Gradient Relaxation Events → Edge Fluctuations and SOL Broadening

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or

“Interesting Things come in Pairs”

Profuse Thanks to:

- F. Khabanov, T. Long (SWIP), R. Hong, G. Yu

  G. Tynan, Z. Yan, G. McKee, Minjun Choi (KFE)

and

- Frontiers/DIII-D Experiment Program

Introduction

- Turbulence spreading, propagation of great interest in context SOL broadening

CF
  - M. Kobayashi +, 2022
  - Chu, P.D., Guo, 2022
  - P.D. TTF 2022
  - Nami Li, Zeyu Li → this meeting

- Idea: pedestal turbulence (includes ELMs, MHD) spreads into stable SOL, thus broadening SOL width. Penetration depth?
- Key Issue: Trade-off? → Need broaden λ_q while maintain good confinement

Introduction, cont'd

- Foundation: Phyiscs of turbulence spreading, avalanches, etc.

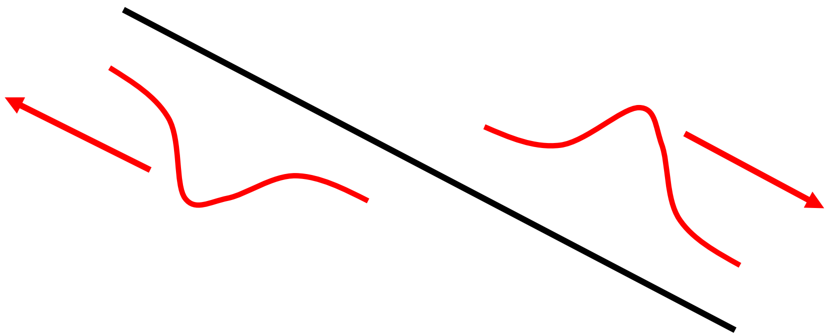
- Avalanches
- Spreading

observed

- M. Choi, 2018 (KSTAR) ECEI
- Khabanov, 2023 (DIII-D) BES velocimetry i.e. $\langle \tilde{V}_r \tilde{n}^2 \rangle$

Introduction, cont'd

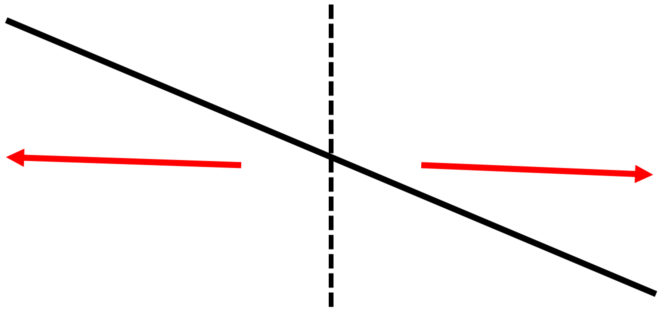
- Avalanches → opposite propagation of bumps and voids



P.D. + Hahm '95 et seq.

N.B.: bump and void propagation observed → Choi, 2018

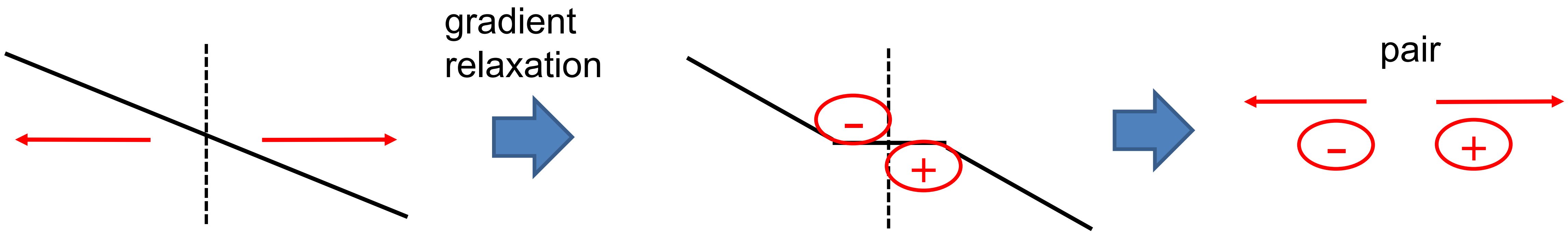
- Hint of opposite $\langle \tilde{v}_r \tilde{n}^2 \rangle$ spreading pulses near sep.



