Properties of plasma turbulence in the periphery of diverted tokamaks

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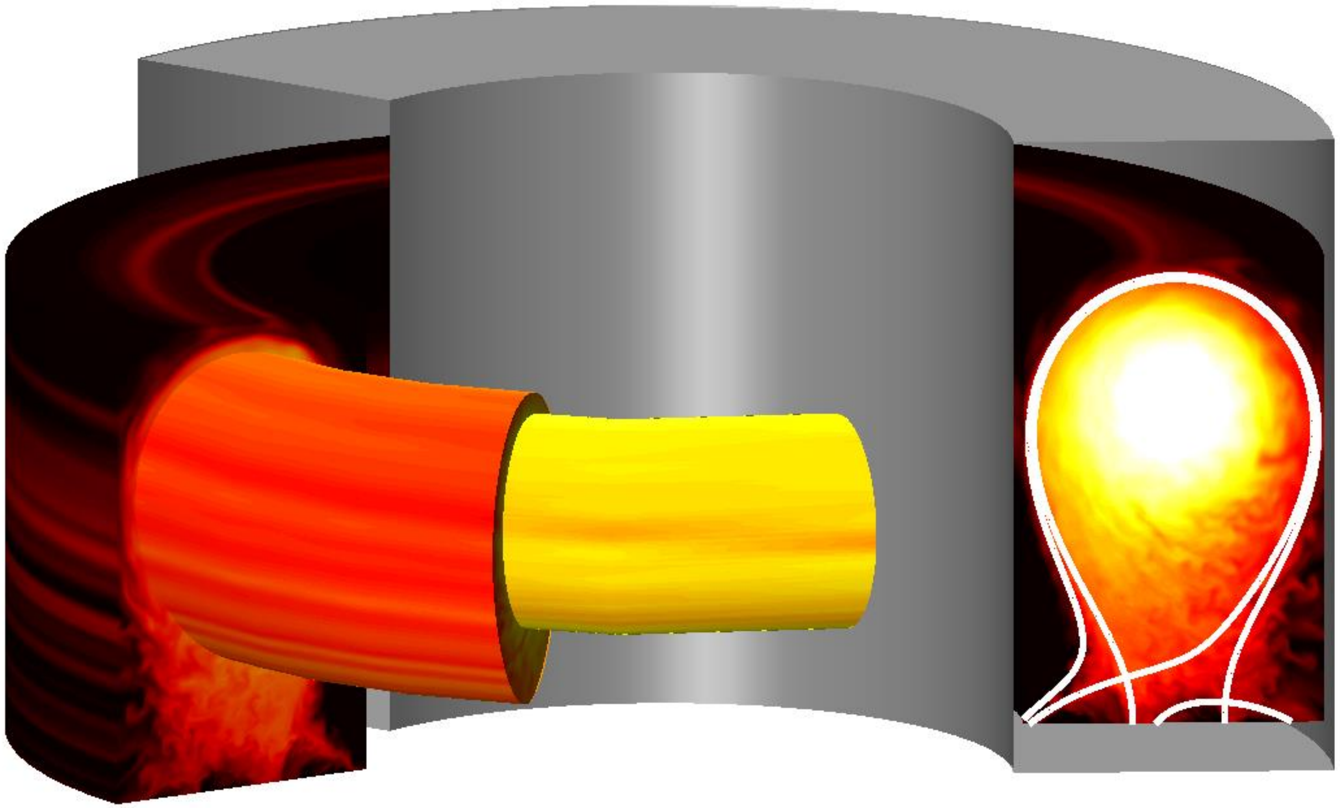

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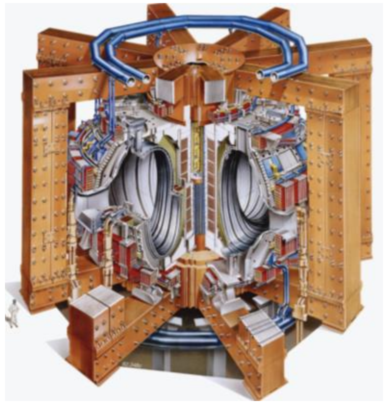
Heat exhaust: a crucial issue

"… heat exhaust is probably the main challenge towards the realisation of magnetic confinement fusion." [EU Fusion Roadmap]

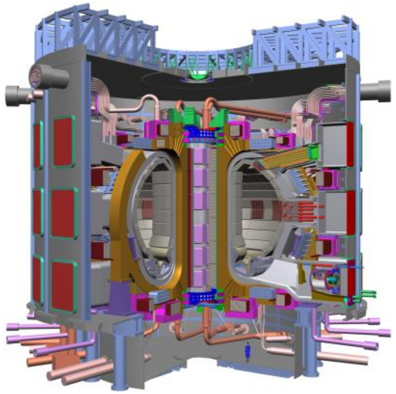
$$P_{\mathrm{wall}} \propto \frac{Q_{\mathrm{sep}}}{R L_{\mathrm{SOL}}} < 10 \frac{\mathrm{MW}}{m^2}$$

JET



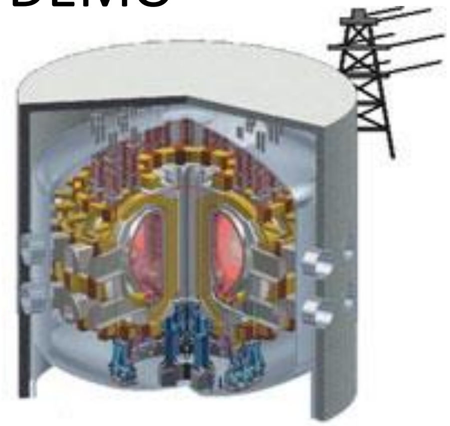
$$\frac{Q_{\mathrm{sep}}}{R} = 7\ \mathrm{MW\ m^{-1}}$$

ITER



$$\frac{Q_{\mathrm{sep}}}{R} = 20\ \mathrm{MW\ m^{-1}}$$

DEMO



$$\frac{Q_{\mathrm{sep}}}{R} = 80 - 100\ \mathrm{MW\ m^{-1}}$$

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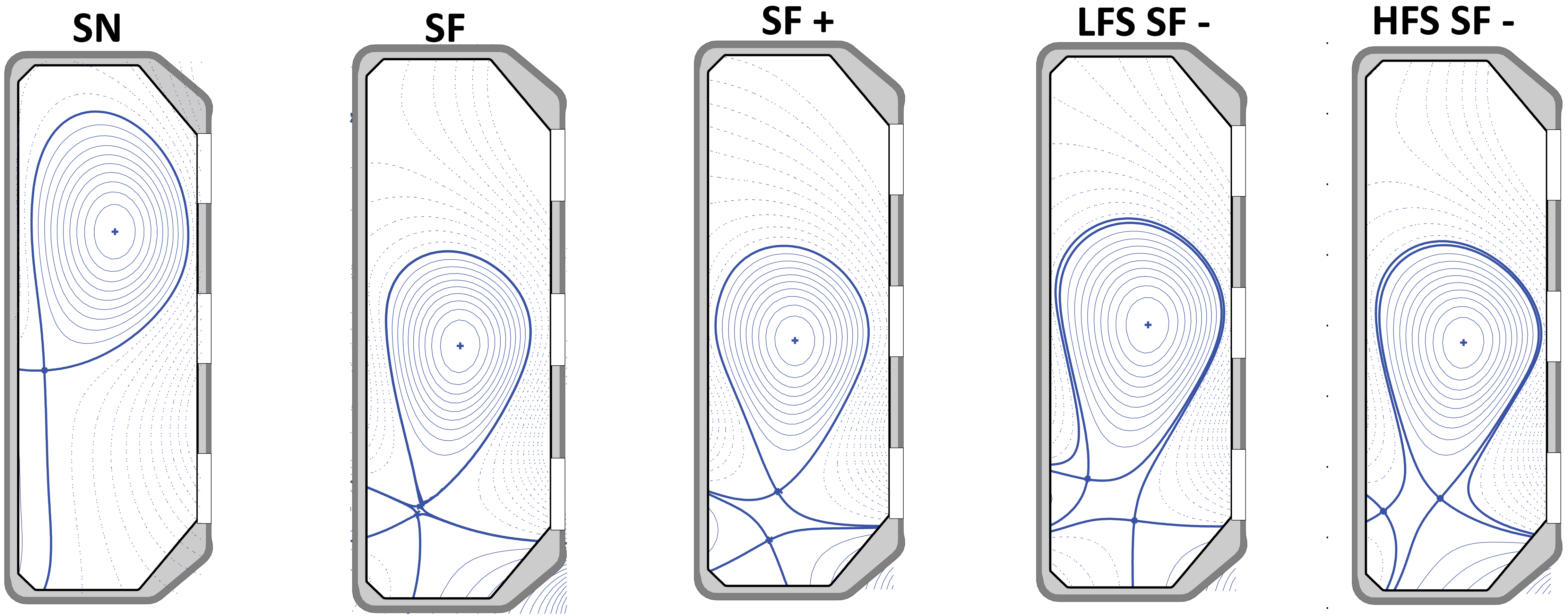
Some heat exhaust solutions: single-null and snowflake



- How does the heat flux depend on the topology?
- How does the heat flux depend on the power?

