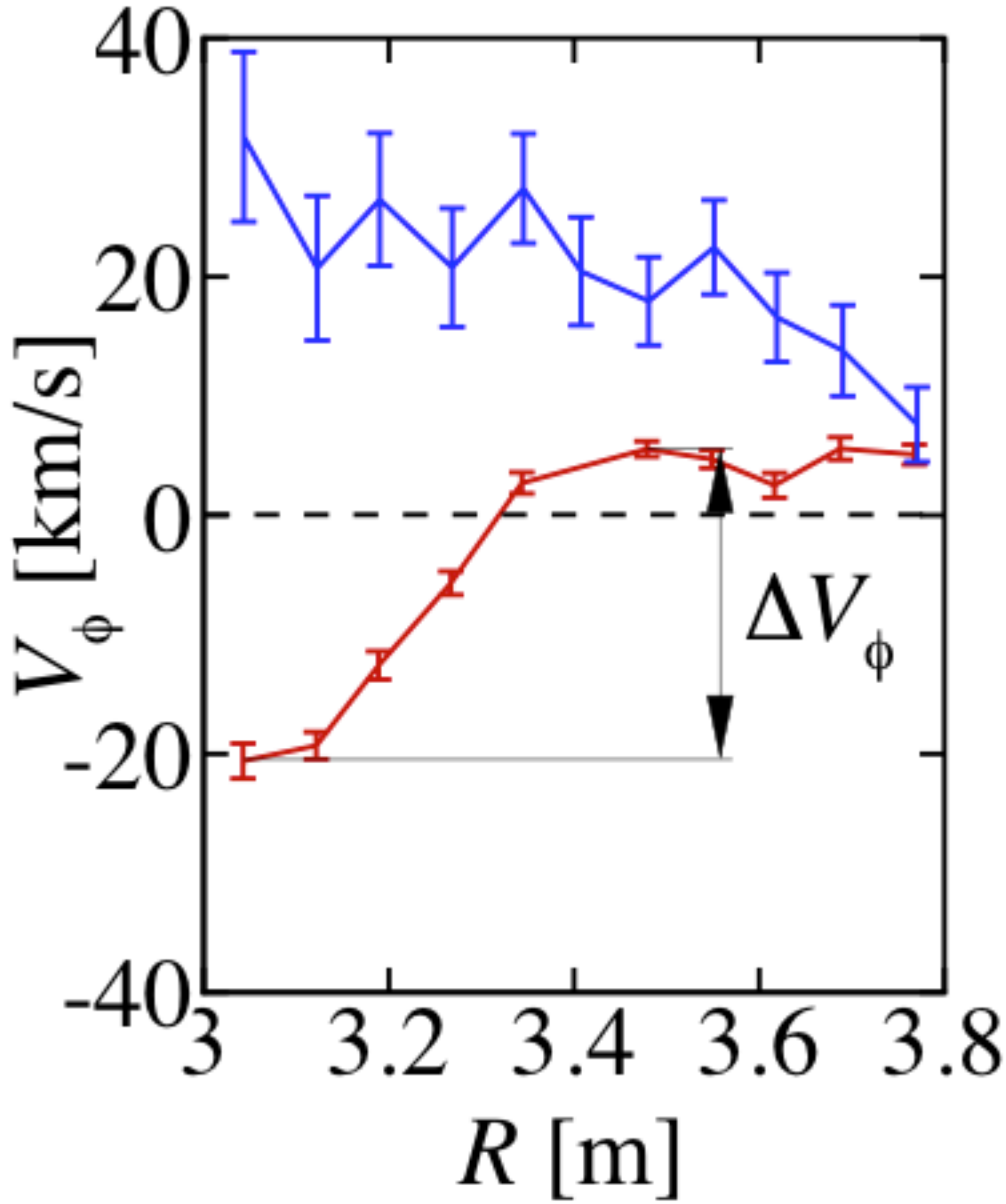
Intrinsic rotation in tokamaks

Michael Barnes
Jungpyo Lee
Felix Parra

Plasma Science & Fusion Center
Massachusetts Institute of Technology

Can we get large rotational shear for free?

- Recent observations of significant rotation (~Mach 0.3) without external momentum injection
- Important because difficult to force rotation in large, dense plasmas (i.e. ITER)
- Complicated dependence on experimental parameters



Parra et al., PRL (2012).

What sets intrinsic rotation?

- For small rotation and rotation gradient:

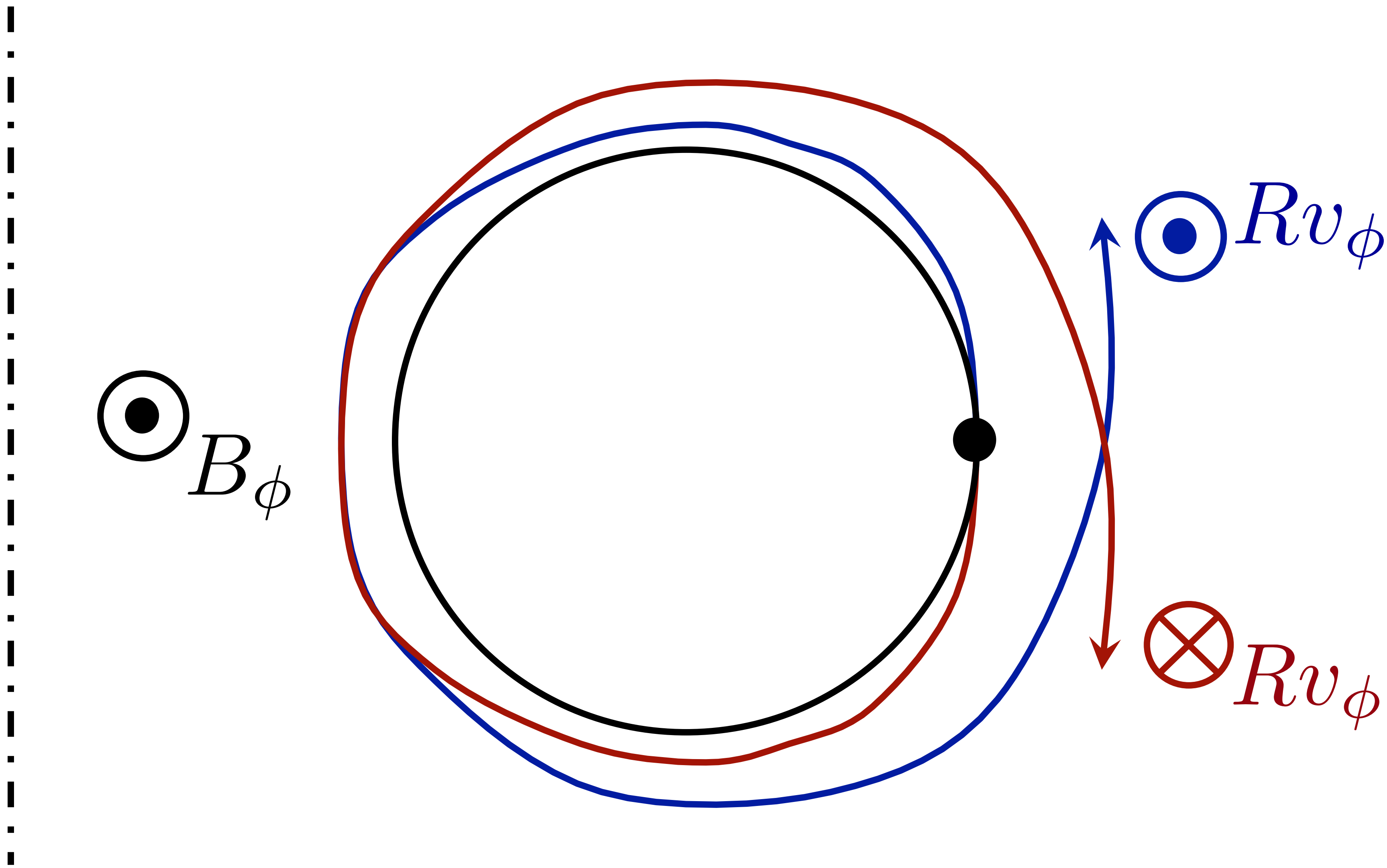
$$\Pi = -C\Omega_\zeta - \nu\Omega'_\zeta$$

