How “the tail wags the dog”: physics of edge-core coupling by inward turbulence propagation

ID: 2660

Mingyun Cao[1], P. H. Diamond[2]

1. Department of Physics and Astronomy, University of California, Los Angeles
2. Departments of Physics and Astronomy & Astrophysics, University of California, San Diego

mcao@physics.ucla.edu

ABSTRACT

- Cherenkov “radiation” of drift waves from inward-moving density voids drives substantial inward turbulence spreading and leads to the formation of the edge-core coupling region, i.e., no man’s land (NML).
- Void-induced turbulence is regulated by a self-generated zonal flow. This qualitatively explains the observed zonal flow power bursts following the detection of voids in experiments.
- By incorporating voids into plasma turbulence dynamics, we develop a first-principles model that resolves several questions surrounding the shortfall problem and the dynamics of edge-core coupling.

BACKGROUND & MOTIVATION

- Coherent structures exist in fusion plasmas as blobs and voids—plasma filaments with large amplitude +/- density fluctuations.
- Existing theories on blobs/voids are incomplete since: (1) no interactions of structures with waves and zonal flow; (2) **millions of papers on blobs, far less attention to voids.**
- Recent experiments indicate: (1) blobs and voids are created in pairs from edge gradient relaxation events (GREs) close to LCFS; (2) while blobs move outward into SOL, **voids move inward, staying in bulk plasma** (messenger from edge to core); (3) **inward moving voids could drive zonal flow**.
- In edge-core coupling region: Fickian gyrokinetic simulations sometimes underpredict the turbulence level (shortfall problem) ⇒ **Maybe the excess turbulence is spread from the edge?** ⇒ the tails wags the dog
- Inward-moving **voids could play an important role in plasma turbulence dynamics** and address the shortfall problem⇒ need a model.

MODEL DEVELOPMENT

BASIC IDEA: CHERENKOV RADIATION + DRESSED TEST PARTICLE MODEL

Moving charged particles emit EM waves ⇔ moving voids also emit waves

From experiments: $u_v \sim v_*$ ⇒ **inward-moving voids radiate drift waves.**

FORMULATION: HASEGAWA-WAKATANI MODEL $\quad \alpha = D_\parallel k_\parallel^2/\omega$

$$\frac{d}{dt}\nabla_\perp^2\varphi + 2\kappa\frac{1}{n_0}\frac{\partial n}{\partial y} = D_\parallel \nabla_\parallel^2\left(\frac{n}{n_0}-\varphi\right),\qquad \frac{1}{n_0}\frac{dn}{dt} = D_\parallel\nabla_\parallel^2\left(\frac{n}{n_0}-\varphi\right)$$

PARTITION OF THE SPACE:

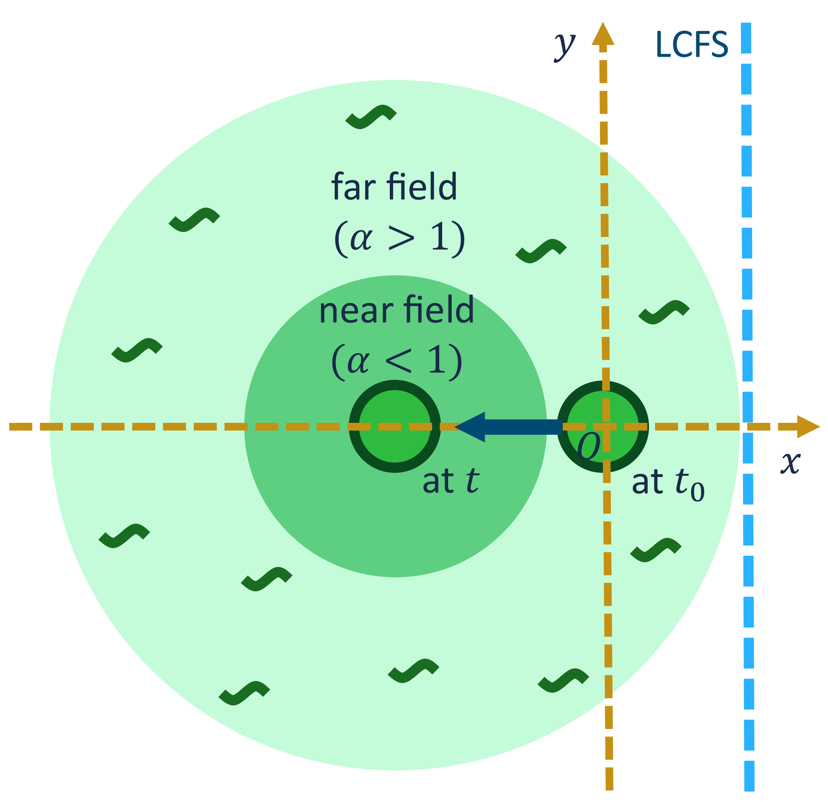
Near field: close to the void, $\alpha < 1$ (density mixing ✓) ⇒ Two-field model