Khabanov, this meeting

Introduction, cont'd

- Why the $\rightleftarrows$?
- Edge gradient relaxation event (GRE)

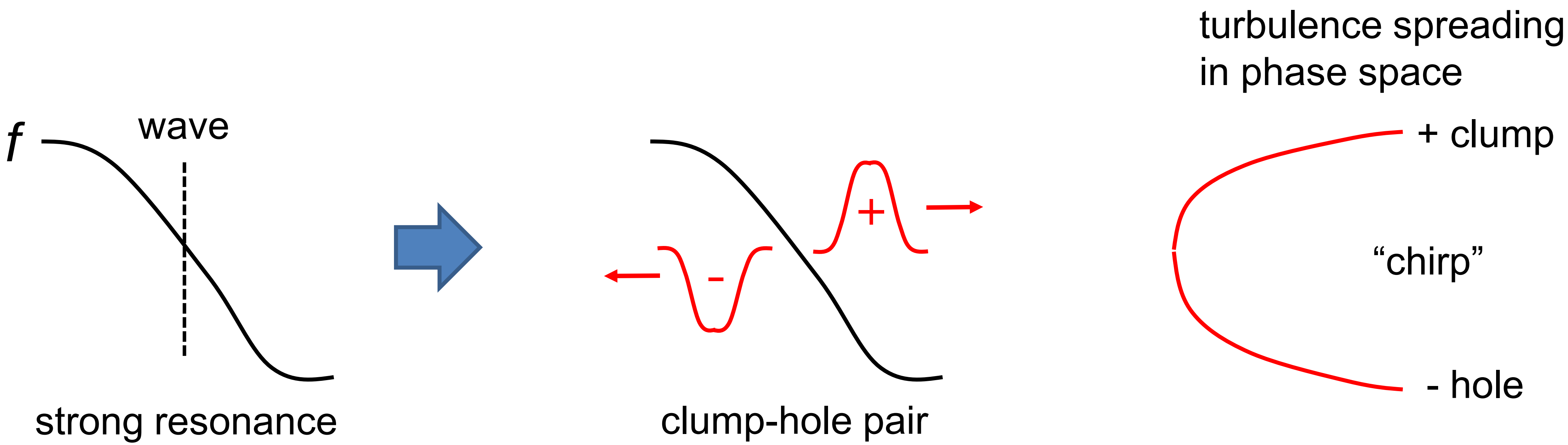


- $\overleftarrow{-}$ → inward propagating "void" or "hole"
- $\overrightarrow{+}$ → outward propagating "clump" or "blob"

←→ Conservative advection

Related: B+B Model (1996→)

- 1D Vlasov mock up of EP resonant instability



- N.B. BB speak and draw "clump-hole pair" but <u>calculate</u> via 3 wave coupling

  ➔ coherence of structure ?!

- Common element: relaxation → structure pair production and propagation

General Question:

"Is there a connection between turbulence spreading and blob-void pairs of structures?"

A) Spreading Pulses Experiments (Ting Long, SWIP) 1

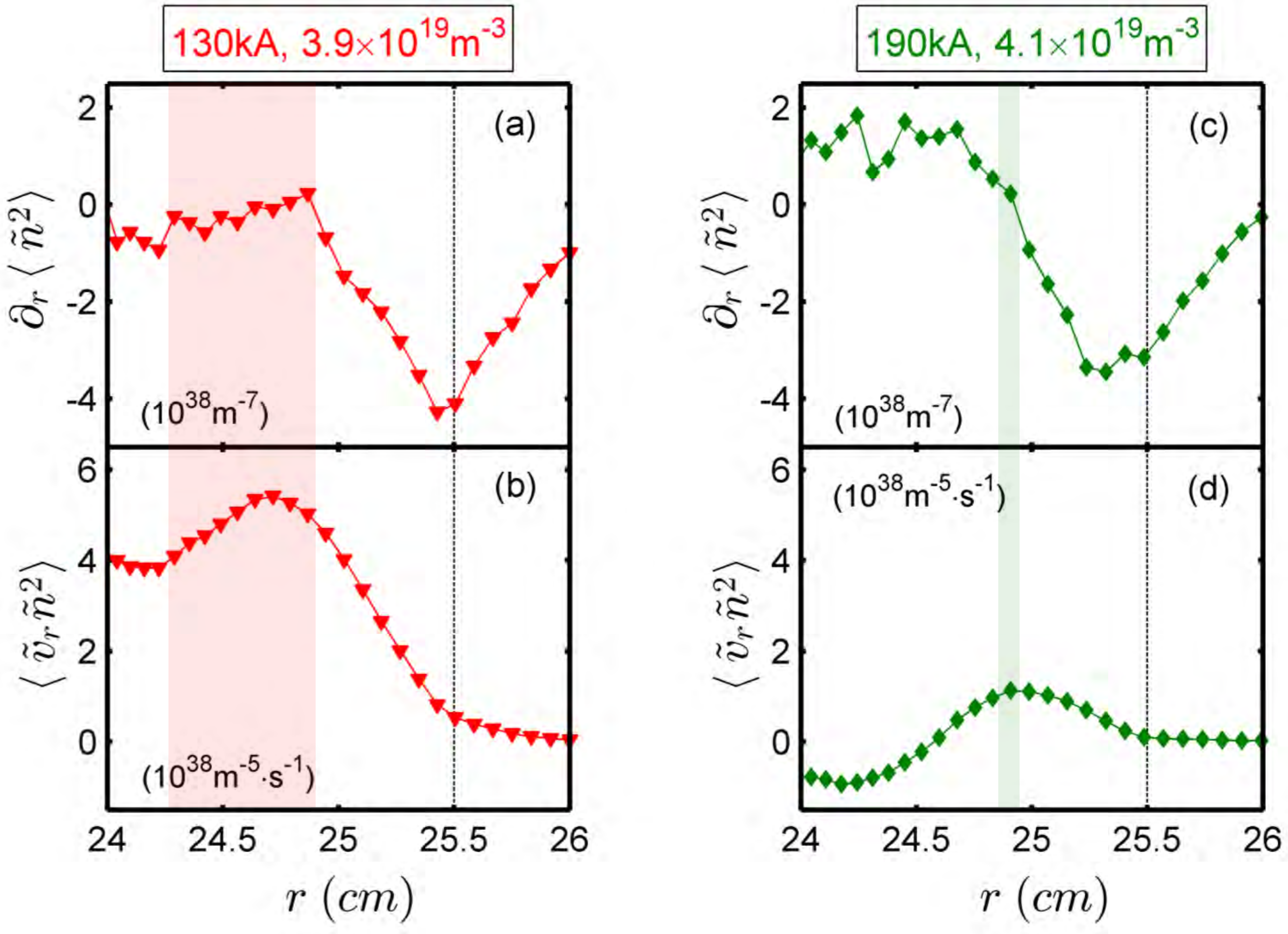
- HL-2A
- Aims:
  - Exploration of intensity flux – intensity gradient relation in edge turbulence (exploits spreading, shear layer collapse and density limit studies Long + NF'21)
  - Physics of "Jet Velocity" profile