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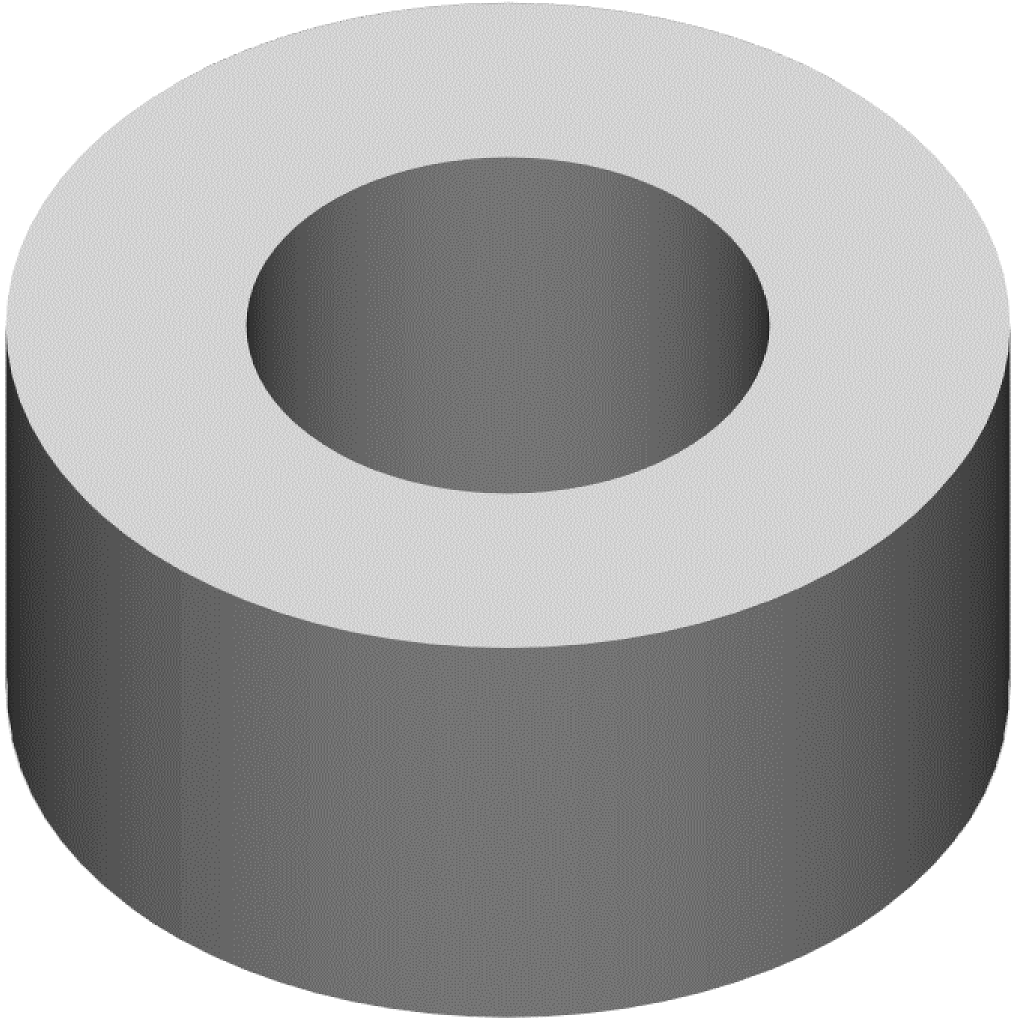
The GBS code



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Drift-reduced Braginskii equations

Collisional plasma → **Braginskii model** → $\rho_i \ll L$, $\omega \ll \Omega_{ci}$ → **Drift-reduced Braginskii equations**

$$\frac{\partial n}{\partial t} = \underbrace{-\frac{R_0}{B}[\phi, n]}_{E\times B\ \text{CONVECTION}} + \underbrace{\frac{2}{B}\Big[C(p_e) - nC(\phi)\Big]}_{\text{DIAMAGNETIC DRIFT}} - \underbrace{\nabla_\parallel (n v_{\parallel e})}_{\text{PARALLEL FLOW}} + \underbrace{S_n}_{\text{SOURCE}}$$

$T_e,\ T_i$ ➡ similar equations

$$\underbrace{\frac{\partial \nabla^2\phi}{\partial t} = -\frac{R_0}{B}[\phi, \nabla^2\phi]}_{\text{POLARIZATION CURRENT}} + \underbrace{\frac{B^2}{n}\nabla_\parallel j_\parallel}_{\text{PARALLEL CURRENT}} + \underbrace{\frac{2B}{n}C(p)}_{\text{DIAMAGNETIC CURRENT}} + \dots$$

$v_{\parallel e},\ v_{\parallel i}$ ➡ Parallel momentum balance

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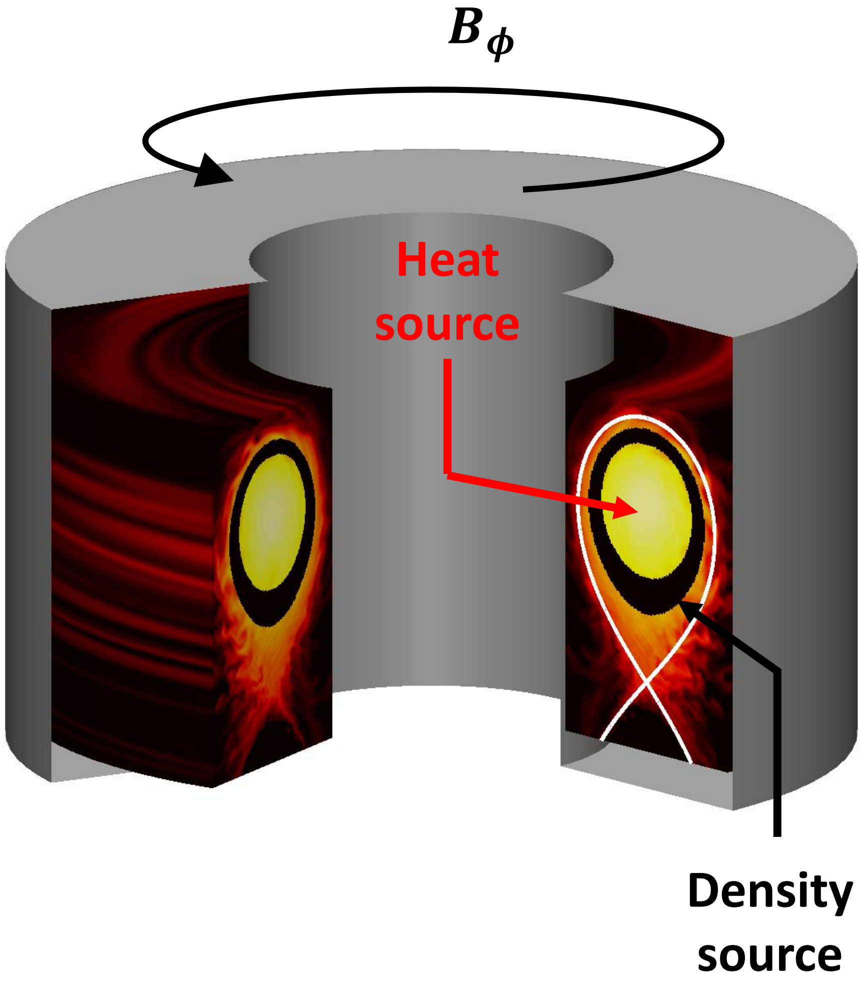
The GBS code

- Arbitrary magnetic configurations
- 4th order centered finite difference scheme in non-field aligned grid
- 4th order Runge-Kutta time stepping method
- Magnetic pre-sheath boundary conditions at the target plates
- Here: no coupling with neutrals
- Heat and density sources in the core



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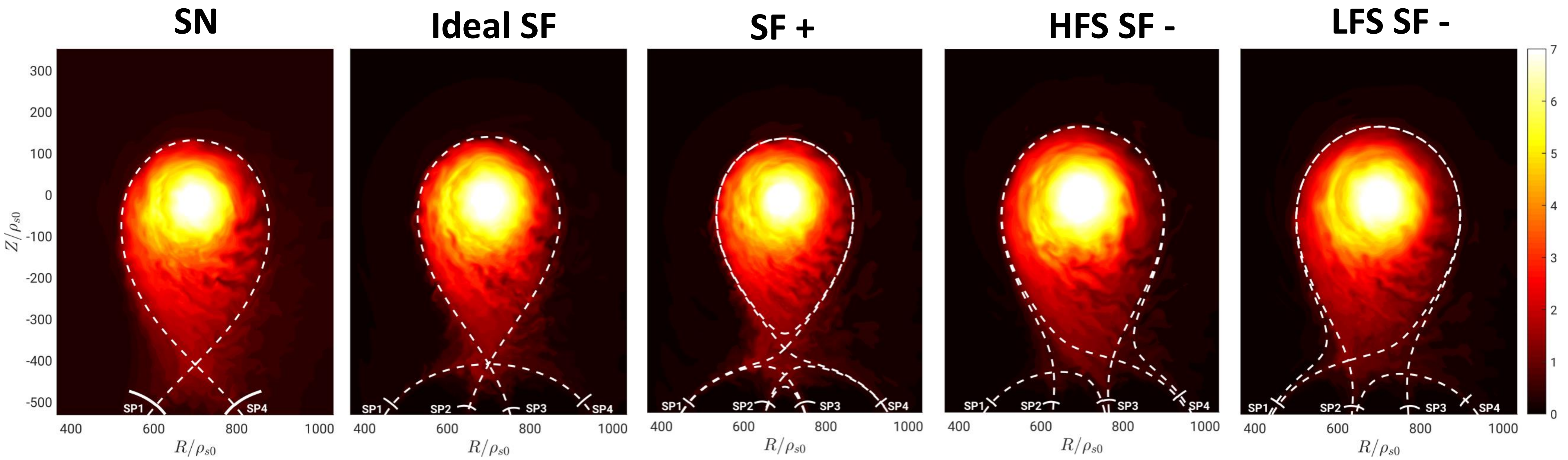
Considered magnetic configurations



- How does the heat flux depend on the topology?
- How does the heat flux depend on the power?

