Simulation of SOL turbulence in tokamak plasmas

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The reduced model to study SOL turbulence

The GBS code and its path towards SOL simulations

Anatomy of SOL turbulence: from linear instabilities to SOL width and intrinsic toroidal rotation

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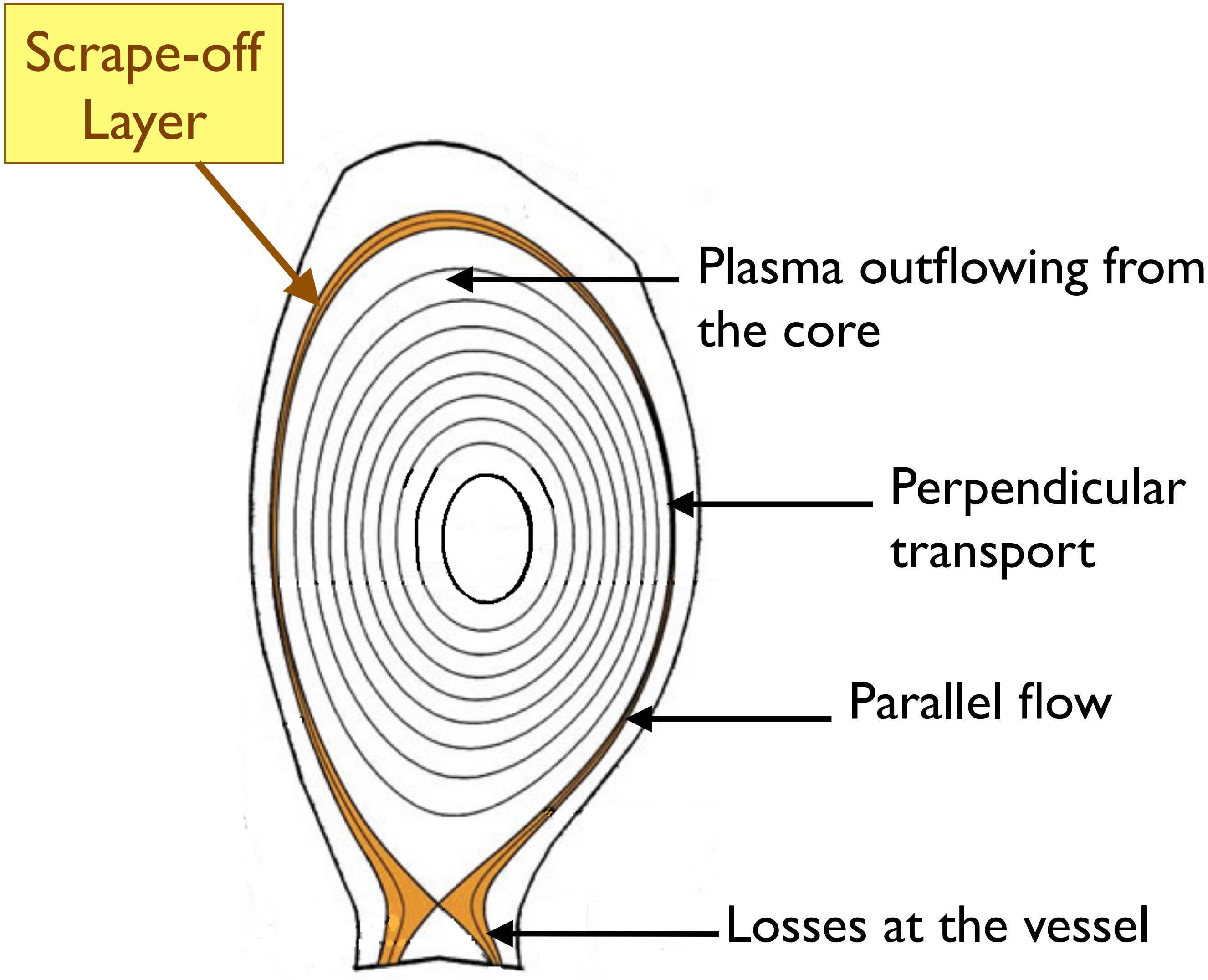
SOL channels particles and heat to the wall



Scrape-off Layer

Plasma outflowing from the core

Perpendicular transport

Parallel flow

Losses at the vessel

The key questions

- What is the mechanism setting the SOL turbulent level and the perpendicular transport?
- How is the SOL width established?
- What are the SOL turbulent regimes?
- How do the SOL properties depend on beta, resistivity, tokamak size, …?
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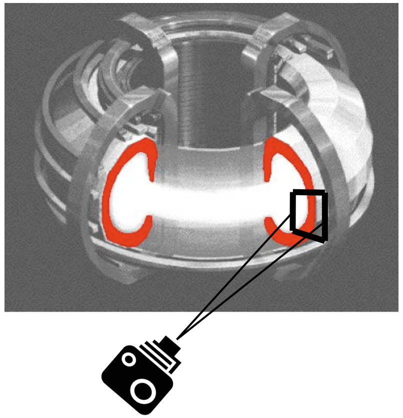
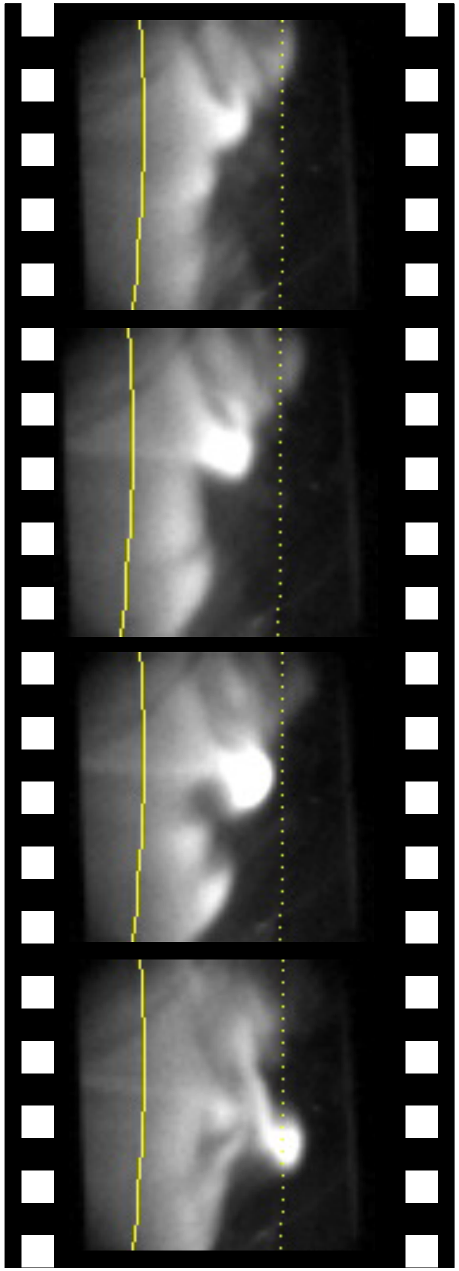
Properties of SOL turbulence





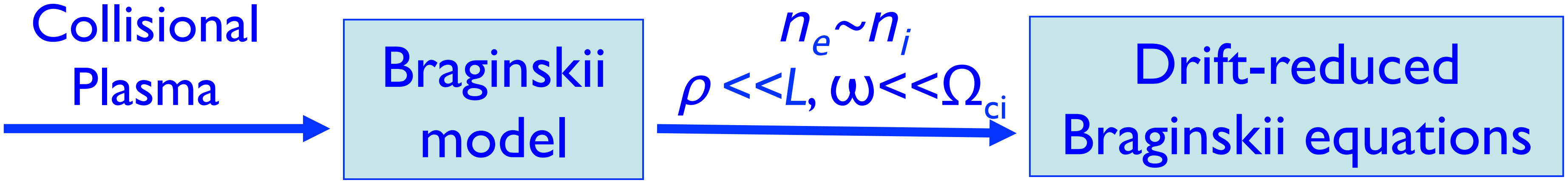
Courtesy of R. Maqueda

- $n_{fluc} \sim n_{eq}$
- $L_{fluc} \sim L_{eq}$
- Fairly cold magnetized plasma

A reduced model for the SOL

- Delta-n vs full-n?
  - ➢ $n_{fluc} \sim n_{eq}$, need **full-n**
- Local vs global?
  - ➢ Flux tube valid for $k_r L_{eq} \gg 1$, but $k_r L_{eq} \gtrsim 1$, need **global**
- Gradient-driven vs flux-driven?
  - ➢ Evolution equilibrium profile needed, need **flux-driven**
- Kinetic vs fluid?
  - ➢ $\lambda_{ei} \ll L_{\|}$, $\nu^* \gg 1$, **fluid** is good starting point
- Full v and FLR vs drift-reduced?
  - ➢ $\omega \ll \omega_{ci}$ and $k_{\perp}\rho \sim 0.1$, **drift-reduced** is reasonable

The GBS code, a tool to simulate SOL turbulence



Collisional Plasma → Braginskii model $\xrightarrow{n_e \sim n_i,\ \rho \ll L,\ \omega \ll \Omega_{ci}}$ Drift-reduced Braginskii equations

$$\overbrace{\frac{\partial n}{\partial t} + [\phi, n]}^{\text{Convection}} = \overbrace{\hat{C}(nT_e) - n\hat{C}(\phi)}^{\text{Magnetic curvature}} - \overbrace{\nabla_{\parallel}(nV_{\parallel e})}^{\text{Parallel dynamics}} + \overbrace{S}^{\text{Source}}$$

