TH/P1-38

Phase Locking, Phase Slips, and Turbulence

—A New Mechanism for Quiescent H-mode
—Implications of Cross-phase Evolution

Z. B. Guo and P. H. Diamond

University of California, San Diego

This work is supported by the U. S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, under Award Numbers DE-FG02-04ER54738 and DE-SC0008378

Two major scenarios for edge plasma relaxation

- Violent relaxation
  - disruption
  - Type-I ELM

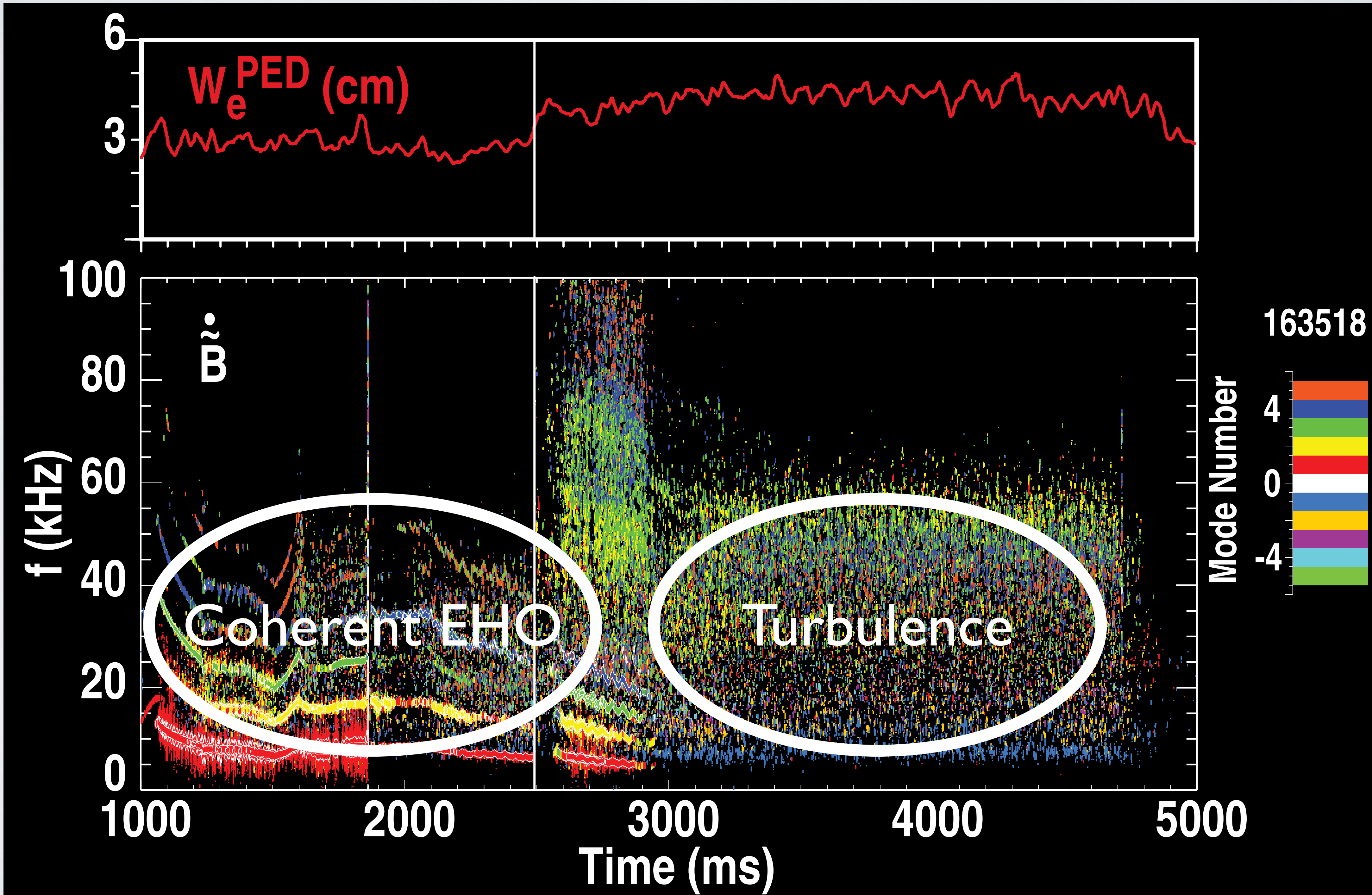
  large amount of thermal energy released in a *short* duration event

- Soft relaxation
  - grassy ELMs
  - Quiescent H-mode

  accompanied by high frequency MHD(coherent or incoherent)

