

The collisional layer connecting bulk fluid plasma with the kinetic sheath

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Exhaust workshop 2026

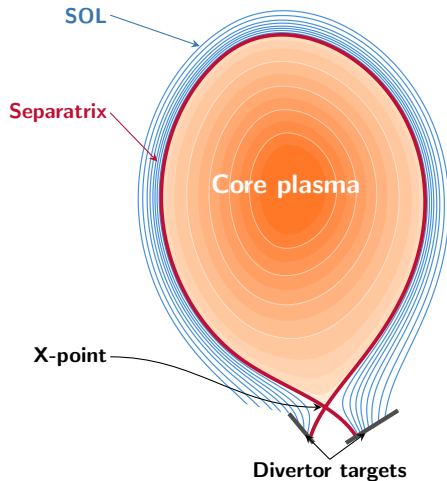


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Fluid SOL codes need boundary conditions at the wall

- ▶ SOL is cold and dense: $\lambda_{MFP} \ll L_{\parallel}$
 $\Rightarrow$ Braginskii fluid codes
- ▶ Field lines hit the divertor at a small angle α
- ▶ TCV-X21: codes tuned to upstream separatrix n , T_e match the midplane, **worse at the targets** — sensitive to **sheath boundary conditions** (Oliveira *et al.* 2022)