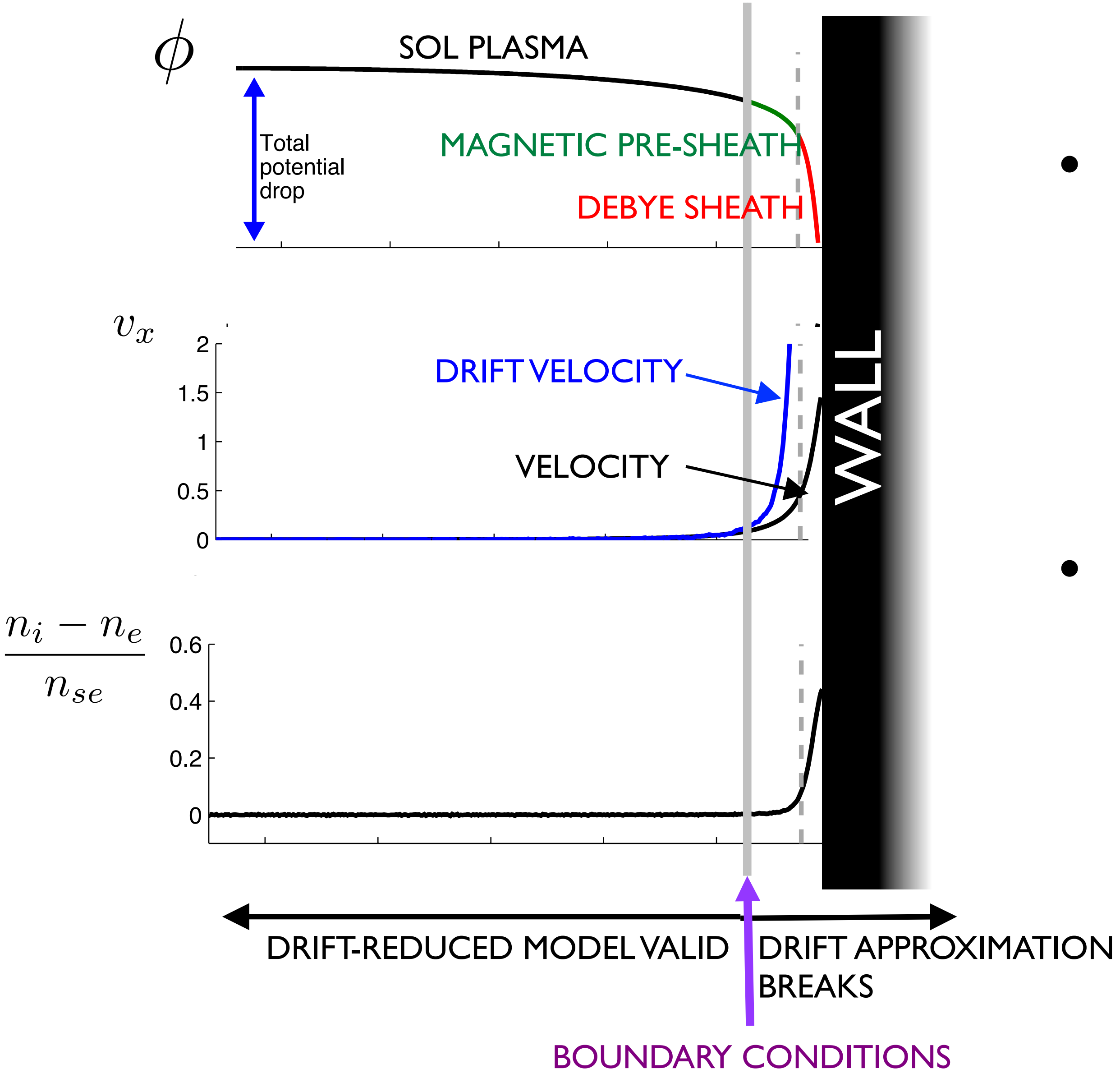
T_e, Ω (vorticity) → similar equations ($T_i \ll T_e$)

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

$$\nabla_{\perp}^{2}\phi = \Omega$$

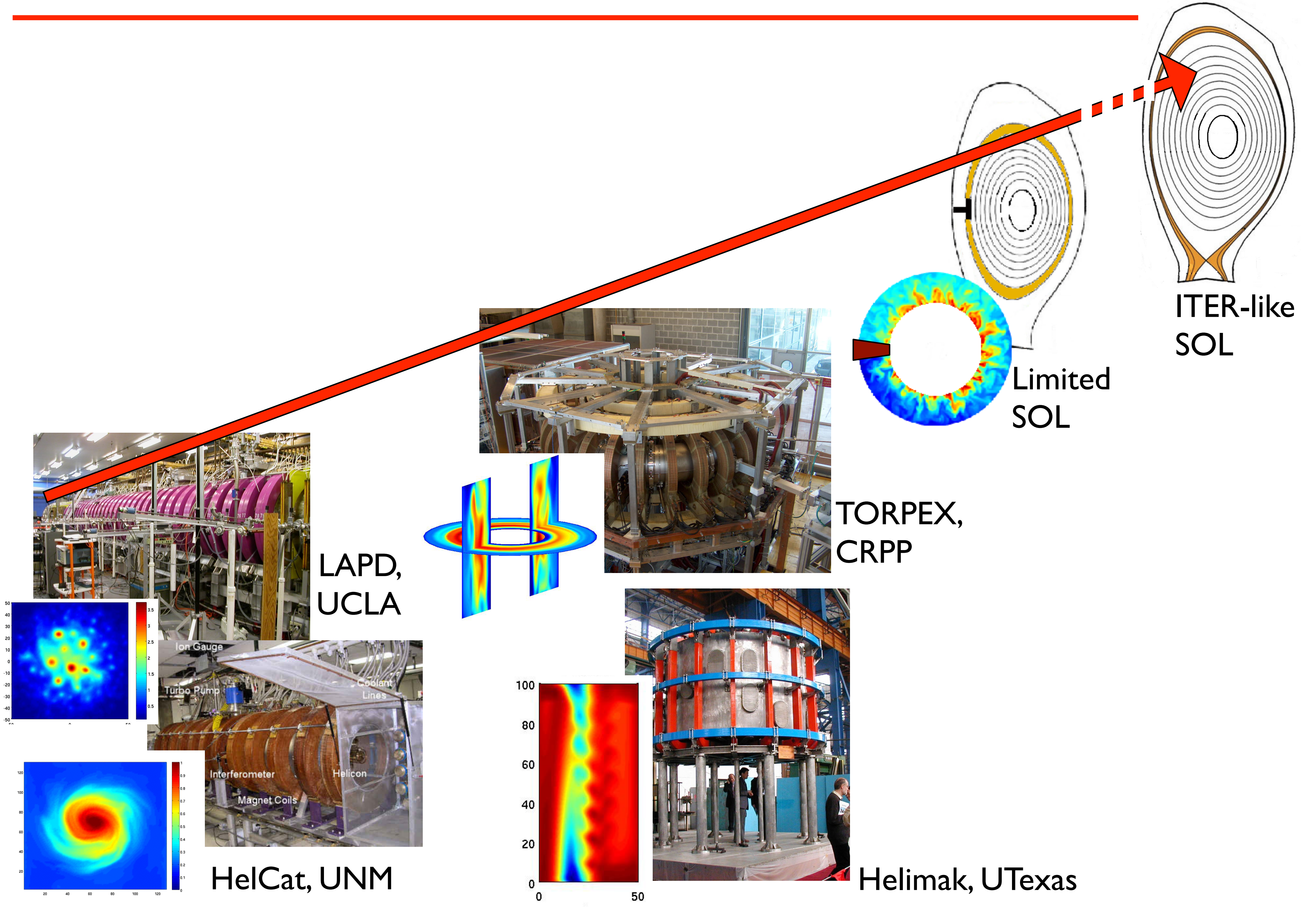
Solved in 3D geometry, taking into account plasma outflow from the core, turbulent transport, and losses at the vessel

Boundary conditions at the plasma-wall interface



- Set of b.c. for all quantities, generalizing Bohm-Chodura
- Checked agreement with PIC simulations