Features of QH-mode: MHD fluctuations

KH. Burrell et al2016



Features of QH-mode: ExB shear

ExB shear is fundamental...(Garofalo 2011)

ion rotation

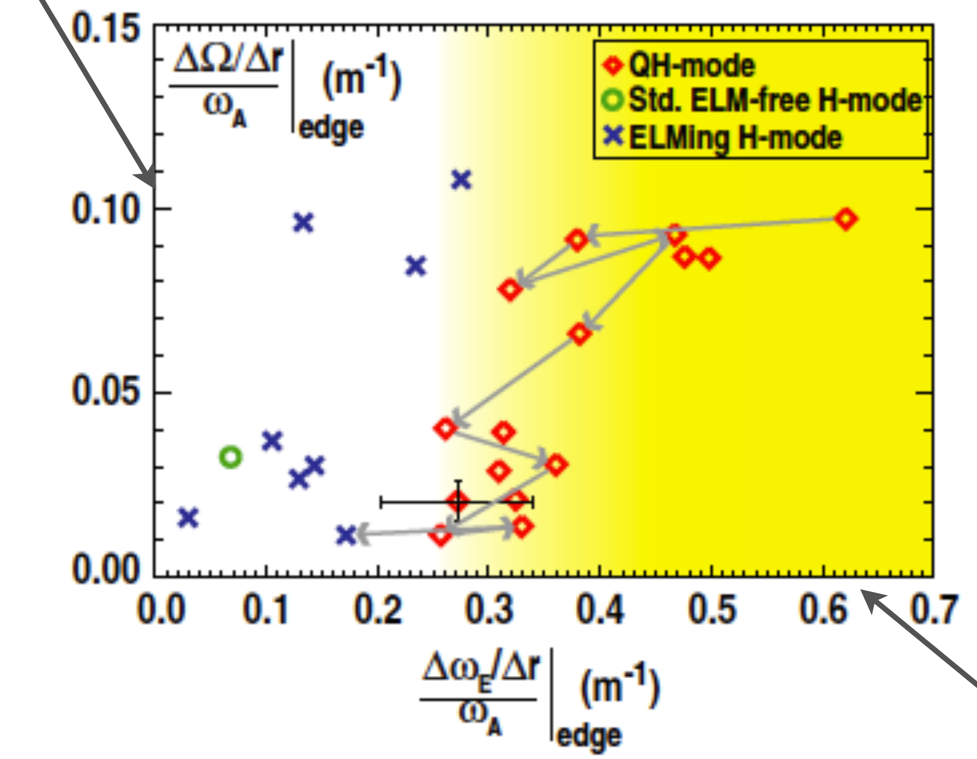
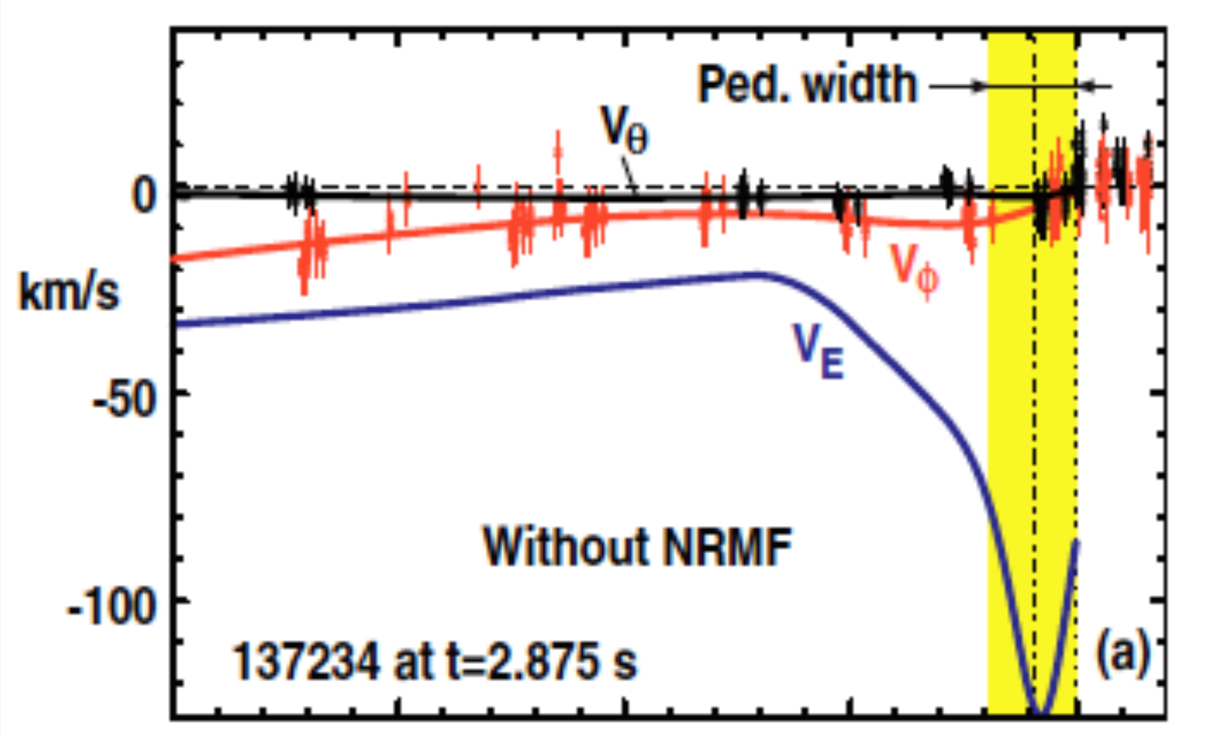