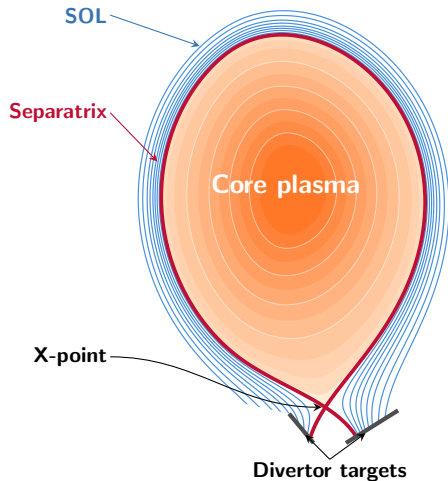
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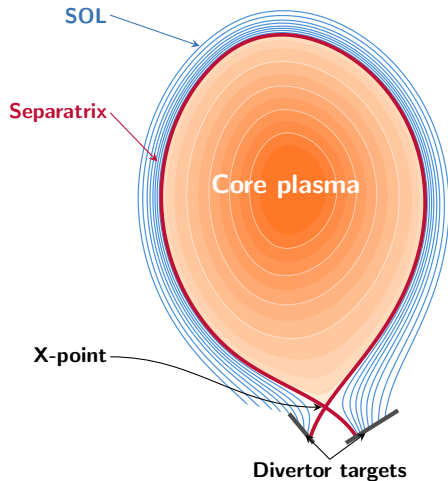
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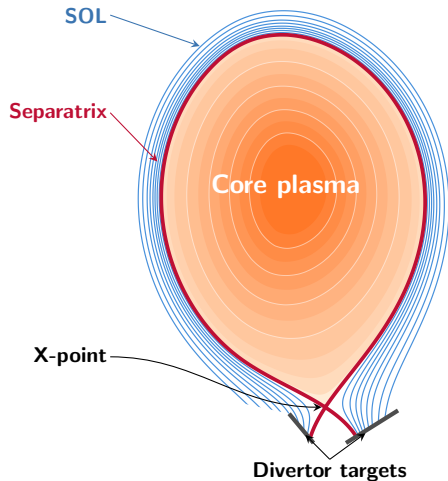
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Blind SOL layers need boundary conditions the break down

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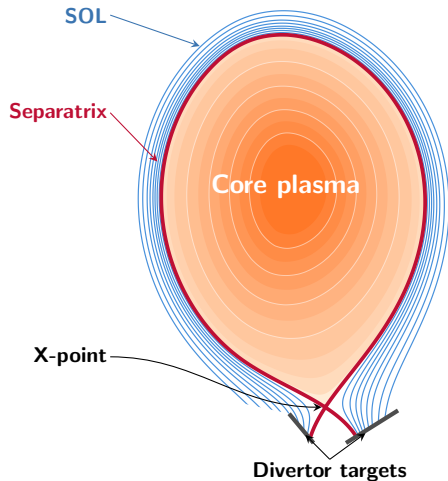
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Boundary layers: where fluid SOL approximations break down

