Models of the L-H Transition: A Look at an Evolving Story

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Why a Model?

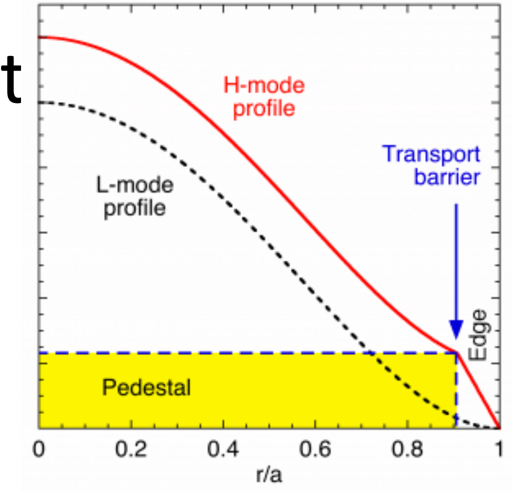
- Theory needed to formulate ideas, ask questions, map approaches.
- Reduced models *distill* and clarify messages from large scale simulations.
- Large scale simulations have NOT contributed to understanding of L-H transition. GK a no-show.
- Reduced models are natural interfaces between confinement experiments and large simulations.

Outline

- A look at
  - Phenomena
  - Model evolution
- The multi-scale DM^2 model
- Beyond 1D
- Things non-trivial
  - Stimulated transitions
  - Power threshold physics
- Predictions
  - Collisionless regimes
  - Transitions sans flows
- A look ahead

The Phenomena

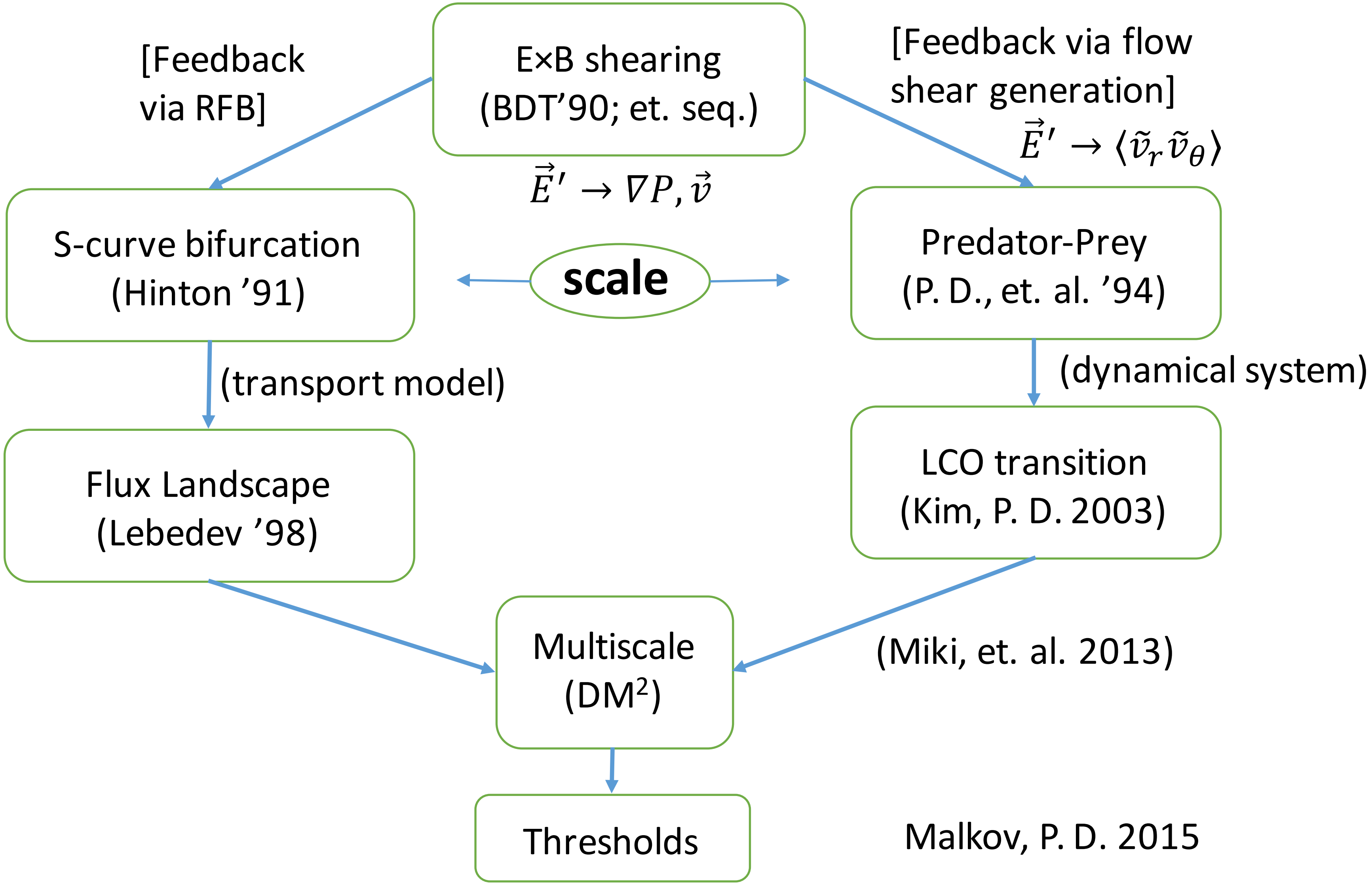
- L-H transition since 1982 → transport bifurcation resulting in ETB and confinement enhancement.
- Mechanism: shear suppression of turbulence, transport via feedback loops.