$$V_I = \langle \tilde{v}_r \tilde{n}^2 \rangle \, / \, \langle \tilde{n}^2 \rangle$$ ➔ spreading flux, normalized

N.B. Identified by Townsend, 1949

Experiments 2

- There exits a region in plasma edge, where the turbulence spreading flux $\langle\tilde{v}_r\tilde{n}^2\rangle/2$ **is large**, but the turbulence intensity gradient $\partial_r\langle\tilde{n}^2\rangle$ **is near zero**



For similar $\bar{n}_e$ values

- Lower current,
  width of region is $\sim 5\ mm$
  ($l_{cr} \sim 4.5\ mm$)

*

- Higher current,
  width of region is $< 1\ mm$
  ($\rho_i \sim 0.25\ mm$)

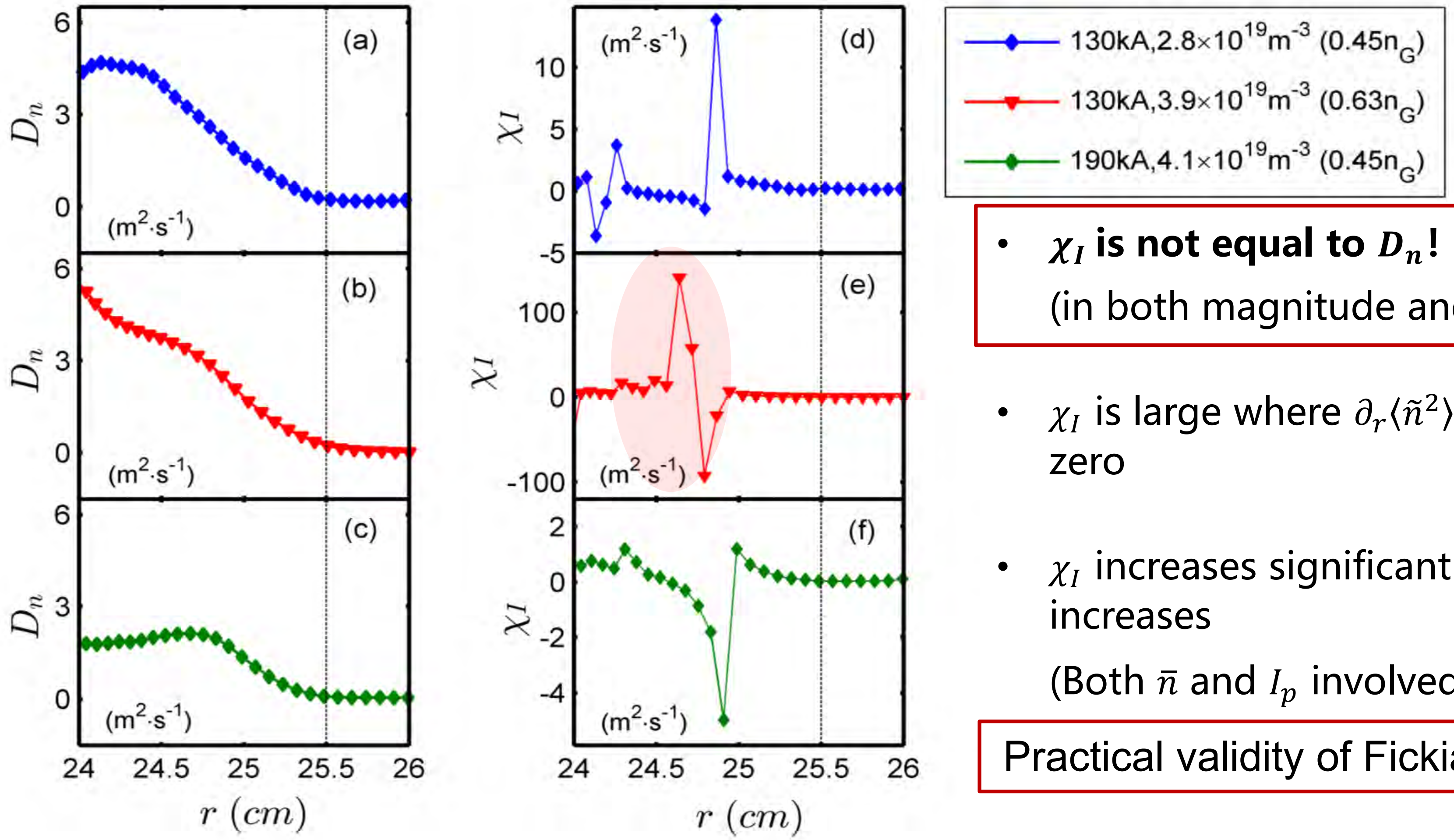
- Note: spreading diffusivity

$$\chi_I = -\frac{\langle\tilde{v}_r\tilde{n}^2\rangle}{\partial_r\langle\tilde{n}^2\rangle}$$

Conventional approach to spreading flux

Experiments 3

- Striking difference between particle diffusivity and energy spreading diffusivity
  - Diffusivity of turbulent particle flux $\langle \tilde{n}\tilde{v}_r \rangle = -\boxed{D_n}\,\partial_r \langle n \rangle$
  - Diffusivity of turbulence spreading $\langle \tilde{v}_r \tilde{n}^2 \rangle = -\boxed{\chi_I}\,\partial_r \langle \tilde{n}^2 \rangle$