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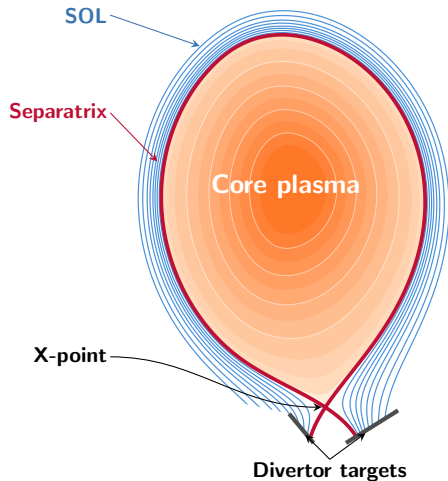
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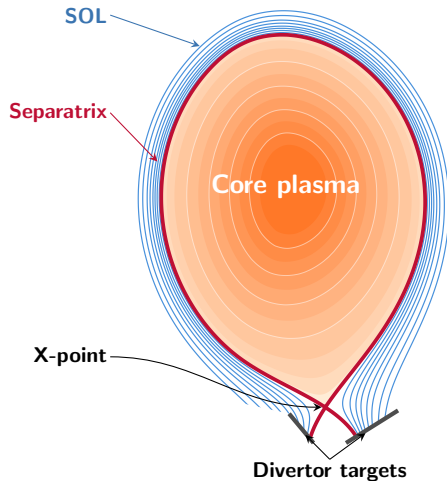
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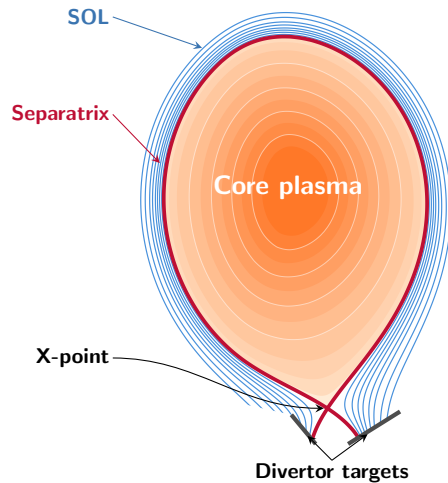
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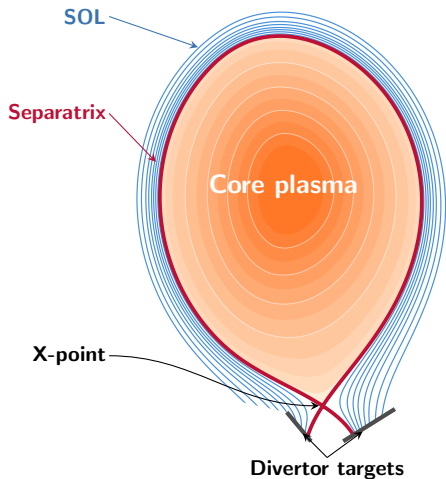
Boundary layers: where fluid SOL approximations break down



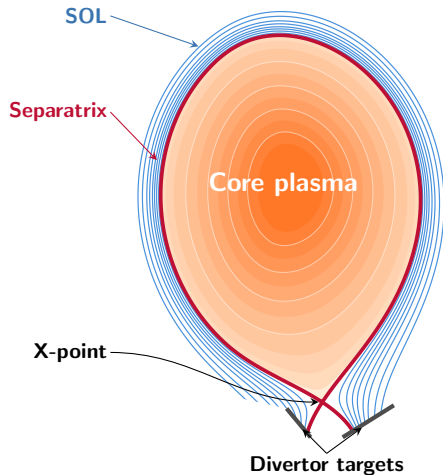
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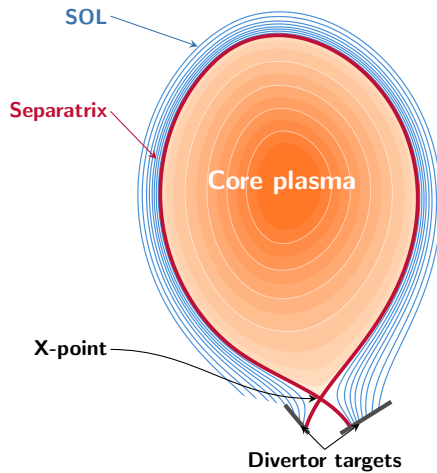