http://wiki.fusenet.eu/fusionwiki/index.php/Pedestal

- Often related to pre-transition flow dynamics and LCO.
- At least a 2D phenomenon – LSN, USN asymmetry.
- Threshold and hysteresis evident and critical to MFE success.

How the Model Evolved



[Feedback via RFB]

E×B shearing (BDT'90; et. seq.)

[Feedback via flow shear generation]

$\vec{E}' \rightarrow \langle \tilde{v}_r \tilde{v}_\theta \rangle$

$\vec{E}' \rightarrow \nabla P, \vec{v}$

S-curve bifurcation (Hinton '91)

scale

Predator-Prey (P. D., et. al. '94)

(transport model)

(dynamical system)

Flux Landscape (Lebedev '98)

LCO transition (Kim, P. D. 2003)

Multiscale (DM^2)

(Miki, et. al. 2013)

Thresholds

Malkov, P. D. 2015

Multi-scale DM^2 Model (Miki 2013 and refs. therein)

- Intensity, turbulence-driven Flow Envelope Eqns.

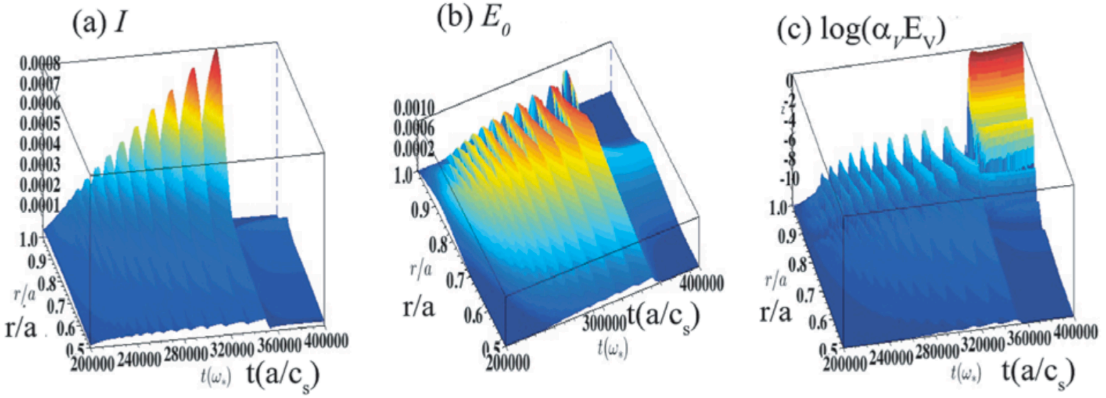
meso-scale

+

Transport Model Eqns: T_0, n, v Eqns.

macro-scale

- Catch: distinction between meso and macro range collapses.



a) I
b) $\langle v_T \rangle^2$
c) $\ln(\langle v_E \rangle^2)$

- Picture: Basic space-time evolution to transition
- Recovers many elements of transition phenomenology.

In Similar Spirit – Reynolds Work Criterion: $\boldsymbol{R_T \geq 1}$

- Idea:
  - to facilitate $\langle v_E \rangle' \uparrow$ via ∇P steepening ↔ turbulence quench.
  - quench via transfer from turbulence → flow, via Reynold stress
  - Need: $\langle \tilde{v}_r \tilde{v}_\theta \rangle \langle v_E \rangle' / \gamma_{eff} \langle \tilde{v}^2 \rangle = R_T \geq 1$

turbulence energy

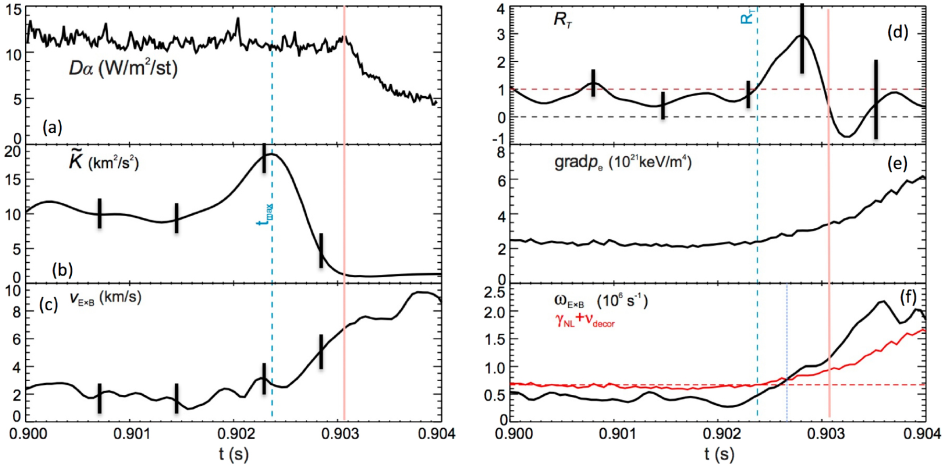
out flow

input

- Also supported by BOUT++ simulations.