Figure 10. Edge shear in C VI impurity ion rotation versus edge shear in ω_E rotation for discharges with different H-mode edge characteristics. Shear is evaluated across the outer half of the H-mode pedestal width, and is normalized to the local Alfvén frequency. The grey line connects data for a single discharge (137234 of figure 2), evolving during the NBI torque ramp-down from a QH-mode phase to ELMing H-mode.

ExB shearing

A.M. Garofalo *et al* Nucl. Fusion **51** (2011) 083018



Strong ExB shear is the most prominent feature of access to QH-mode with EHO.

Role of Cross Phase Dynamics in Edge Pressure Relaxation

Heat flux $\Gamma_Q = \langle \delta V_{MHD} \delta P \rangle \sim \cos\Theta$

Near marginal stable state, evolution of is governed by the cross phase dynamics.

the way of edge pressure profile relaxation

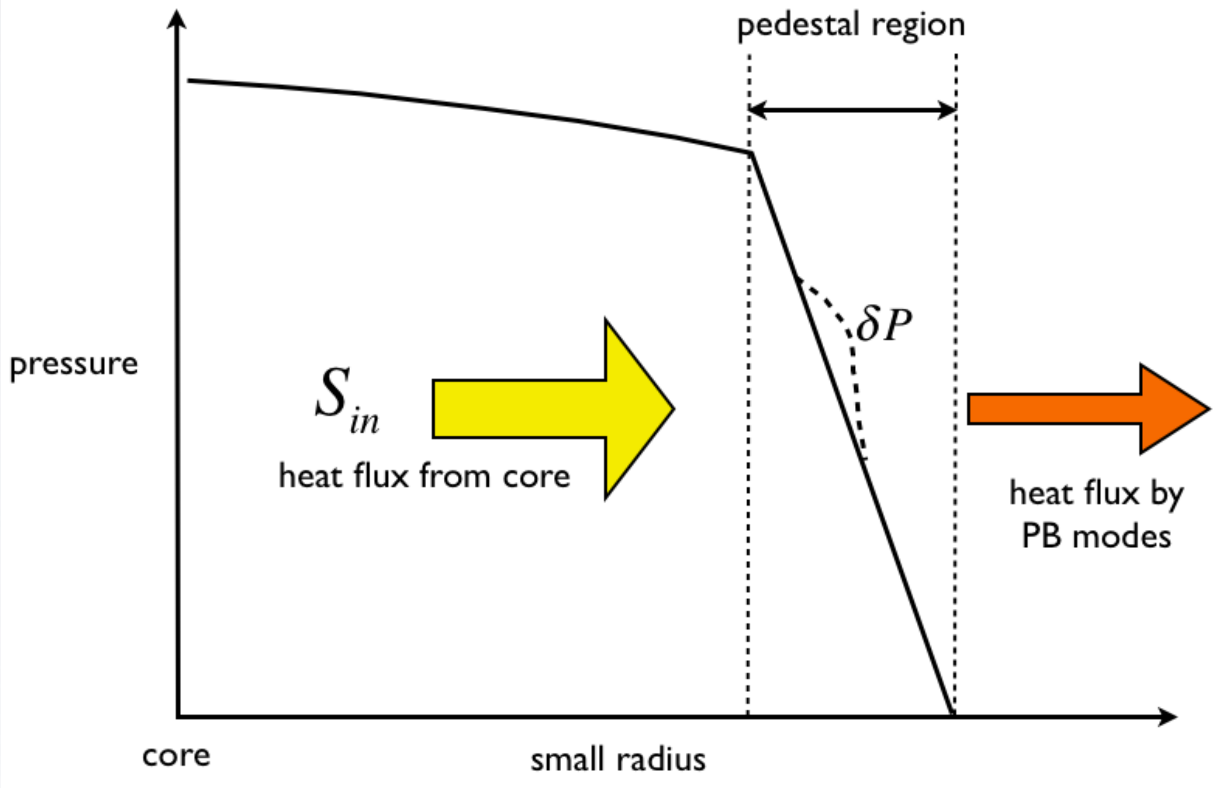
Violant relaxation: $\cos\Theta \sim 1$

Soft relaxation: $\cos\Theta \sim 0$

—To know the behavior of the cross phase, one needs study its evolution and dynamics;

—Nearly all models treat cross-phase as time-independent parameter.