- Steady-state with no momentum input ($\Pi = 0$):

$$\Omega_\zeta \propto \exp\left(-\int_0^\psi d\psi' \frac{C(\psi')}{\nu(\psi')}\right)$$

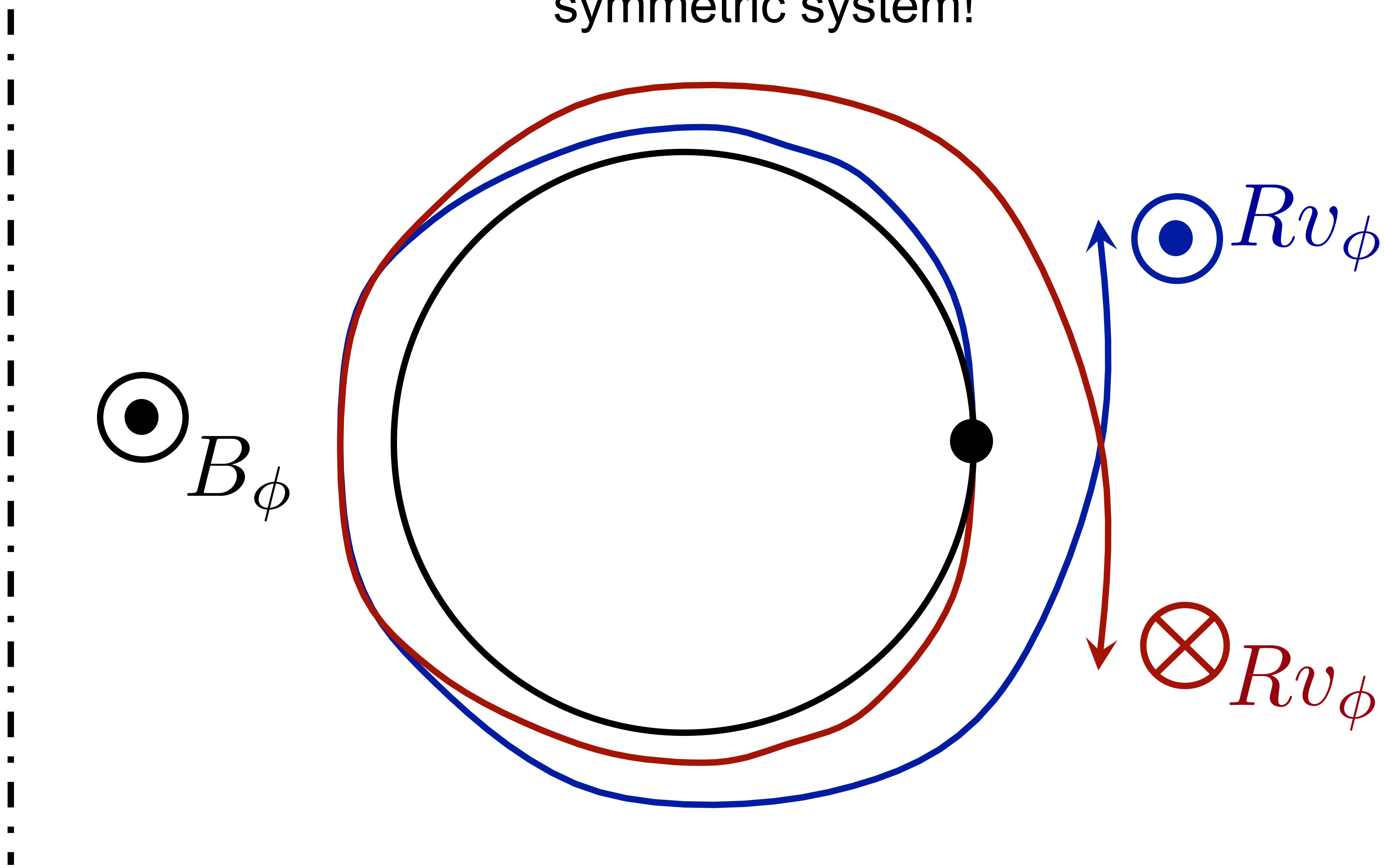
- No rotation sign reversal possible, so can't explain many experimental observations
- Must consider additional physics (not just diffusion + pinch)

Symmetry property



Symmetry property

No momentum transport from local turbulence in up-down symmetric system!



Symmetry of gyrokinetic system

- Lowest-order GK system invariant under up-down reflection about equatorial plane, reversal of rotation and rotation gradient, and

$$v_{\parallel} \longrightarrow -v_{\parallel}, \;\; \theta \longrightarrow -\theta, \;\; \partial_{\psi} \longrightarrow -\partial_{\psi}$$

$$\delta f \longrightarrow -\delta f, \;\; \Phi \longrightarrow -\Phi$$

- Consequently, momentum flux must vanish for zero rotation and rotation gradient (relevant for intrinsic rotation):

$$\Pi(\Omega_{\zeta}, \Omega_{\zeta}') = -\Pi(-\Omega_{\zeta}, -\Omega_{\zeta}') \Rightarrow \Pi(0,0) = 0$$

Parra, Barnes, and Peeters, Phys. Plasmas (2011).

Symmetry in GS2 simulations

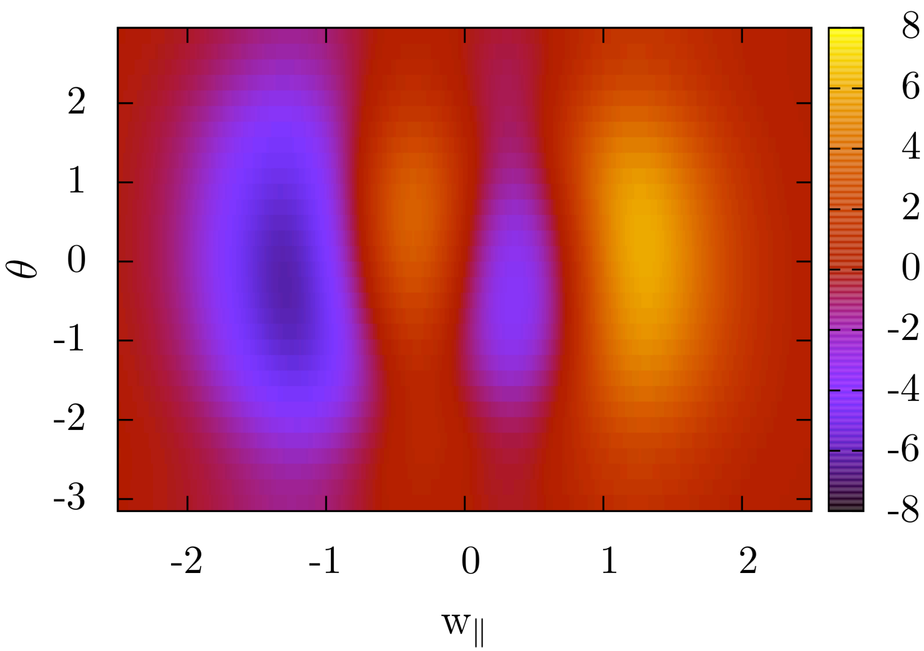
$\mathsf{P}(\theta, k_\psi, k_\alpha, v_\parallel, \mu)$ is the time-averaged momentum flux integrand

Symmetry constraints:

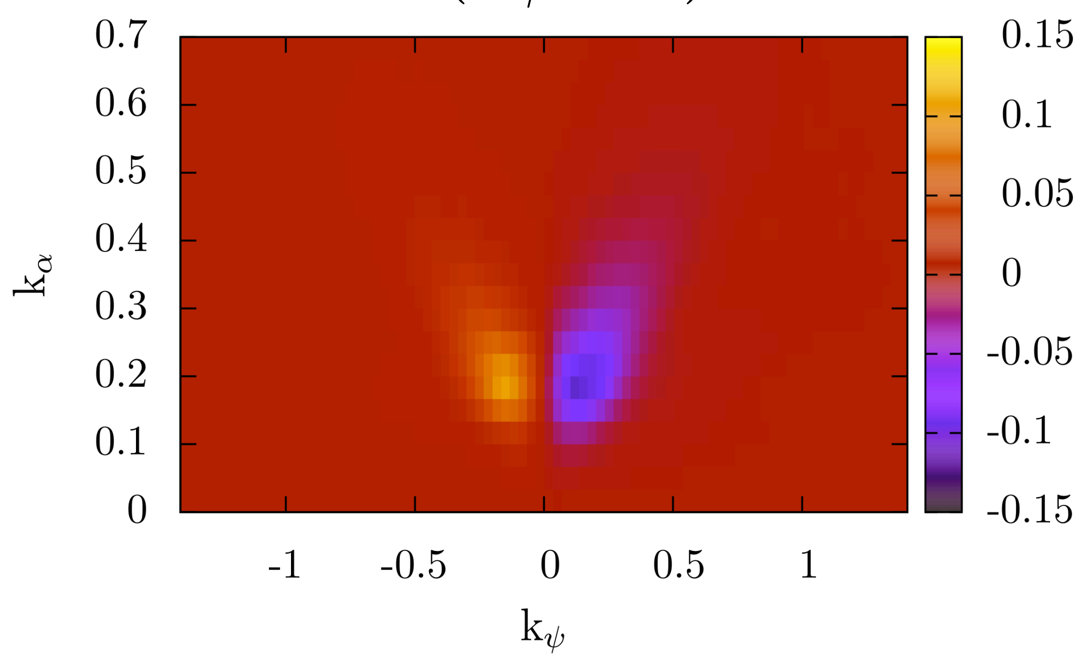
$$\mathsf{P}(v_\parallel, \theta) = -\mathsf{P}(-v_\parallel, -\theta) \qquad \mathsf{P}(k_\psi, k_\alpha) = -\mathsf{P}(-k_\psi, k_\alpha)$$