GBS analysis of configurations of increasing complexity



LAPD, UCLA

HelCat, UNM

TORPEX, CRPP

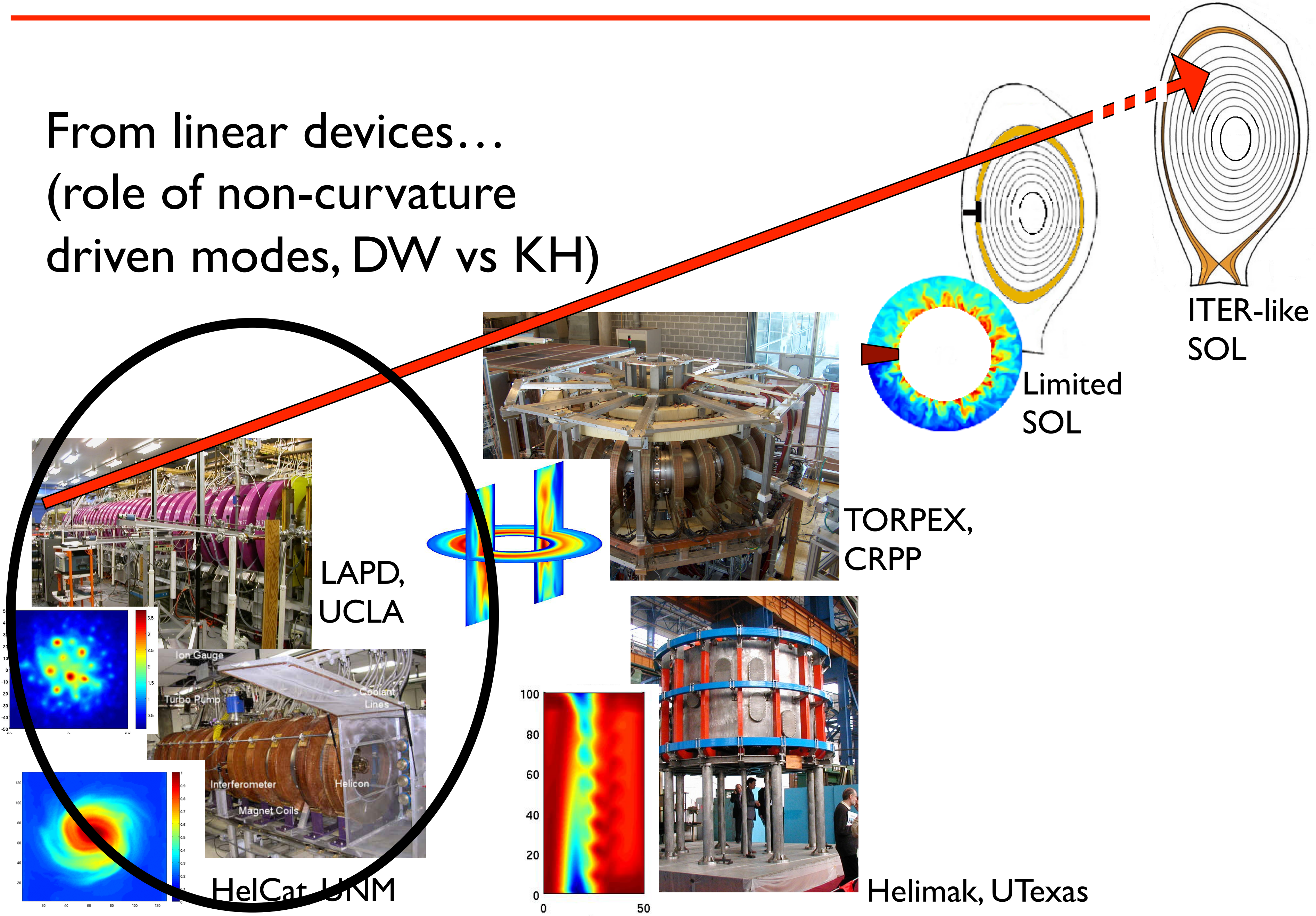
Helimak, UTexas

Limited SOL

ITER-like SOL

GBS analysis of configurations of increasing complexity

From linear devices…
(role of non-curvature
driven modes, DW vs KH)



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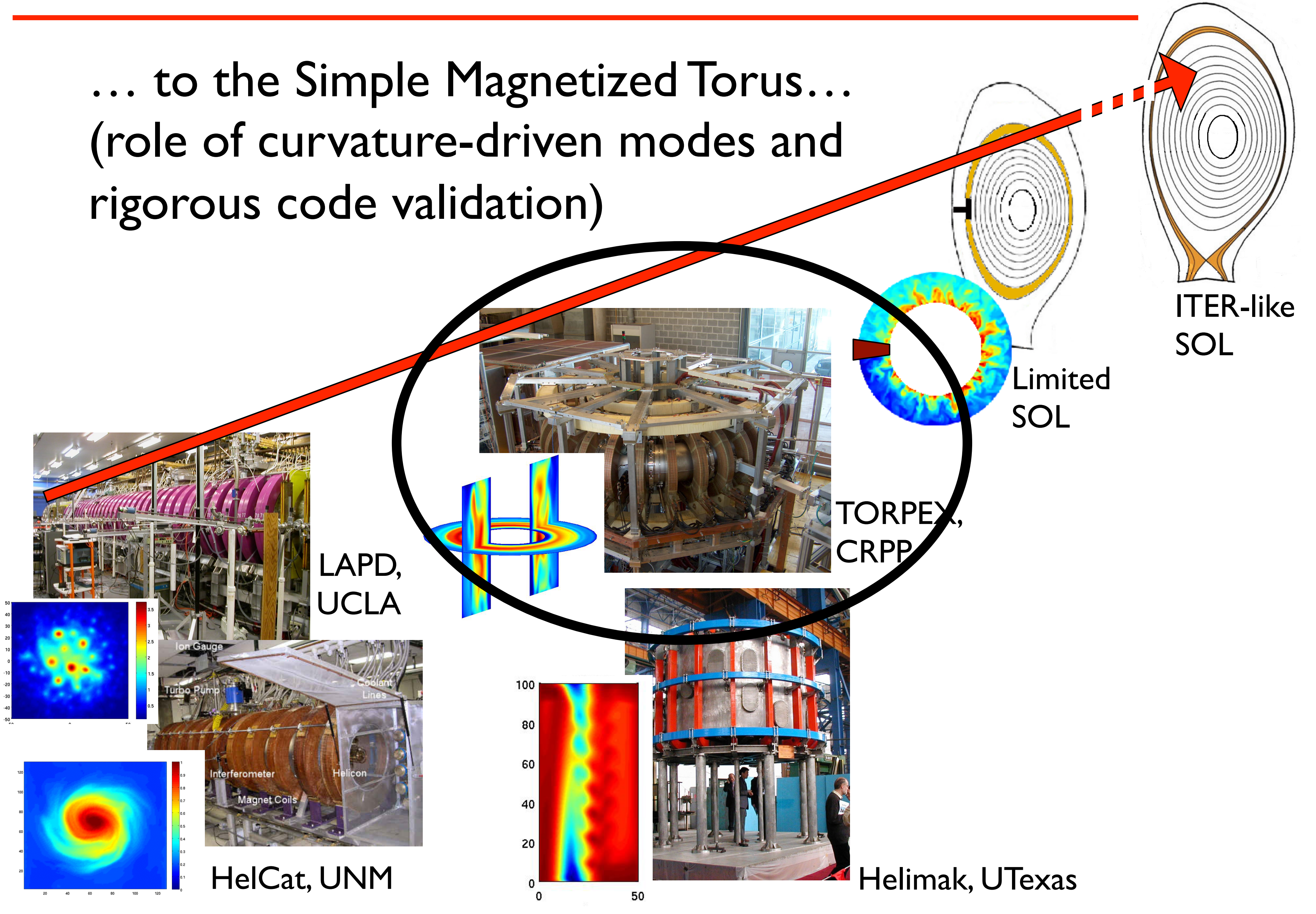
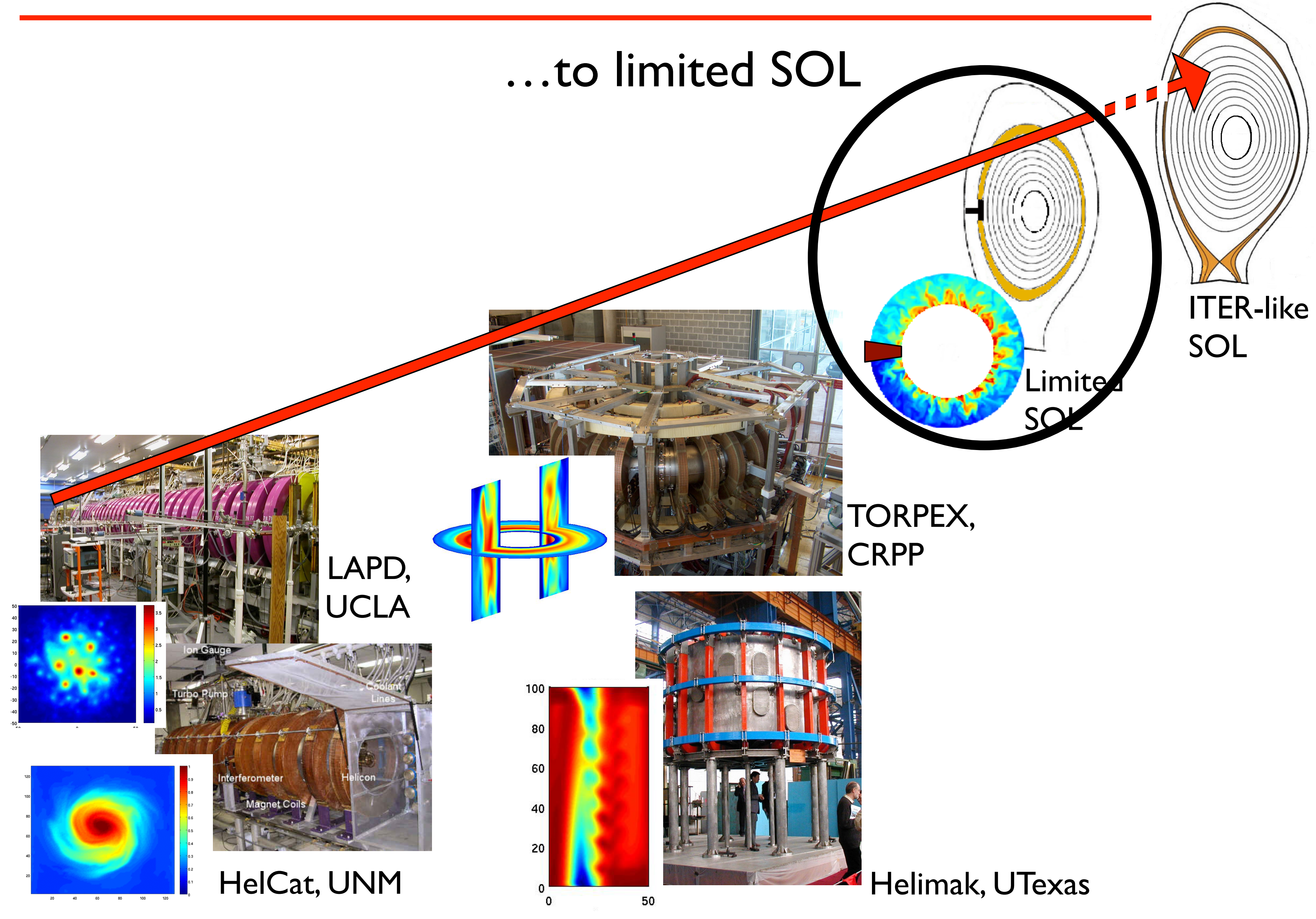
GBS analysis of configurations of increasing complexity