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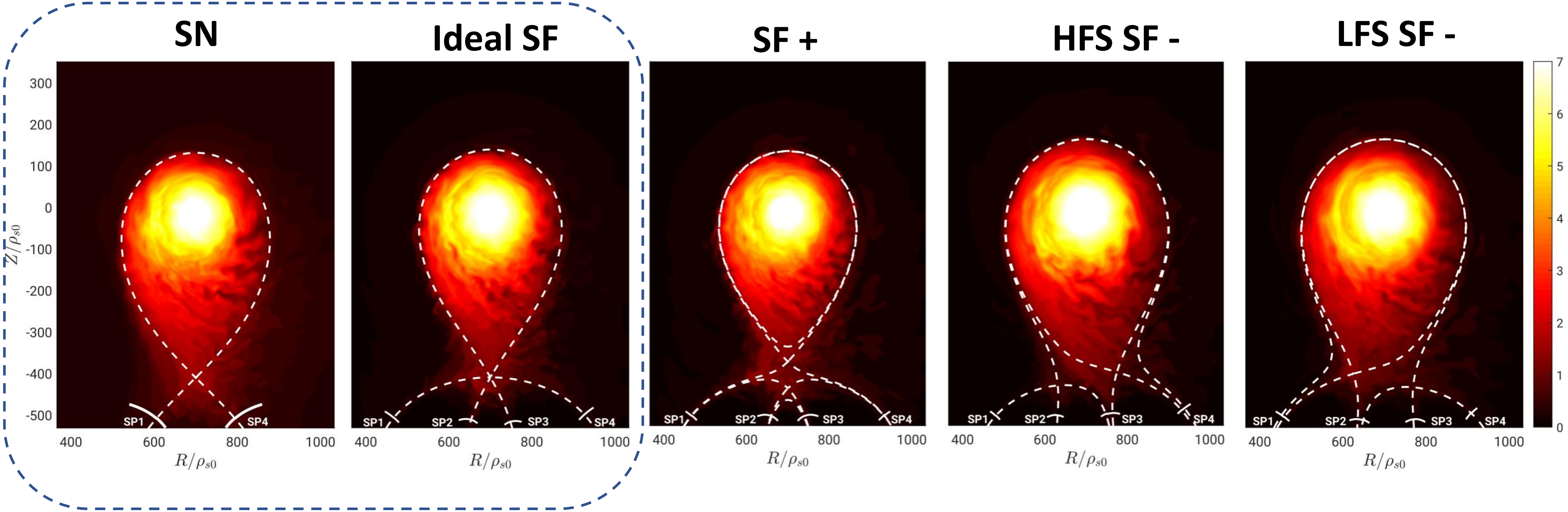
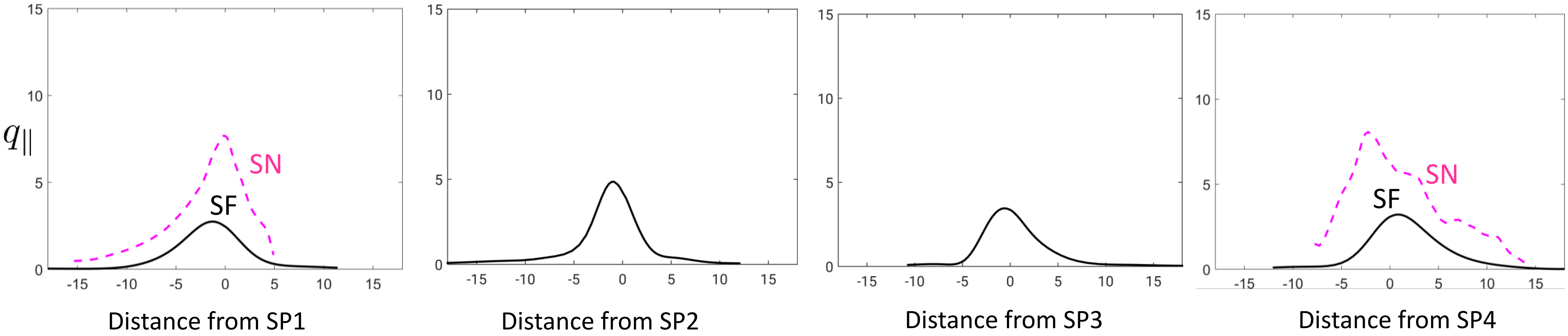
Effect of topology



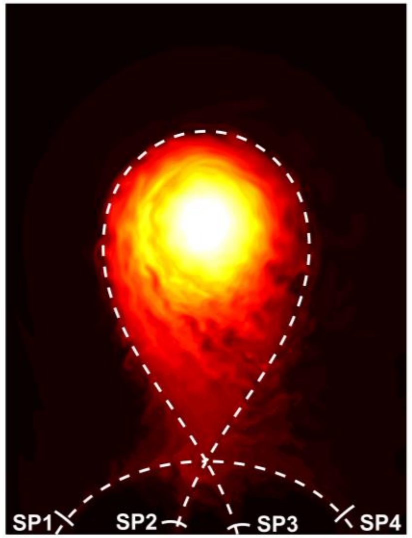
[M. Giacomin *et al.*, Submitted to Nucl. Fusion]

Uniform heat flux redistribution in the ideal SF



- **Uniform redistribution on SP1, SP2, SP3, and SP4**
- **Peak of the heat flux reduced w.r.t. SN**

Why are the unconnected SPs activated?



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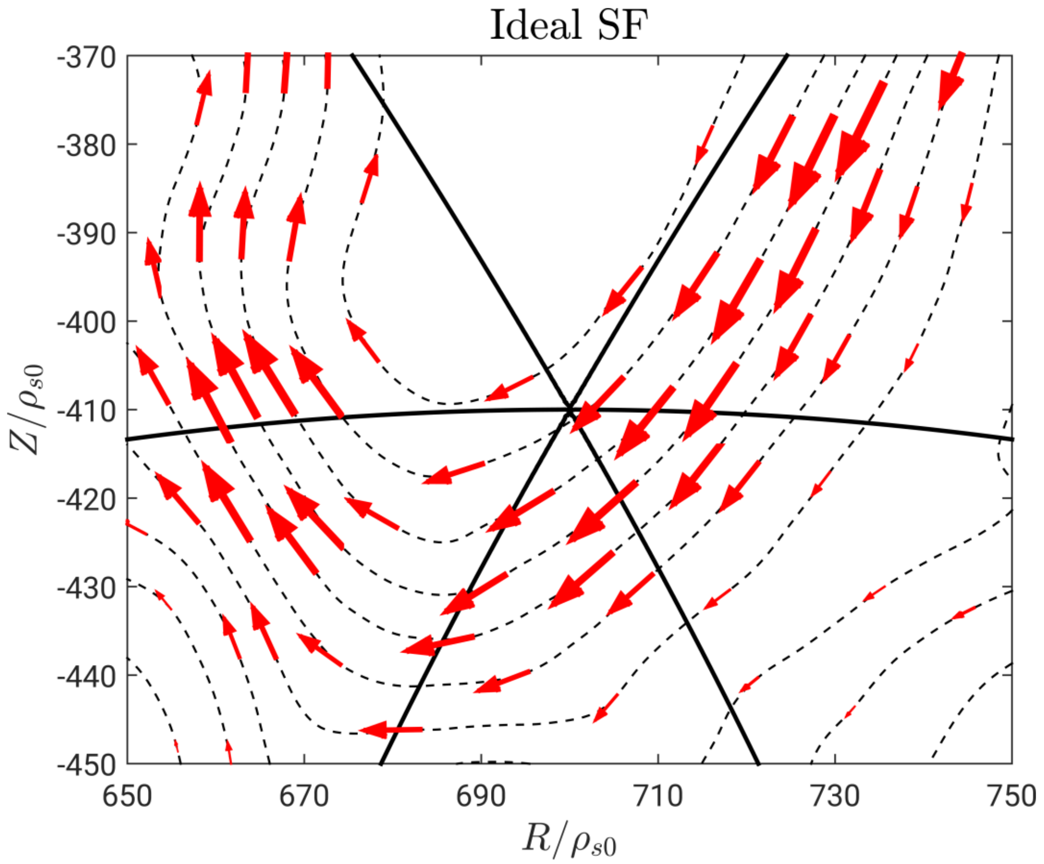
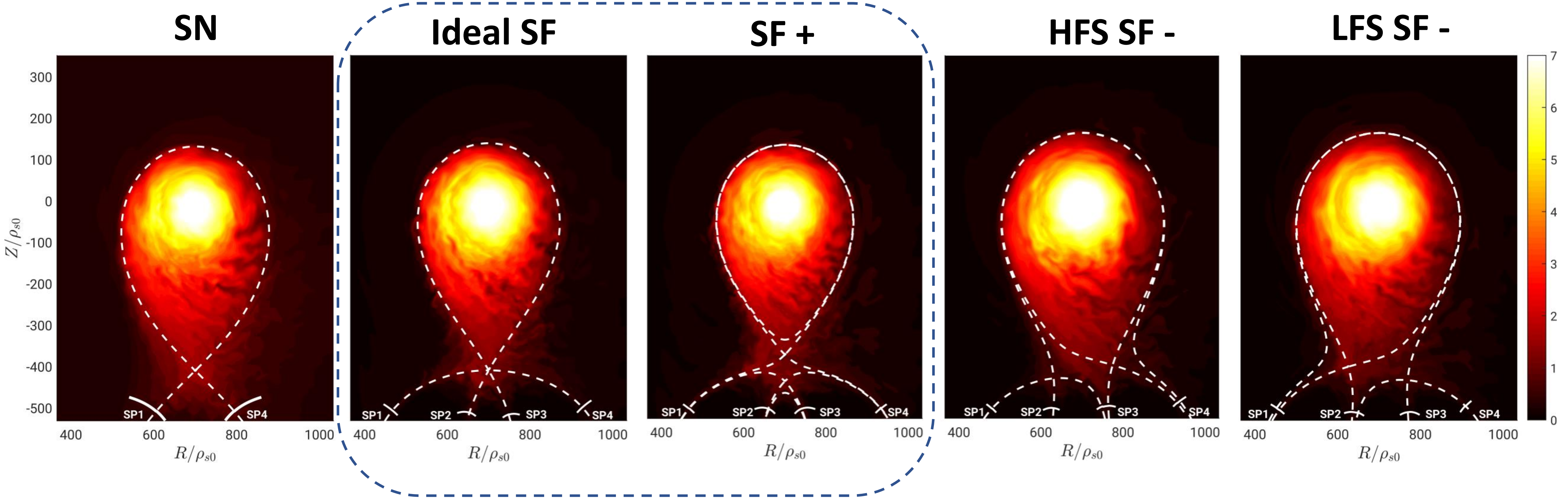
Convective $\boldsymbol{E} \times \boldsymbol{B}$ cell around the null-point