  -G. Y. Park, et. al.

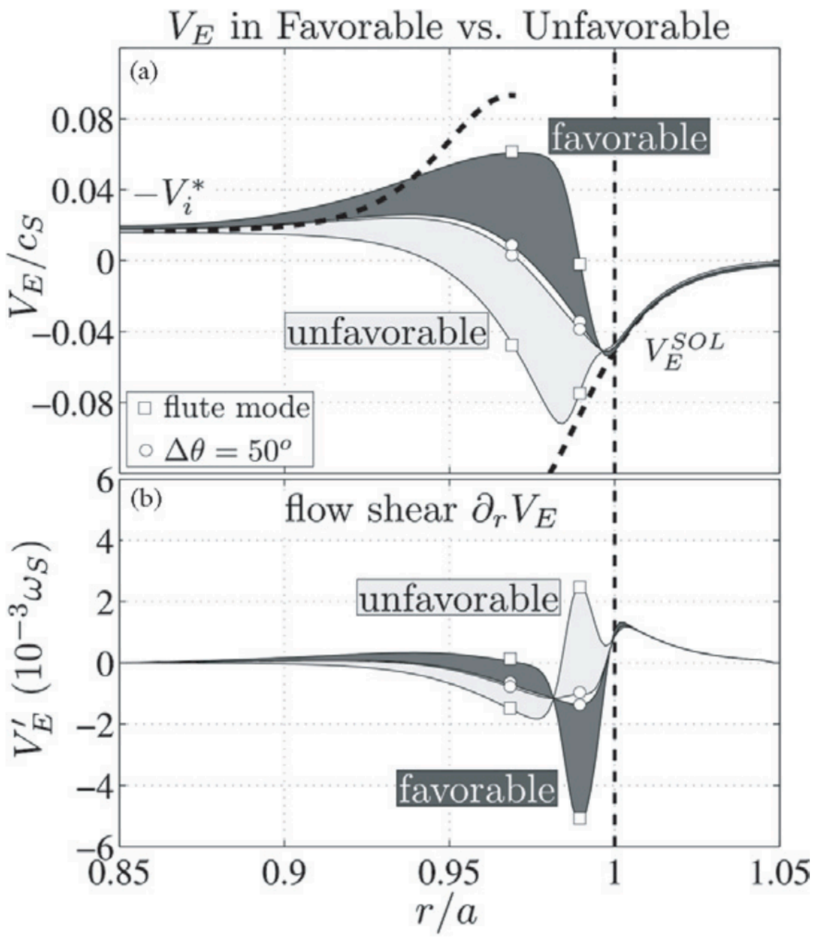
  (Flux driven RBM)



Alcator C-Mod. Tynan et. al. 2016.

Beyond 1D (Fedorczak et. al. 2012)

- LSN vs USN asymmetry in P_T.
- Competition between:
  - E×B shear
  - Magnetic shear
- Magnetic shear tends 'cancel', unless up-down symmetry broken → x-point.
- Bottom line:
  - LSN → shears 'add', larger, broader layer
  - USN → shears compete, smaller, narrower layer
- Pre-transition flow shear layer naturally stronger for LSN.
- Recover trend of ∇B-drift asymmetry in P_T.



