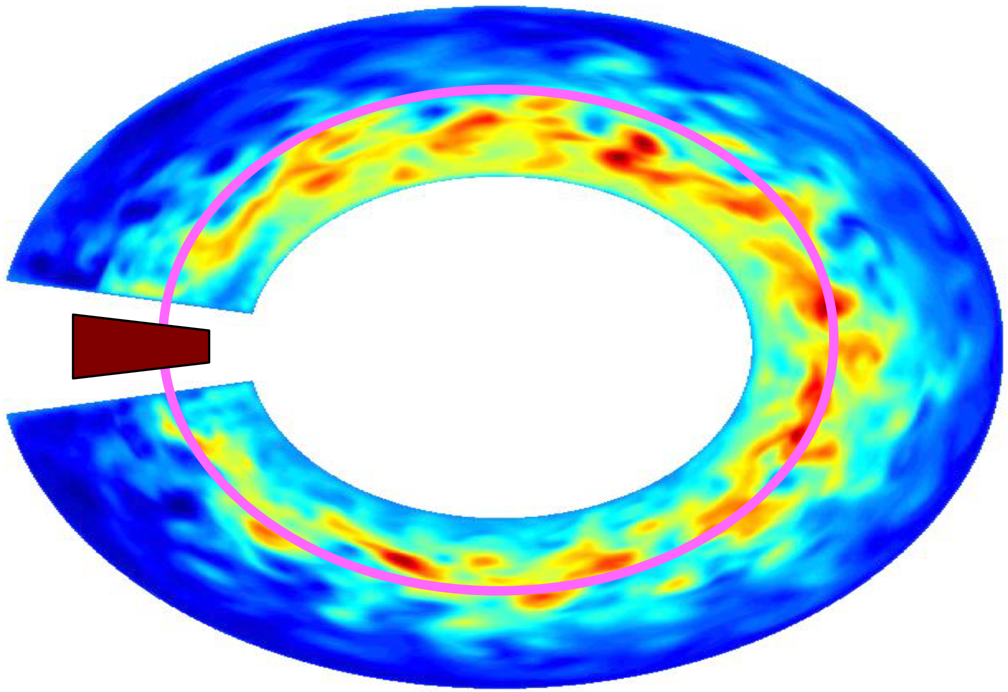
$R^2 = 93\%$



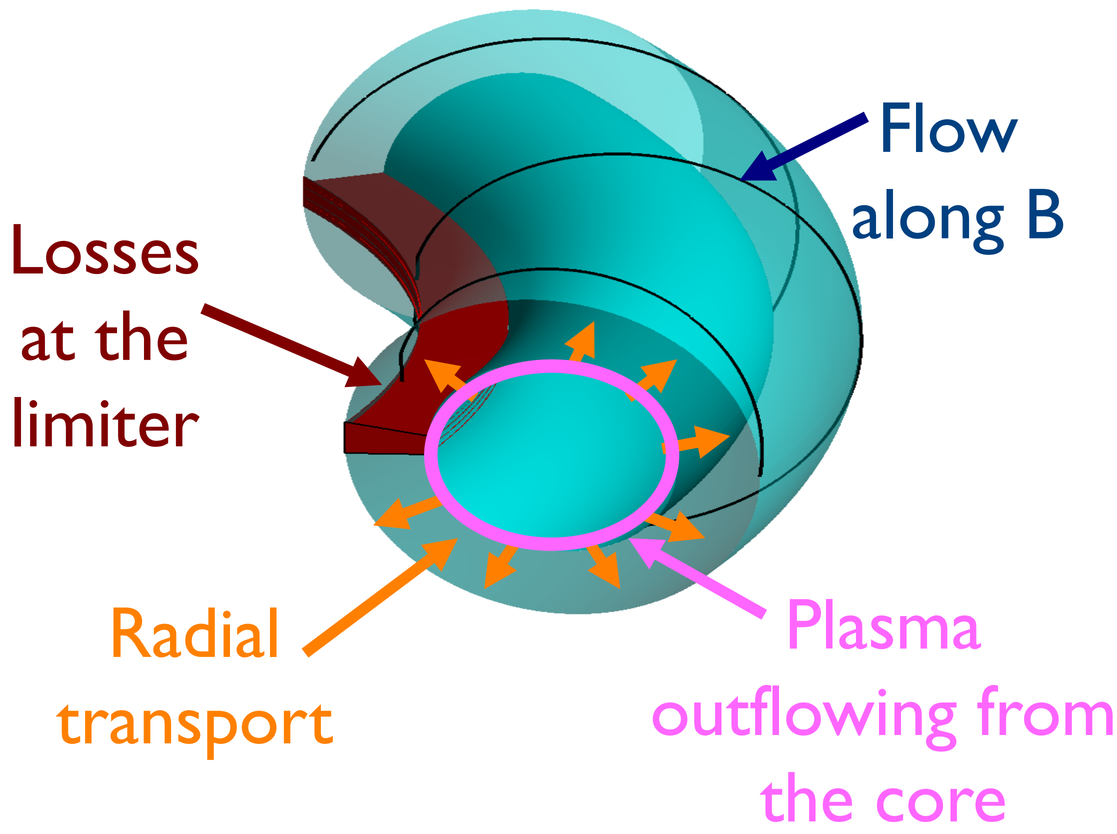
$R^2 = 80\%$



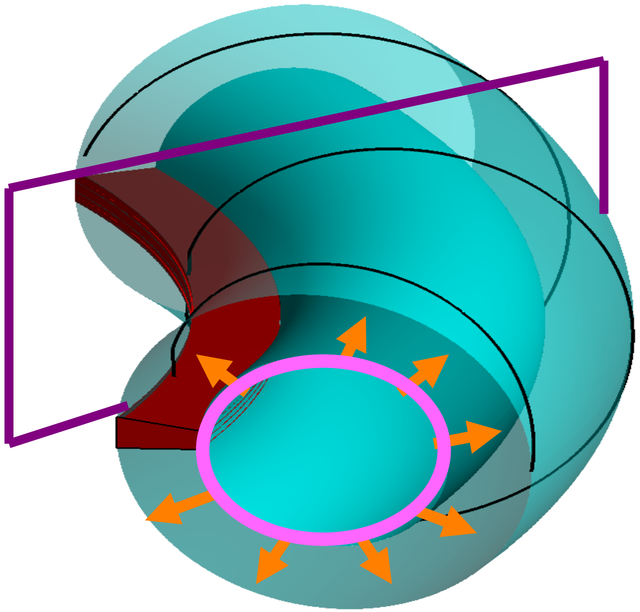
Details of the source



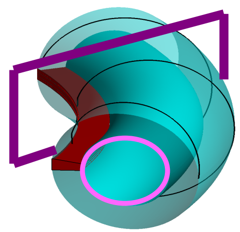
Tokamak SOL simulations