$\mathbf{q}_E^{eq} = \overline{p_e \mathbf{v_E}} \approx \bar{p}_e \bar{\mathbf{v}}_\mathbf{E}$ (turbulent component is negligible)



Effect of topology



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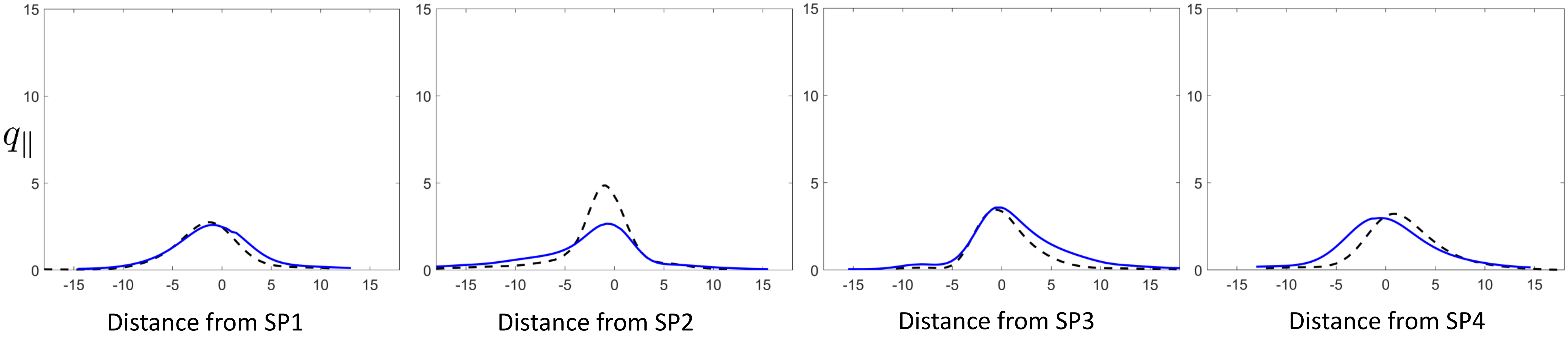
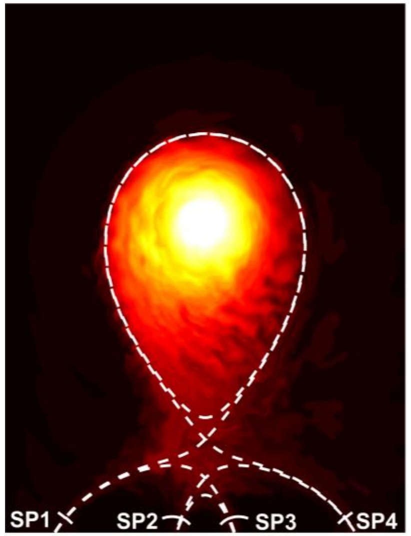
Uniform heat flux redistribution in the SF+

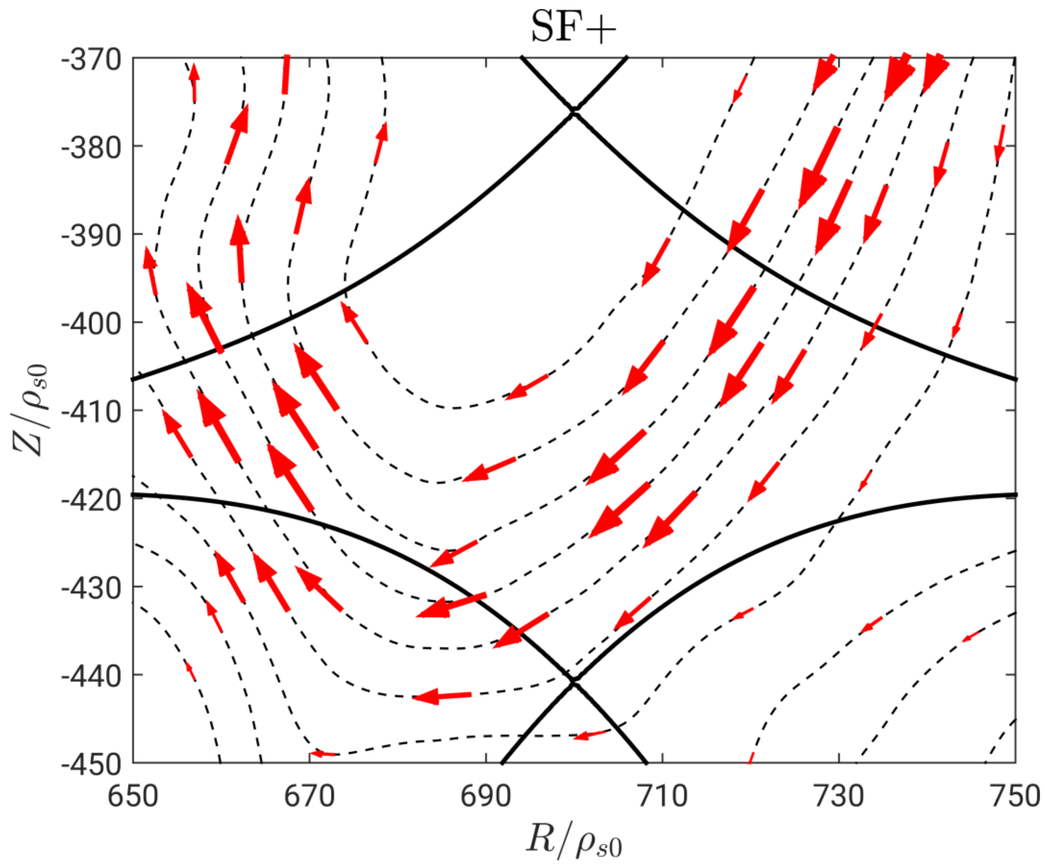


- **Unconnected SPs activated**
- **Reduction on SP2 (40%)**



Convective $\boldsymbol{E} \times \boldsymbol{B}$ cell in the null-region

$$\mathbf{q}_E^{eq} = \overline{p_e \mathbf{v_E}} \approx \bar{p}_e \bar{\mathbf{v}}_\mathbf{E}$$ (turbulent component is negligible)



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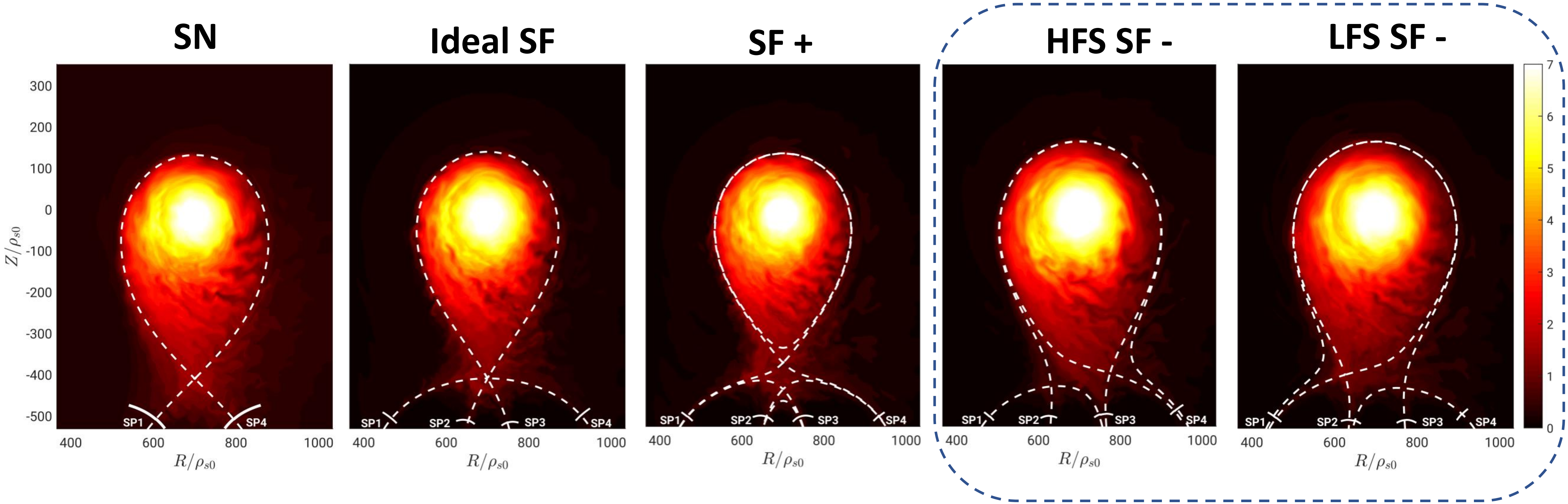
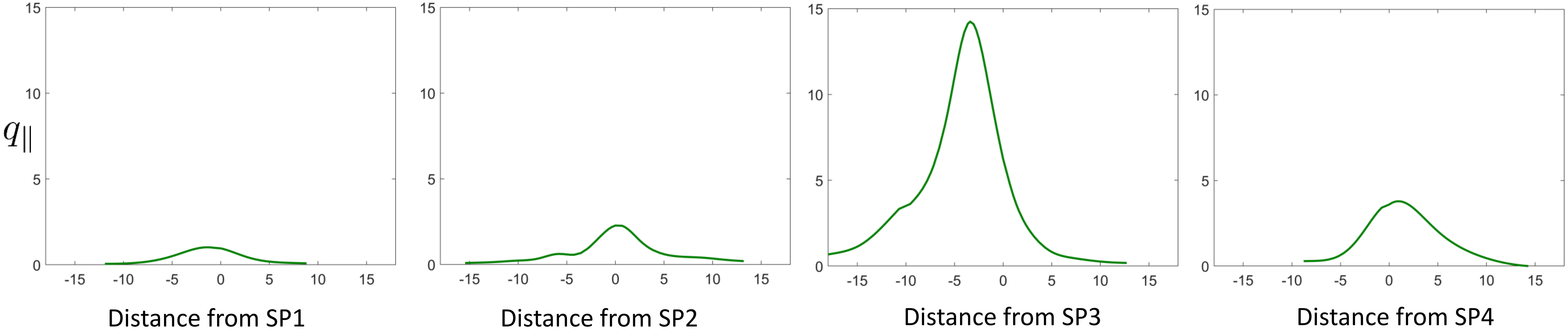
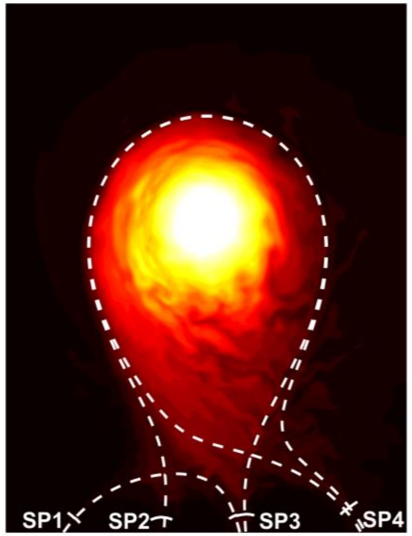
Effect of topology



Parallel heat flux distribution in the HFS SF-



- **Heat flux on primary SPs**
- **SP1 and SP2 are only marginally activated**



What is the sharing of the flux among the HFS SPs?