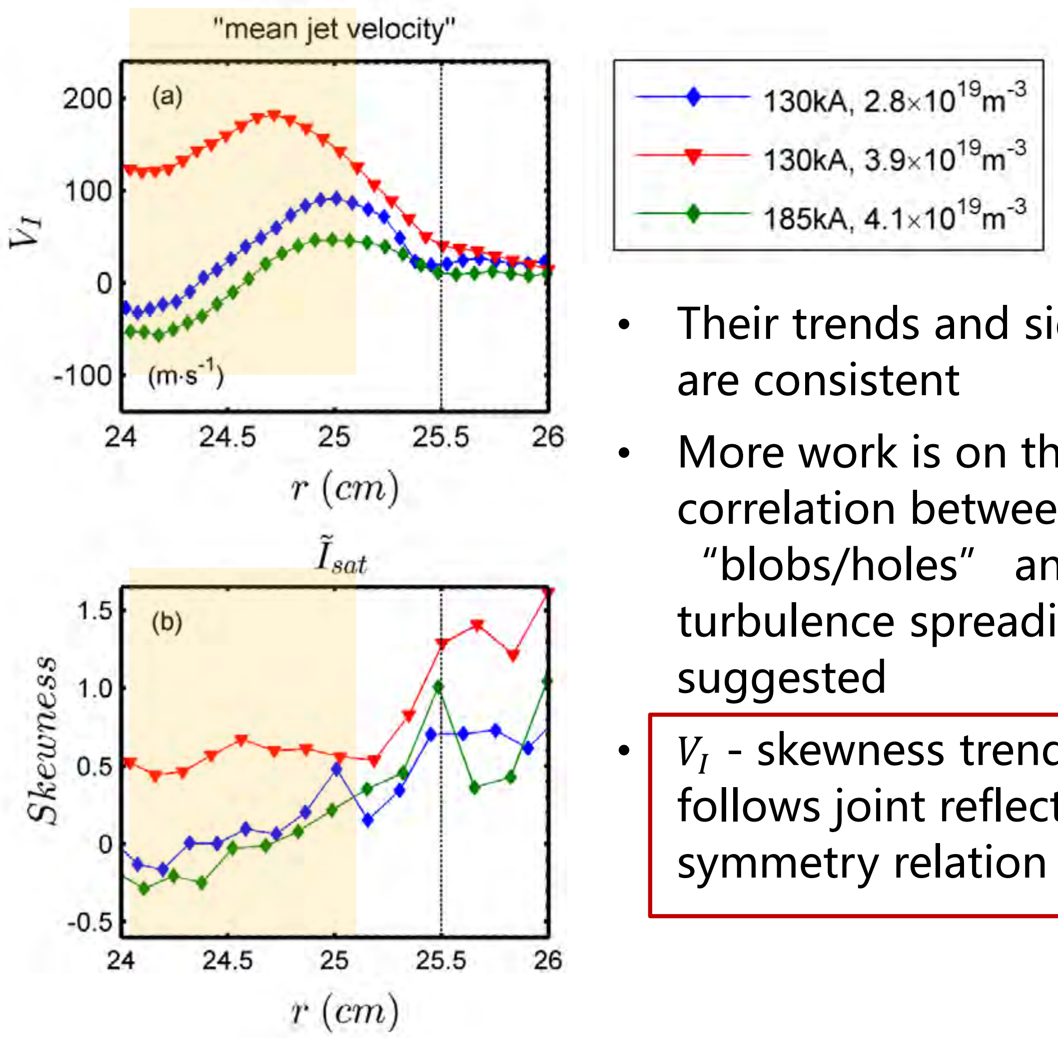


- **χ_I is not equal to D_n!**
  (in both magnitude and sign)
- χ_I is large where $\partial_r \langle \tilde{n}^2 \rangle$ is near zero *
- χ_I increases significantly as $\bar{n}/n_G$ increases *
  (Both $\bar{n}$ and I_p involved)

Practical validity of Fickian model is dubious

Experiments 4

- The "mean jet velocity" of turbulence spreading $V_I = \frac{\langle \tilde{v}_r \tilde{n}^2 \rangle}{\langle \tilde{n}^2 \rangle}$ and skewness of density fluctuations show strong correlation



- Their trends and signs are consistent
- More work is on the correlation between "blobs/holes" and turbulence spreading is suggested
- V_I - skewness trend follows joint reflection symmetry relation

← suggests that spreading flux is carried by pulses and structures

This all brings us to…

A, Cont'd

- Theoretical Problem #1
  - How formulate spreading model with pulse fluctuations?
  - How do pulses interact with SOL environment?

Spreading as Fluctuation Pulses

- Edge turbulence intermittent:
  - Strong $\langle V_E \rangle'$ → ~ marginal avalanching state
  - Weaker $\langle V_E \rangle'$ → 'blobs', etc. $\Gamma_e = \langle \Gamma_e \rangle + \tilde{\Gamma}_e$
- $\boxed{\text{Pulses / Avalanches are natural description}}$

$\delta P \equiv$ deviation of profile from criticality

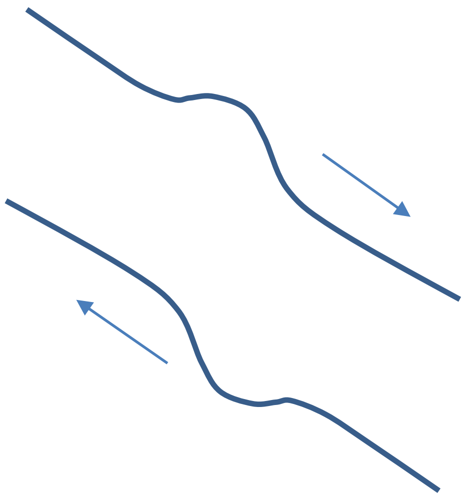
