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A PENALIZED MODEL FOR PLASMA-WALL INTERACTION VALID IN THE GYROKINETIC FRAMEWORK

Context: gyrokinetic edge modelling requires plasma-wall interaction

- turbulent transport degrades tokamak confinement quality [Wootton 1990]
- Turbulence regulation mechanism: ExB sheared flows [Diamond 2005]
- Transport barriers formation at the separatrix is related to sheared flows [Wagner 1982]
- Global gyrokinetic codes need plasma-wall interaction to describe edge plasmas
 - Plasma-wall interaction triggers turbulence in edge plasma [Dif-Pradalier 2022]
 - Plasma-wall interaction influences the SOL radial electric field $E_r \propto -\nabla T_e/e$ [Stangeby]

Difficulty: plasma-wall interaction is subgrid for gyrokinetic codes

Debye sheath

(usual sheath-limited SOL values)

Length scale $\lambda_D = \sqrt{\frac{\epsilon_0 T}{ne^2}} \approx 10 \mu\text{m}$

Timescale $\omega_{pe} = \sqrt{\frac{ne^2}{m_e \epsilon_0}} \approx 200 \text{ GHz}$

Debye sheath **positively charged**

Gyrokinetic theory

Length scale $\rho_i = \frac{m_i v_i}{eB} \approx 100 \mu\text{m}$

Timescale $\Omega_{ci} = \frac{eB}{m_i} \approx 100 \text{ MHz}$

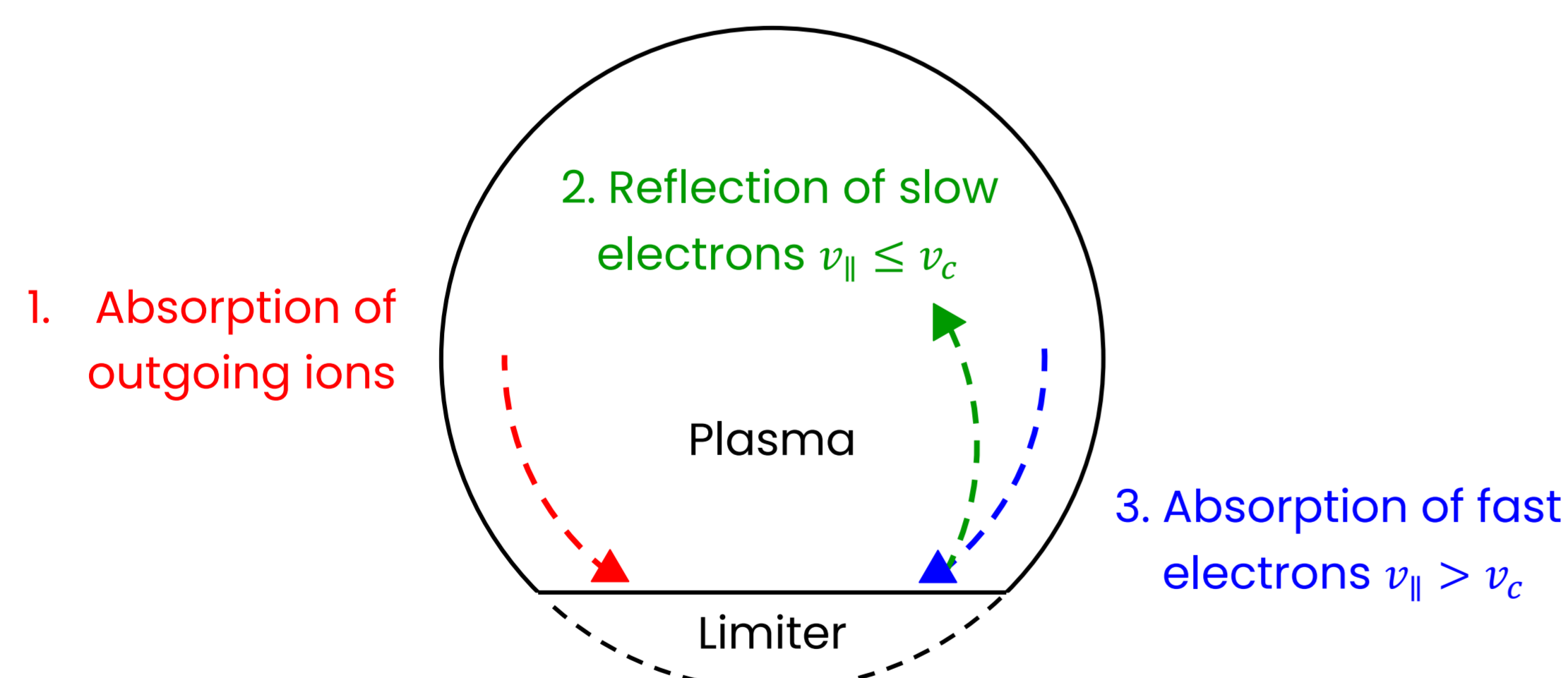
Quasineutral plasma

Plasma-wall interaction model must ensure quasineutrality

- Preliminary study of plasma wall interaction : 1DIV kinetic model using Voice code [Munsch et al. 2024 Nucl. Fusion **64** 056027 & **64** 046013]