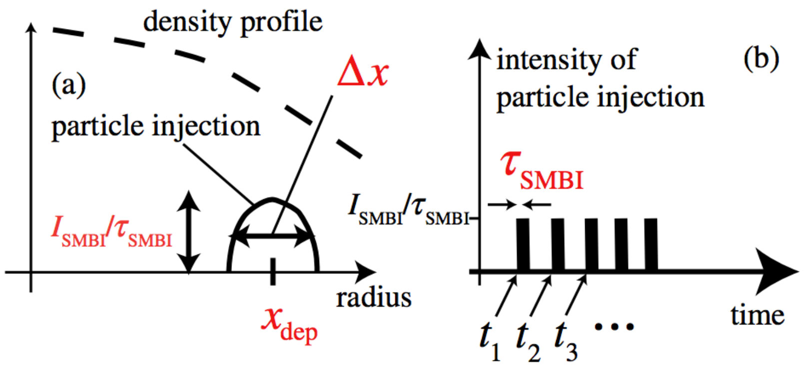
Miki et. al. 2013

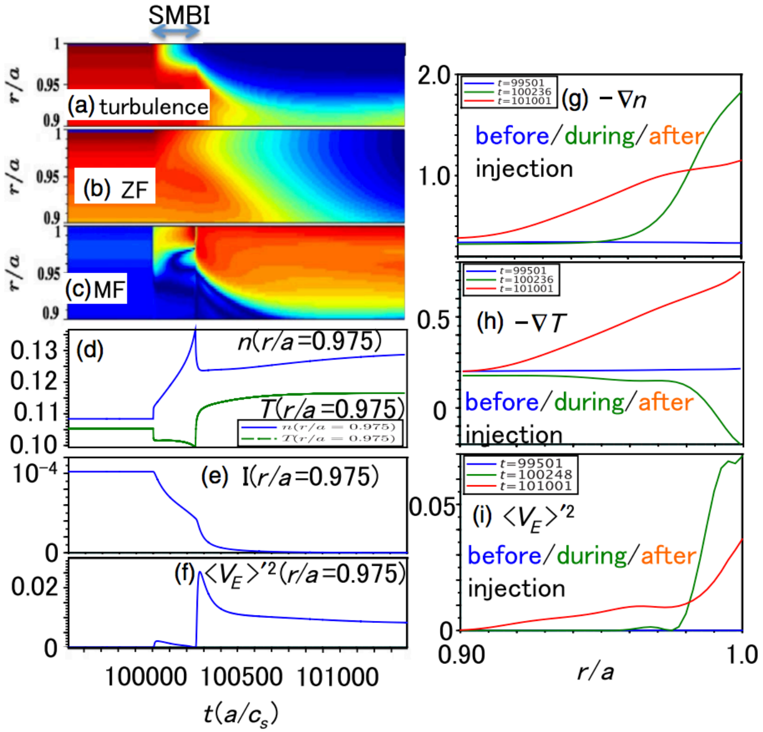
Some Non-trivial Challenges

- Can model be stretched beyond local ‘postdiction’? Address different issues?
- Specifically:
  - stimulated transitions: i.e. pellets, SMBI, etc. can *lower* L-H threshold. Why? Are dynamics significantly different? How?
  - ★ Power thresholds (c.f. Ryter; 2012,13)
    - recover $P_{Th}(n)$
    - why the minimum in n?
    - global-local connection?
    - prediction

Simulated Transitions (Miki, P. D., Hahn et. al. PRL 2013)

- Pulsed, interior deposition
  - particles deposited inside boundary
  - pressure balance → ∇T adjustment
- Injection works directly on $\langle v_E \rangle'$ via profiles
  - injection directly affects local electric field shear at separatrix
  - direct knob on transition