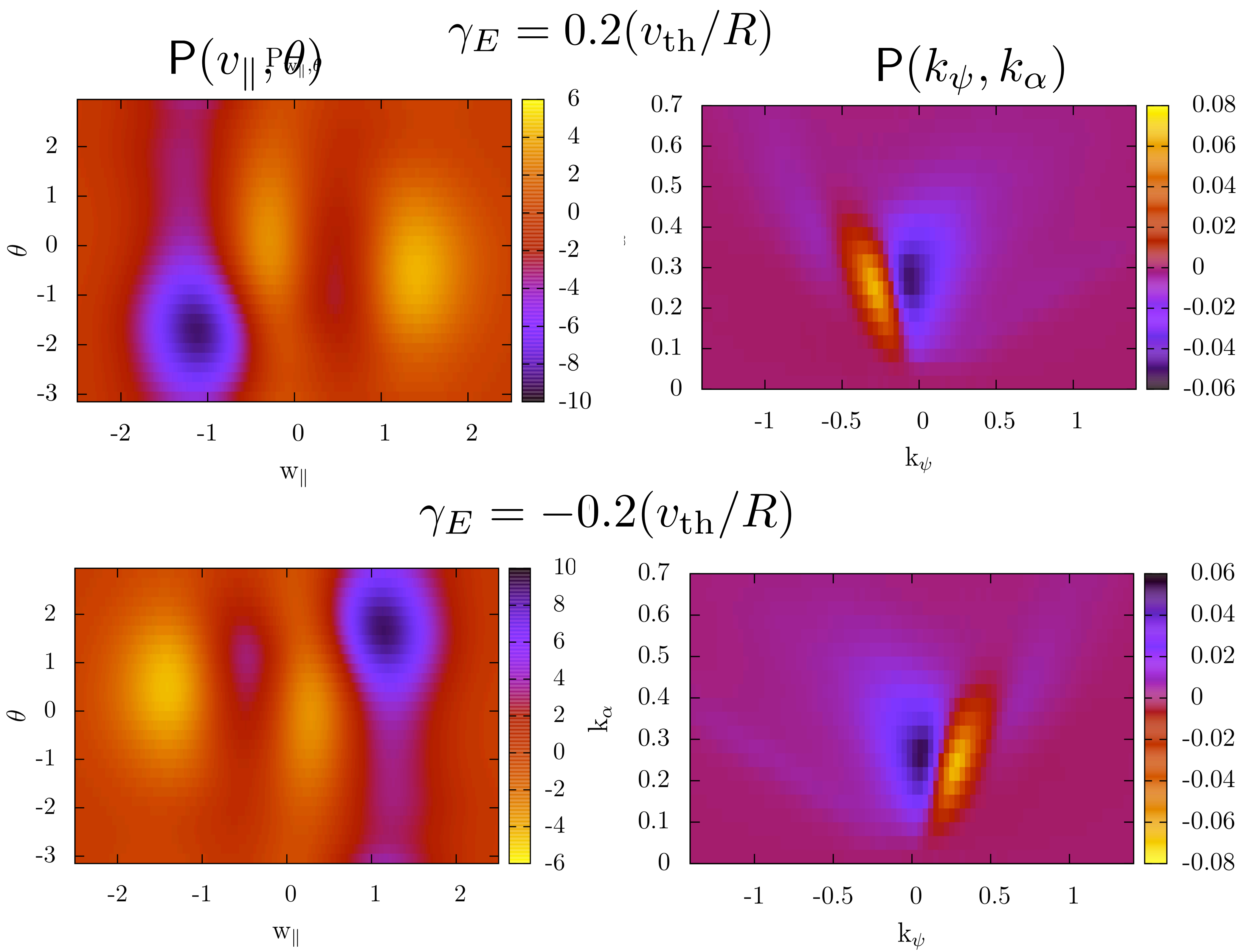
$$\gamma_E = 0$$

$\mathsf{P}(v_\parallel, \theta)$



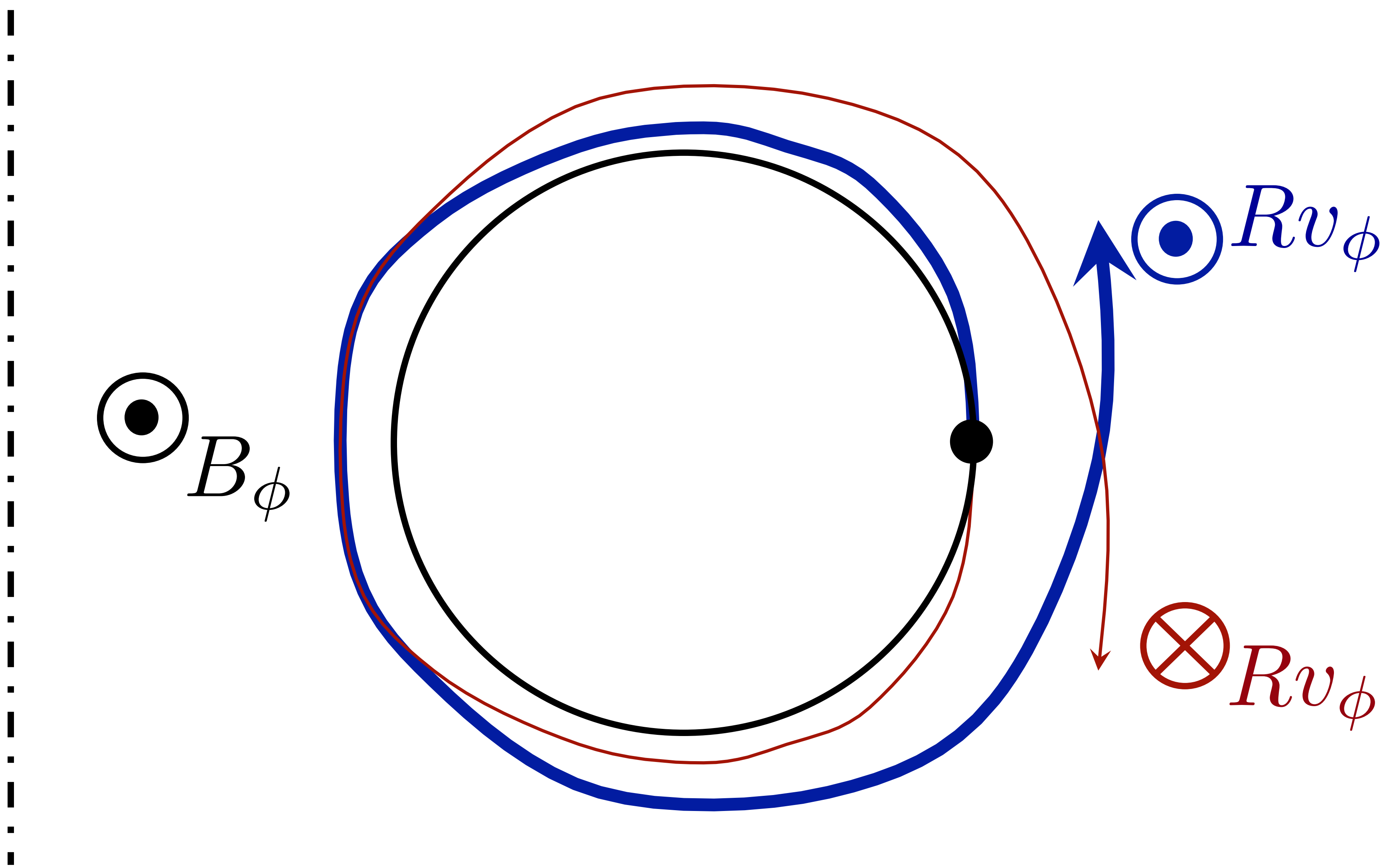
$\mathsf{P}(k_\psi, k_\alpha)$



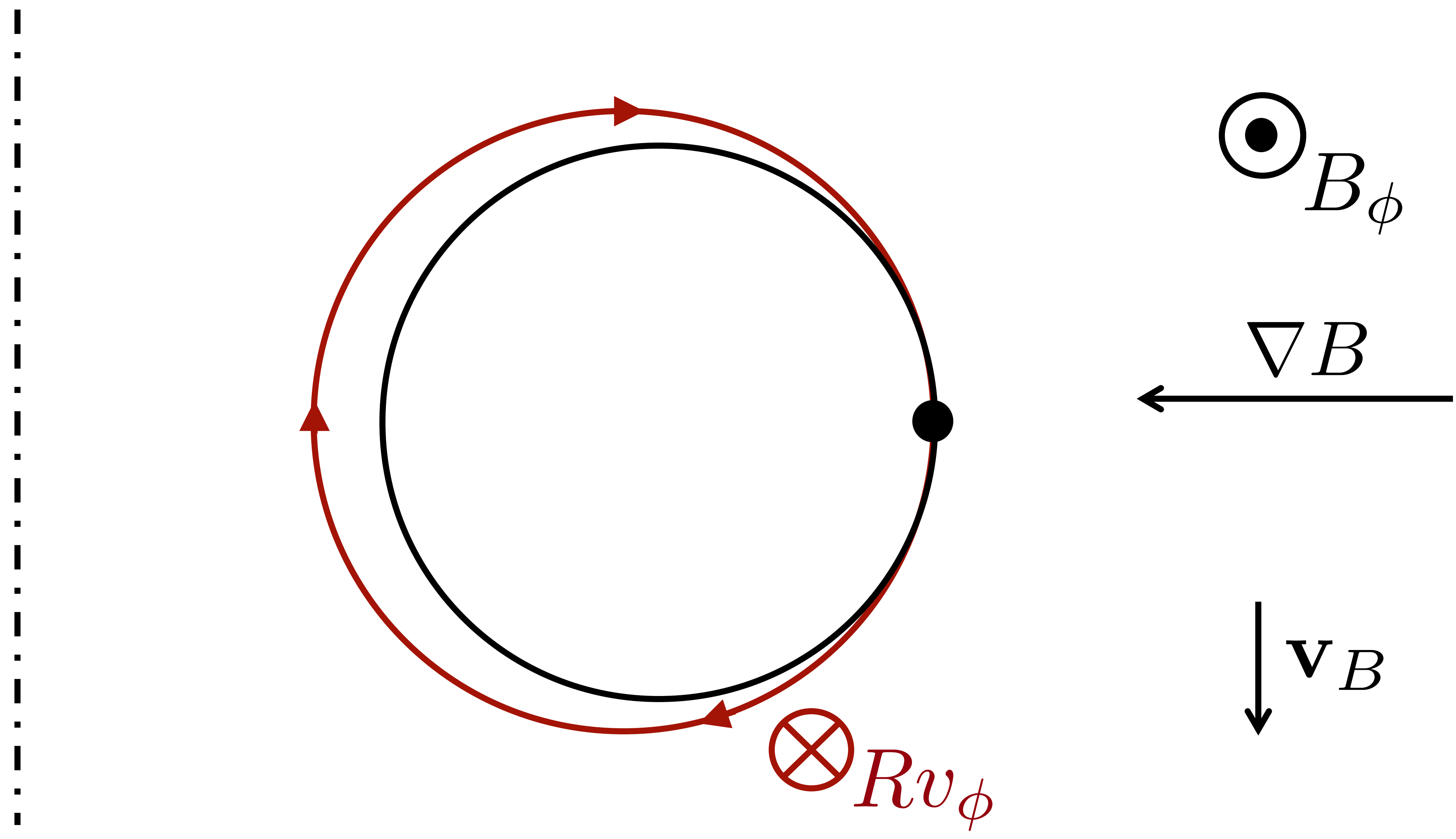


$\gamma_E = 0.2(v_{\rm th}/R)$
$\mathsf{P}(v_\parallel, \theta)$
$\mathsf{P}(k_\psi, k_\alpha)$
θ
$\mathrm{w}_\parallel$
k_ψ
$\gamma_E = -0.2(v_{\rm th}/R)$
k_α