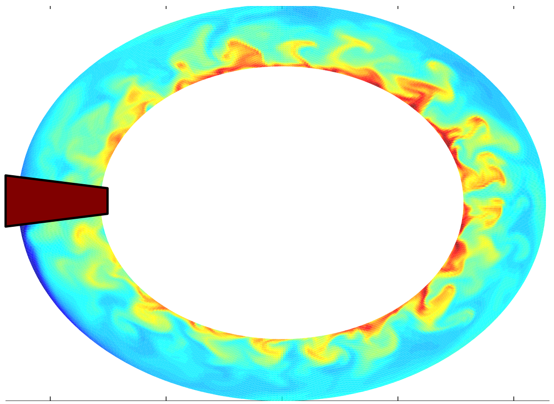


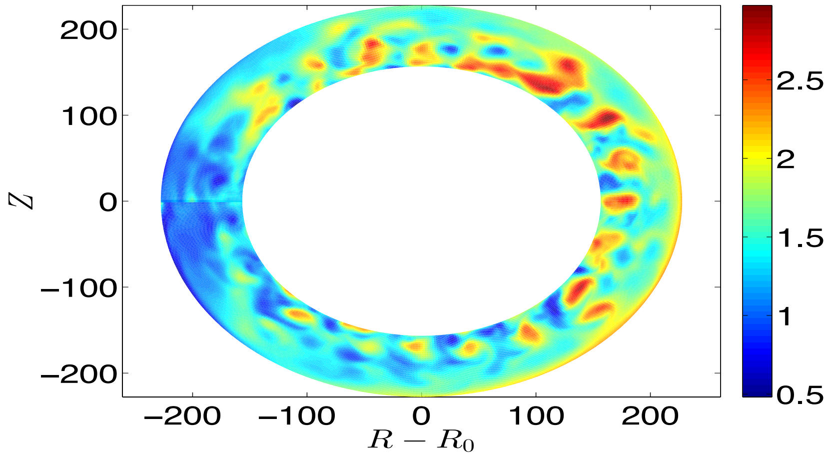
Tokamak SOL simulations



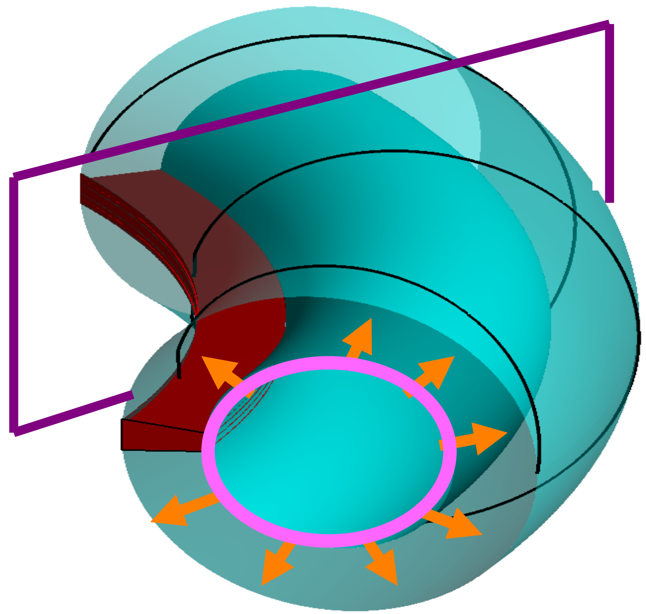
Tokamak SOL simulations

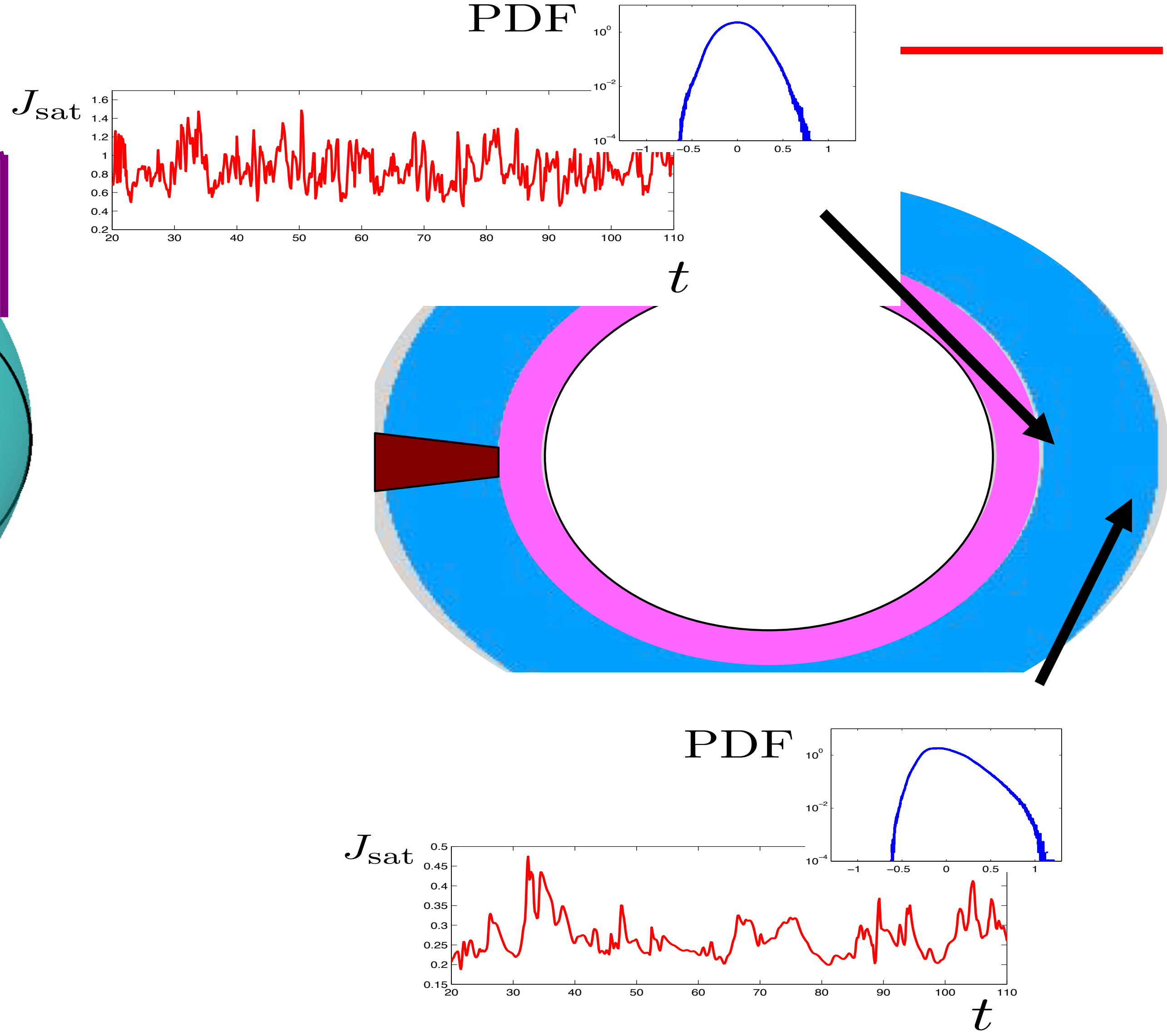




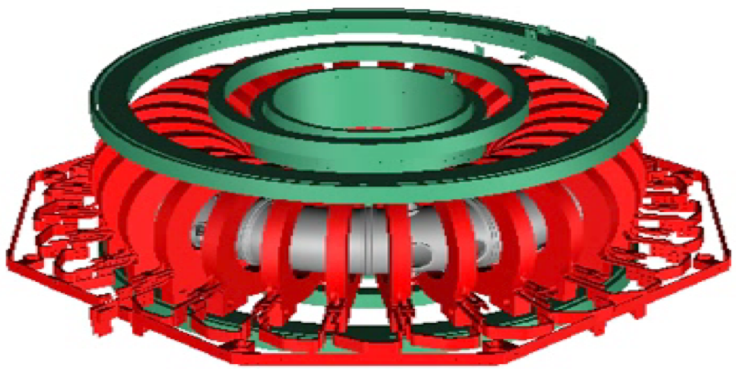


Tokamak SOL simulations