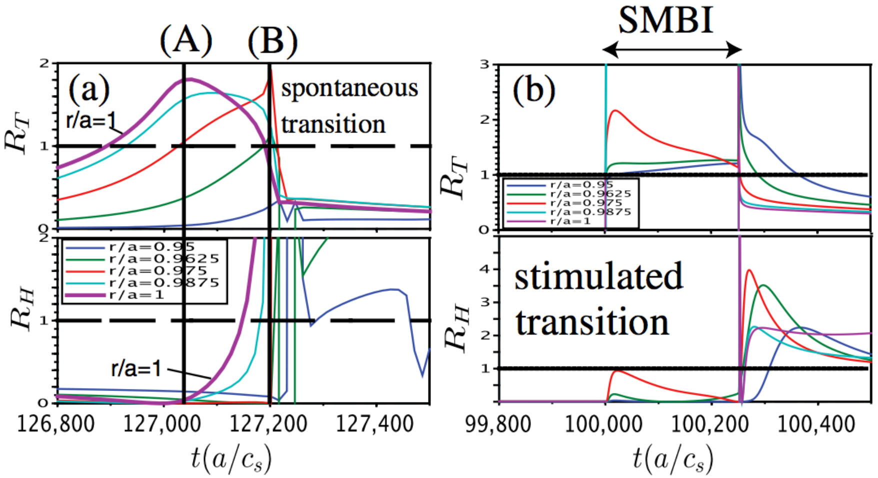




Miki et. al. PRL 2013

Interesting Comparison

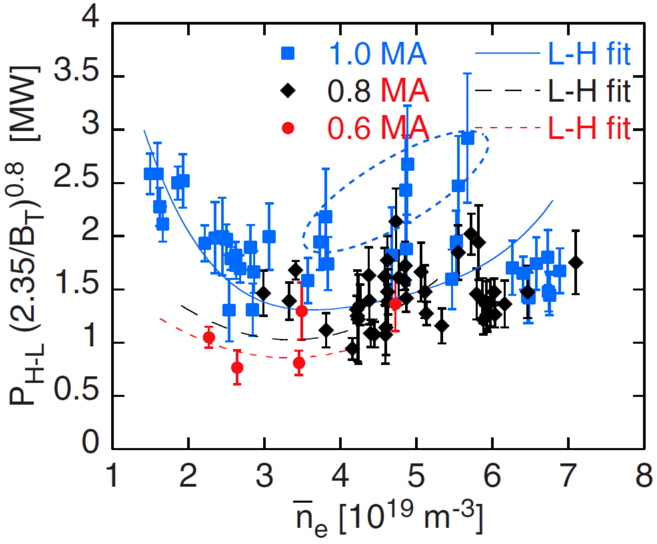
- Can define shearing ratios for:
  - Turbulence driven → R_T → Reynolds work
  - Mean flow (∇P) → R_H → Mean flow shearing, $\sim \langle v_E \rangle' / \Delta\omega$
- Standard fueling: R_T 'leads' R_H → turbulence collapse precedes $\langle v_E \rangle'$ change.
- Injection: R_T and R_H changes coincident in time
  - suggests direct effect controls transition
- Supports *model flexibility*.



Miki et. al. PRL 2013

Thresholds

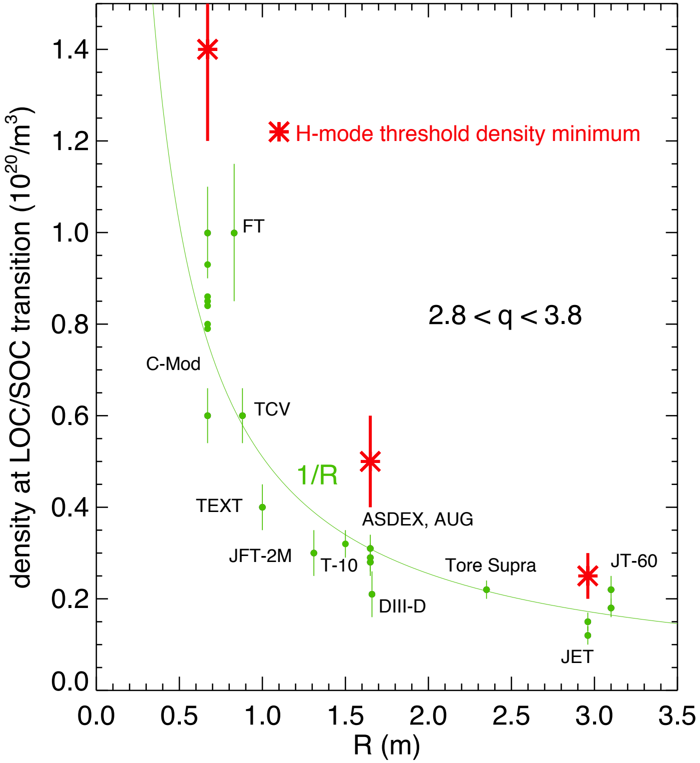
- $P_{Th}(n)$ has minimum. –Why?
- How is the scenario related to the Power Threshold?
  - Is P_{Th} minimum recoverable?
- What is the physics/origin of P_{Th}? Energy coupling?
- How does micro-physics determine threshold scaling?
- Will P_{min} persist in collisionless, electron-heated regimes (ITER)?



Ryter et. al. 2013

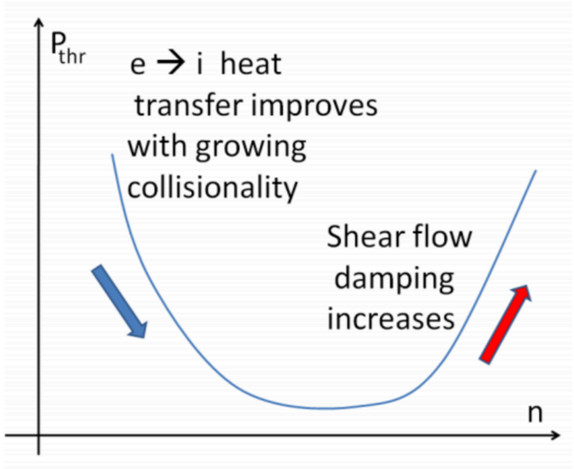
Questions and Clues (J. Hughes, Y. Ma, J. Rice, 2011,12)

- Is P_{Th} set only by local properties at the edge? (conventional wisdom)
- Is P_{Th} minimum related to collisional energy transfer? i.e. $\nu n(T_e - T_i)$. Low n branch couples to ions, enables ∇P_i?
- Note P_{Th} minimum correlates with 'LOC-SOC' transition → i.e. min power related to collisional inter-species transfer!
- Threshold controlled by *global* transport processes!?