$$\delta P \quad \leftrightarrow \quad (\nabla P - \nabla P_{crit})/P$$

Naturally: $\delta P \sim \delta \varepsilon$

→ Spreading as intensity pulses

(after Hwa, Kardar, P.D., Hahm)

→ But what happens in SOL ?



Pulse, void symmetry arguments etc.

Fluctuation Energy Pulses, cont'd

- Generalized Burgers model coming
- Elements:
  - $\delta P > 0$ turbulence ejected into SOL

    $\delta \varepsilon > 0$ positive intensity fluctuation
  - $V_D > 0$ mean drift out – curvature
- * Scale independent damping
  - $(1/\tau)\delta P$ due finite dwell time in SOL → order parameter not conserved
- "Noise" is b.c.
  - $\tilde{\Gamma}_{0,e}|_{sep}$ drives system, space-time
  - Variability in sparatrix fluctuation energy flux is key

Fluctuation Energy Pulses, cont'd

- Pulse model:

1 drift

2 dwell time decay

3 spreading

$$\underset{1}{\partial_t \delta P + V_D \partial_x \delta P} + \underset{3}{\alpha \delta P \partial_x \delta P} - D_0 \partial_x^2 \delta P + \underset{2}{\frac{\delta P}{\tau}} = 0$$

regularization

$$\delta P(0,t) \leftrightarrow \tilde{\Gamma}_{sep}(t)$$

- Some limits:
  - $\varepsilon \to 0$, $V_D \partial_x \delta P \sim \frac{\delta P}{\tau} \to \lambda \sim \lambda_{HD}$ scale 1 vs 2
  - For ε to matter:

$\alpha \delta P > V_D$ → amplitude vs neo drift comparison 1 vs 3

- Structure is Burgers + Krook → Crooked Burgers ?!

Fluctuation Energy Pulses, cont'd

- Predictions?