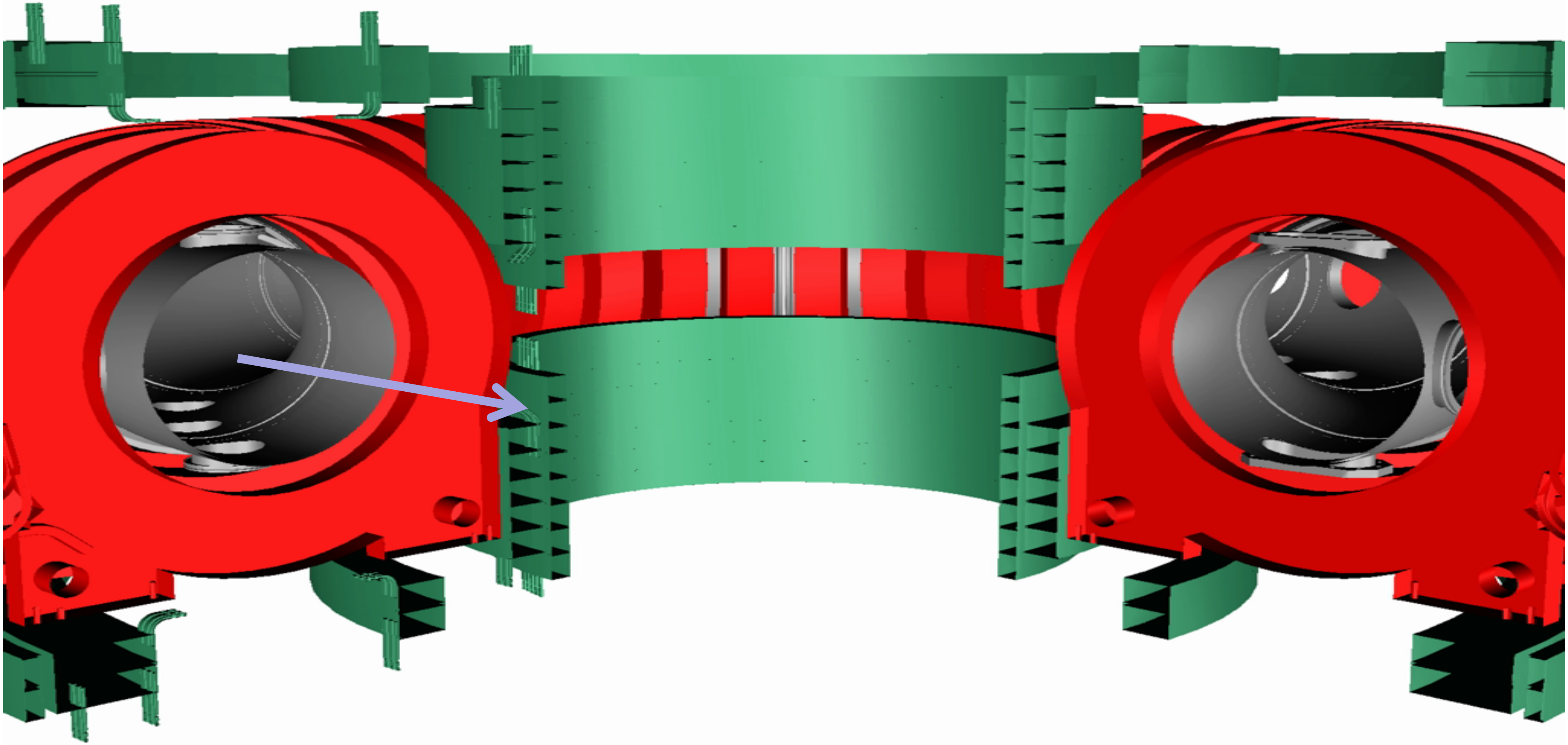




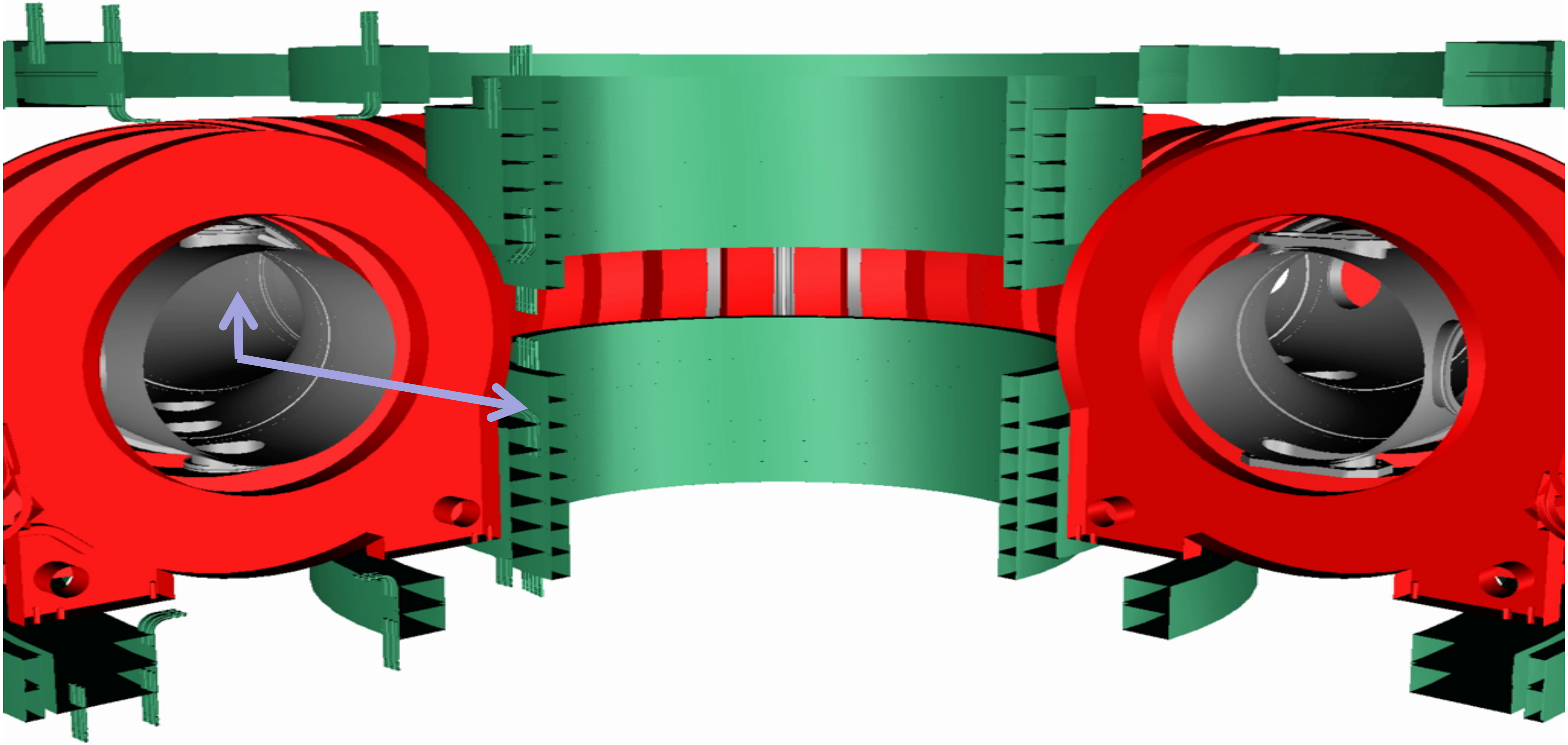
The TORPEX device



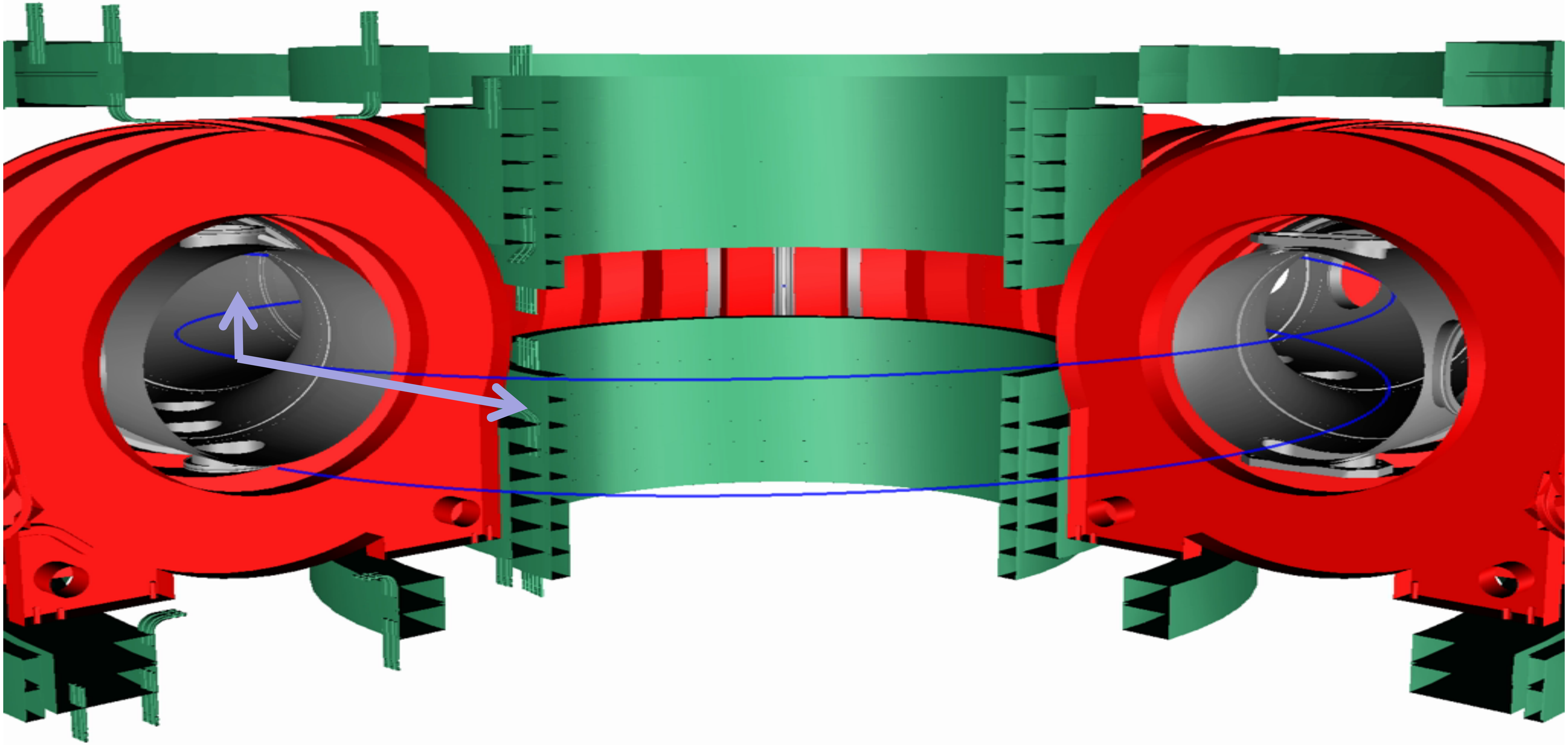
The TORPEX device



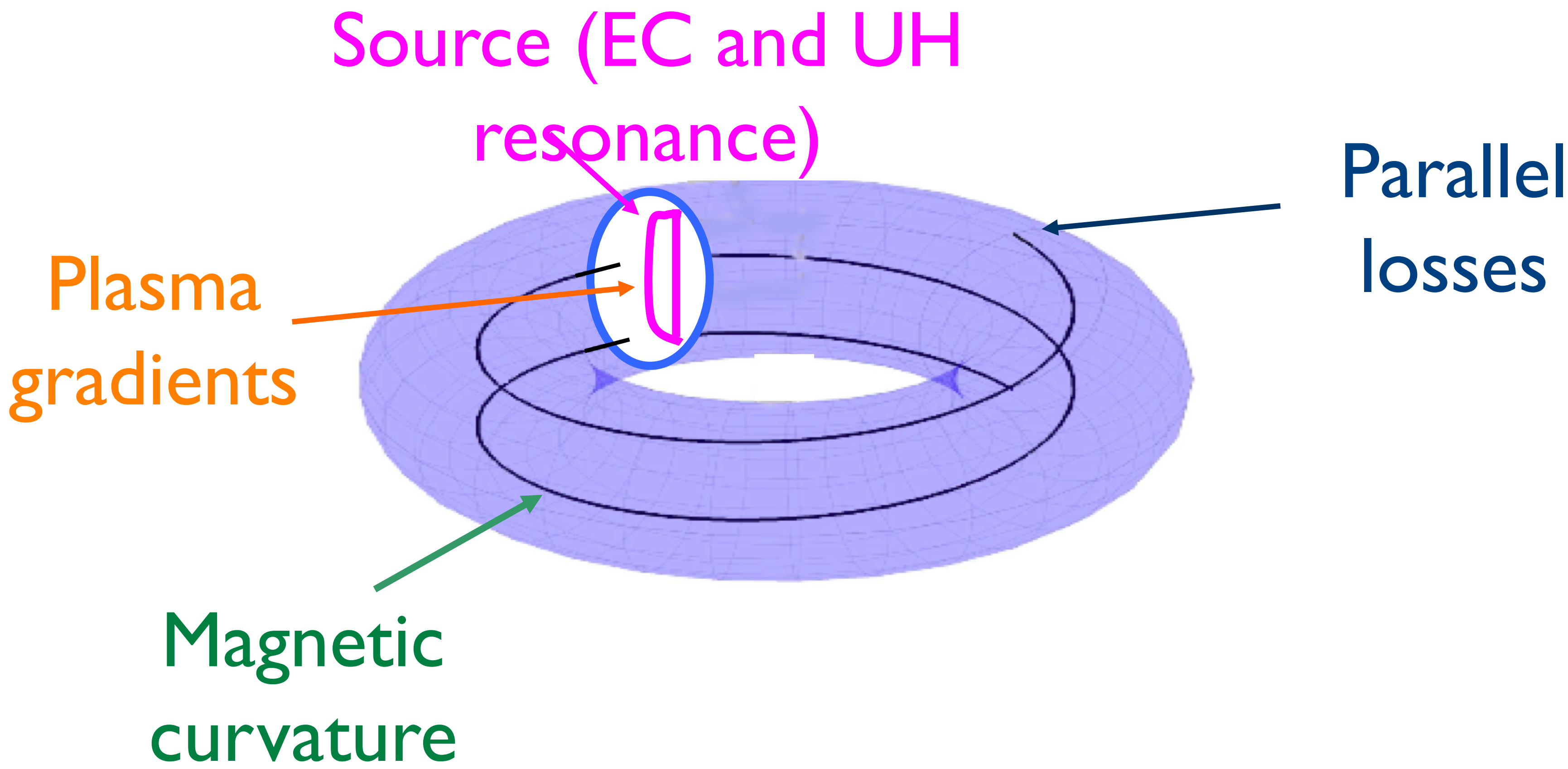
The TORPEX device



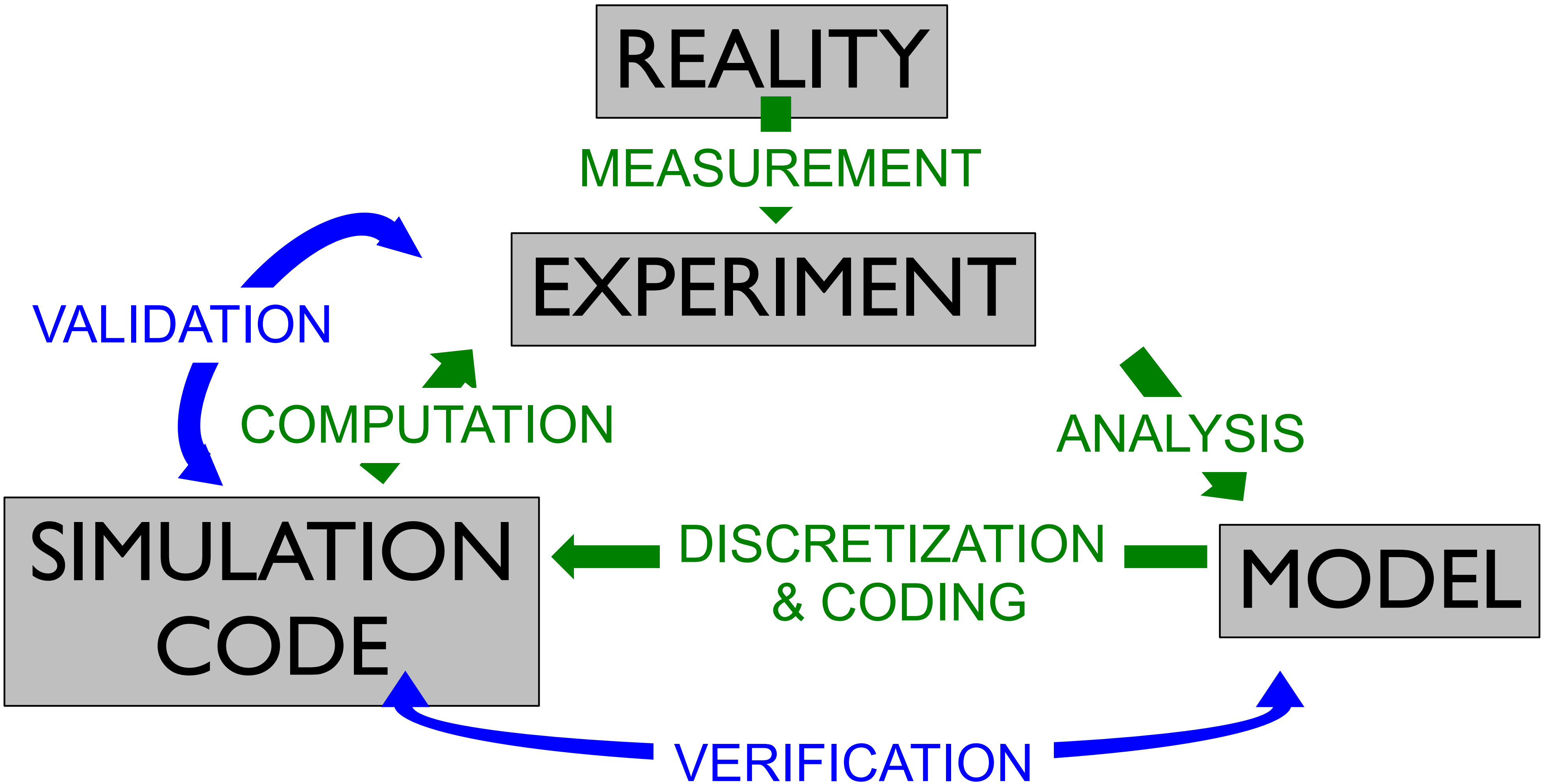