… to the Simple Magnetized Torus…
(role of curvature-driven modes and rigorous code validation)



GBS analysis of configurations of increasing complexity

…to limited SOL



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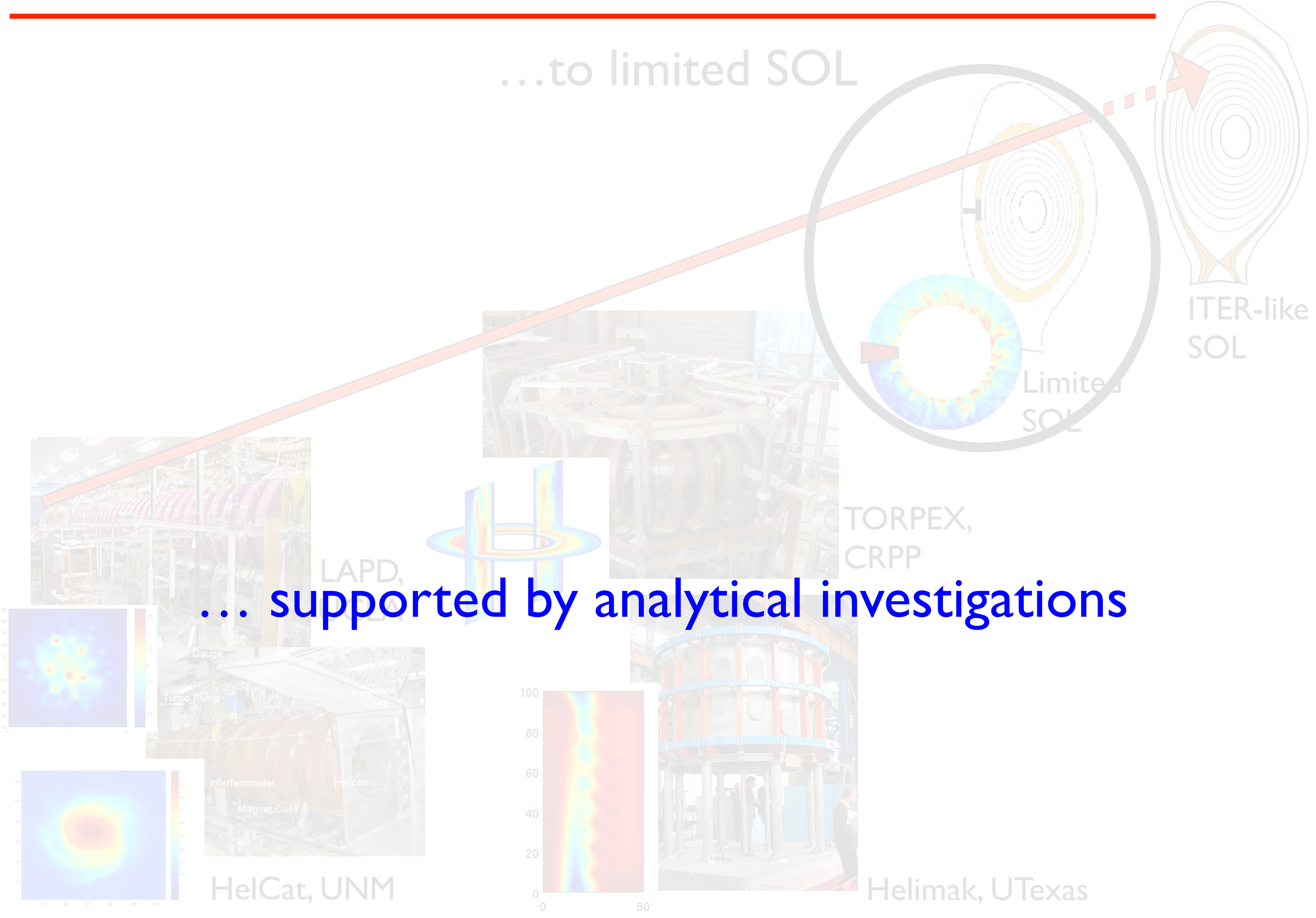
Limited SOL

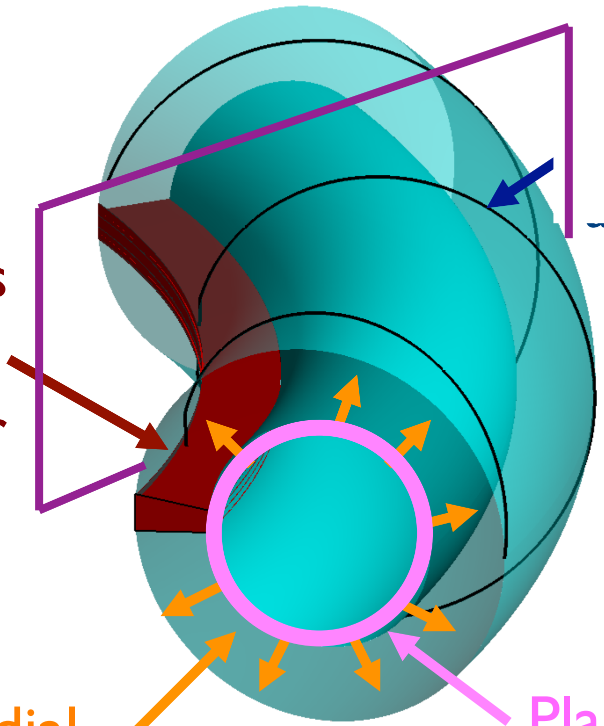
ITER-like SOL

GBS analysis of configurations of increasing complexity



… supported by analytical investigations

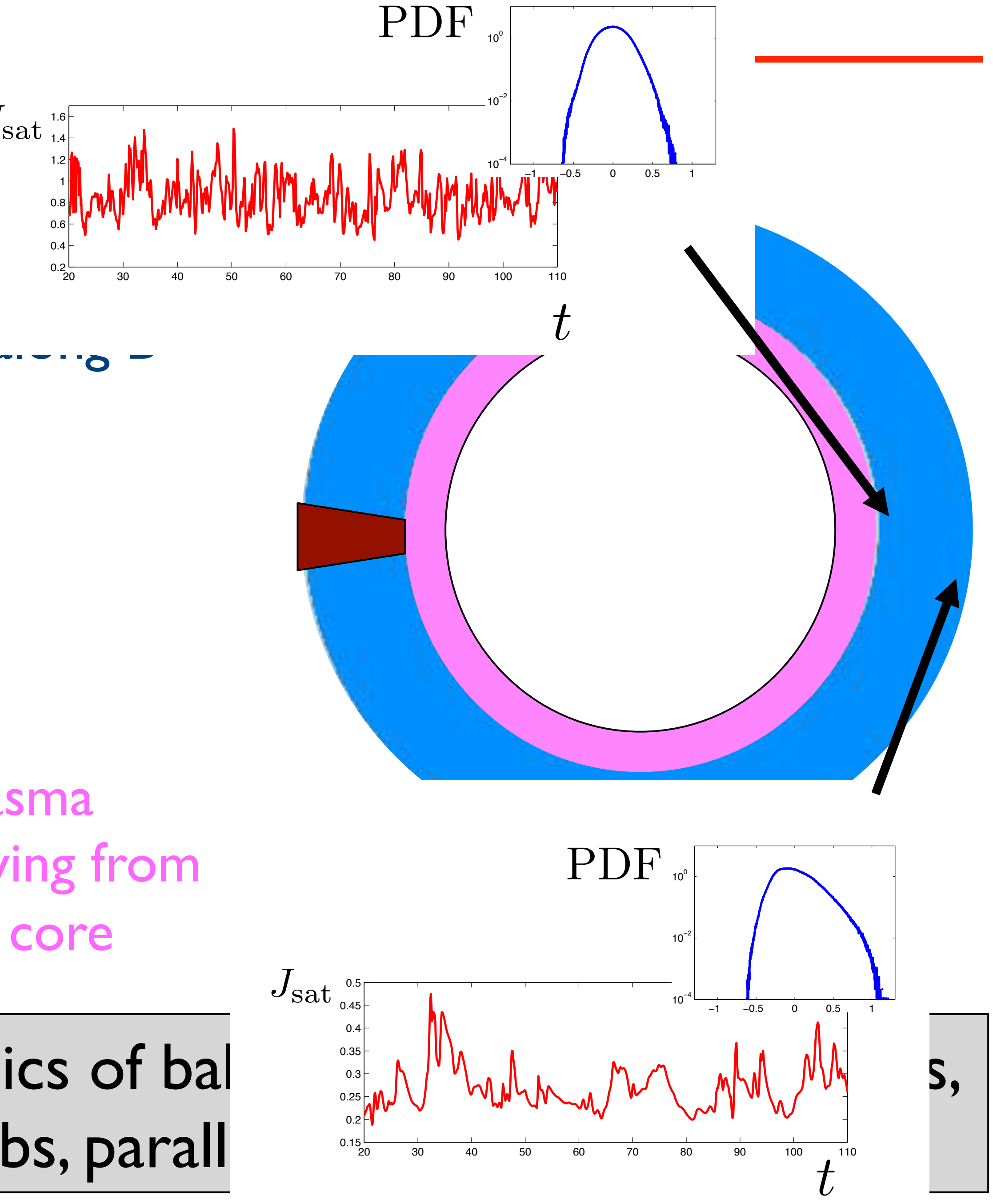
Tokamak



Losses at the limiter

Radial transport

Plasma outflowing from the core



Simulations contain physics of bal s,
Kelvin-Helmholtz, blobs, parall

The key questions

- What is the mechanism setting the SOL turbulent level and the perpendicular transport?
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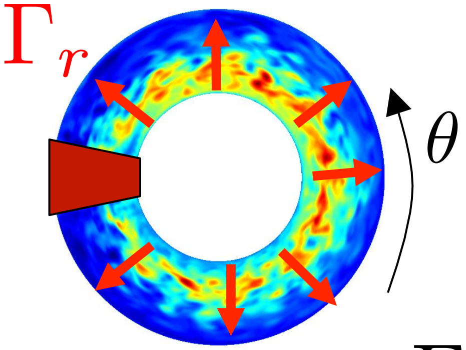
Turbulent transport with gradient removal (GR) saturation