Rice et. al. 2013

Scenario (c.f. F. Ryter)



- $\nabla P_i|_{edge}$ essential to 'lock in' transition
- To form ∇P_i at low n, etc. need (*collisional*) energy transfer from electrons to ions

$$\frac{\partial T_e}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}r\Gamma_e=-\frac{2m}{M\tau}(T_e-T_i)+Q_e$$

$$\frac{\partial T_i}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}r\Gamma_i=+\frac{2m}{M\tau}(T_e-T_i)+Q_i$$

- Suggests that the minimum is due to:
  - P_{Th} decreases due to increasing heat transfer from electrons to ions, with density
  - P_{Th} increases (stronger edge ∇P_i driven needed) due to increase in shear flow damping
  - Power and edge heat flux are not the only critical variables: also need the ratio of electron energy confinement time to exceed that of e-I temperature equilibrium $\tau_T = \tau_{Ee}/\tau_{ei}$ >1.
    - $\tau_T \gg 1$ somewhat equivalent to direct ion heating → Q_{iedge}
    - $\tau_T \ll 1$ ions remain cold → no L-H transition (or else, anomalous!) → alternative energy transfer mechanism

Extending the Model

- Based on 1D numerical 5-field model (Miki & Diamond 2012,13+).
- Currently operates on 6 fields ($+P_e$) with self-consistently evolved transport coefficients, anomalous heat exchange and NL flow dissipaiton (M. M. , et. al. PoP 2015).
- Heat transport, + *two species*, with *energy coupling*, i.e. (anomalous heat exchange in color):

$$\frac{\partial P_e}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}r\Gamma_e=-\frac{2m}{M\tau}(P_e-P_i)+Q_e-\gamma_{CTEM}\cdot I$$

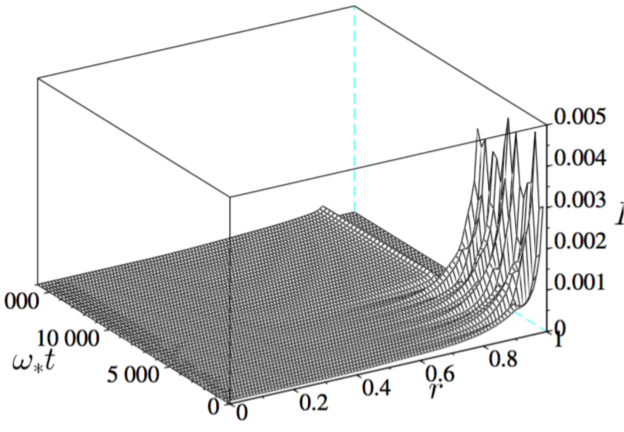
$$\frac{\partial P_i}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}r\Gamma_i=+\frac{2m}{M\tau}(P_e-P_i)+Q_i+\gamma_{CTEM}\cdot I+\gamma_{ZFdiss}\cdot I$$

$$\Gamma=-(\chi_{neo}+\chi_t)\frac{\partial P}{\partial r},\ \gamma_{ZFdiss}=\gamma_{visc}\left(\frac{\partial\sqrt{\varepsilon}}{\partial r}\right)^2+\gamma_{Hvisc}\left(\frac{\partial^2\sqrt{\varepsilon}}{\partial^2 r}\right)^2$$

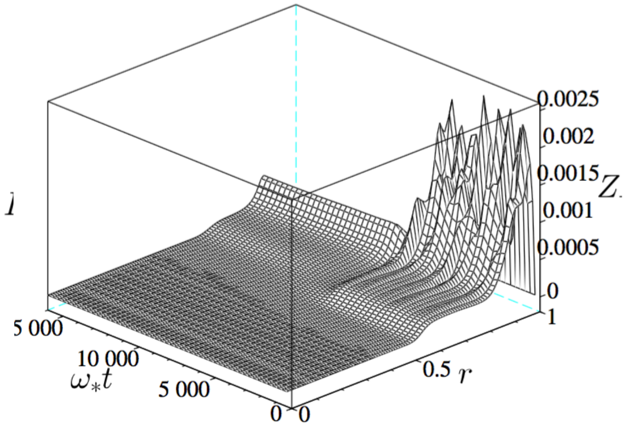
- And DW and ZF energy, plasma density and the mean flow, as before.
- First, only collisional coupling.

Model Studies – Collisional Coupling

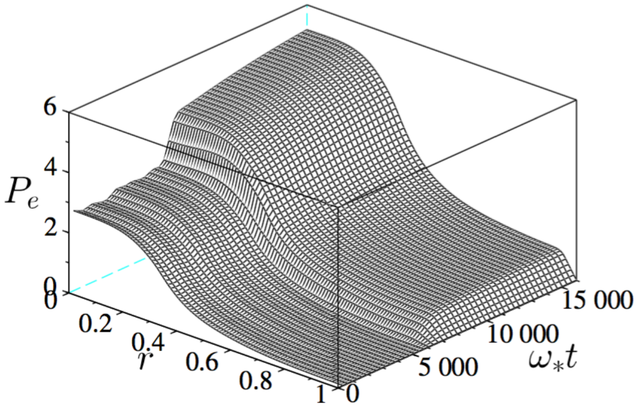
- Heating ratio H_i/H_{i+e} enters as control parameter
- Ion heat dominated transition
- Strong pre-transition fluctuations of all quantities
- Well organized post-transition flow
- Strong P_e edge barrier