The TORPEX device



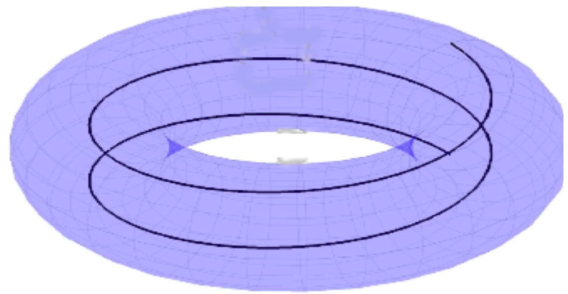
Key elements of the TORPEX device

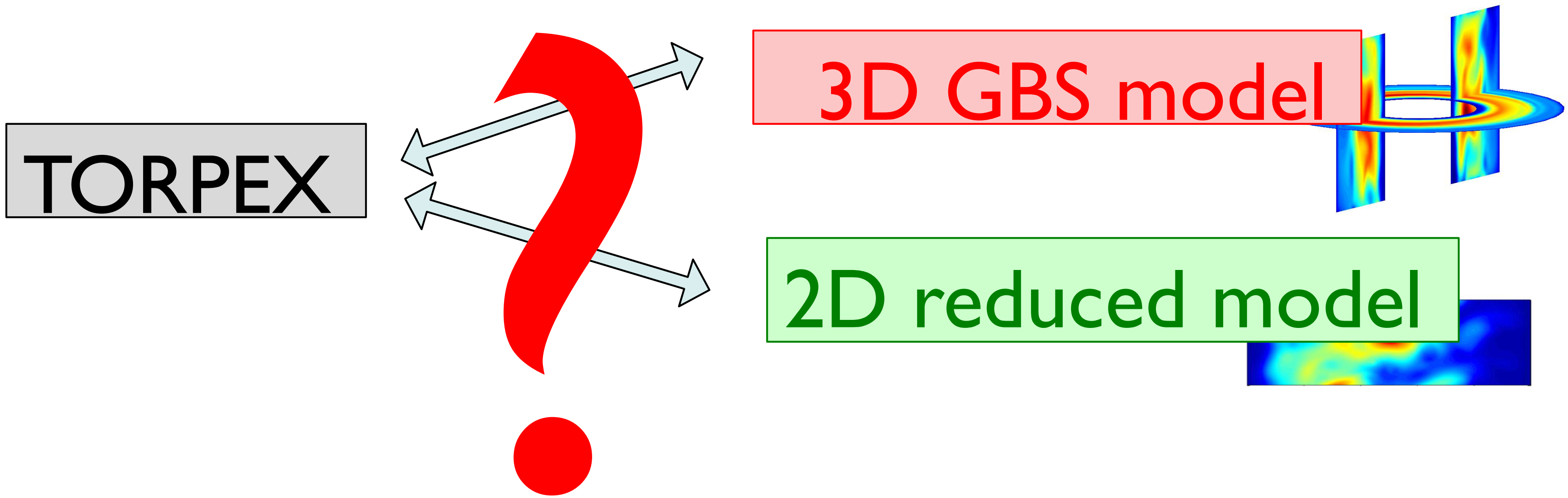


Verification & Validation



Our project, paradigm of ~~turbulence code validation~~