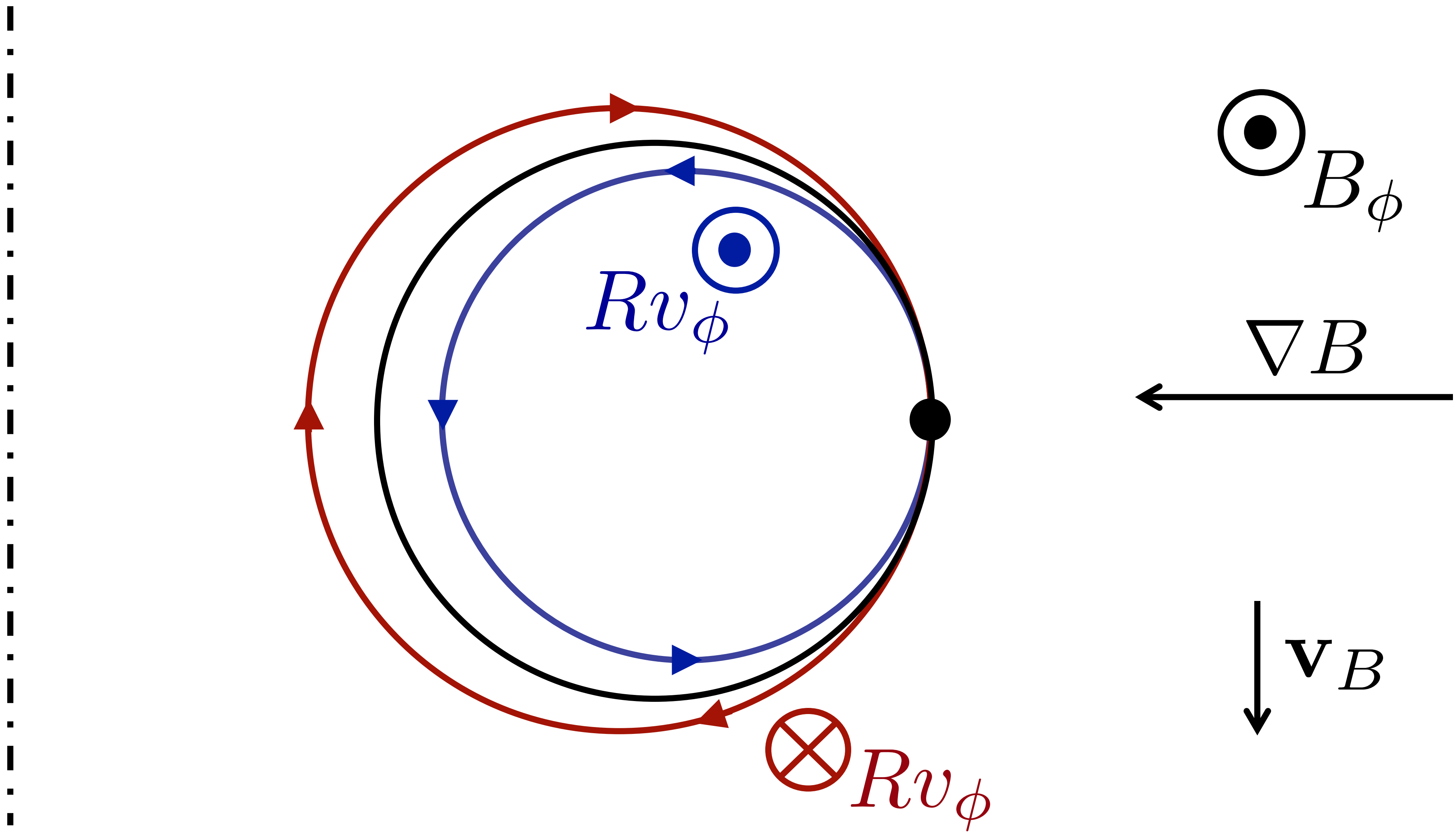
Symmetry breaking: mean flow



Mean flow generation

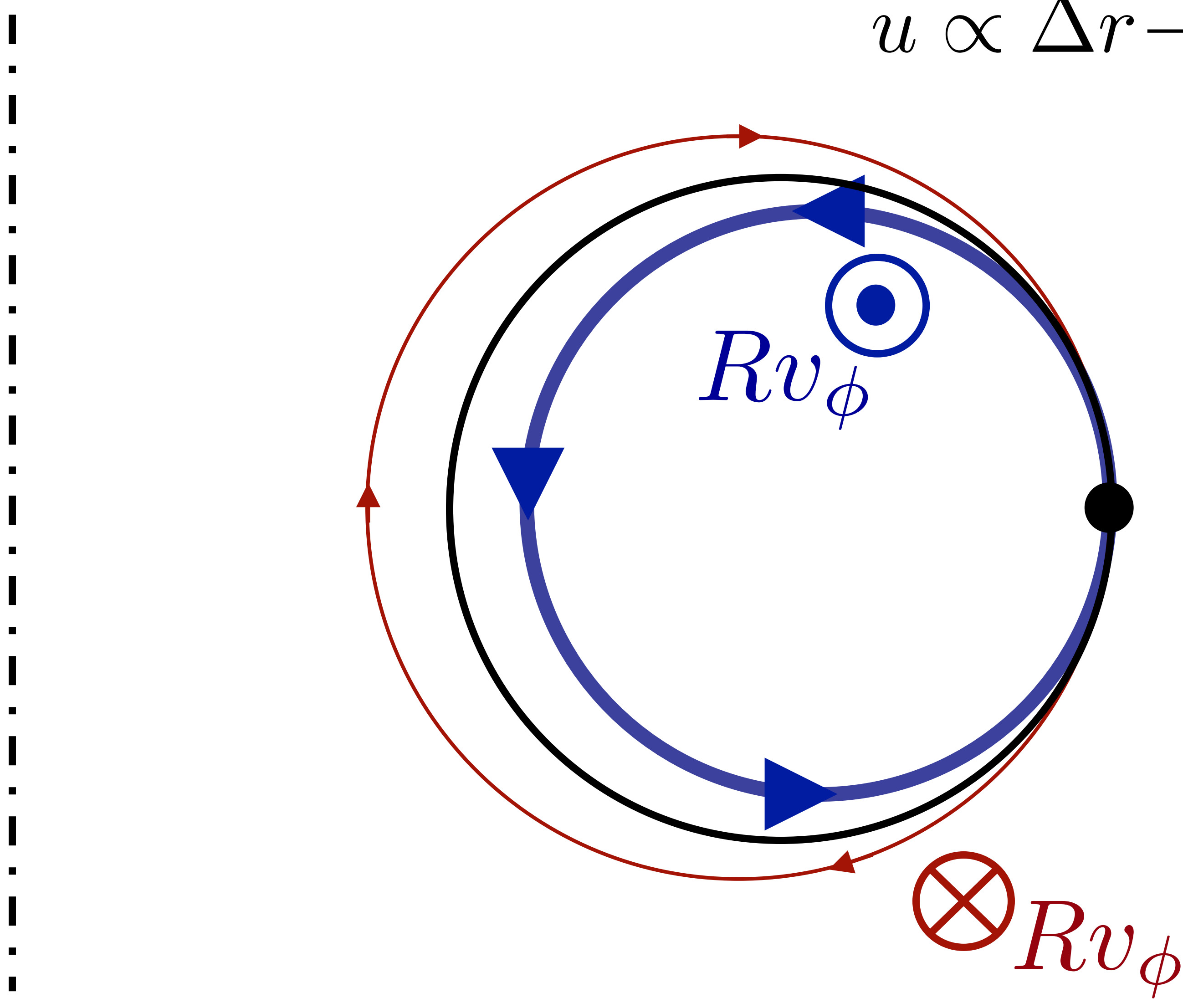


Mean flow generation



Mean flow generation

$$u \propto \Delta r \frac{d \ln p}{dr} v_t \sim \frac{\rho_\theta}{L_p} v_t$$



How big is the effect?

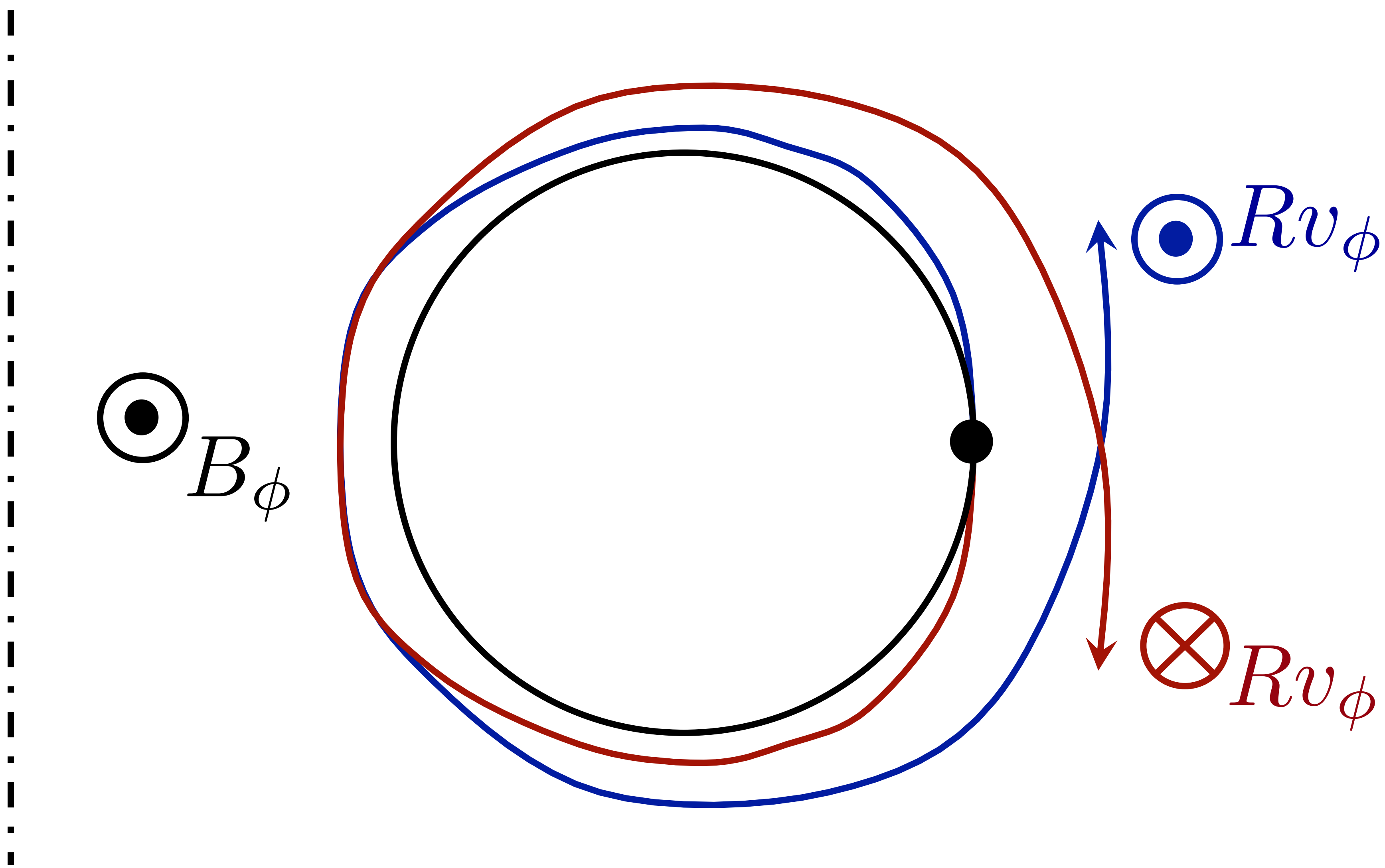
$$u \propto \Delta r \frac{d \ln p}{dr} v_t \sim \frac{\rho_\theta}{L_p} v_t$$