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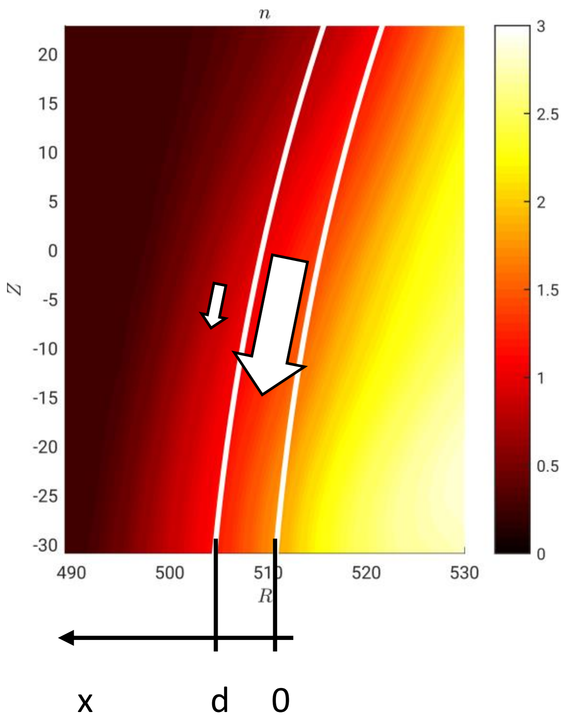
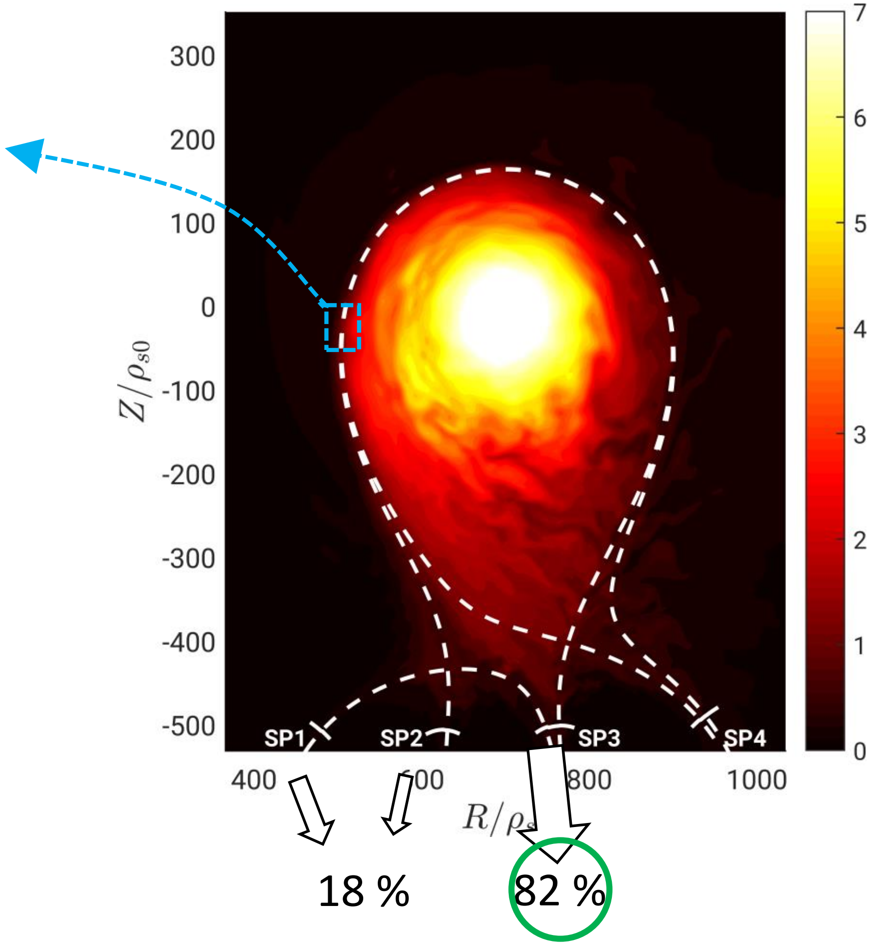
Role of the secondary X-point: HFS SF-

$$f_{SP3} = \frac{\int_0^d \Gamma_{\|}(x)\mathrm{d}x}{\int_0^{+\infty} \Gamma_{\|}(x)\mathrm{d}x} = 85\%$$

The agreement is good





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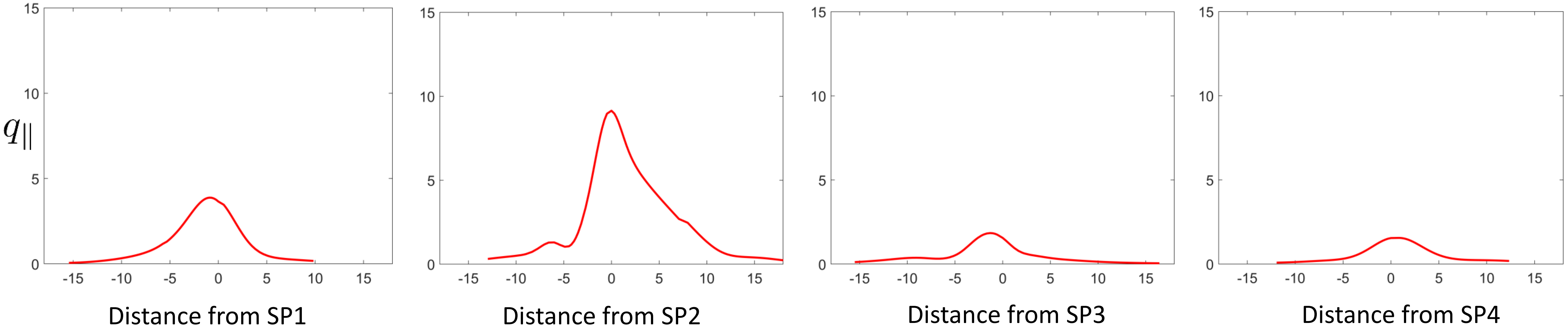
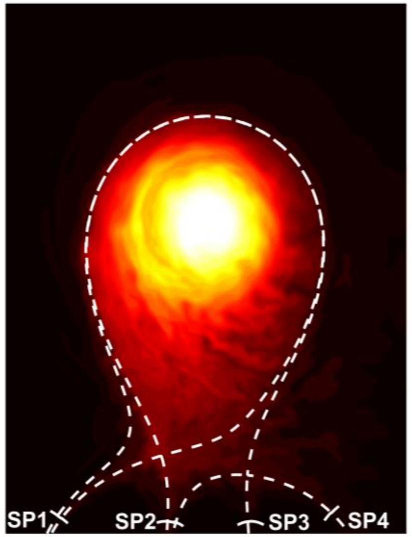
Parallel heat flux distribution in the LFS SF-

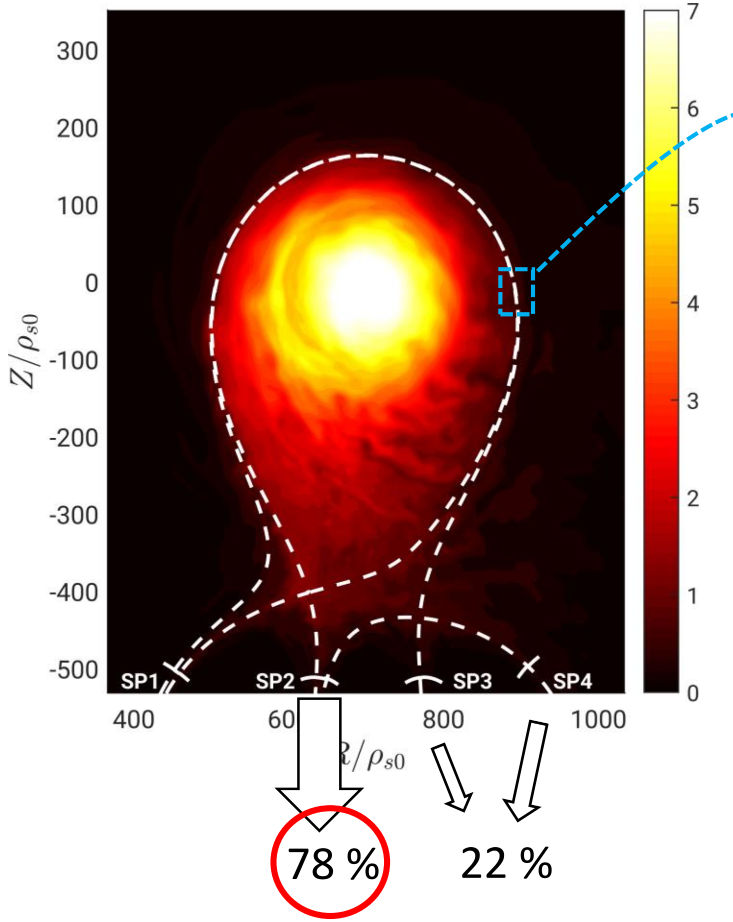


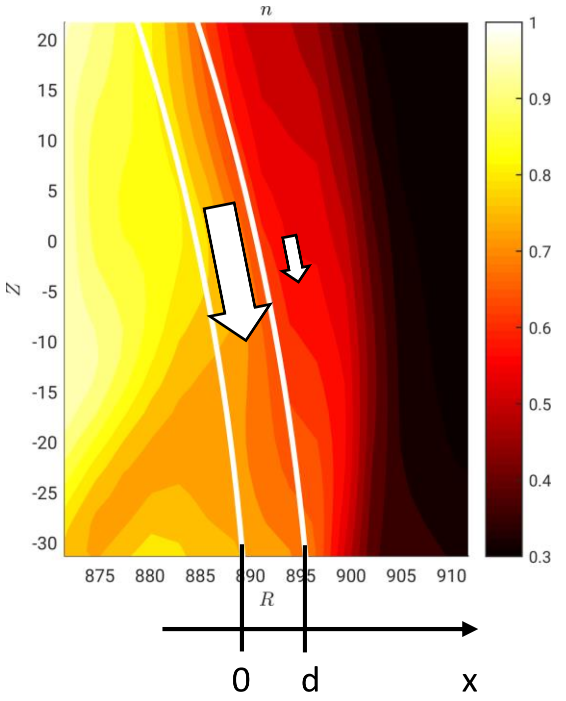
- **Heat flux on primary SPs**
- **SP3 and SP4 are only partially activated**



What is the sharing of the flux among the LFS SPs?