The Setup



$$P = \langle P \rangle + \delta P$$
$$V = \langle V \rangle + \delta V$$

$$\frac{\partial}{\partial t} P + V \bullet \nabla P = D \nabla^2 P + S_{in}$$

Mean pressure:

$$\frac{\partial}{\partial t} \langle P \rangle = -\nabla \bullet \langle \delta V_{MHD} \delta P \rangle + (D + D_T) \nabla^2 \langle P \rangle + S_{in}$$

heat flux by MHD fluctuation

neoclassical diffusion

anomalous diffusion by small scale turbulence

Cross Phase Evolution Equation

Fourier transformation: $\delta P \Rightarrow \delta P_k = |\delta P_k| e^{i\vec{k}\bullet\vec{x}+i\Theta}$ $\delta V_{MHD} \Rightarrow \delta V_{MHD,k} = |\delta V_{MHD,k}| e^{i\vec{k}\bullet\vec{x}+i\alpha}$

Approximations:

(1) taking reference phase $\alpha = 0$ $\Longrightarrow$ kinetic velocity perturbation

(2) $|\delta P_k|, |\delta V_{MHD,k}|$ vary slowly in time and space, $\Longrightarrow$ near marginal state

(3) $|\nabla\Theta| \ll |k|$ $\Longrightarrow$ 0D phase evolution

A nonlinear equation for the cross phase:

(Adler'46,Kuramoto'78)

$$\delta V_{MHD} = R_{MHD}\delta P$$

$$\frac{d}{dt}\Theta = k_y \langle V \rangle' \Delta x - R_{MHD} \langle P \rangle' \sin\Theta + \tilde{s}_k^{\Theta}$$

Cross Phase Evolution Equation

$$\frac{d}{dt}\Theta = k_y \langle V \rangle' \Delta x - R_{MHD} \langle P \rangle' \sin\Theta + \tilde{s}_k^{\Theta}$$

detuning by ExB shear

increasing the cross-phase,
so that reducing heat flux

pinning force

attracting the cross-phase to a low value,
so that the MHD turbulence is pumped and
the heat flux is enhanced

random phase scattering

coming from nonlinear mode coupling,
reducing the coherence of the cross-phase

Scenario 1: QH with EHO $\Leftrightarrow$

Phase Locking for Weak ExB shear

$$\frac{d}{dt}\Theta = k_y \langle V \rangle' \Delta x - R_{MHD} \langle P \rangle' \sin\Theta + \tilde{s}_k^{\Theta}$$