Structure formation → Shock Criterion !

i.e. Recall: $\frac{d\delta P}{dt} = -\frac{\delta P}{\tau}$, $\frac{dx}{dt} = \alpha\delta P$

- Solve via characteristics:

$$x = \alpha\left[z + \frac{\left(1-e^{-\frac{t}{\tau}}\right)}{(1/\tau)}f(z)\right]$$

Shock for: $f'(z) < -1/\tau$

→ inital slope must be sufficiently steep to shock before damped by $1/\tau$

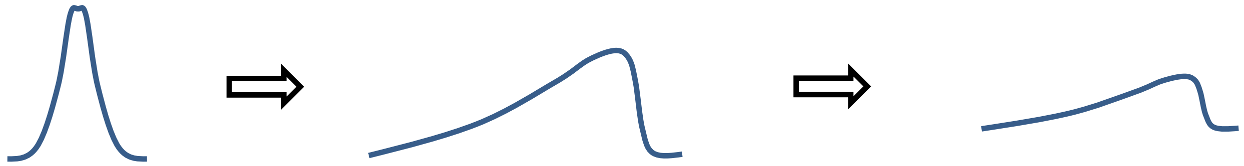
➔ Relates pulse shape for shock to SOL dwell time

Spreading as Intensity Pulses, cont'd

- $\alpha \frac{\partial \delta P}{\partial x}|_{sep} < -\frac{1}{\tau}$ → $\boxed{\text{pulse formation criterion} \rightarrow \text{intensity gradient at sep.}}$

→ dwell rate vs sep. intensity gradient

- Fate ?



$\alpha \delta P < V_D$ → defacto 'evaporation criterion'

→ defines <u>penetration depth</u> of pulse by $\alpha \delta P \rightarrow V_D$ relaxation

- Aim to characterize <u>statistics</u> of pulses, penetration depth distribution… in terms Pdf($\tilde{\Gamma}_{0,e}$) . Challenging…

➔ Meaningful output for SOL broadening problem

$\delta P \gtrless V_D/\alpha$ sets penetration depth

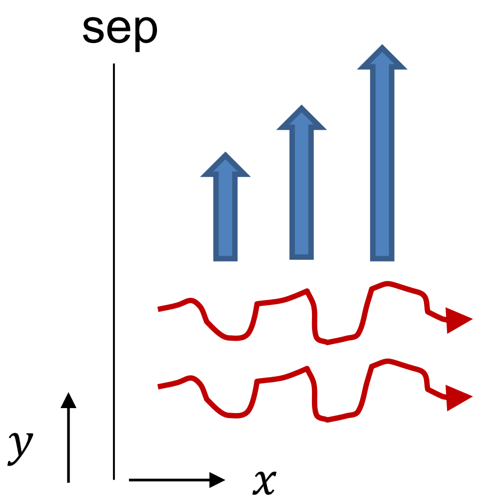
$\partial \delta P/\partial x|_{sep}$ is critical quantity

Spreading as Intensity Pulses, cont'd

- ~ 2D Model
- How address shearing → c.f. P.D., Hahm '95 → "Double" Burgers

$$\partial_t \delta P + V_D \partial_x \delta P + V_E(x) \partial_y \delta P + \alpha \delta P \partial_x \delta P - D_0\left(\partial_x^2 + \partial_y^2\right)\delta P = 0$$

$\tilde{\Gamma}(x = 0, y, t)$ specified



- Shearing + scattering will couple $V_E(x)$ to $\alpha \delta P \partial_x \delta P$. Model required

→ TBC…

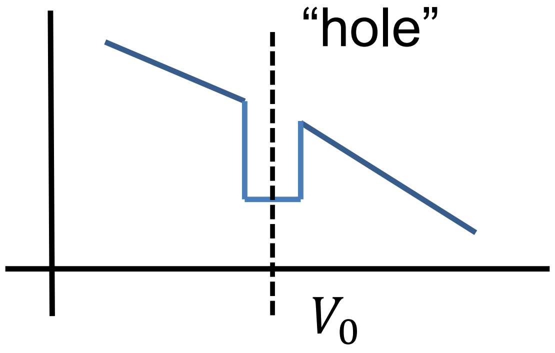
B,

- Theoretical Problem #2
  - What holds blob/void structures together – especially in shear flow? → Physics of self-coherence?

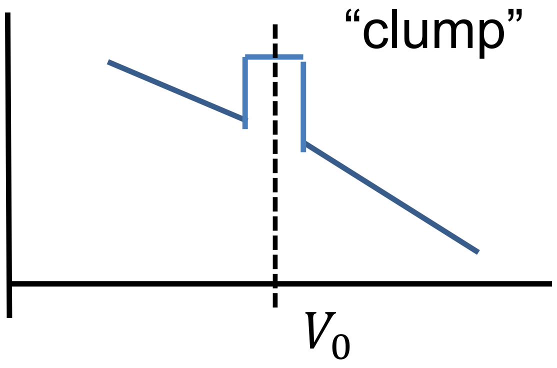
B) Blob-Void Pair: Basic Structure

- What makes a coherent structure “coherent” ?