Far field: far from the void, $\alpha > 1$ (drift wave) ⇒ Hasegawa-Mima (HM) eqn

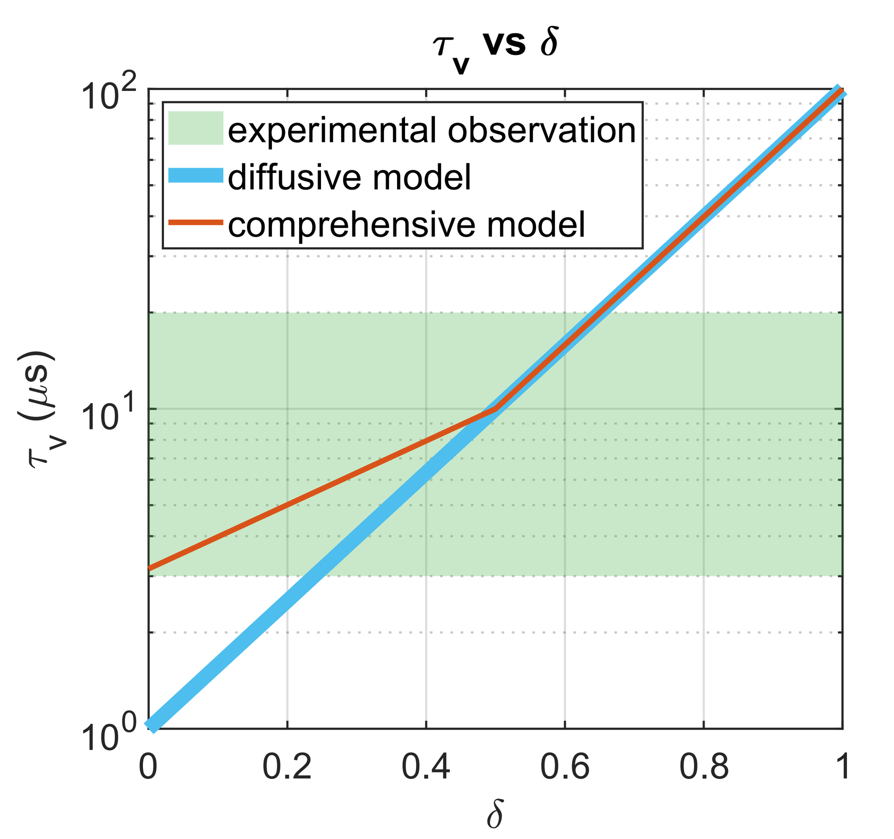
Focus: far field ⇒ void enters via profile modulation: $n = n_0 + n_v + \tilde{n}$

$$\frac{d}{dt}(\nabla_\perp^2\varphi - \varphi) - v_*\frac{\partial\varphi}{\partial y} = \frac{1}{n_0}\frac{dn_v}{dt}$$

$$n_v = 2\pi n_0 h\Delta x\Delta y\,\delta(x+u_x t)\,\delta(y-u_y t)\,H(t)\,H(\tau_v - t)$$



Division of space



Void lifetime as a function of mixing length

CHALLENGES & SCHEME

WORKFLOW

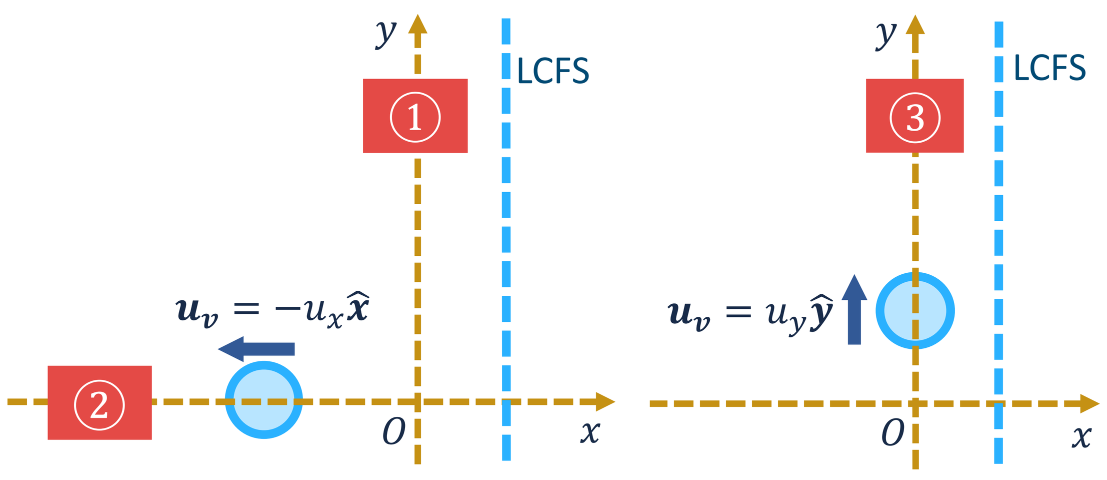
Solve φ via Green’s func of linearized HM equation ➔ Estimate void-induced turbulence flux & NML width ➔ Compute shearing rate of void-driven zonal flow