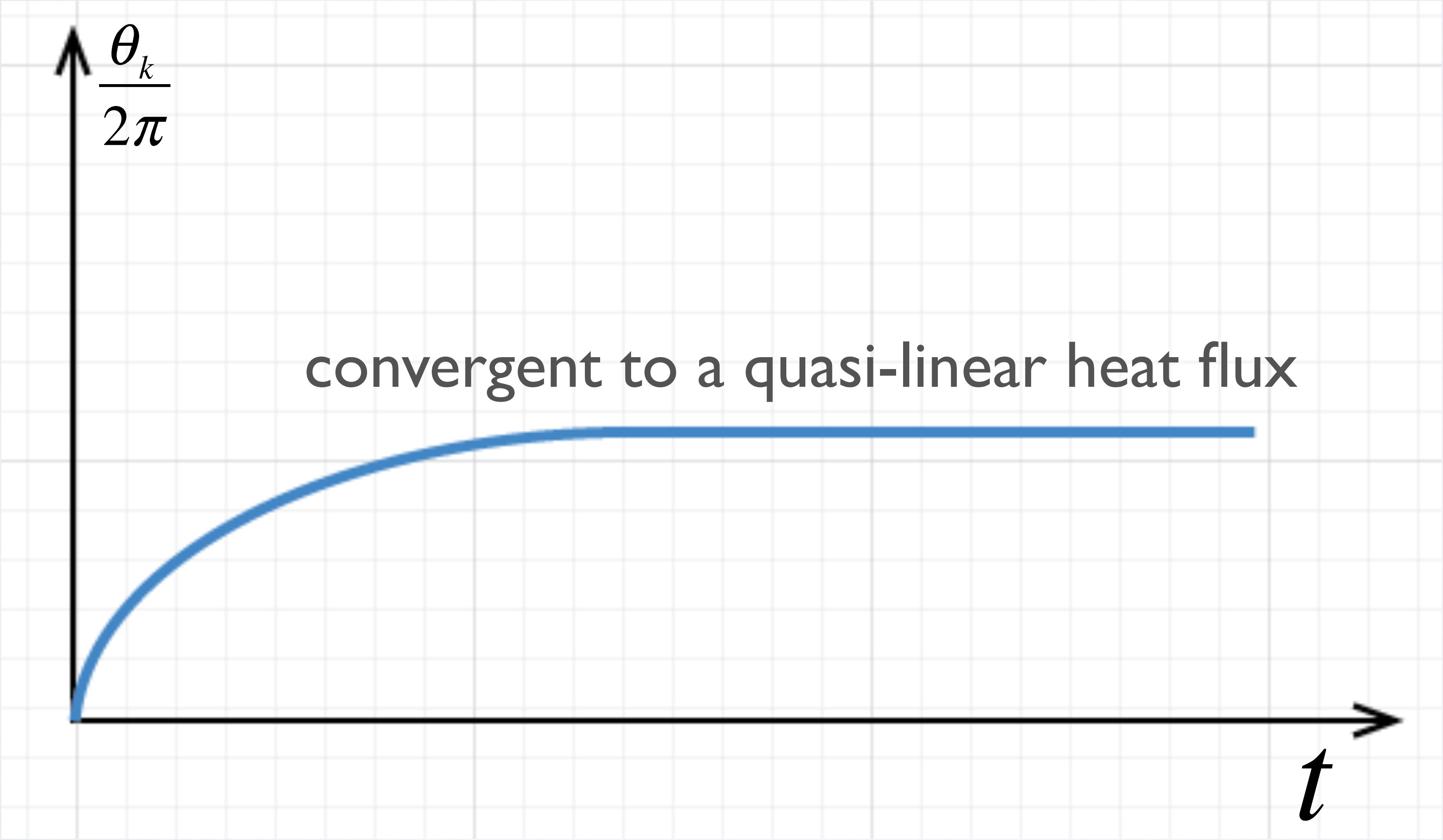
(1) If $\left| k_y \langle V \rangle' \Delta x \right| < \left| R_{MHD} \right| \left| \langle P \rangle' \right|$: phase locking

$$\Theta = \arcsin \frac{k_y \langle V \rangle' \Delta x}{\left| R_{MHD} \right| \langle P \rangle'} < \frac{\pi}{2}$$

Cross phase is ‘attracted’ to a fixed value

Phase locking

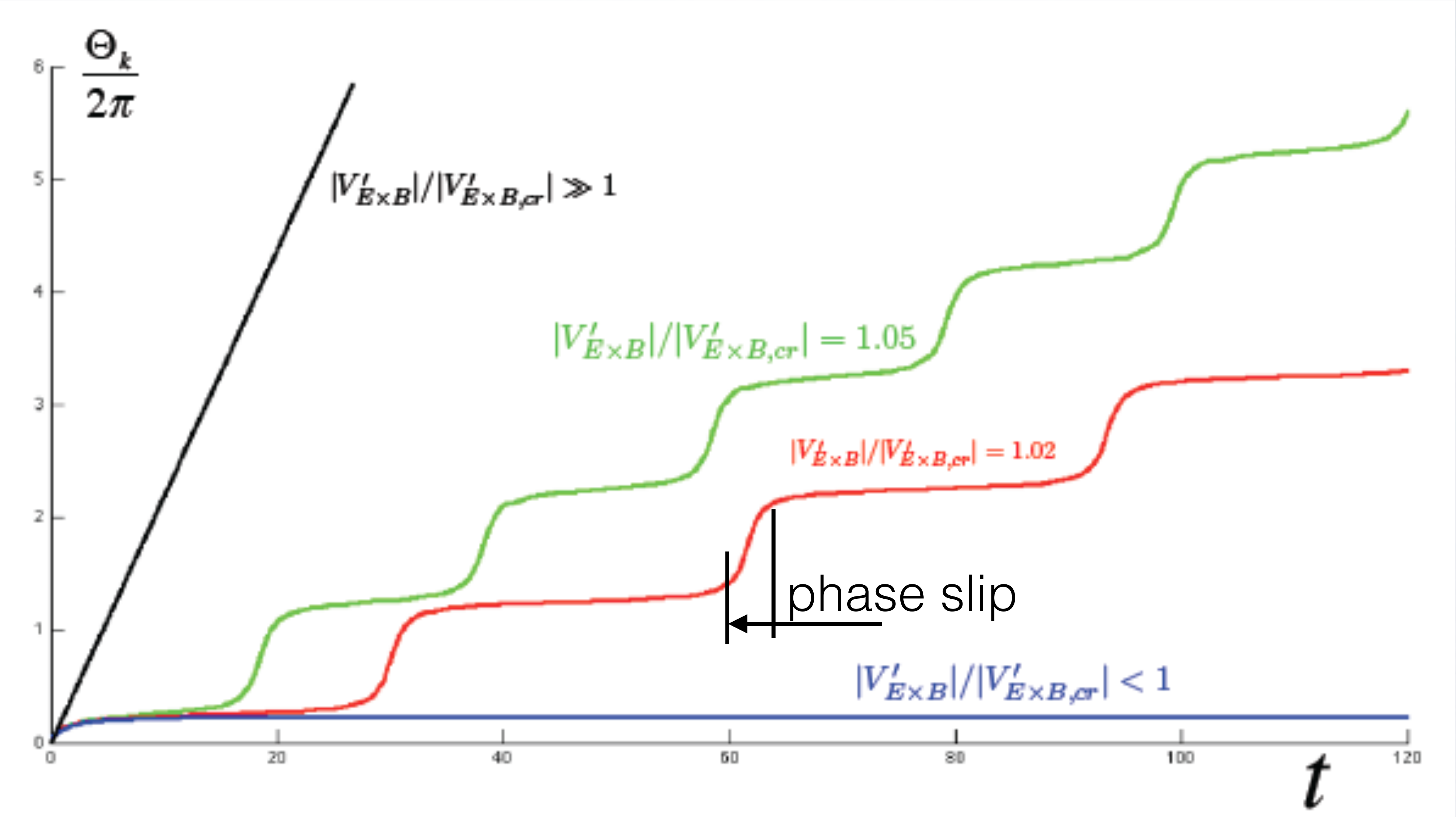
$$\langle \delta V_{PB} \delta P \rangle_k \sim \cos\Theta \neq 0 \quad \overset{}{\underset{\textit{phase locked}}{\Longrightarrow}}$$ Turbulence fields are continuously pumped $\Longrightarrow$ **burst:**ELMy H-mode