- 1D plasma along field line, with two penalized models for the wall region: with / without currents in the wall;
- in both cases: **equality of ion and electrons fluxes** at the plasma boundary

Logical and conducting sheath approaches

- Methods applied on **last grid point** (\neq penalization)
 - Limiter **not included** in simulation domain



Logical sheath [Parker 2015]

$$\Gamma_e = \Gamma_i$$

Imposed on each point of limiter surface determines v_c

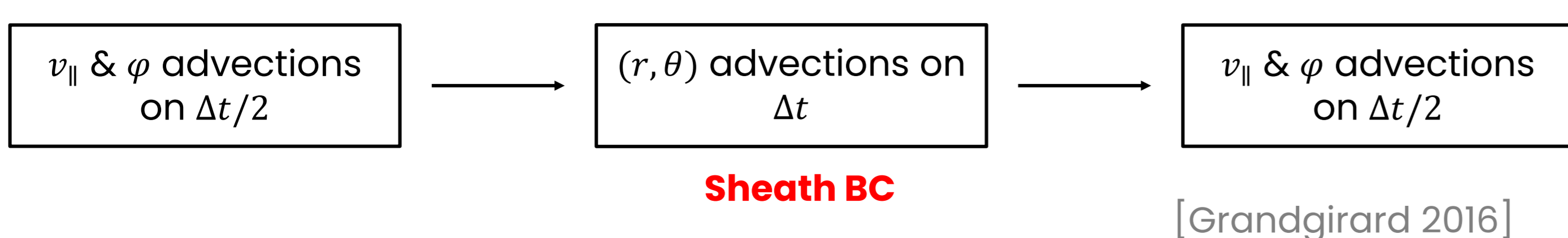
Conducting sheath [Shi2015]

$$v_c = \sqrt{2e\phi_w/m_e}$$

$\phi_w(r, \theta, \varphi)$ electric potential on limiter surface

The 5D global full-f Gysela code

- With Strang splitting for gyrokinetic equation, advections with backward semi-Lagrangian scheme



Penalized sheath model valid in gyrokinetic framework

- Limiter **included in simulation domain** (immersed/penalized BC)
- Ion absorption in limiter using *infinite penalization* [Caschera 2018]

$$F_s(r, \theta, \varphi, v_{\parallel}, \mu) = F_s(1 - M_{lim}) + F_T M_{lim} \quad F_T \ll 1 \text{ Maxwellian} \quad M_{lim} = 1 \text{ in limiter}$$
- Slow electrons reflected taking advantage of backward semi-Lagrangian method

$$F_e(t + \Delta t, X_{GC}) = F_e(t, X_{GC}^{\delta x})$$

$$\langle \Gamma_i \rangle_{lim} = \langle \Gamma_e \rangle_{lim} - \int_{S_{lim}} d^2S \int_{-\infty}^{-v_c} dv_{\parallel} \int_0^{+\infty} d\mu J_v J_0 F_i(v_{\parallel} \mathbf{b}_{\parallel}^* + \mathbf{v}_{\perp}) \cdot \mathbf{n}$$