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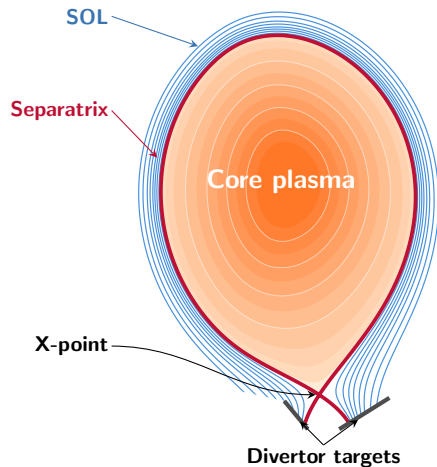
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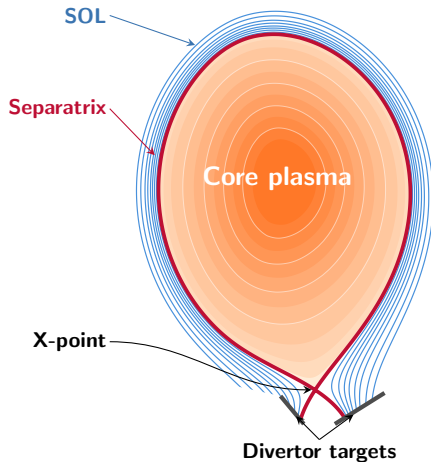
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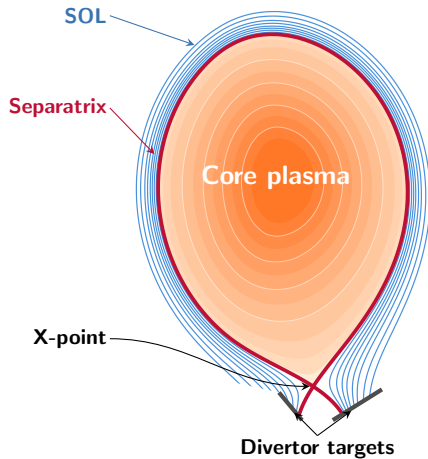
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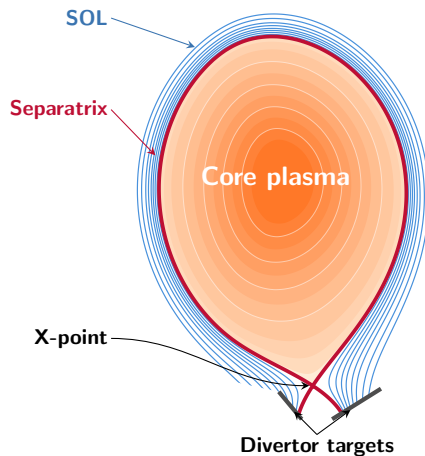
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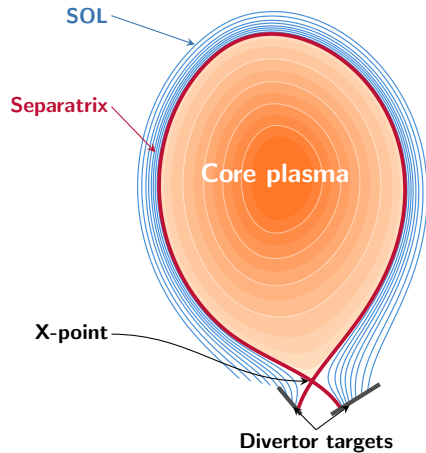
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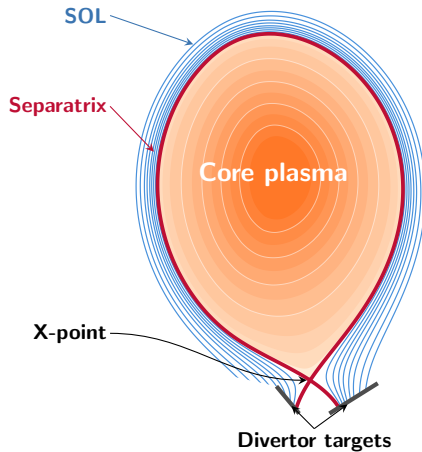