Scenario 1: QH with EHO $\Longleftrightarrow$

Coherent Phase Slips — EHO for $V'_{E\times B} > V'_{E\times B,cr}$

(2) $\left|k_y \langle V\rangle' \Delta x\right| > \left|R_{MHD}\right| \left|\langle P\rangle'\right|$



Periodic phase slips(SHORT) $\Longleftrightarrow$ Periodic cross-correlation(SHORT)

turbulence fields are transiently pumped during the short phase slips

Scenario 1: QH with EHO $\Longleftrightarrow$

Frequency of Coherent Phase Slips

Phase slip(EHO) frequency:

poloidal mode # dependence

$$\Omega_{slip} = k_y V'_{E\times B,y} \Delta x \frac{\sqrt{K^2 - 1}}{K}$$

$$K = \frac{k_y V'_{E\times B,y} \Delta x |\delta P_k|}{\langle P\rangle' |\delta V_{PB,kx}|}$$

E.g., DIIID

$\Omega_{slip} < \langle V_{E\times B} \rangle' \sim 100\text{kHz}$ $\qquad$ $\Omega_{EHO} \sim 10\text{kHz}$

Energy release in each phase slip: $\Omega_{slip} \Delta E \simeq S_{in} \Rightarrow \Omega_{slip} \nearrow, \Delta E \searrow$

Scenario 1: QH with EHO $\Longleftrightarrow$

Scaling of the Critical ExB Shear:

$$\frac{d}{dt}\Theta = k_y \langle V \rangle' \Delta x - R_{MHD} \langle P \rangle' \sin\Theta + \tilde{s}_k^{\Theta}$$

Ions' Radial momentum equation:

$$m_i n_i (\gamma_{\mathrm{MHD}} \delta V_{\mathrm{MHD},kx} + i k_y V'_{E\times B} \Delta x \delta V_{\mathrm{MHD},kx}) = -j_{BS,k} B_\theta - i k_x \delta P_k$$

Perturbed Bootstrap current: $j_{BS,k} = -i k_x \epsilon^{1/2} \delta P_k / B_\theta$

$$|V'_{E\times B,cr}| \simeq \tau_A^{-1} \left(1 - \epsilon^{1/2}\right)^{1/2} \frac{\beta^{1/2}}{|k_y \Delta x|} \left(\frac{L_P}{\Delta x}\right)^{1/2}$$

$$L_P^{-1} = \left|\frac{<P>}{<P>'}\right|, \tau_A = \frac{V_A}{L_P}, \beta = \frac{2<P>}{B^2}, \varepsilon = \frac{a}{R}$$