Role of the secondary X-point: LFS SF-



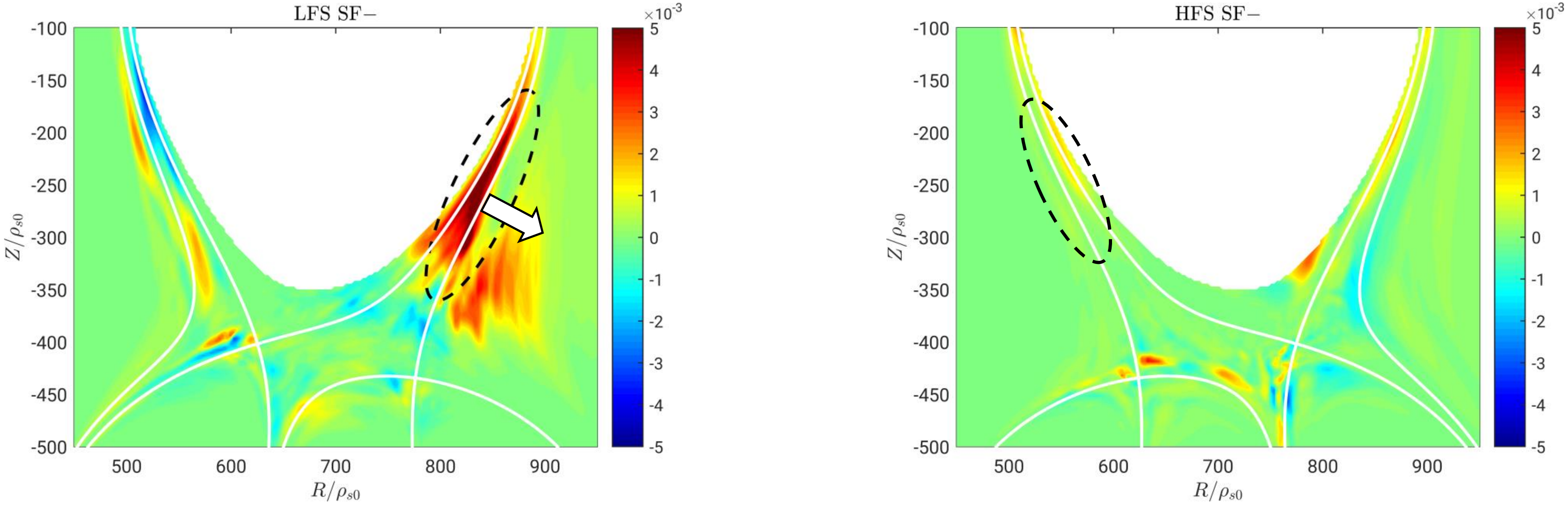


$$f_{SP2} = \frac{\int_0^d \Gamma_\parallel(x)\mathrm{d}x}{\int_0^{+\infty} \Gamma_\parallel(x)\mathrm{d}x} = 87\%$$

A small amount of heat flux seems to cross the secondary separatrix

Strong turbulent transport in the LFS SF-

$$\mathbf{q}_E^t \cdot \frac{\nabla\psi}{||\nabla\psi||} = \overline{\tilde{p}_e \tilde{\mathbf{v}}_\mathbf{E}} \cdot \frac{\nabla\psi}{||\nabla\psi||}$$



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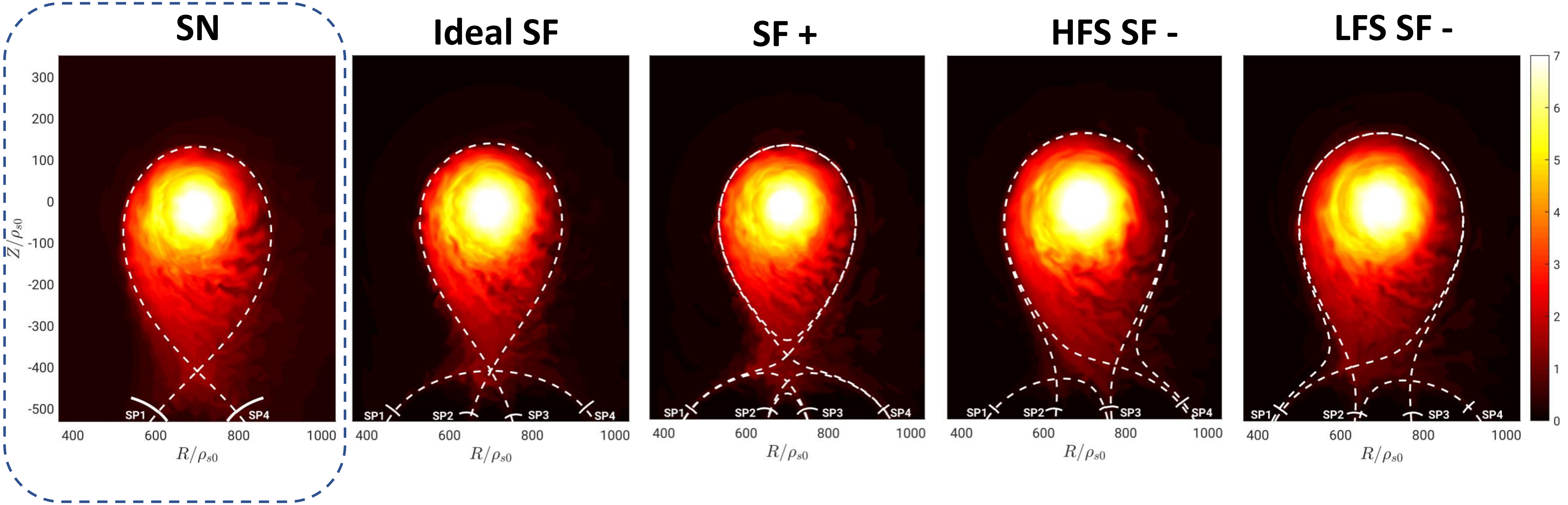
Effect of heat source at fixed topology



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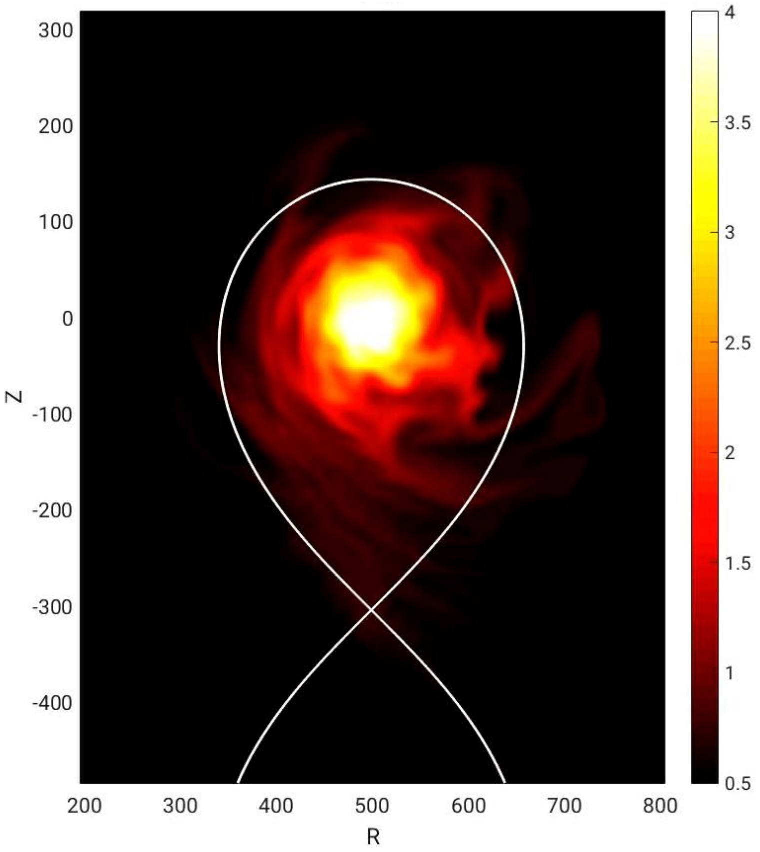
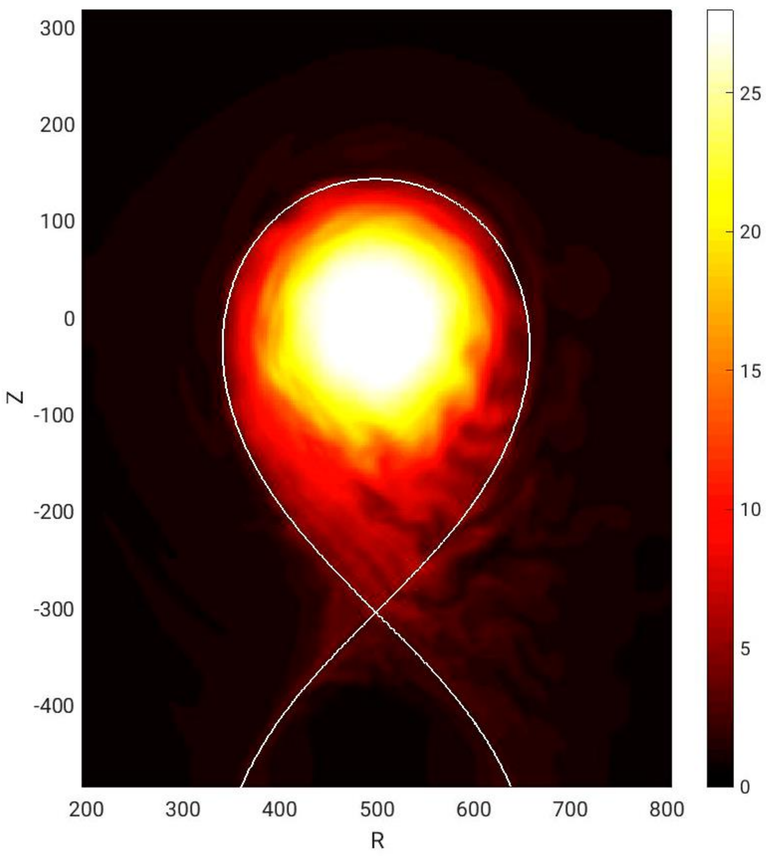
Dependence on the heat source