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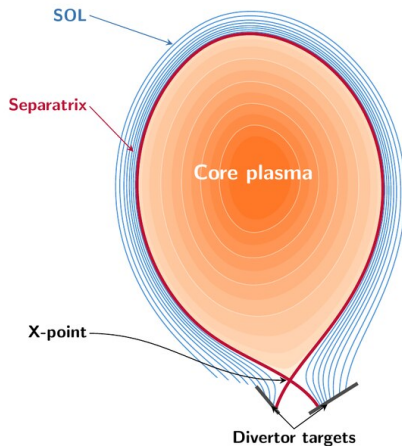
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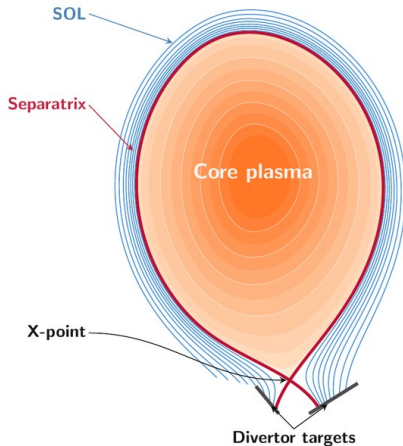
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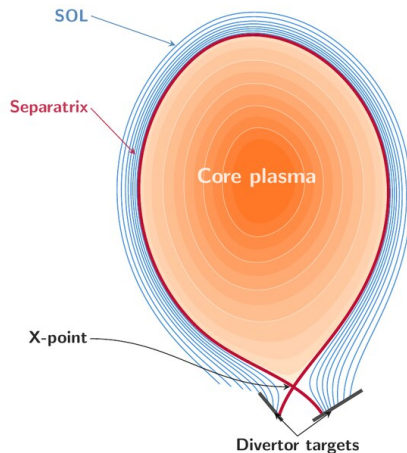
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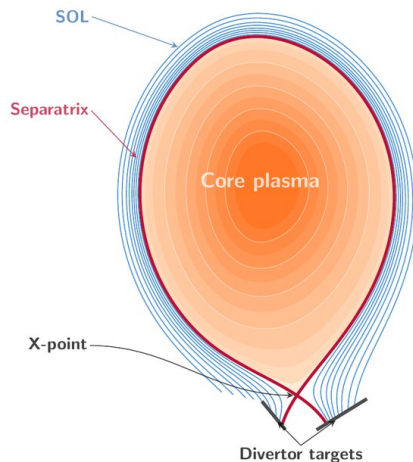
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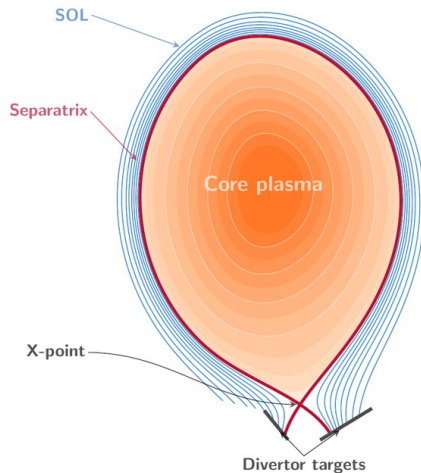
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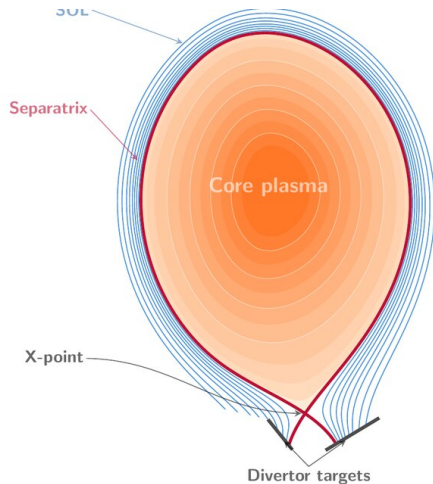