Turbulence saturates when it removes its drive → $\frac{\partial p_{e1}}{\partial r} \sim \frac{\partial p_{e0}}{\partial r} \rightarrow k_r p_{e1} \sim p_{e0}/L_p$



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

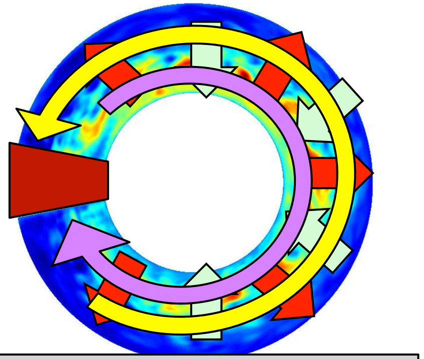
$$\Gamma_r = \left\langle p_{e1} \frac{\partial \phi_1}{\partial \theta} \right\rangle_t$$

GR hypothesis

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

$$D_{GR} = \frac{\Gamma_r}{p_{e0}/L_p} \sim \frac{\gamma L_p}{k_\theta}$$

Turbulence saturation due to Kelvin-Helmholtz instability (KH)



Primary instability grows until it causes KH unstable shear flow → $\frac{\partial \omega}{\partial t} \sim [\phi, \omega] \rightarrow \phi_1 \sim \frac{\gamma}{k_\theta^2}$

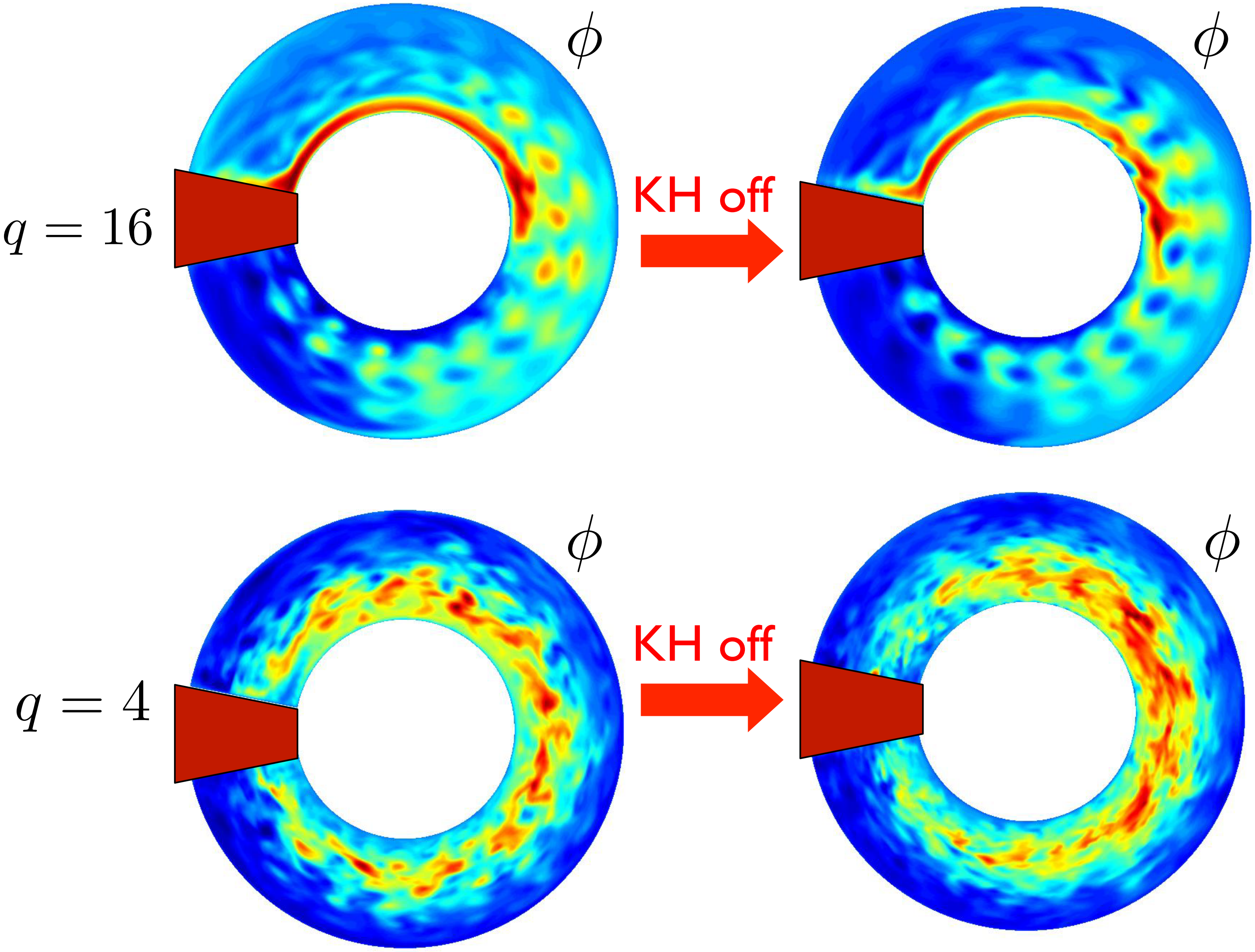
$$\Gamma_r = \left\langle p_{e1} \frac{\partial \phi_1}{\partial \theta} \right\rangle_t \sim \frac{\gamma p_{e0}}{L_p k_\theta^2} \Rightarrow \boxed{D_{KH} \sim \frac{\gamma}{k_\theta^2}}$$

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?