$$\Pi = -mRn\nu \frac{du}{dr}, \; Q = -n\chi \frac{dT}{dr}$$

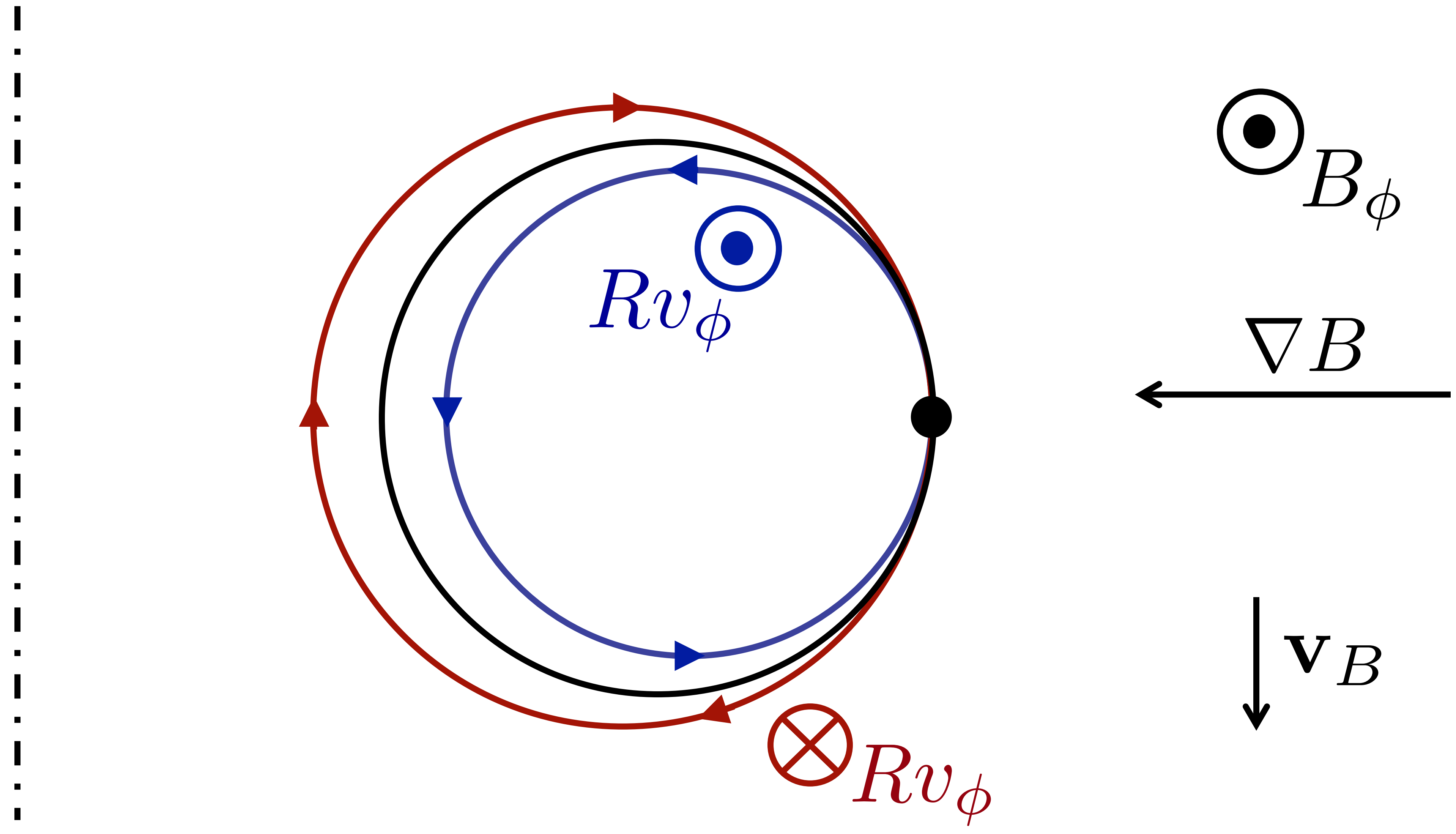
$$\nu \sim \chi \sim qR \frac{\rho_\theta^2}{v_t}$$

$$\frac{\Pi}{Q} \frac{Q_{GB}}{\Pi_{GB}} \sim m v_t \frac{du}{dr} \left(\frac{dT}{dr} \right)^{-1} \sim \rho_i \left(\frac{dT}{dr} \right)^{-1} \frac{d}{dr} \left(\frac{q}{\epsilon} \frac{dT}{dr} \right)$$