What is the agreement of experiment and simulations as a function of *N* (number of field line turns)? Is 3D necessary?

The validation methodology

[Based on ideas of Terry *et al.*, PoP 2008; Greenwald, PoP 2010]

What quantities can we use for validation? The more, the better…

- Definition & evaluation of the validation observables

What are the uncertainties affecting measured and simulation data?

- Uncertainty analysis

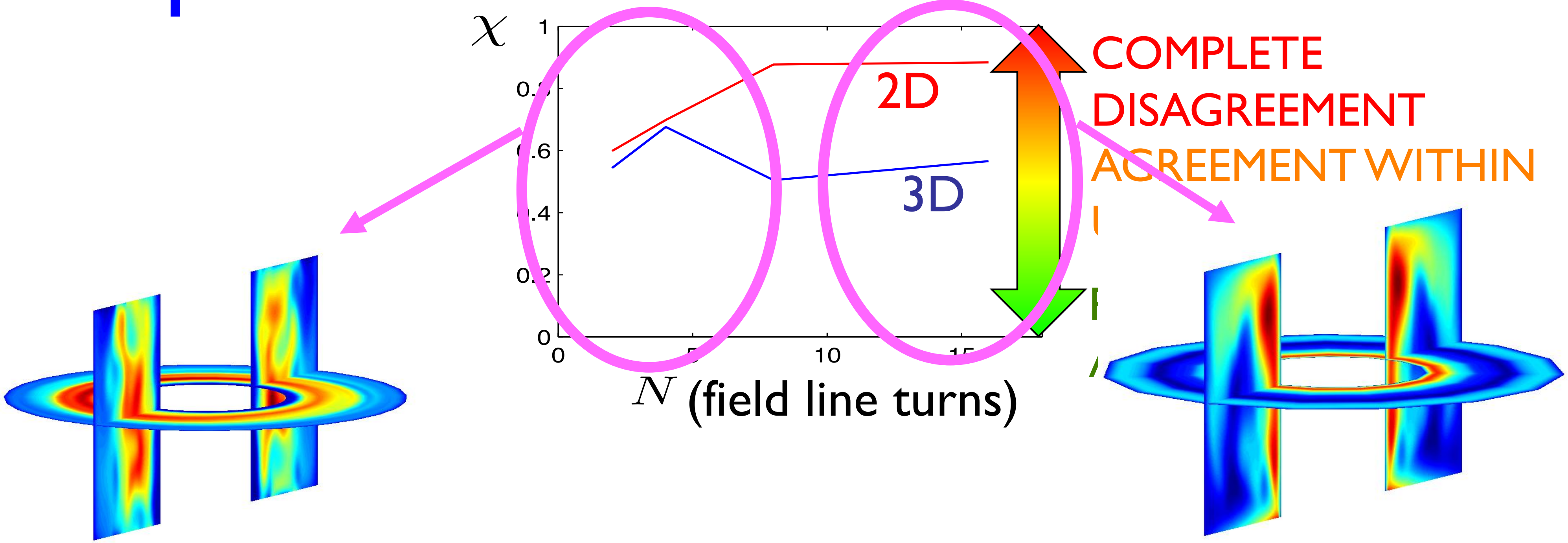
For one observable, within its uncertainties, what is the level of agreement?