Heat source





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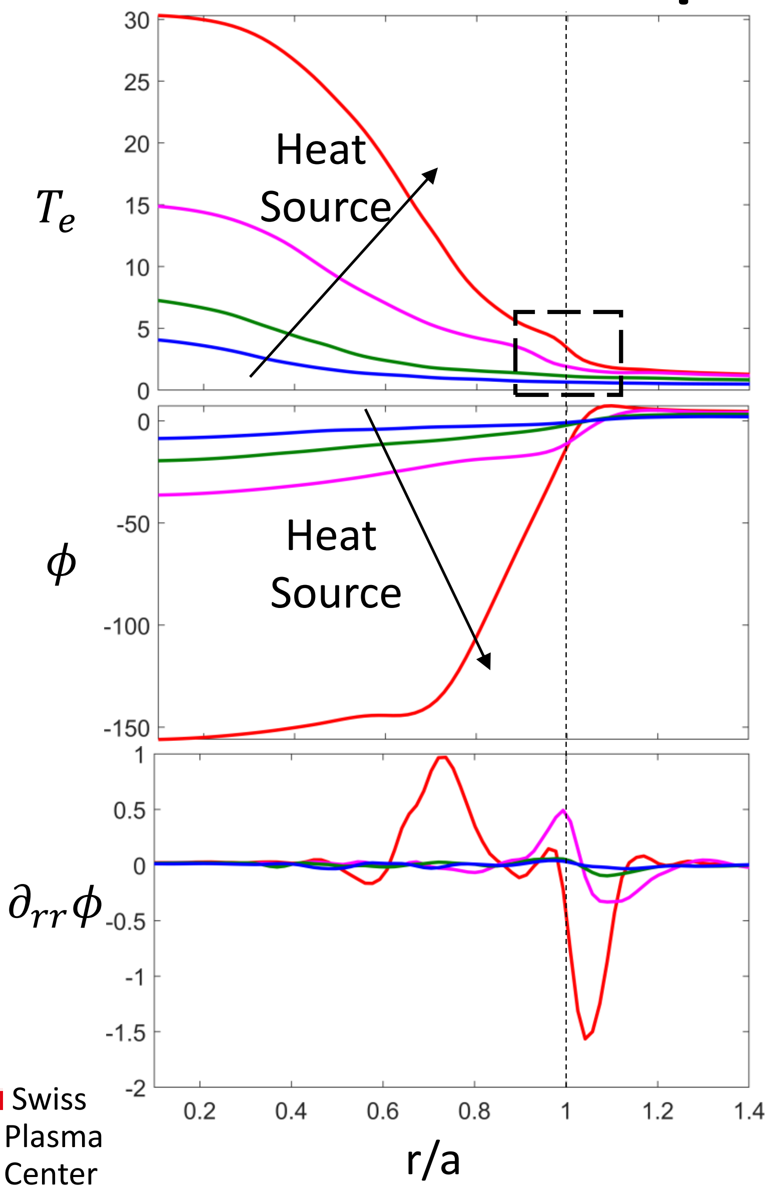
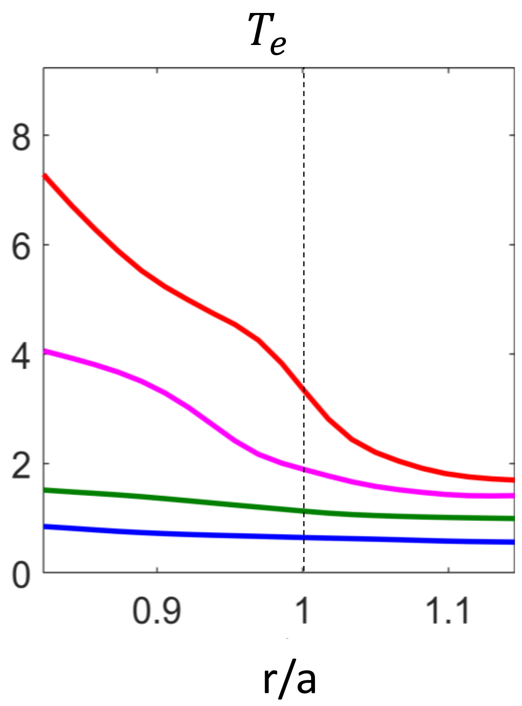
Dependence on the heat source





- Heat source increases and temperature becomes steeper in the edge
- Electrostatic potential decreases
- Strong $E \times B$ shear in the edge and formation of transport barrier

Which are the mechanisms determining the transport?

Low heat source

High heat source

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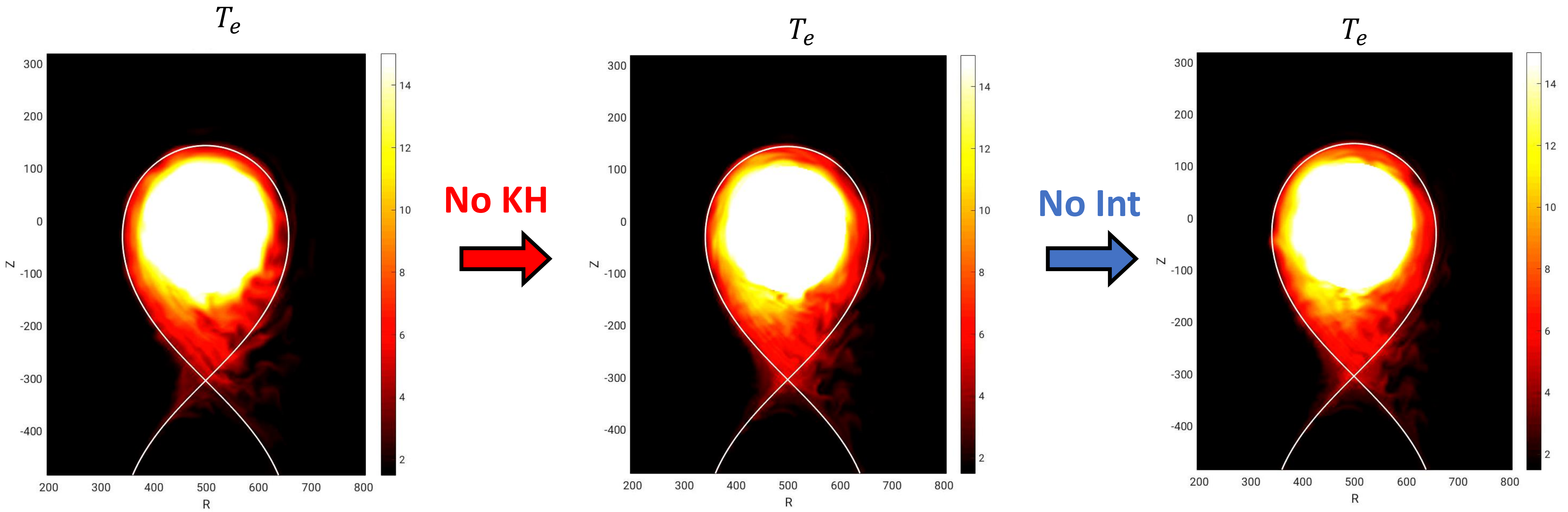
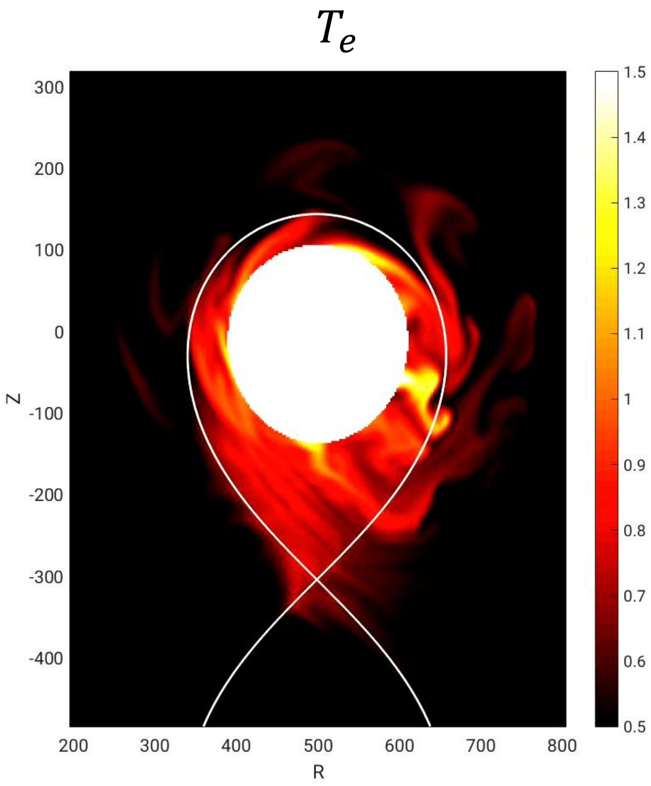
Kelvin-Helmholtz instability at high source values

$$\frac{\partial}{\partial t}\left(\nabla_\perp^2\phi+\tau\nabla_\perp^2 T_i\right) = -\frac{R_0}{B\rho_{s0}}\left[\phi,\nabla_\perp^2\phi\right]-\tau\frac{R_0}{B\rho_{s0}}\left[\phi,\nabla_\perp^2 T_i\right]+\frac{B^2}{n}\nabla_\parallel j_\parallel+\frac{2B}{n}C(p)+\cdots$$