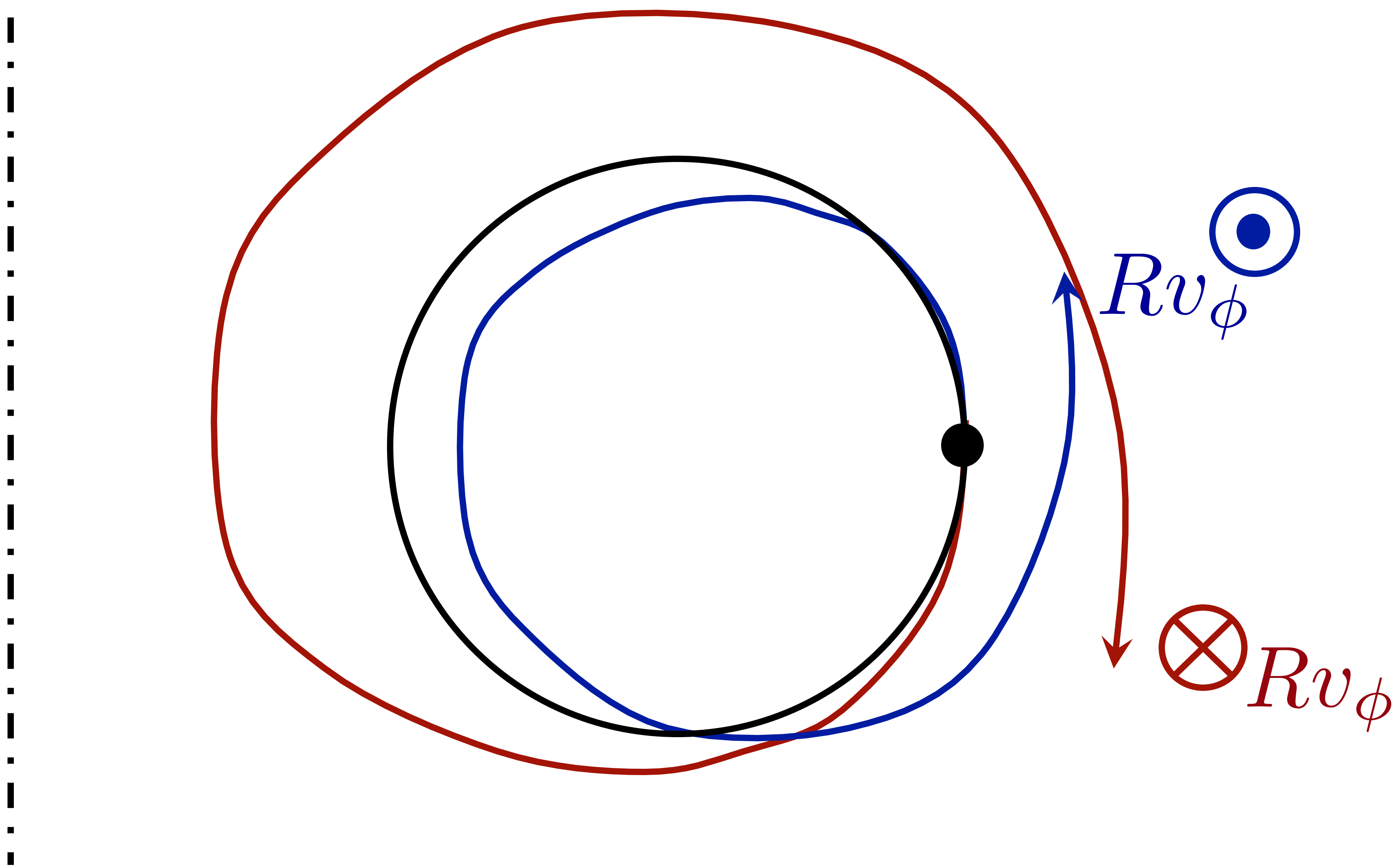
Symmetry breaking: up-down asymmetry



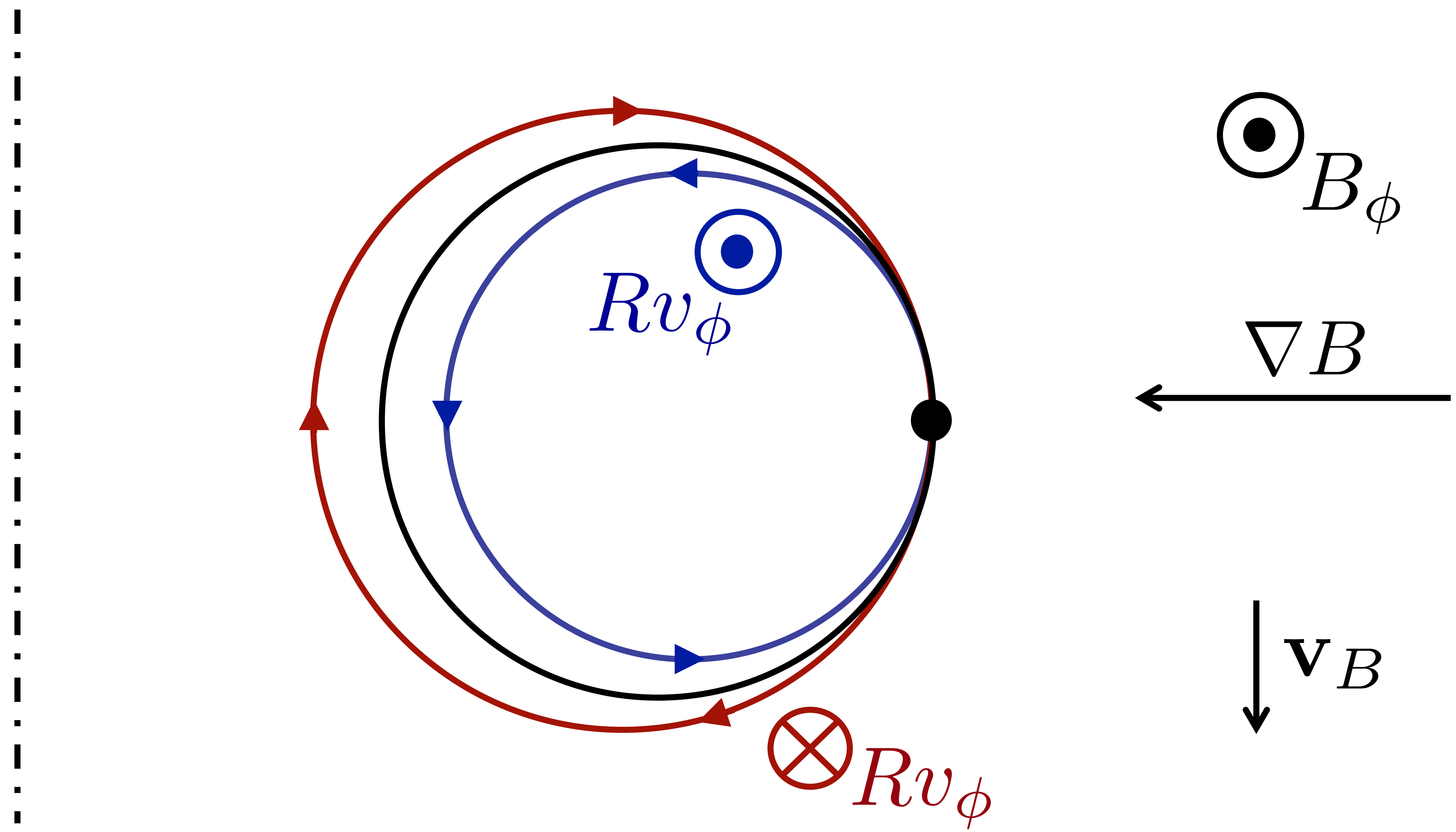
Symmetry breaking: orbit length



Symmetry breaking: orbit length



Symmetry breaking: radial profile variation



Higher-order GK equation (B_θ/B small)

(R,E,μ) variables

Parra, Barnes, and Catto, Nucl. Fusion (2011).

$$\frac{dg_s}{dt} + \mathbf{v}_\parallel \cdot \nabla \left(g_s - Z_s e \langle \Phi \rangle \frac{\partial F_{0s}}{\partial E} \right) + \langle \mathbf{v}_E^\perp \rangle \cdot \nabla F_{0s}$$

$$+ \left(\mathbf{v}_{Cs} + \mathbf{v}_{Ms} + \langle \mathbf{v}_E^\perp \rangle \right) \cdot \nabla_\perp \left(g_s - Z_s e \langle \Phi \rangle \frac{\partial F_{0s}}{\partial E} \right)$$