CHALLENGES

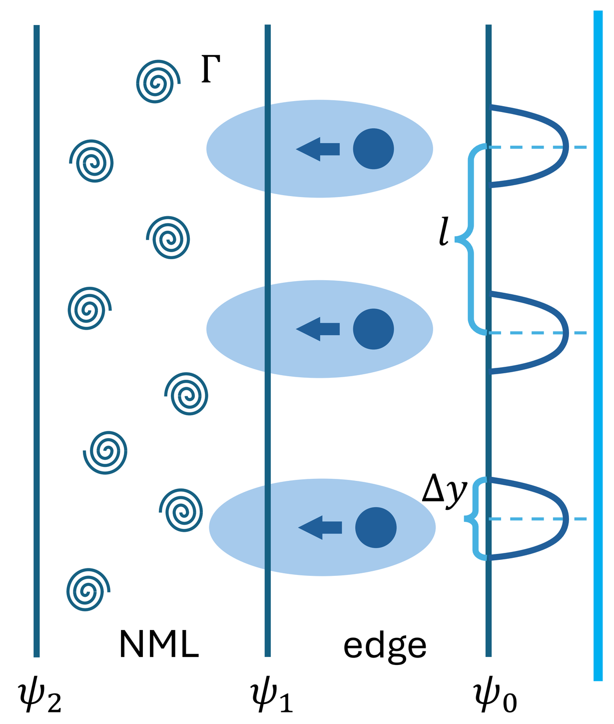
- Green’s function of linearized HM equation is too complicated.
- Motion of voids has both radial and poloidal components.

SCHEME

- Seek only local solutions of three limiting cases.



Schematic of specific cases



Void-induced turbulence flux

RESULTS

VOID-INDUCED TURBULENCE INTENSITY FLUX Γ & NML WIDTH w_{nml}

- After each waiting time τ_w, N voids are emitted from GRES simultaneously.
- Γ is the superposition of the pulses contributed from each void ⇒

$$\Gamma = \sum_{i,j} u_x \Delta I 2\pi\Delta y \tau_v \delta(y - il)\delta(t - j\tau_w)$$

- Balancing nonlocal turbulence spreading with local production ⇒

$$w_{nml} \sim \frac{2\pi}{\kappa\langle\tilde{v}\tilde{n}\rangle}\left(\frac{h\Delta x\Delta y}{u_x\tau_v}\right)^2 \frac{1}{v_*\tau_v^2}\frac{N\Delta y}{L_y}\frac{\tau_v}{\tau_w}$$

- For $N \sim \mathcal{O}(1)$ (strong ballooning), $w_{nml} \sim 100\,\rho_s$ for typical parameters.

SHEARING RATE OF VOID-DRIVEN ZONAL FLOW

Case	ω_s^v/ω_s^a	If $v_F^a \sim v_*$, $\Delta_F^a \sim 10\rho_s$
$\boldsymbol{v_h} = -u_x\hat{\boldsymbol{x}}$ away from x-axis	$\frac{\omega_s^h}{\omega_s^a} \sim \left(\frac{h\Delta x\Delta y}{v_* u_x\tau_v a}\right)^2 \frac{\Delta_F^a}{v_F^a/v_*}$	$\frac{\omega_s^v}{\omega_s^a} \sim 10h^2$
$\boldsymbol{v_h} = -u_x\hat{\boldsymbol{x}}$ near x-axis	$\frac{\omega_s^h}{\omega_s^a} \sim \left(\frac{h\Delta x\Delta y}{v_* u_x\tau_v}\right)^2 \frac{2\ln(a/v_*)\,\Delta_F^a}{x^3 v_F^a/v_*}$	$\frac{\omega_s^v}{\omega_s^a} \sim (10h)^2 \quad \left(\frac{x}{\rho_s} \sim 10^2\right)$
$\boldsymbol{v_h} = u_y\hat{\boldsymbol{y}}$ near y-axis	$\frac{\omega_s^h}{\omega_s^a} \sim \frac{\pi(1+k_0^2)}{4k_0}\left(\frac{h\Delta x\Delta y}{v_* u_y\tau_v}\right)^2 \frac{x}{a^3}\frac{\Delta_F^a}{v_F^a/v_*}$	$\frac{\omega_s^v}{\omega_s^a} \sim h^2 \quad \left(\frac{x}{\rho_s} \sim 10, k_0 = 1\right)$

ESTIMATE OF VOID LIFETIME: A DIFFUSIVE MODEL

- Turbulence and shear can smear/shear the void ⇒ constrain void lifetime.
- When magnitude decays by half, void is vanished ⇒ $\tau_v = 2\Delta x^2/D$
- Predicted τ_v ranges from a few to 100 μs, bracketing experimental results.

CONCLUSION

- Voids, drift waves, and zonal flow constitute **a new feedback loop that goes well beyond the traditional drift wave–zonal flow paradigm**.
- How the tail wags the dog: **emission of drift waves from inward-moving voids drives substantial inward turbulence spreading**.
- Model **applies not only to L-mode but also provides insights into H-mode**.

REFERENCES

- Mingyun Cao and P. H. Diamond, “Physics of edge-core coupling by inward turbulence propagation,” Phys. Rev. Lett. 134, 235101 (2025).