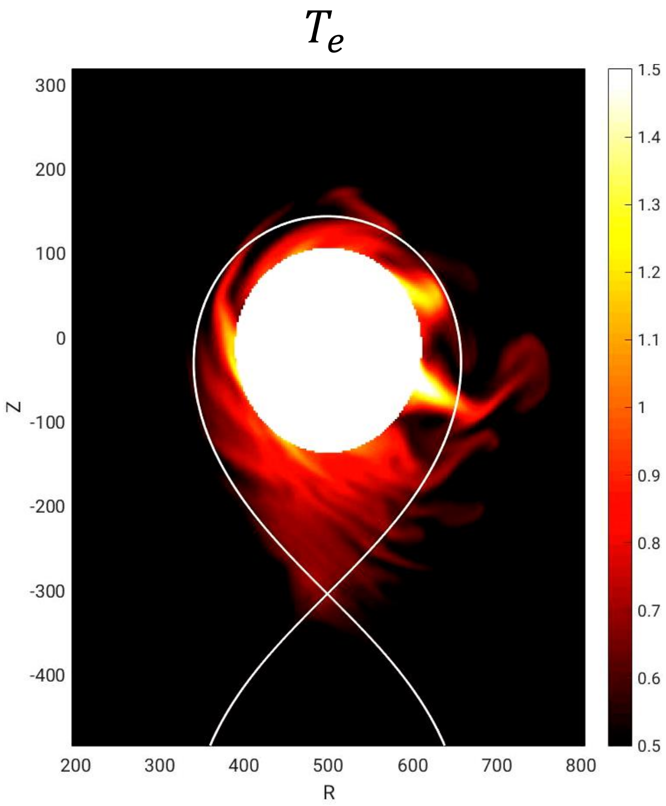


Interchange instability at low source values

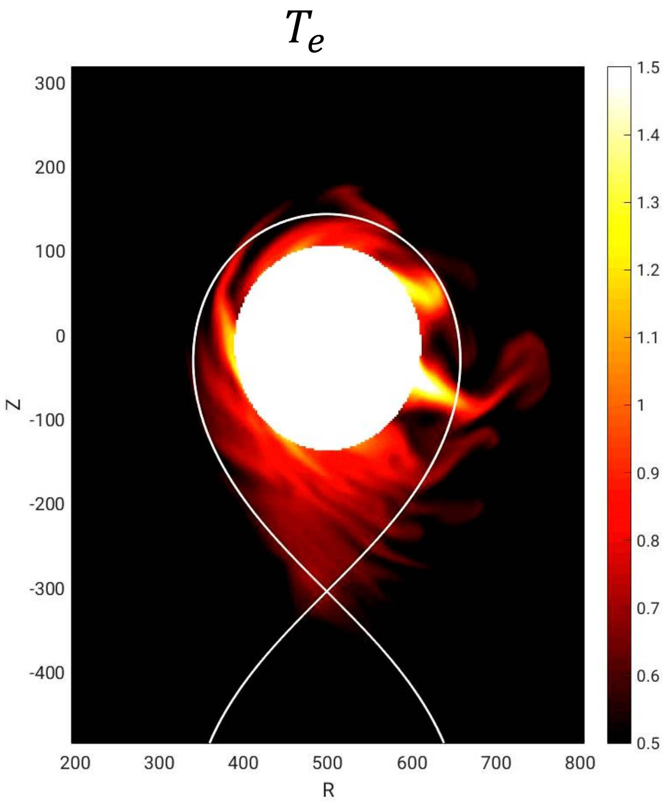
$$\frac{\partial}{\partial t}\left(\nabla_\perp^2\phi+\tau\nabla_\perp^2 T_i\right) = \boxed{-\frac{R_0}{B\rho_{s0}}[\phi,\nabla_\perp^2\phi]} - \tau\frac{R_0}{B\rho_{s0}}[\phi,\nabla_\perp^2 T_i] + \frac{B^2}{n}\nabla_\parallel j_\parallel + \boxed{\frac{2B}{n}C(p)} + \cdots$$



No Int



No KH



Equilibrium pressure gradient estimate

Power crossing the separatrix = total heat source

$$\oint_{\chi(\Psi_1)} q_\Psi \, \mathrm{d}\chi = S_{\mathrm{TOT}}$$

Perpendicular turbulent heat flux

$$q_\Psi = \frac{\gamma}{k_\Psi^2} \frac{p_{e0}}{L_p} \frac{1}{R_0}$$

$$L_p^{\mathrm{INT}} \sim (\nu q^2 n_0)^{2/3} \left(\frac{1}{2R_0}\right)^{1/3} \left(\frac{L_\chi}{S_{\mathrm{TOT}}}\right)^{4/3} T_{e0} p_{e0}^{4/3} \quad , \quad L_p^{\mathrm{KH}} \sim \frac{L_\chi}{2S_{\mathrm{TOT}}} p_{e0}^2$$

[P. Ricci *et al.*, PRL 2008]

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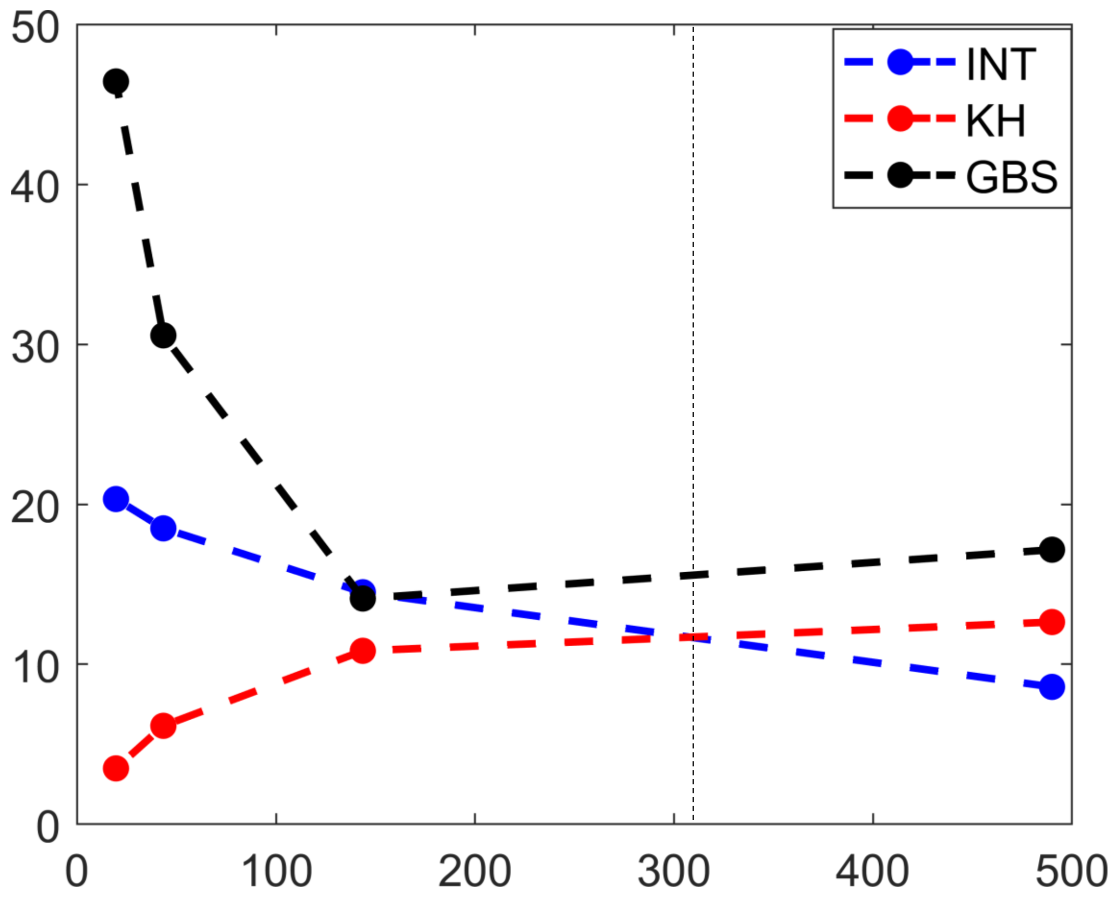
Equilibrium pressure gradient estimate

- **Low heat source:** transport due to resistive ballooning mode and small pressure gradient (large L_p)
- **High heat source:** transport due to Kelvin-Helmholtz and large pressure gradient (small L_p)
- **Intermediate heat source:** transport due to resistive ballooning mode and Kelvin-Helmholtz, transition between the two regimes

$$L_p = \left(\frac{\partial}{\partial r}\log p\right)^{-1}$$



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Conclusions

- **Dependence of heat flux on the magnetic topology**
  - **Ideal snowflake**
    - Uniform heat flux distribution among the four strike points
    - Peak heat flux reduced w.r.t. the single-null
    - Equilibrium $E \times B$ convective cell allows for activation of the unconnected strike points
  - **Snowflake plus**
    - Almost uniform heat flux distribution among the four strike points
    - Effect of the $E \times B$ convective cell reduced w.r.t. the ideal configuration
  - **Snowflake minus**
    - Secondary strike points only marginally activated
    - No activation through the equilibrium $E \times B$ convective cell
    - Turbulent transport in the LFS SF-
- **Dependence on the heat source**
  - Two transport regimes that regulate the pressure gradient: interchange and Kelvin-Helmholtz