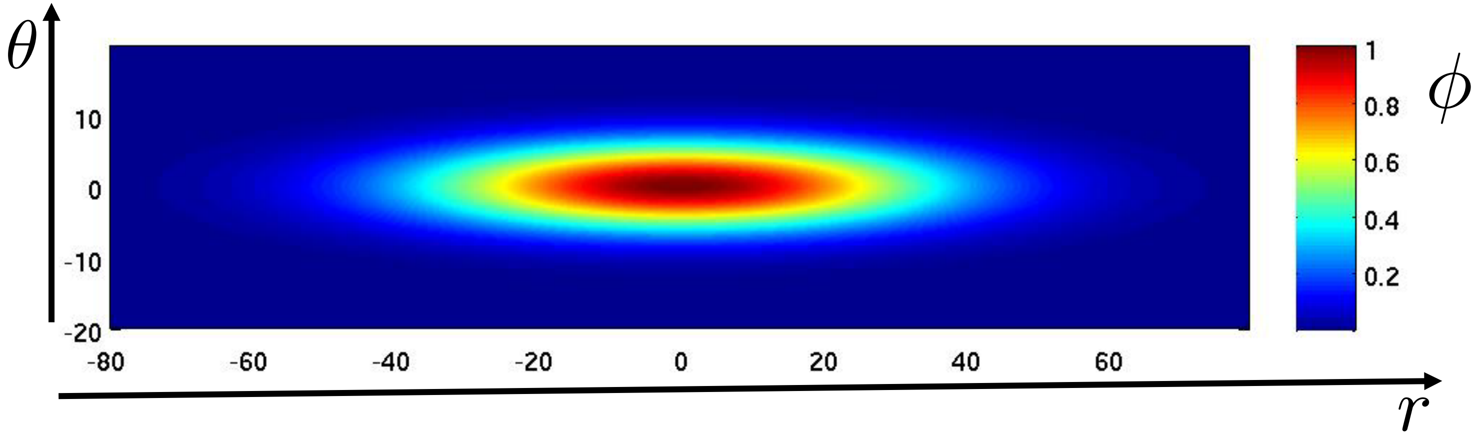


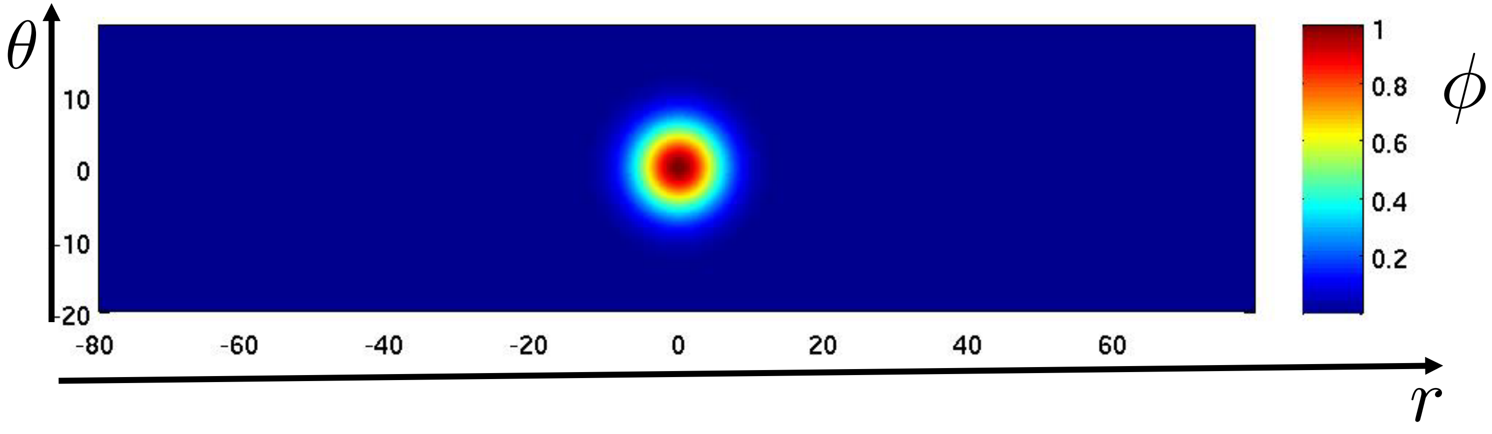
KH
saturates
turbulence

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: $\sqrt{k_\theta L_p} > 3$ (as in the $q = 16$ case)

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Transport and profile scaling for KH stable cases

Balance of perpendicular transport and parallel losses

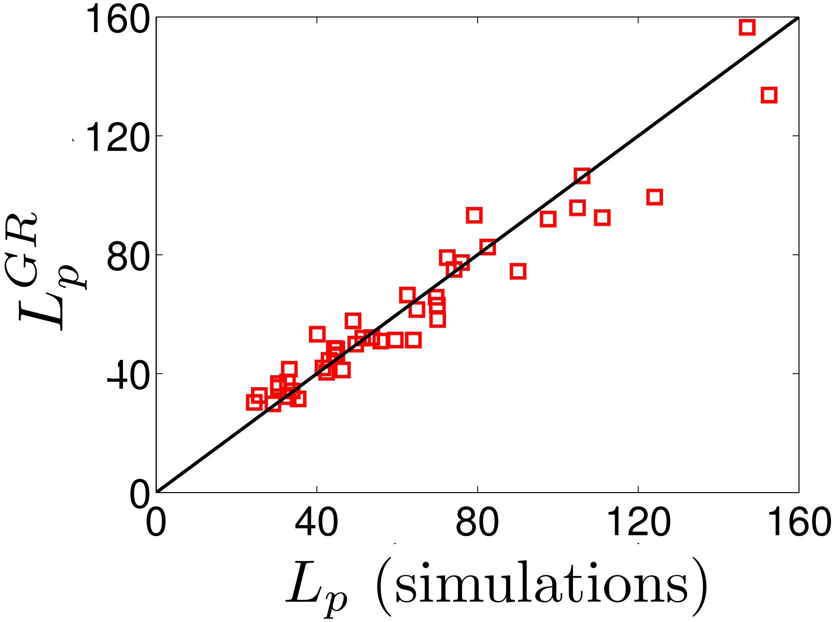
$$\frac{d\Gamma_r}{dr} \sim L_\parallel \sim \frac{n_0 c_s}{qR}$$

Bohm's

$$\boxed{L_p^{GR} \simeq q\left(\frac{\gamma}{k_\theta}\right)_{\max}}$$

$$\boxed{L_p^{GR} = L_p^{GR}(R, q, \hat{s}, \nu)}$$

Simulations show expected scaling



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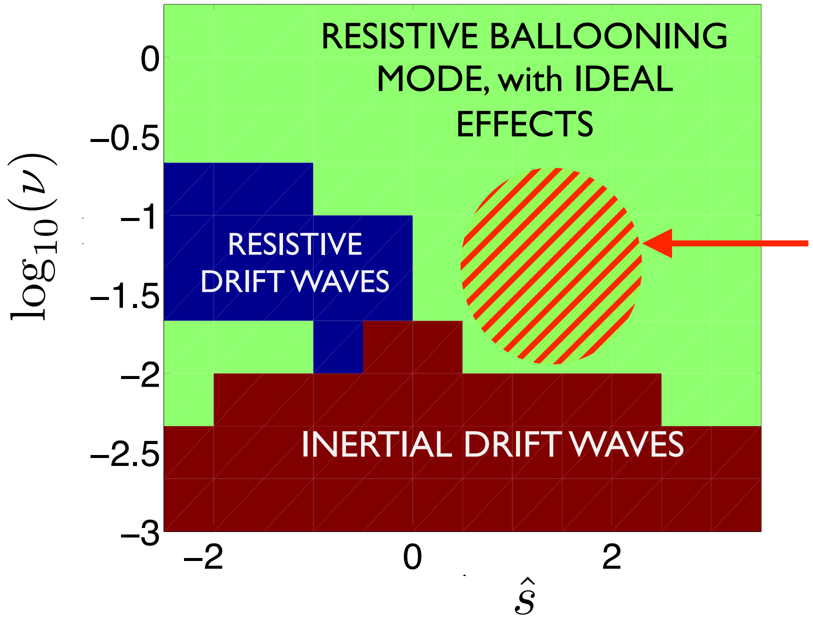
SOL Turbulent regimes

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



TYPICAL LIMITED SOL OPERATIONAL PARAMETERS

LIMITED SOL: $L_p^{GR} \simeq q \left(\frac{\gamma}{k_\theta}\right)_{\max}$

RBM $\gamma \sim \gamma_b = \sqrt{2R/L_p}$

RBM $k_\theta \sim k_b = \sqrt{\frac{1-\alpha_{\mathrm{MHD}}}{\nu q^2 \gamma_b}}$

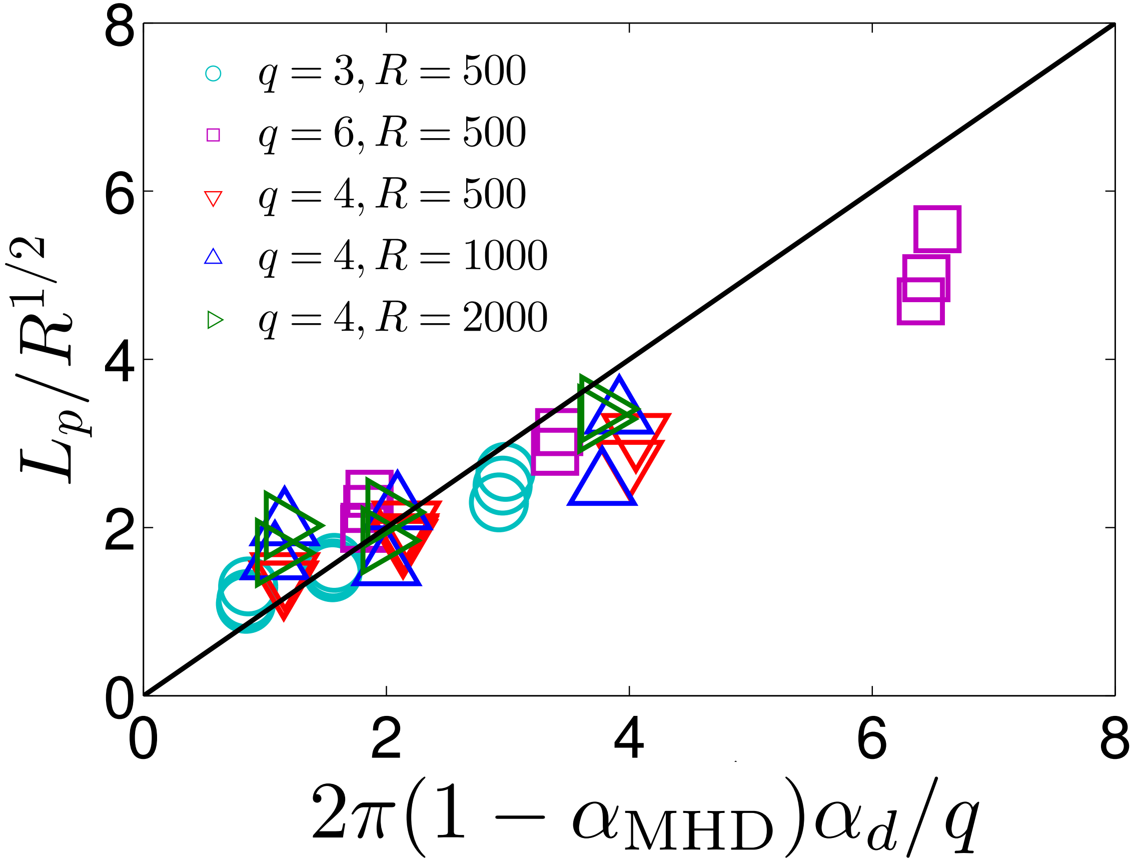
$$\boxed{L_p = R^{1/2}[2\pi(1-\alpha_{\mathrm{MHD}})\alpha_d/q]}$$