Scenario II: turbulent QH mode $\Longleftrightarrow$

Random Phase Slips

$$\frac{d}{dt}\Theta = k_y \langle V \rangle' \Delta x - R_{MHD} \langle P \rangle' \sin\theta_k + \tilde{s}_k^{\Theta}$$

$$\tilde{s}_k^{\Theta} \sim \Delta\omega_k$$

Phase scattering effect is more prominent if

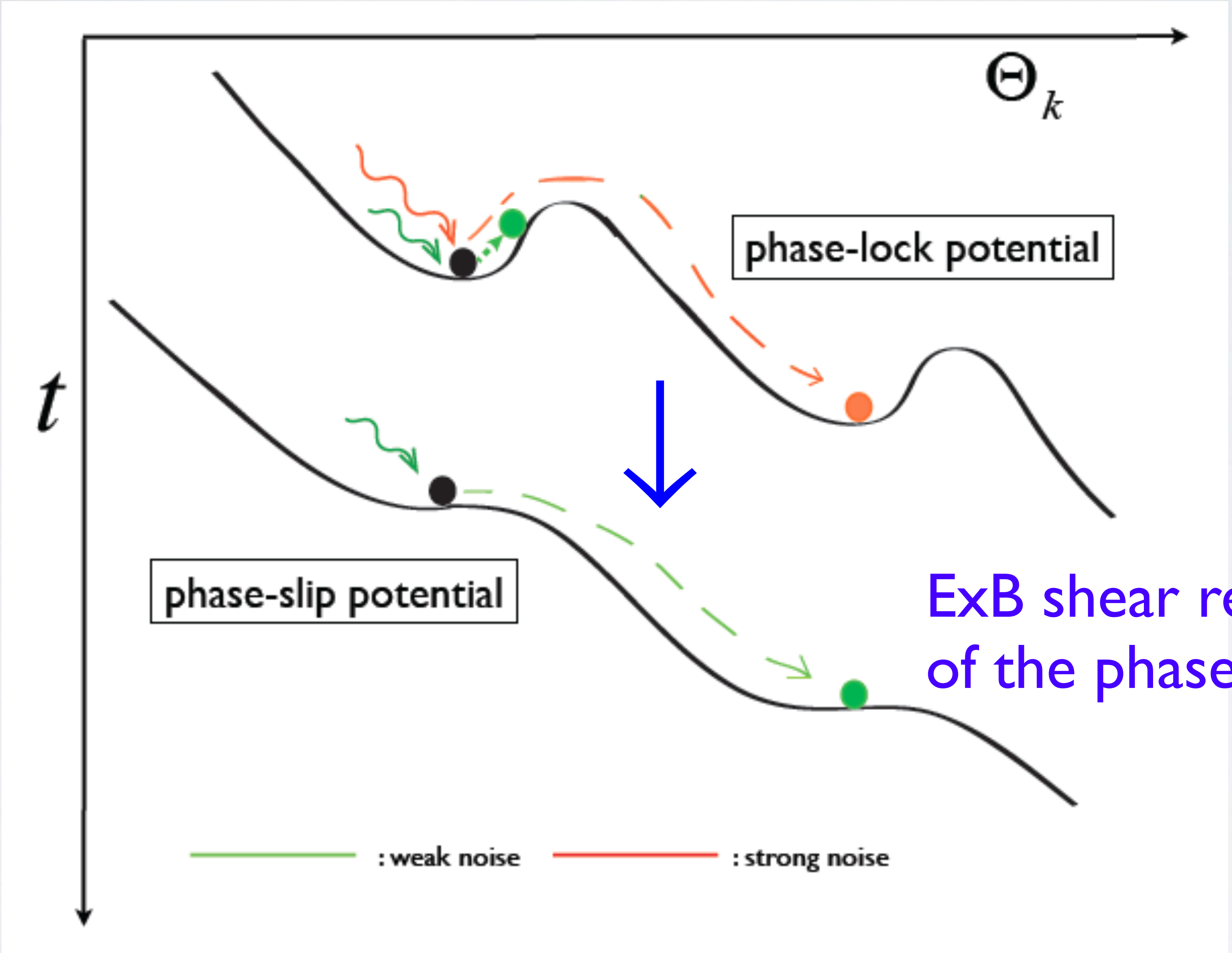
$$k_y \langle V \rangle' \Delta x - R_{MHD} \langle P \rangle' \sin\theta_k \to 0$$

Near the critical state ($V'_{E\times B} \to V'_{E\times B,cr}$), the cross-phase is easier to lose coherence and evolves into a turbulence state.