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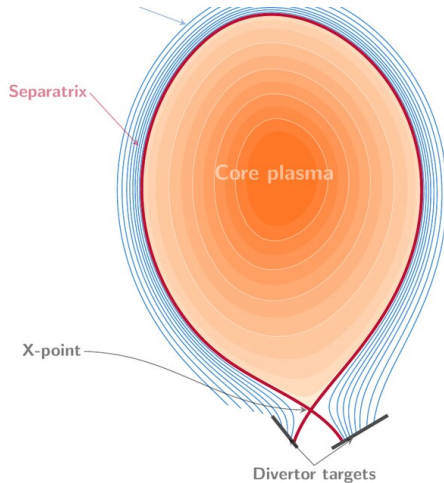
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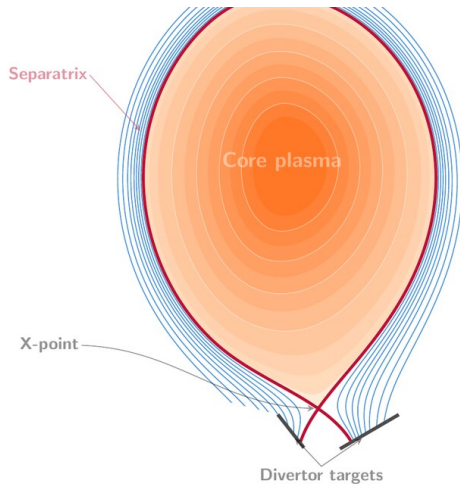
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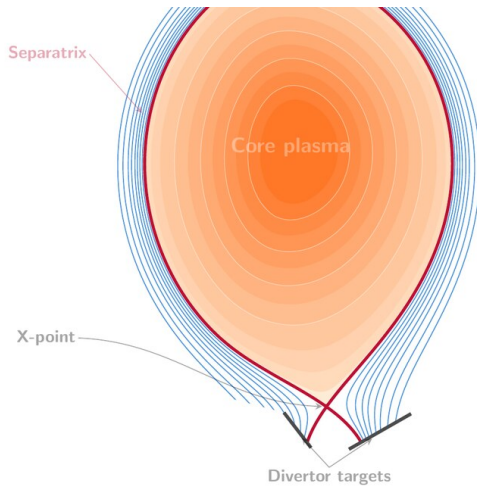
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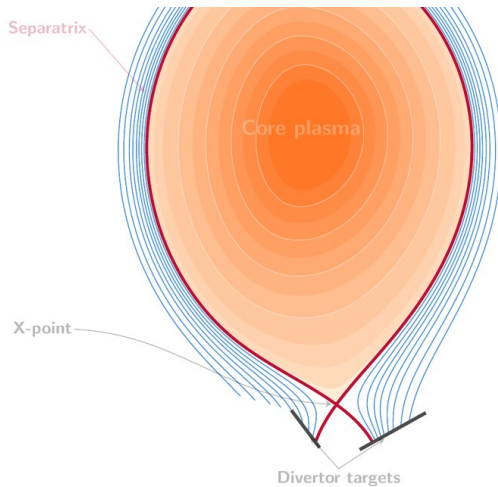
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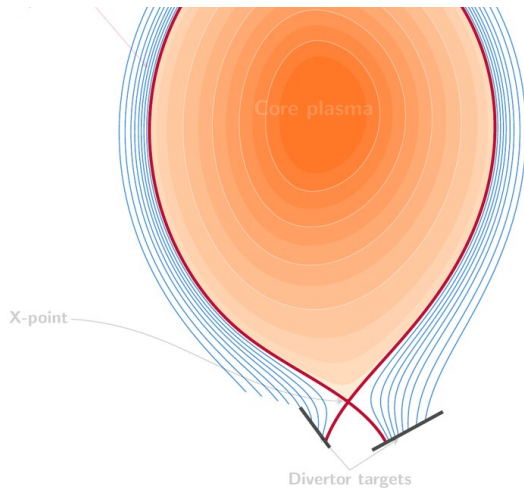
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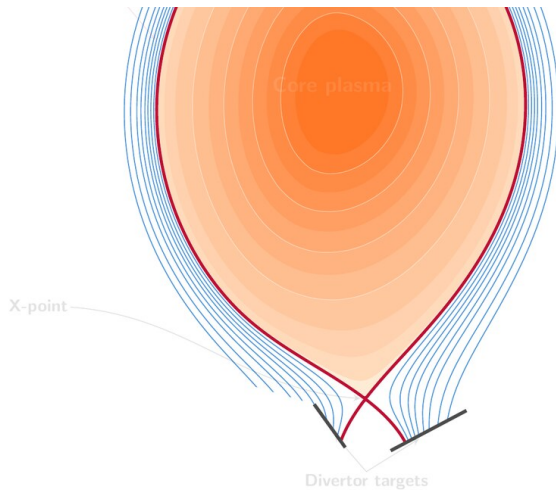