- Level of agreement for an individual observable

How directly can an observable be extracted from simulation and experimental data? How worthy is it, i.e. what should be its weight in a composite metric?

- The observable hierarchy

Interpretation of the validation results



$k_{||} = 0$

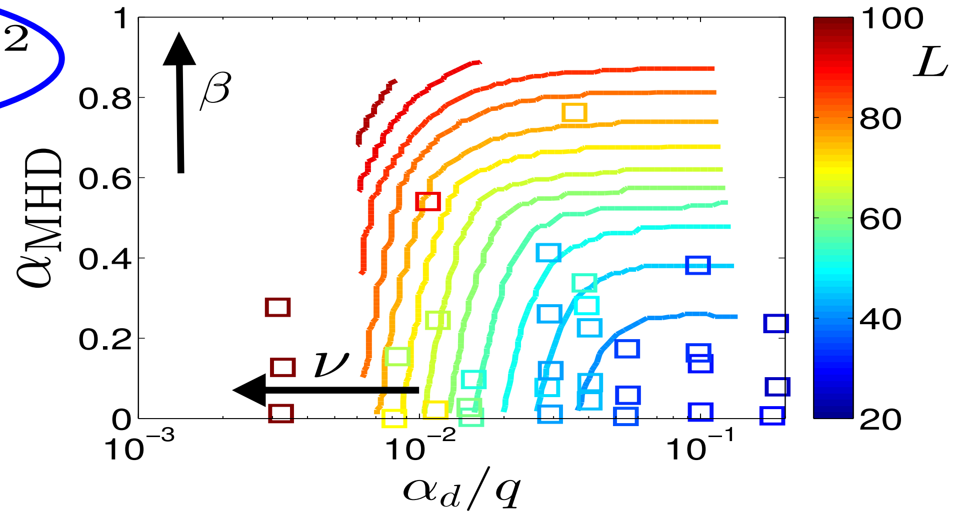
- Ideal interchange turbulence
- 2D model appropriate

$k_{||} \neq 0$

- Resistive interchange turbulence
- 2D model not

Limited SOL transport increases with β and ν

$$L_p = R^{1/2}[2\pi(1-\alpha_{\mathrm{MHD}})\alpha_d/q]^{-1/2}$$



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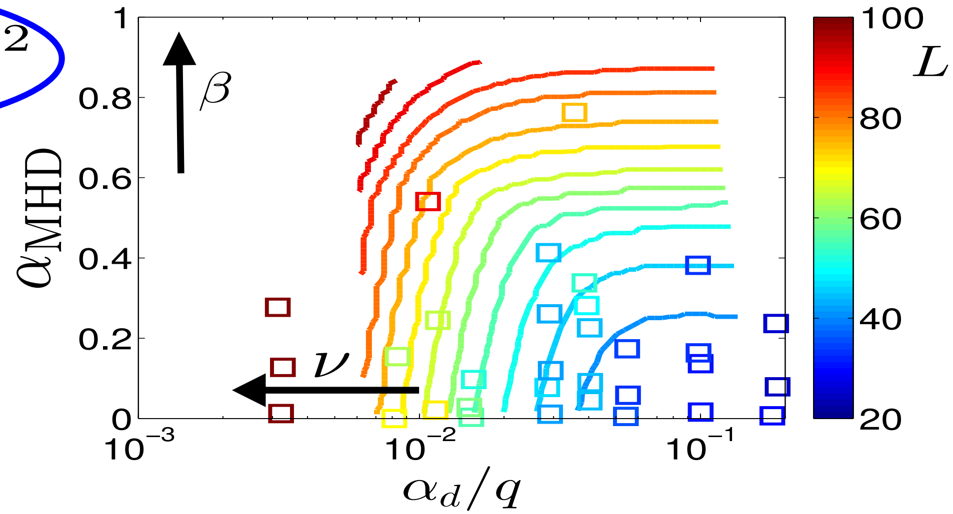
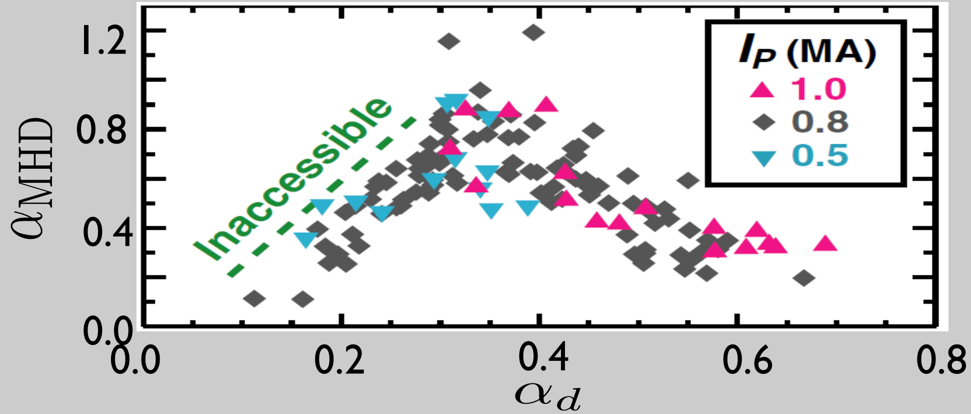


Maybe related to the density limit?