MAJOR RADIUS

$\alpha_{MHD} \sim q^2 \beta R/L_p$

$\alpha_d \sim (R/L_p)^{1/4}\nu^{-1/2}/q$

Simulations agree with ballooning estimates



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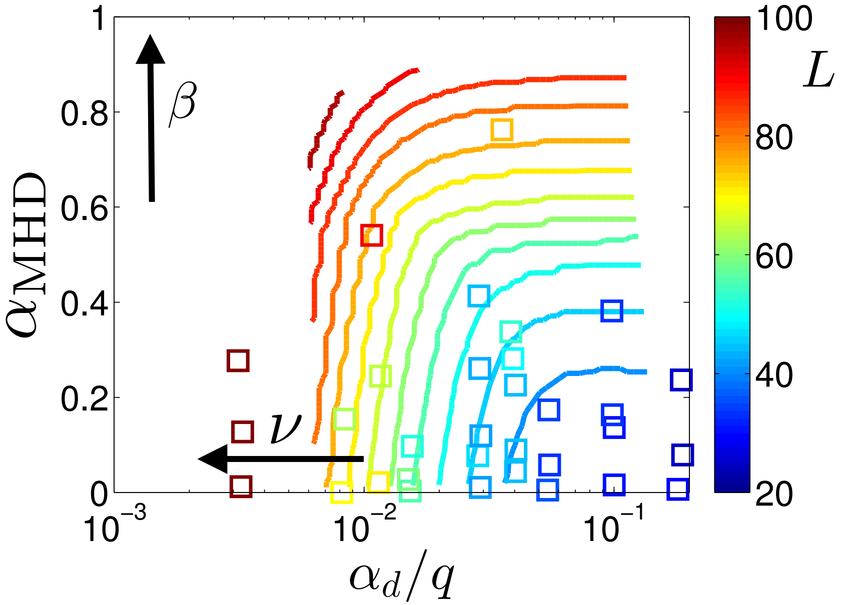
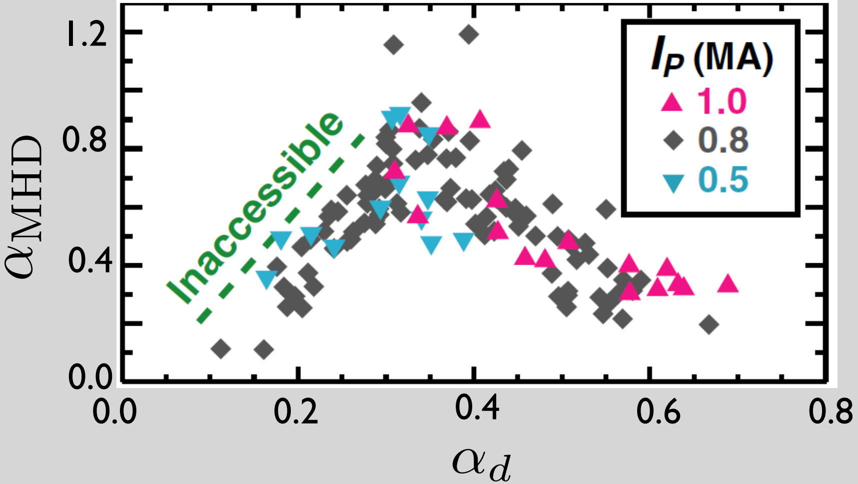
Limited SOL transport increases with β and ν

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



Maybe related to the density limit?

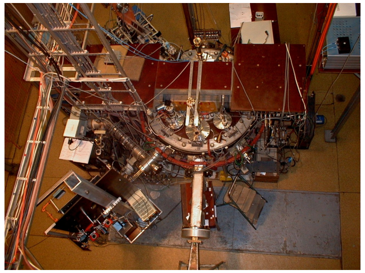
Coupling with core physics needs be addressed…



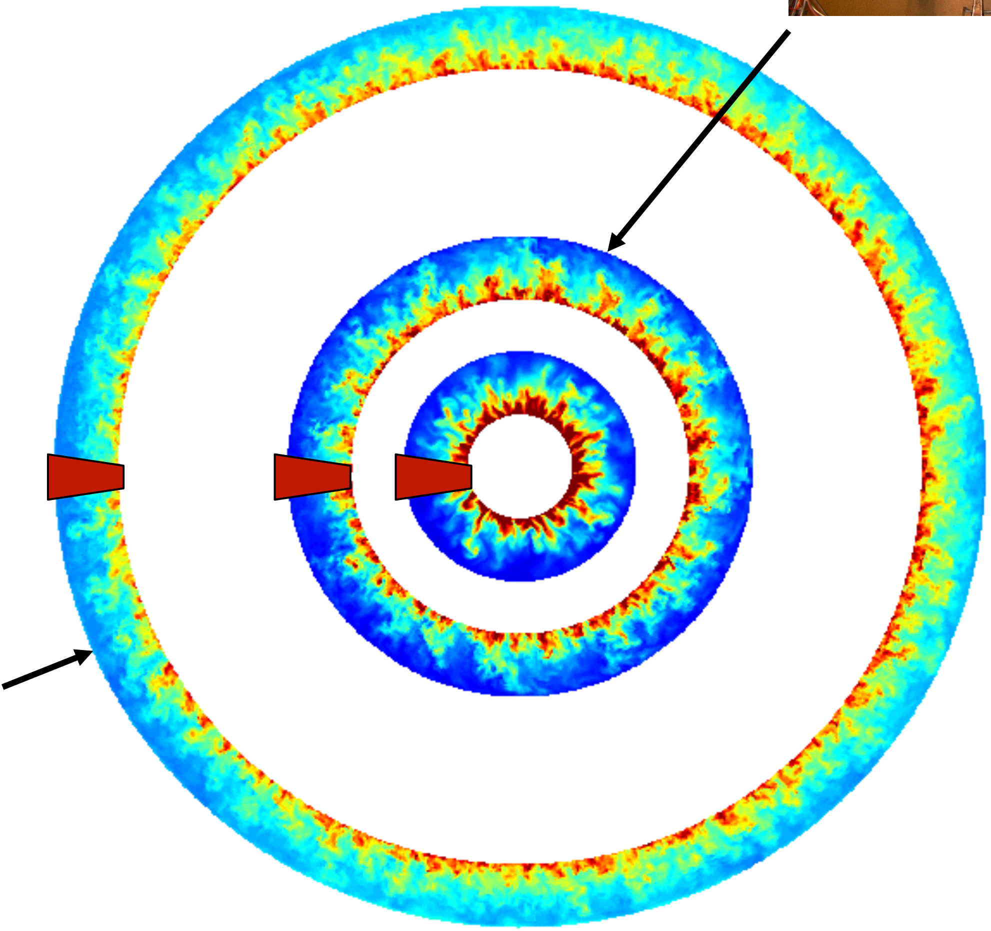
LaBombard, NF 2005

Limited SOL width widens with R

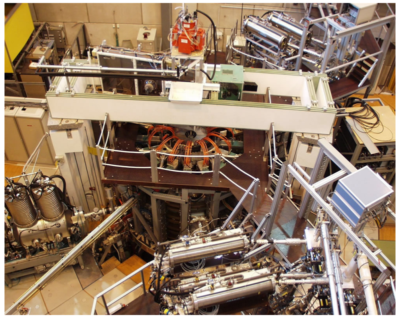
$$L_p = \boxed{R^{1/2}}[2\pi(1-\alpha_{\mathrm{MHD}})\alpha_d/q]$$



CASTOR



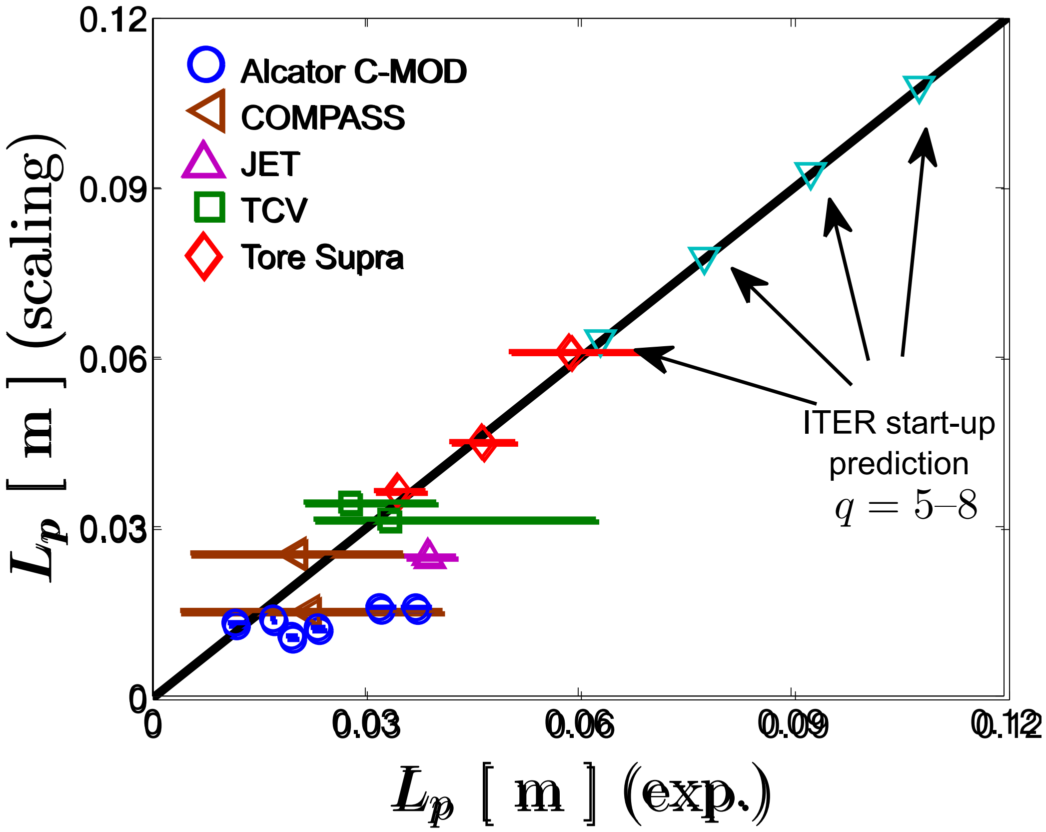
TCV



Good agreement with multi-machine measurements

The ballooning scaling, in SI units:

$$L_p \simeq 7.97 \times 10^{-8} q^{8/7} R^{5/7} B^{-4/7} T_e^{-2/7} n_e^{2/7}$$



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Potential in the SOL set by sheath and electron adiabaticity