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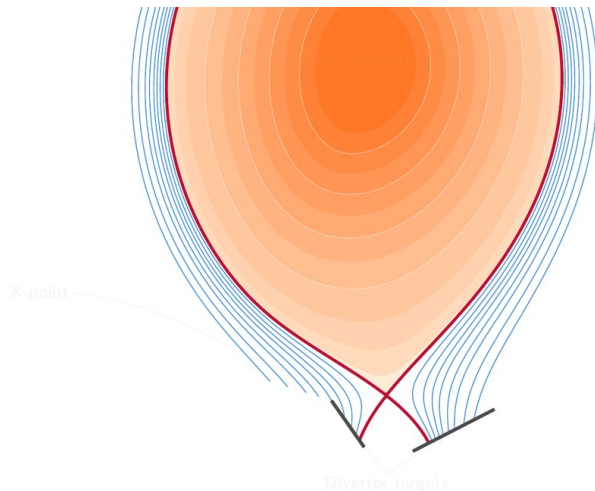
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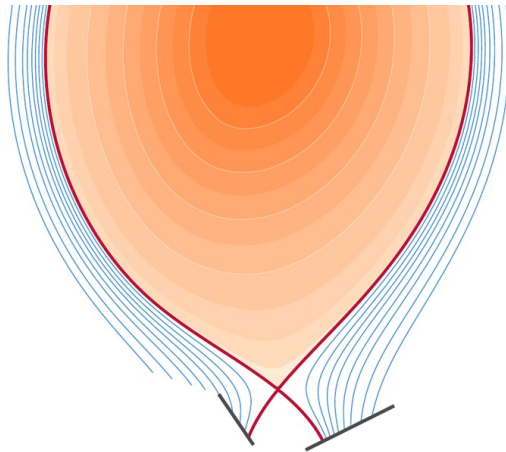
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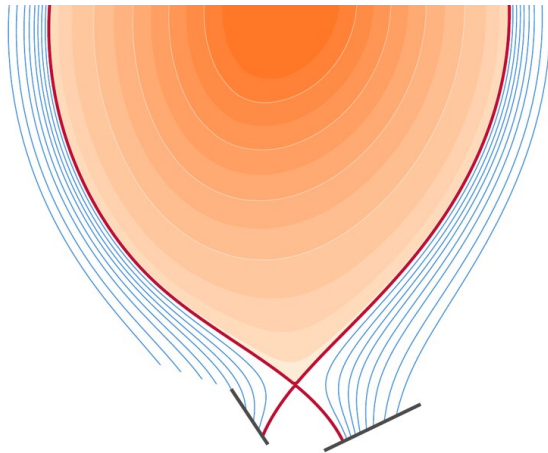
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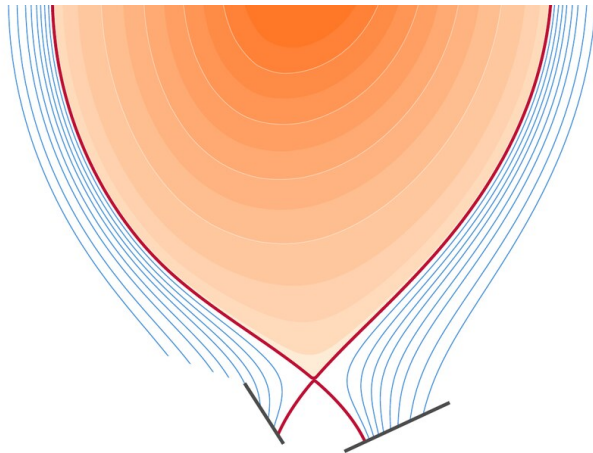
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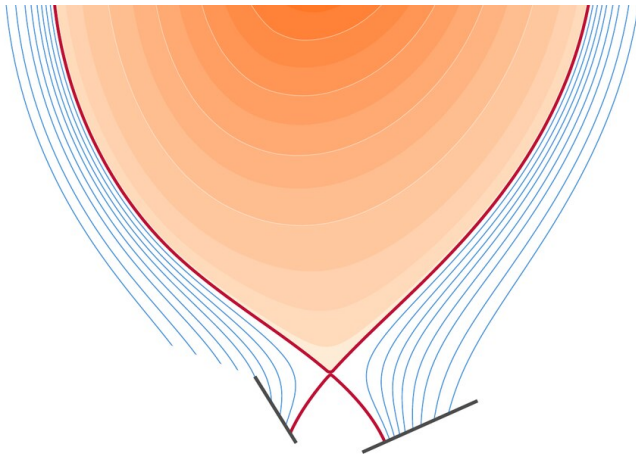
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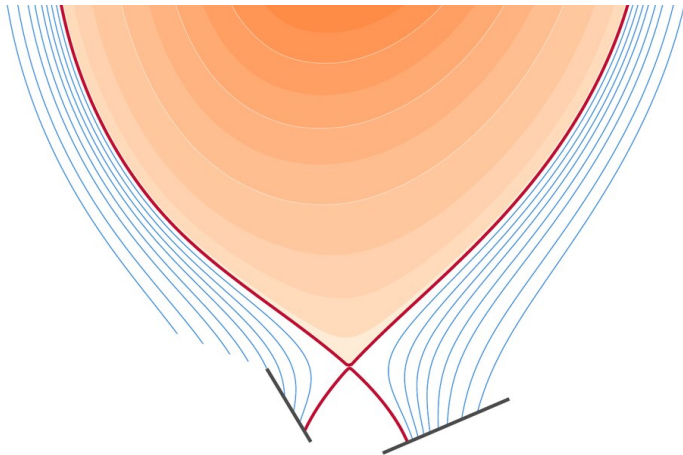