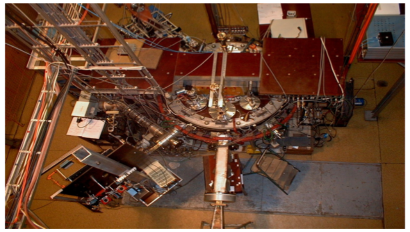
Coupling with core physics needs be

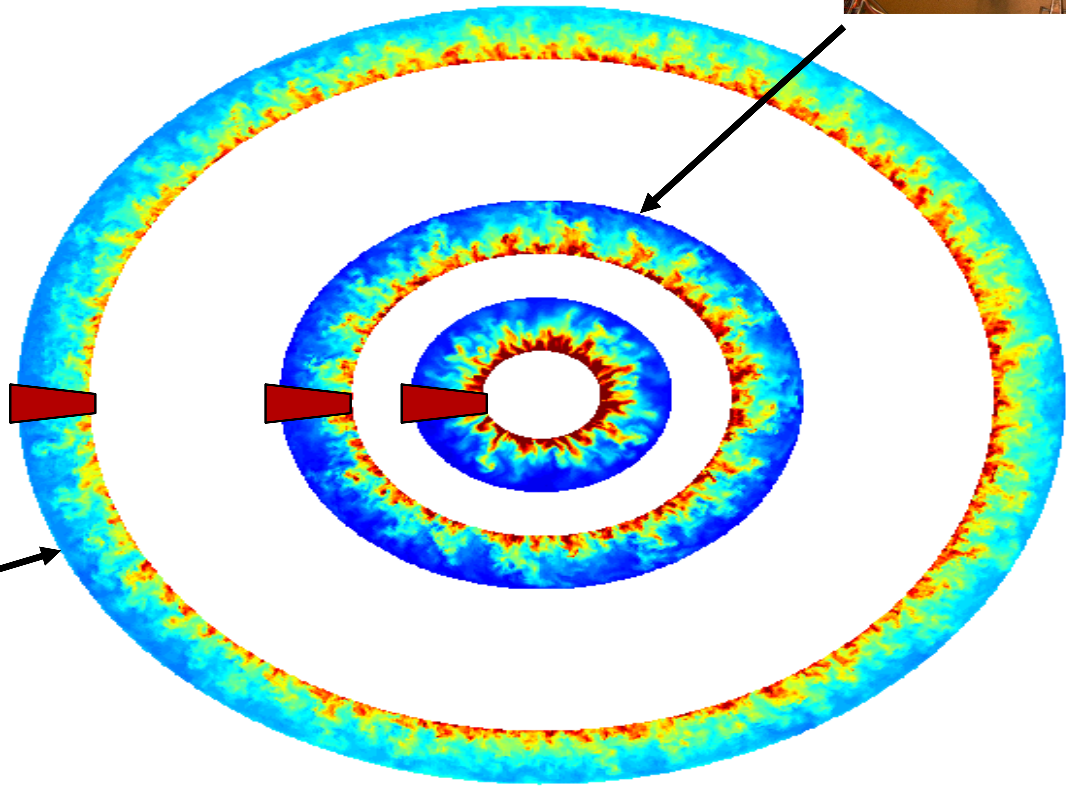


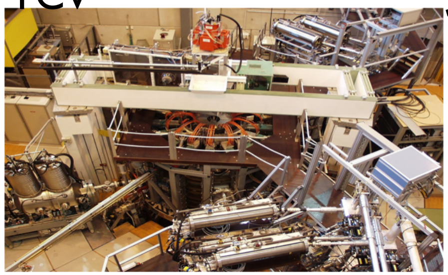
LaBombard, NF 2005

Limited SOL width widens with R

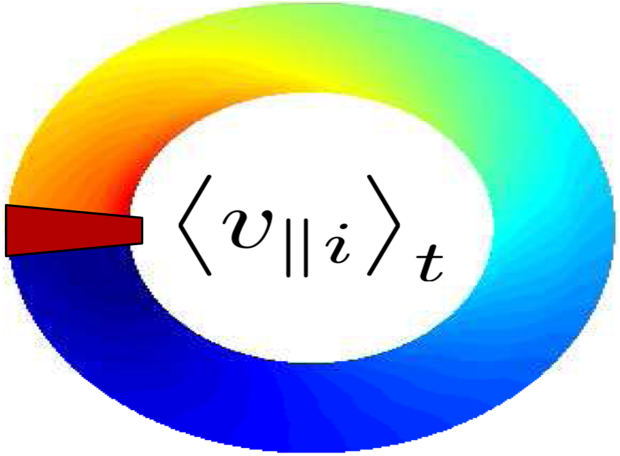
$$L_p = R^{1/2}[2\pi(1-\alpha_{\mathrm{MHD}})\alpha_d/q]^{-1/2}$$



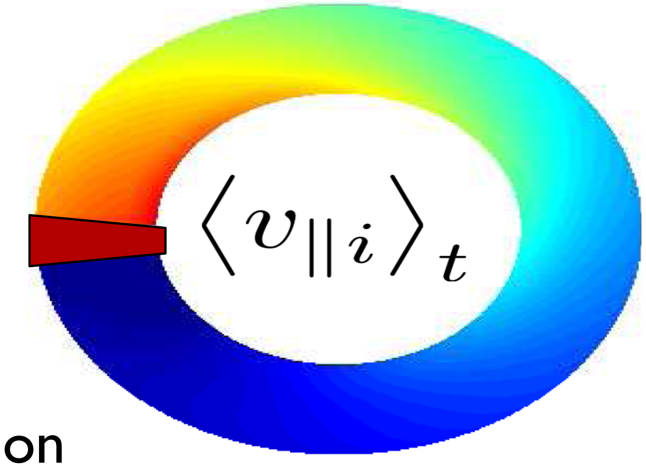




Our model well describes simulation results…



Model



Simulation

… and experimental trends

Analytical solution, far from limiter:

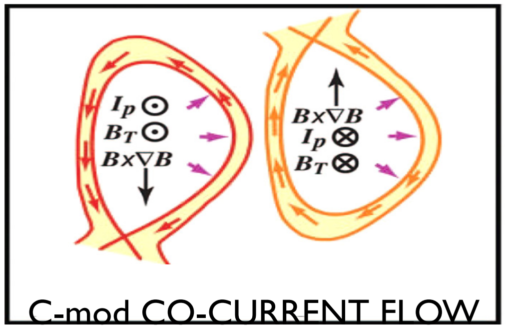
$$M = M_s e^{-r/l} + \left[\frac{\Lambda}{2\alpha} \frac{\rho_s}{L_T} e^{-r/L_T} - \frac{\sigma_\varphi}{2} \left(\frac{\delta n}{n} + \frac{\delta T}{T} \right) \right] \left(1 - e^{-r/l} \right)$$

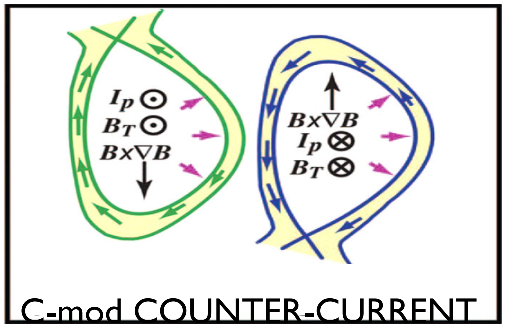
Core coupling

Sheath contribution, co-current

Pressure poloidal asymmetry at divertor plates, due to ballooning transport, direction: depends

- $M_{\parallel} \lesssim 1$
- Typically co-current
- Can become counter-current by reversing $\mathbf{B}$ or divertor position





Loizu et al., PoP 2014