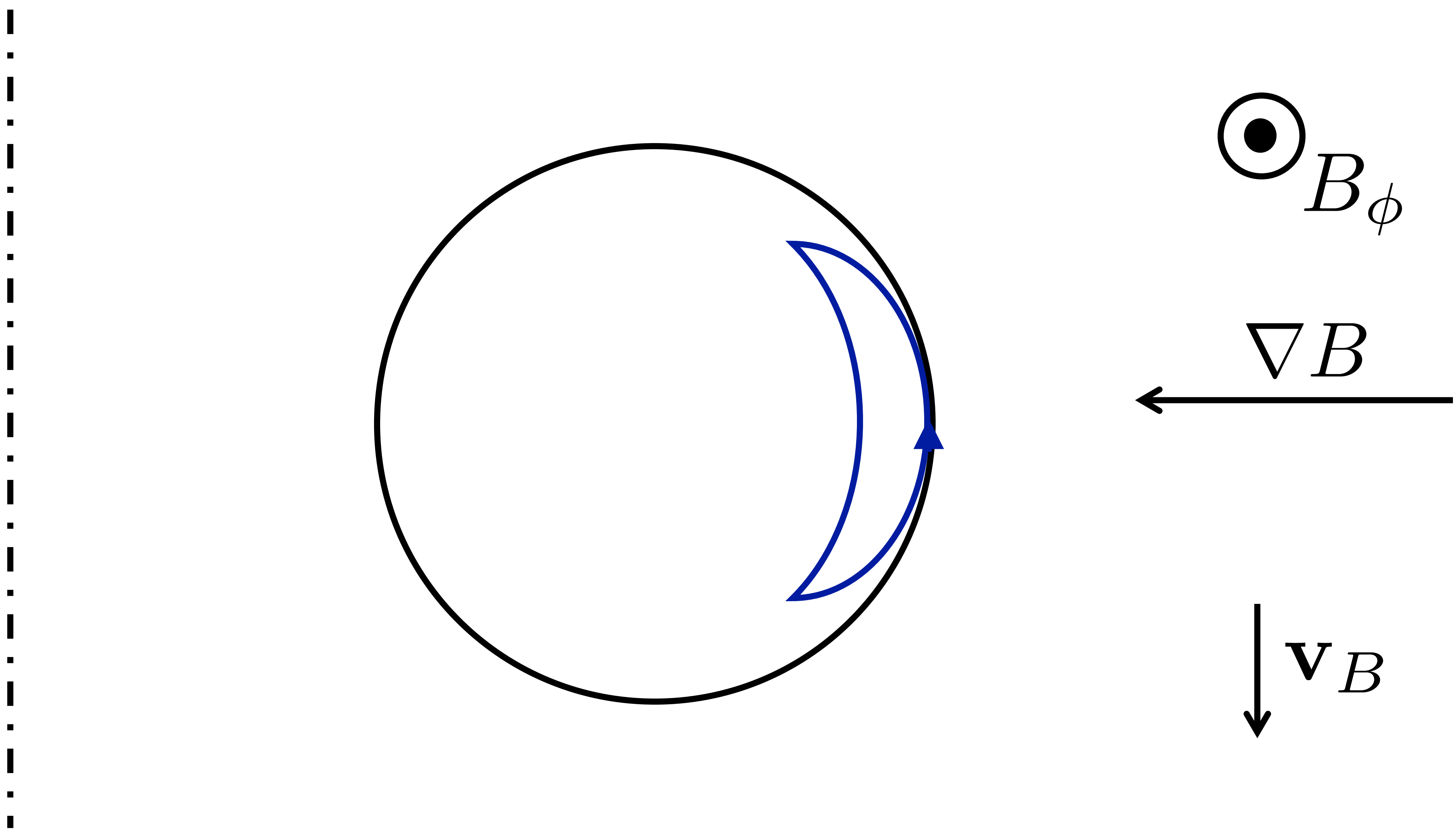
$$= - \mathbf{v}_{Ms} \cdot \nabla\theta \frac{\partial}{\partial\theta} \left(g_s - Z_s e \langle \Phi \rangle \frac{\partial F_{0s}}{\partial E} \right) - \left\langle \mathbf{v}_E^\parallel \right\rangle \cdot \nabla_\perp g_s$$

$$- \langle \mathbf{v}_E^\perp \rangle \cdot \nabla\theta \frac{\partial g_s}{\partial\theta} - \left\langle \mathbf{v}_E^\parallel \right\rangle \cdot \nabla F_{0s} - \langle \mathbf{v}_E^\perp \rangle \cdot \nabla F_{1s}$$

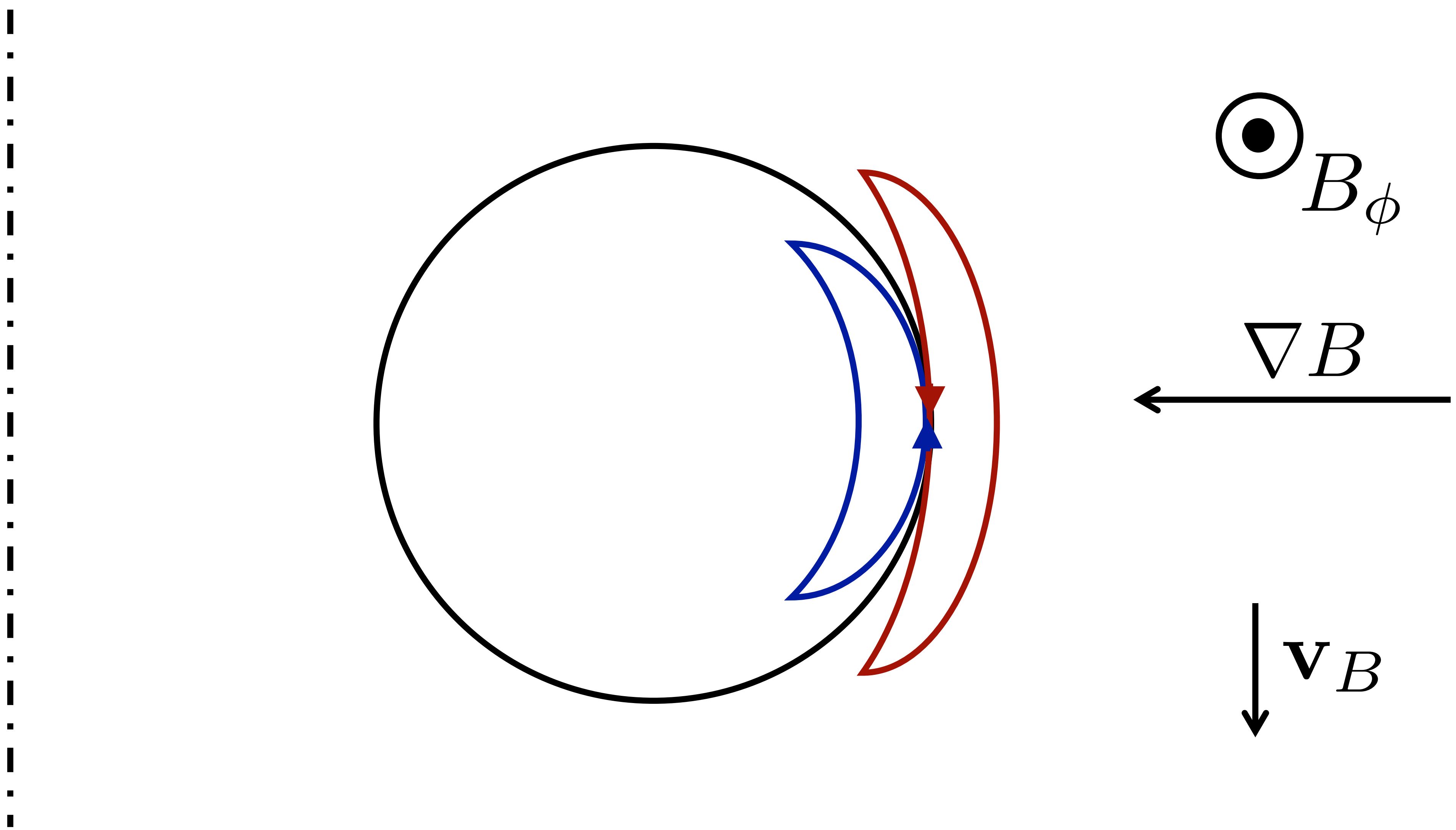
$$+ Z_s e \left(\mathbf{v}_\parallel \cdot \nabla \langle \Phi \rangle + \mathbf{v}_{Ms} \cdot \nabla_\perp \langle \Phi \rangle \right) \left(\frac{\partial g_s}{\partial E} + \frac{\partial F_{1s}}{\partial E} \right)$$

$$- \mathbf{v}_E^{nc} \cdot \nabla_\perp g_s + Z_s e \mathbf{v}_\parallel \cdot \nabla \Phi^{nc} \frac{\partial g_s}{\partial E} + \psi\text{-profile variation}$$

Symmetry breaking



Symmetry breaking



Symmetry breaking