The underlying physics of the noise effect can be understood as follows:

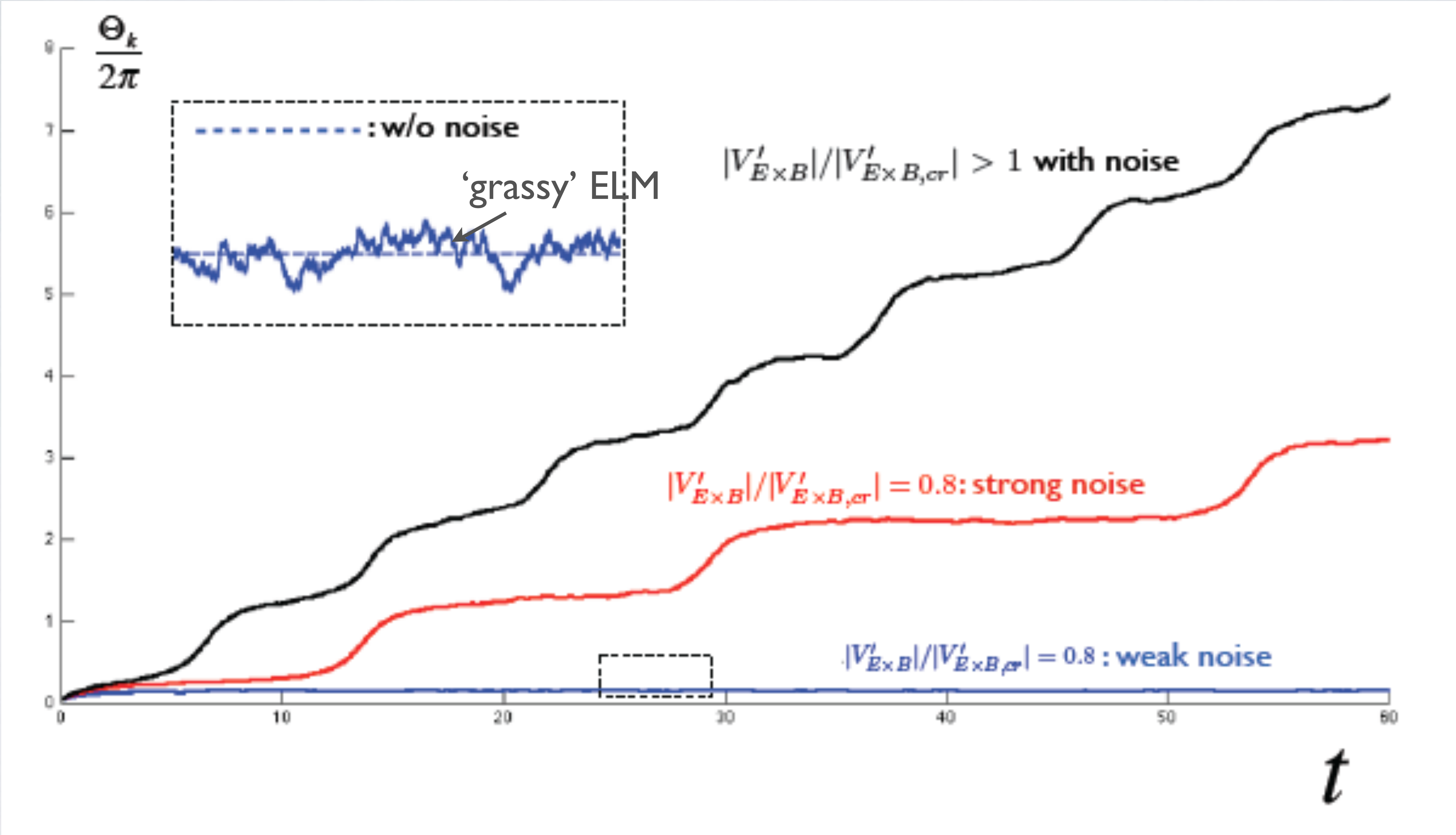
Physics of random phase slips

Phase potential



ExB shear reduces the depth of the phase potential

Turbulent QH mode



phase slip is randomized
by turbulence, EHO loses coherence

Summary

★ Cross-phase dynamics governs edge plasma relaxation:

phase locking ⟶ violent relaxation

phase locking ⟶ soft relaxation

★ When $V'_{E\times B} > V'_{E\times B,cr}$, coherent phase slips are induced and hence the edge relaxation enters a "soft" stage: QH mode with EHO.

★ Nonlinear mode coupling (i.e., phase scattering) can make the cro phase lose coherence, so that induces another scenario of soft relaxation—turbulent QH mode

References: Z. B. Guo and P. H. Diamond, Phys. Rev. Lett. 114, 145002 (2015)

Z. B. Guo and P. H. Diamond, Phys. Rev. Lett. 117, 125002 (2016)