Typical estimate: at the sheath

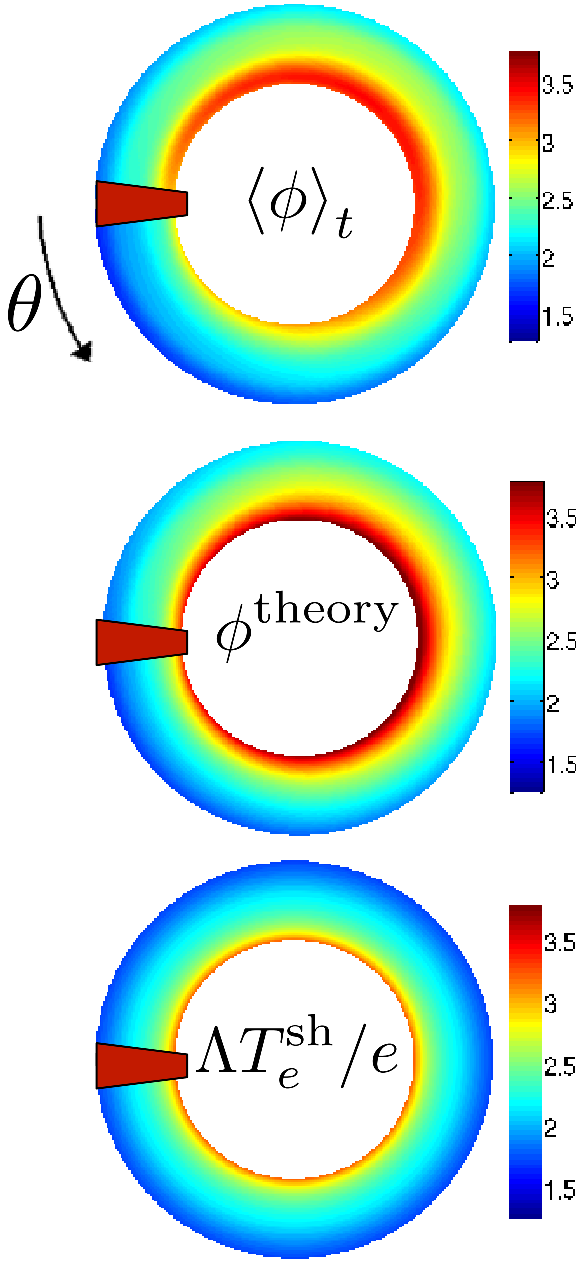
$$v_{\parallel i} = c_s \qquad v_{\parallel e} = c_s \exp(\Lambda - e\phi/T_e^{\rm sh})$$

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

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

Our more rigorous treatment, from Ohm's law

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



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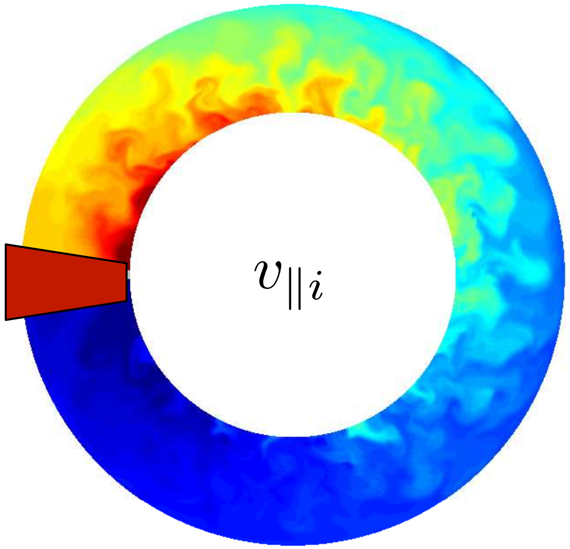
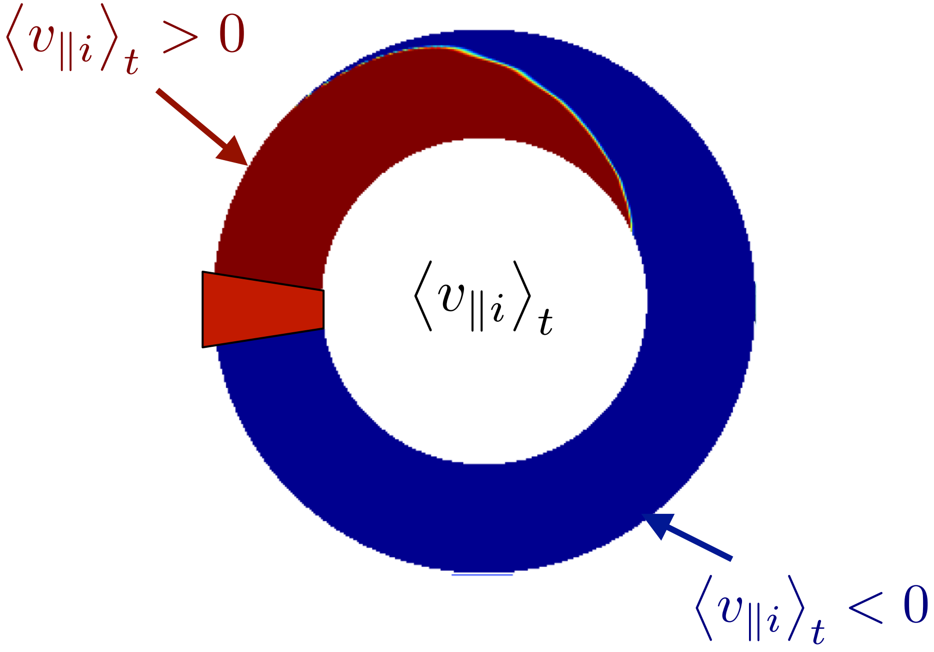
GBS simulations show intrinsic toroidal rotation





A model for the SOL intrinsic toroidal rotation

Time-averaging the momentum equation:

$$\frac{\partial}{\partial r} D \frac{\partial v_{\parallel i}}{\partial r} + \frac{\partial \phi}{\partial r}\frac{\partial v_{\parallel i}}{\partial \theta} + \epsilon \frac{v_{\parallel i}}{q}\frac{\partial v_{\parallel i}}{\partial \theta} + \frac{\epsilon}{nq}\frac{\partial p}{\partial \theta} = 0$$

Turbulent driven radial transport, gradient-removal estimate

Poloidal convection

Parallel convection

Pressure poloidal asymmetry

solved with boundary conditions:

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

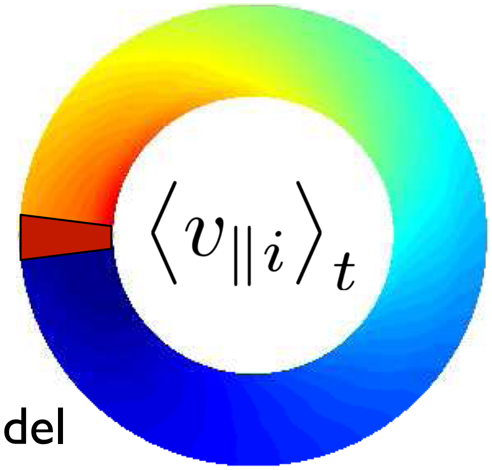
Bohm's criterion

ExB correction

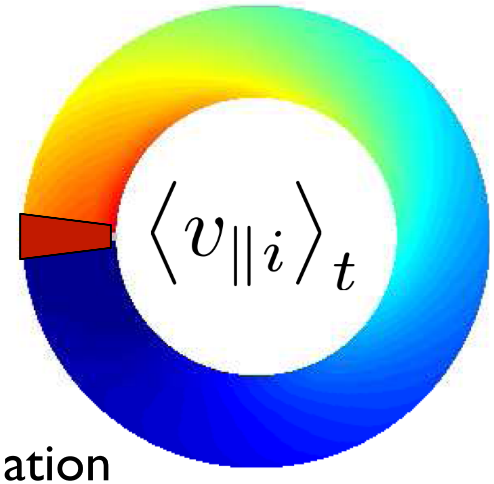
Sources of toroidal rotation

Our model explains experimental and simulation rotation

Good agreement between model and simulations:



Model



Simulation

Able to explain the experimental trends:

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

Incidentally, a Rice Scaling is observed, $v_\varphi \sim T_e / I_p$

What are we learning from GBS simulations?

- The use of a progressive simulation approach to investigate plasma turbulence, supported by analytical investigations
- SOL turbulence:
  - Saturation mechanism given by gradient removal or Kelvin-Helmholtz instability
  - Turbulent regimes: in limited plasmas, resistive ballooning modes
  - Good agreement of the scaling of the pressure scale length with multi-machine measurements
  - Sheath dynamics and electron adiabaticity set the electrostatic potential in the SOL
  - Toroidal rotation generated by sheath dynamics and pressure poloidal asymmetry