- Fast electrons absorbed during reflection procedure
- Cutoff v_c computed to ensure vanishing current **on spatial average over limiter surface**

$$\langle \Gamma_i \rangle_{lim} = \langle \Gamma_e \rangle_{lim} - \int_{S_{lim}} d^2S \int_{-\infty}^{-v_c} dv_{\parallel} \int_0^{+\infty} d\mu J_v F_e(v_{\parallel} \mathbf{b}_{\parallel}^* + \mathbf{v}_{\perp}) \cdot \mathbf{n}$$

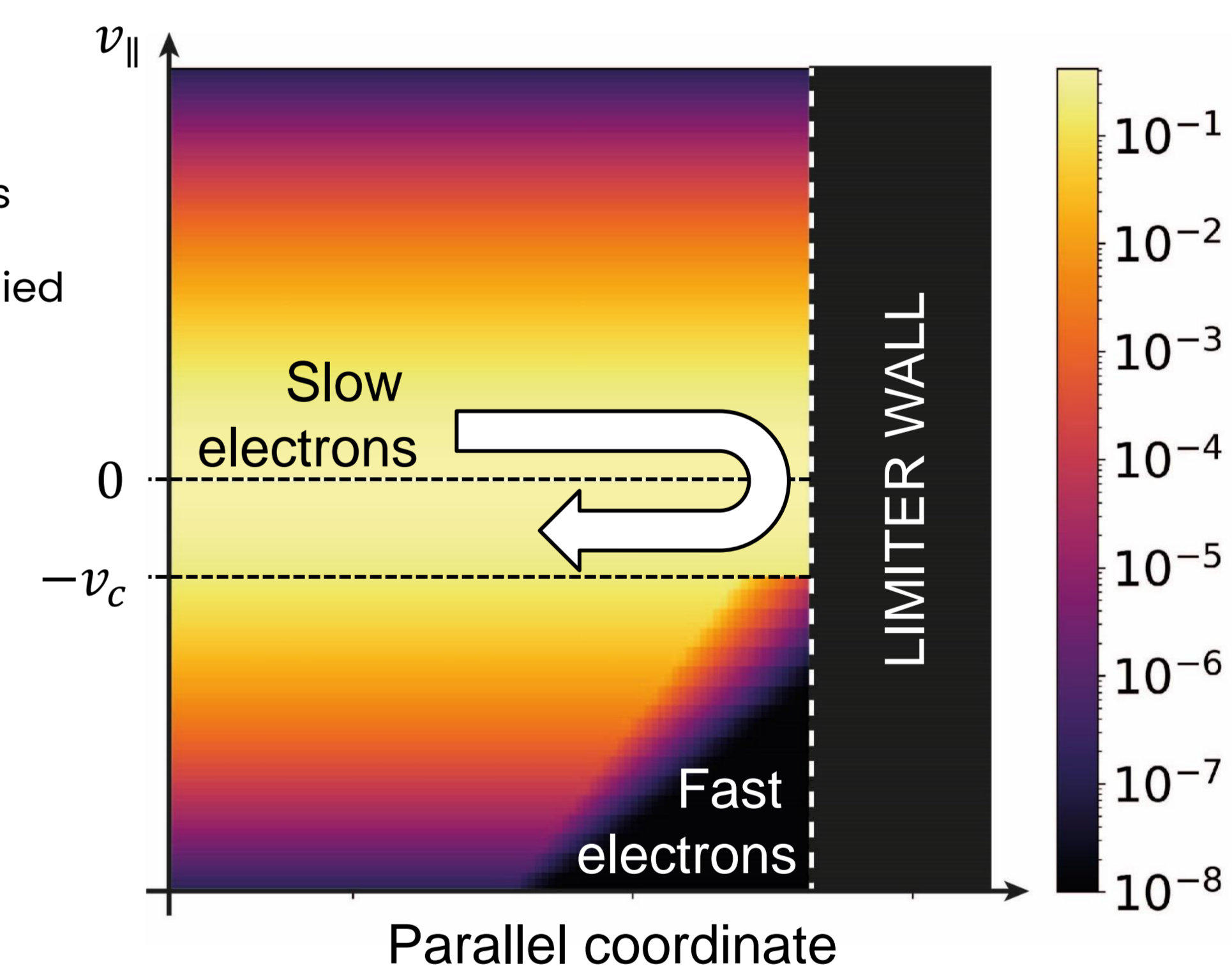
$\langle \dots \rangle_{lim}$ limiter spatial avg.