- Clue: Vlasov Plasma



Or



$$\left.\begin{array}{l}\tilde{f}\\ \Delta V\end{array}\right\}$$

$\langle f \rangle = f_0 + \tilde{f}$ $\leftrightarrow$ structure distorts equilibrium

- then: $-(\omega - kv)\tilde{f} = -\frac{q}{m} k\hat{\phi}\frac{\partial}{\partial v}\left[f_0 + \tilde{f}\right]$

  $\nabla^2\phi = -4\pi n_0 q \int f\,dv$

- and standard analysis, ala’ ‘waterbag model’ collisionless gravitation cf: Berk + ‘60s, Dupree ‘82

B) Blob-Void, cont'd

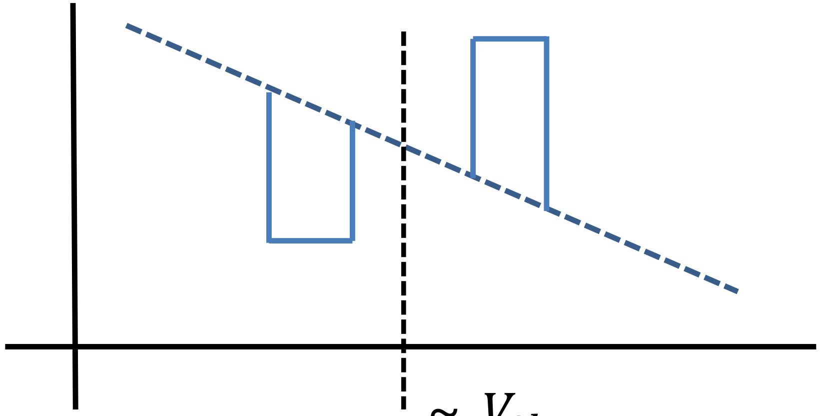
➔ $(\omega - kV_0)^2 = \frac{2\omega_p^2}{k} \frac{\tilde{f}\Delta V}{\epsilon(k,kV_0)} + k^2(\Delta V)^2$

screening

dispersion of structure

- key: $\tilde{f}\Delta V$ → strength/charge sign $\tilde{f}$ → $\gtrless$ 0

  screening $\epsilon(k, kV_0)$ → $\gtrless$ 0



➔

  – "clump" : $\epsilon < 0$ for $\tilde{f}$ > 0 → $V_0 > V_{th}$
  – "hole" : $\epsilon > 0$ for $\tilde{f}$ < 0 → $V_0 < V_{th}$

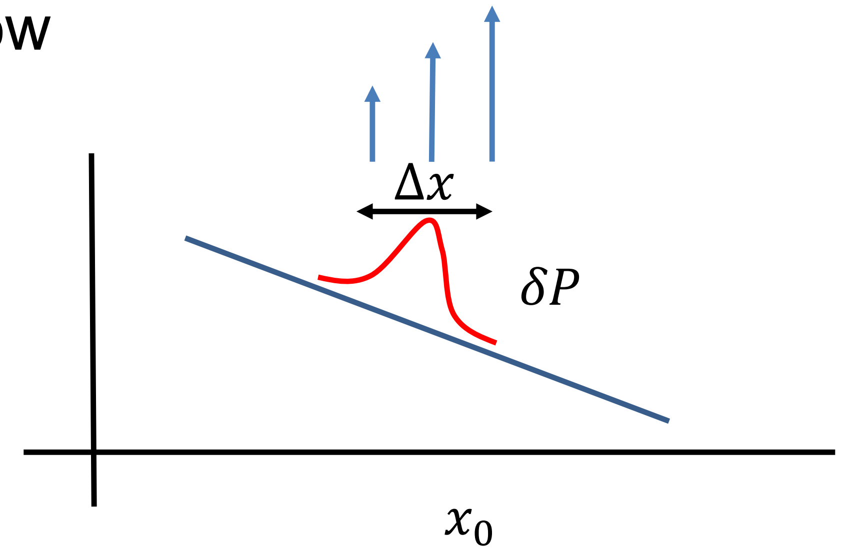
- N.B.: Coherence ←→ Self-field induced stability

B) Blob-Void, cont'd

- Relevant example: Pressure Blob in Shear Flow

$$-i(\omega - kV_0)\hat{P} = -\hat{V}_r \frac{\partial}{\partial r}\left[\langle P_0\rangle + \delta P\right]$$

δP in shear flow



$$-i(\omega - kV_0)\nabla_\perp^2\hat{\phi} = -\kappa\, \nabla_y \hat{P}$$

$$\nabla_\perp^2\, \hat{\phi} \;-\; \frac{\kappa \nabla_y \tilde{V}_r\, \partial_r P_0}{(\omega - kV_0)^2} = \frac{\kappa \nabla_y \tilde{V}_r\, \partial_r \delta P}{(\omega - kV_0)^2}$$

$$\hat{\phi} = \int dx'\, G(x,x')\, \frac{\kappa k^2\, \hat{\phi}\,\delta P(x')}{\left(\omega - kV_0(x')\right)^2}$$

N.B. After Taylor-Goldstein Eqn.