I



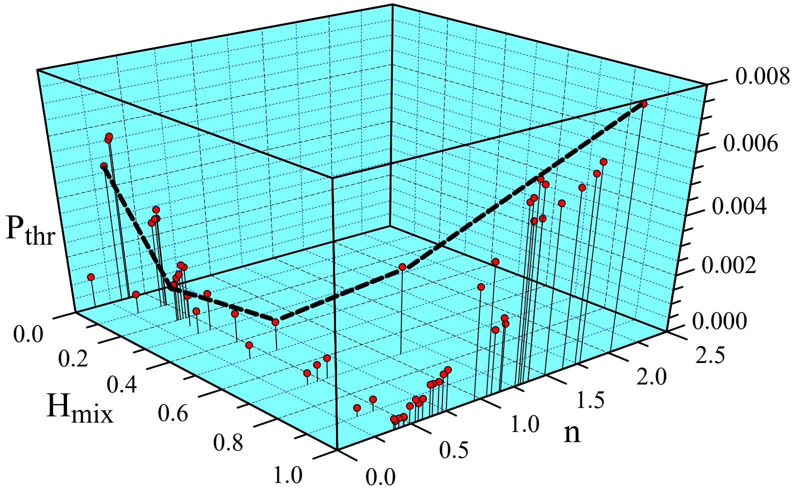
ZF

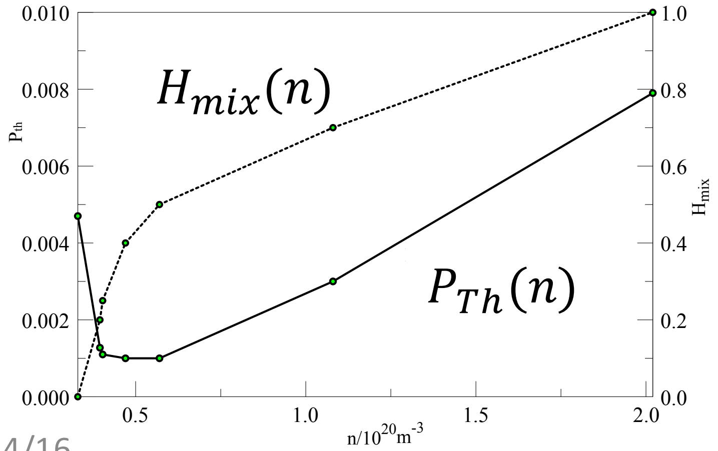


P_e

$\boldsymbol{P_{Th}(n, H_{i/(i+e)})}$ Scans – Recovering the Minimum

- Point: Heating mix H_i/H_{i+e} is ‘hidden variable’ in $P_{Th}(n)$ plot, i.e. $P_{Th}(n, H_{i/(i+e)}) \rightarrow P_{Th}(n)$.





- $P_{Th}(n, H_{i/(i+e)})$:
  - Electron heating at lower densities
  - Ion heating at higher densities
- Relate $H_{i/(i+e)}$ and n by a monotonic $H_{i/(i+e)}(n)$
- $P_{Th}(n)$ minimum recovered!

Summary of Results with Collisional Coupling

- $P_{Th}(n)$ *grows monotonically* in both pure ion $H_{i/(i+e)} = 1$ and pure electron $H_{i/(i+e)} = 0$ heating regimes with collisional coupling.
- The descending (low-density) branch, followed by a distinct minimum, results from a combination of:
  1. increase in electron-to-ion collisional heat transfer, and
  2. growing fraction of heat $H_{i/(i+e)}$ deposited to ions (relative to total heat)
- The later upturn of $P_{Th}(n)$ is due to increase of shear flow damping, with increasing density.
- The heating mix ratio $H_{i/(i+e)} \neq 0$ is essential for the heat transport from the core to build up the ion pressure gradient at the edge, ∇P_i, which is the primary driver of the L-H transition.
- There are many possibilities to render $H_{i/(i+e)} \neq 0$.
- Critical to note:
  - role of ‘true’ heating mix
  - implication for collisionless, electron heated regimes.

Towards Prediction

- Can model *predict* novel phenomena, as yet unobserved?

- Two examples:
  - collisionless, electron-heated transitions: how does energy couple to ∇P to trigger edge bifurcation?
  - multiple pathways – transitions without Reynolds stress driven flows?

Collisionless Electron Regimes

- Novel feature: treatment of species coupling
  - separate species
  - collisionless transfer → L. Zhao P. D. PoP 2012. (c.f. Manheimer ’78, flawed)

★ – Flows

- collisionless damping
→ hyper-viscosity model: P.-C. Hsu, et. al. (minimum enstrophy)
- collisionless *ion heating → direct*

another case where collisionless flow satn. emerges as crucial!

  - Complicates/enriches feedback loop connectivity
  - but must ultimately couple to $\nabla P_i|_{edge}$.