\mathbf{n} limiter normal vector

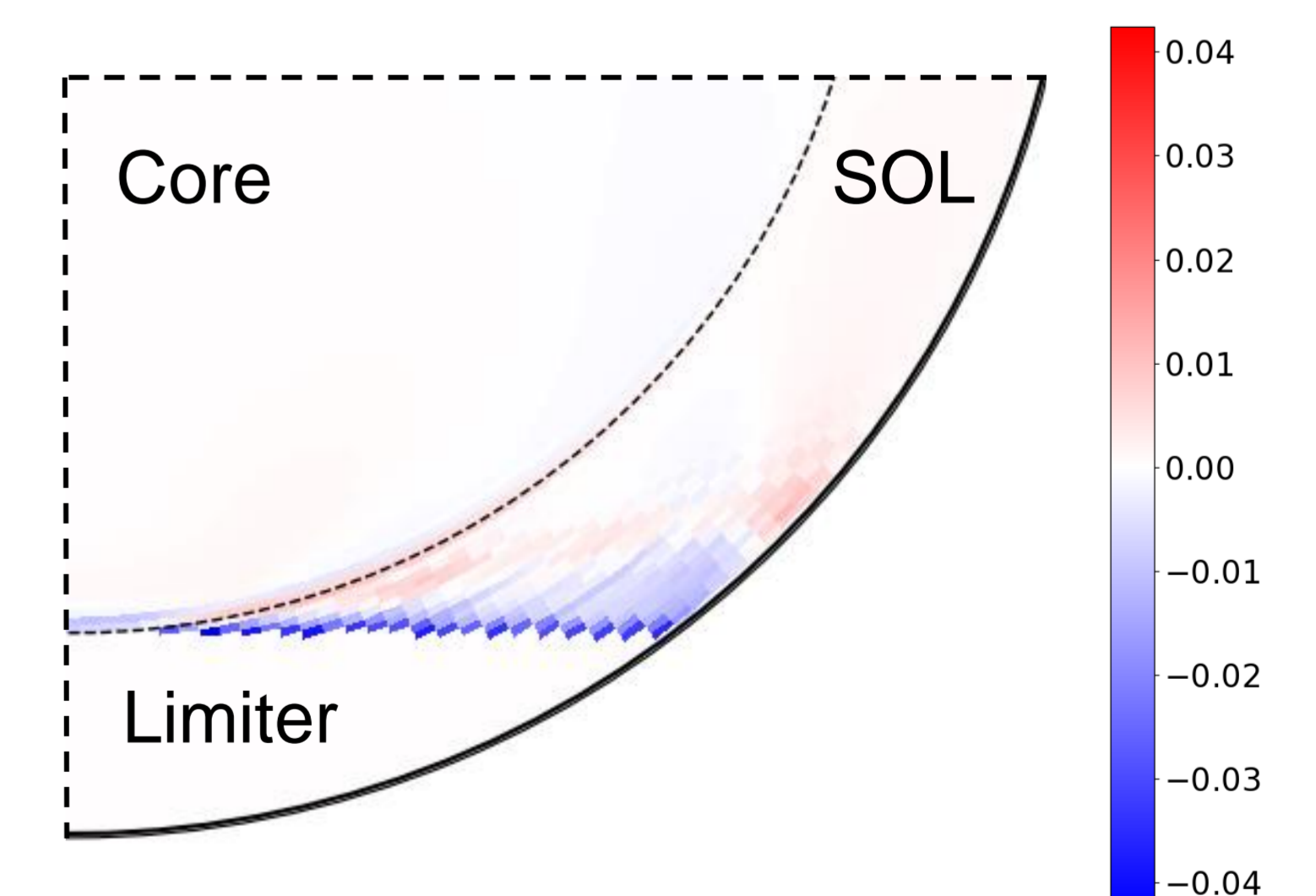
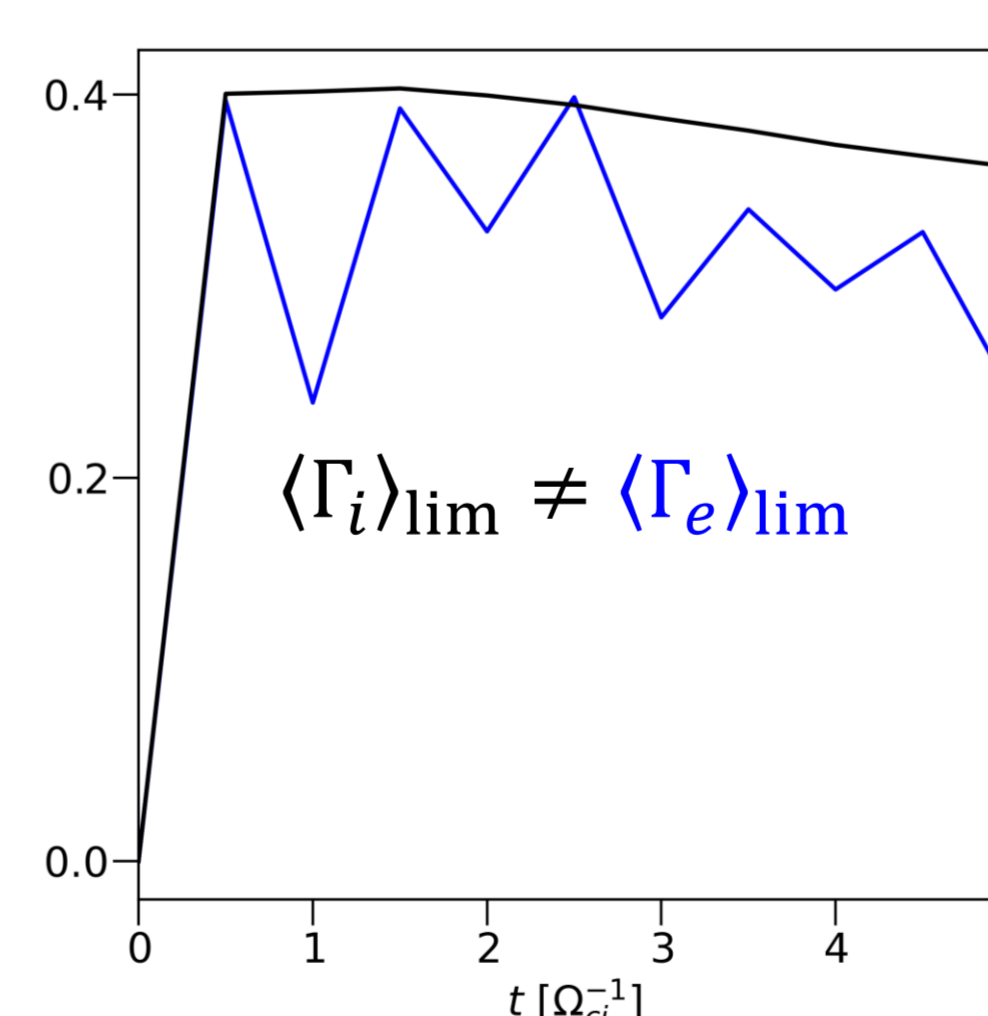
Results

- Electron distribution function from GYSELA code (after few iterations, fixed v_c)

- Reflection slow electrons
- Absorption of fast electrons
- Smoothing procedure applied to fast electrons for easing interpolation step



- Gyrocenter charge density $\rho_{GC} = e(Z_i n_{Gi} - n_e)$ close to limiter region



- Negative charge density on the limiter surface causes simulation to break
- Currents are not matched precisely enough on limiter surface

Conclusion

- Absorption of ions & fast electrons, reflection of slow electrons : with penalized limiter;
- Electron and ion fluxes matched on spatial average over limiter surface;
- Kinetic electron response required in SOL;
- Apparition of negative charge on limiter surface to investigate. Possible causes:
 - Numerical implementation « cleanliness » (limiter not aligned with mesh) ;
 - QN solver operates on whole plasma + limiter domain ;