→ screened structure. Base state need not be unstable

→ with box model, considerable simplification possible

B) Blob-Void, cont'd

$$\rightarrow \ \phi(x) = G(x, x_0)\,\kappa\, k^2\, \phi(x_0)\delta P \left[\frac{1}{\left(\omega - kV_0(x_0-\Delta x)\right)^2} - \frac{1}{\left(\omega - kV_0(x_0+\Delta x)\right)^2}\right]$$

- So for $x \sim x_0$:

$$\boxed{(\omega - kV_0)^2 = \overset{1}{k^2\, V_0'^2\, (\Delta x)^2} - \overset{2}{\left[2G\kappa k^2(\delta P)\left(V_{ph} - V_0\right)k^2 V_0'\, \Delta x\right]^{\frac{1}{2}}}}$$

- Competition:
  - Shear across structure ←→ dispersion 1
  - δP → strength
  - G → screening by system

  $\}$ 2

- Does blob hold itself? together vs shear ? → key question

B) Blob-Void, cont'd

- The critical balance:

$$G\,\kappa\,\delta P\left(V_{ph}-V_0\right) \text{ vs } V_0'^2(\Delta x)V_0'$$

➔ $\boxed{\dfrac{G\kappa\delta P/\Delta x}{V_0'^2} \text{ vs } \left[\left(V_{ph}-V_0\right)^{-1} V_0'\Delta x\right] \sim \text{O(1)}}$

←→ Richardson # (screened) for blob ~ 1

Ri $= \omega_B^2/V'^2$ → buoy energy vs shear

- Consistent with qualitative expectations of marginality. Note screening enters !

- Blob vs Void → sign G ! (screening)

←→ location relative to shear layer ($V_{ph}=\omega/k$ vs $V_0(x)$)

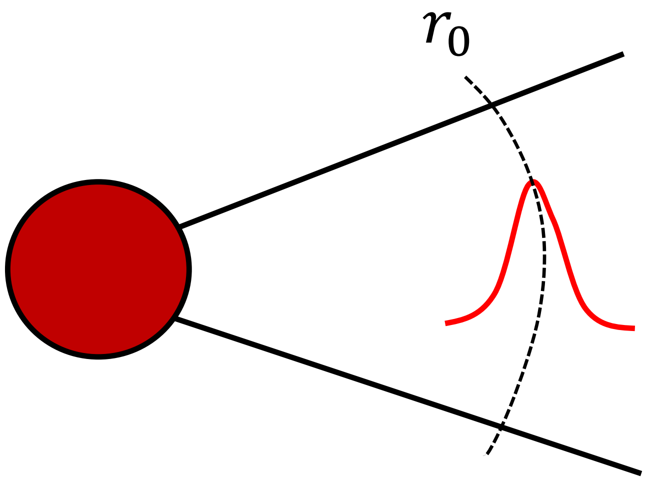
N.B.: Begs question of SOL blob data vs Ri

N.B.: Boedo 2003, et. seq noted pronounced effect of shearing on blob population

B) Blob-Void, cont'd

- Message: Can formulate physically meaningful coherecy or 'self-binding' criterion for blobs, voids in base state
- ~ Richardson # criterion interesting
  - amplitude δP and extent Δx combine vs shear ➔ minimal structural characterization. Screening enters.
  - how does it fare vs data?
- Need better understanding of role of resonance between V_{ph} and $V_0(x)$

From "Blobs" to "Bump"



- Samantha Chen +, this meeting
  - – density bump in disk
  - – modifies PV profile ➔ stability etc. to Rossby wave
  - – Rossby wave ➔ momentum transport ➔ accretion
- When would localized $\delta\beta(r)$ self-bind for Rossby wave system?
- i.e. $\omega = -k_x\beta/k^2$ now $\beta \rightarrow \beta + \delta\beta(x)$ localized defect. Persistence?
- so $\left(\omega - kV_0(x)\right) k_\perp^2\phi = -k_x\left(\beta + \delta\beta(x_0)\right)\phi$

From "Blobs" to "Bump", cont'd

- Similar analysis ➔

$$(\omega - kV_0)^2 = (k_x V_0' \Delta x)^2 + G\, k_x^2 V_0' \delta\beta \Delta x$$

(shearing) (self-field of bump)

- Critical competition:

$\boxed{V_0' \quad \text{vs} \quad G\delta\beta/\Delta x}$ set bump size, scale

- Reminiscent of shearing vs vorticity gradient drive

Thoughts for Experiment and Analysis

- Pulse propagation studies in SOL environments, i.e. Tubes?
- Track blob-void:
  - Pair size distribution. Plot vs GRE strength
  - Separation speed and growth. Plot vs. GRE strength

    → momentum relation ?
- Test Ri,s scaling of ejected blob distribution via electrode bias-driven shear layer (JTEXT)

A Concluding Thought

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