Model Structure

$\frac{\partial}{\partial t} T_i$ + [transport] = Q_i + [collisional transfer] + [collisionless heating]

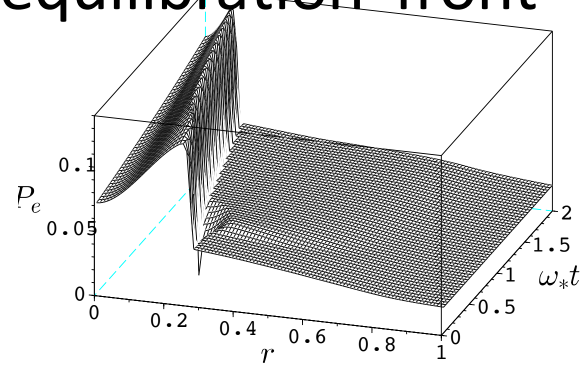
- Collisionless heating due to shear flow and turbulence

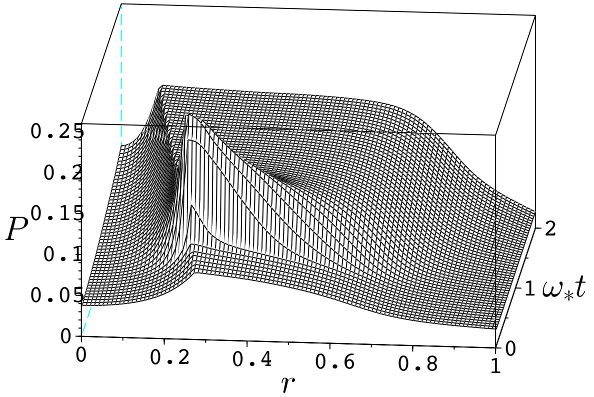
$\frac{\partial}{\partial t} T_e$ + [transport] = Q_e − [collisional transfer] − [collisionless transfer]

- Collisionless transfer via $\langle \tilde{E} \cdot \tilde{J} \rangle_T$
- $\gamma_{ZF} \cong \gamma_{visc} \left(\frac{\partial \sqrt{\varepsilon}}{\partial r}\right)^2 + \gamma_{Hvisc} \left(\frac{\partial^2 \sqrt{\varepsilon}}{\partial^2 r}\right)^2$

Collisionless Electron Heated Transitions

- Coupling anomalous, $\langle J_{i,e} \cdot E \rangle$, not $\propto T_e - T_i$
- Can't represent as γ_{eff}
- Flow damping: turbulence hyper-viscosity (c.f. P.-C. Hsu, et. al. PoP 2015)
- Transition mechanism: anomalous $e \rightarrow i$ thermal equilibration front



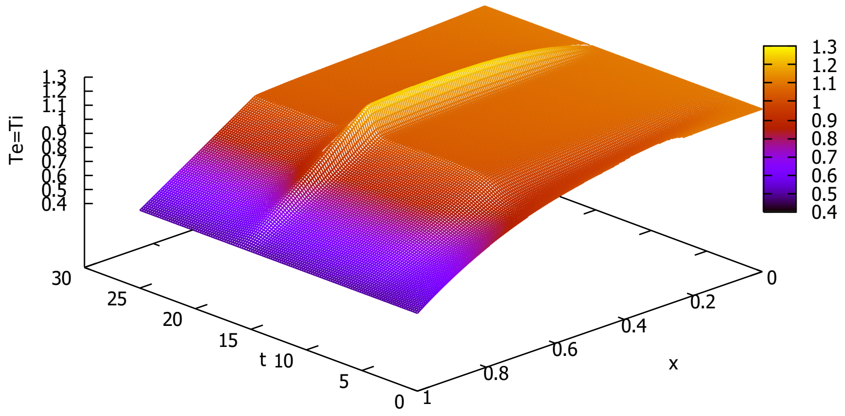


- Transition occurs when P_i front approaches edge → triggers increase in ∇P_i at boundary
- Point: anomalous coupling only route to sharpen ∇P_i

Something Different: transitions sans flows

- New transition scenario: *occurs in the absence of turbulence driven shear flow*
- Sensitive to pre-existing L-mode density profile
- Need to understand how to optimize, for best access to H-mode
- Spontaneous L-H transition with suppressed shear flow. The heat pulse applied mid-time of integration with no effect on the H-state established spontaneously.

- Questions:
  - → What characteristics of pre-transition profile allow access to H-mode?
  - → Multiple pathways?
  - → Basics of attractors? P_{Th}?



Broader Implications

- Expectations of unique pathway seem unfounded.

- Easy to fool oneself with:
  - Purely local observations
  - Purely local models → 1D, 2D essential!
  - Adjustable/fit turbulence intensities
  - Unrelenting focus on single case or regime

Where to?, in L-H Model Studies

- Back transition, hysteresis
- Understand low collisionality regime
- High n ($n \sim n_g$) transitions; also CX effects
- 2D, 3D (i.e. RMP) models
  Physics of RMP effect on P_{Th} (Leconte, P.D., Xu)
- How avoid H-mode
- I-mode ↔ channel asymmetry

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