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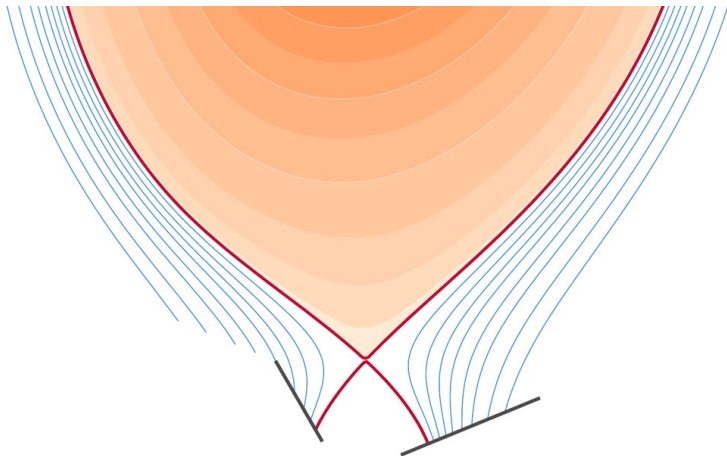
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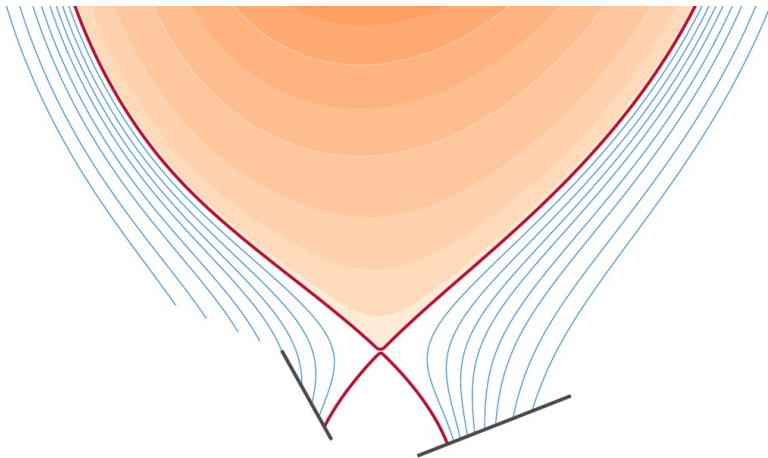
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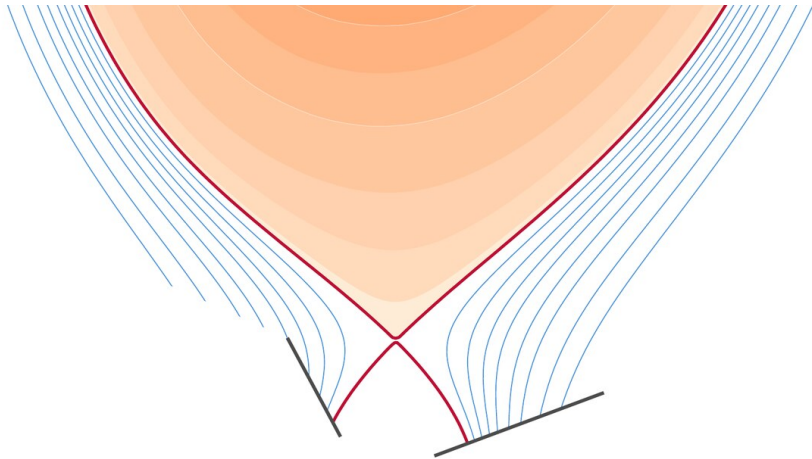
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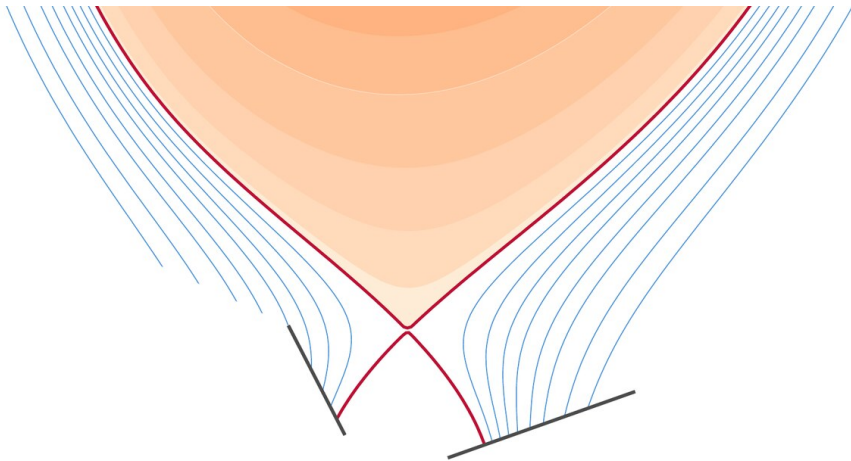
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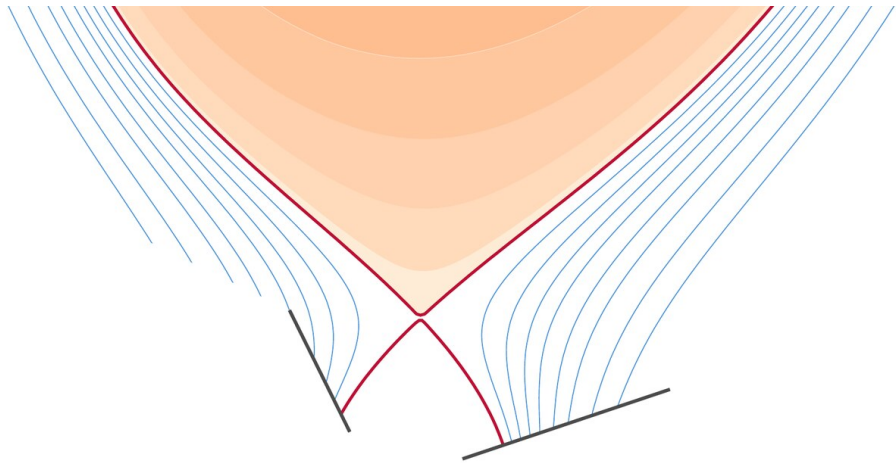
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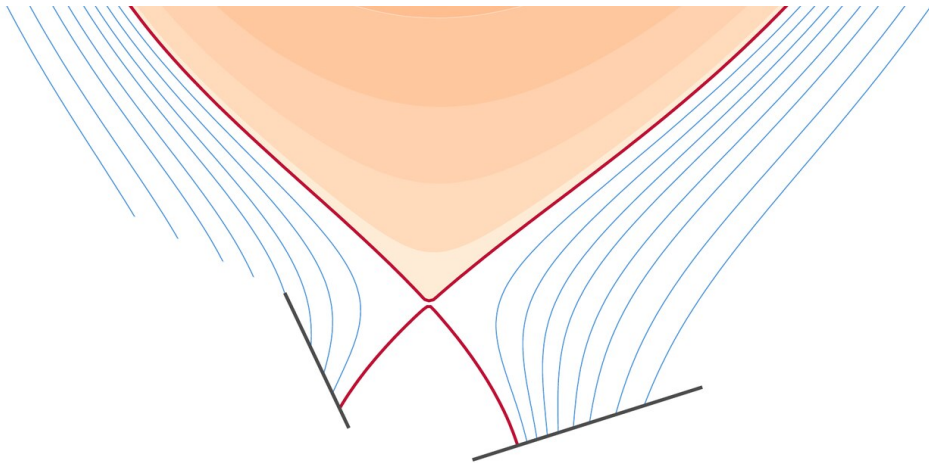
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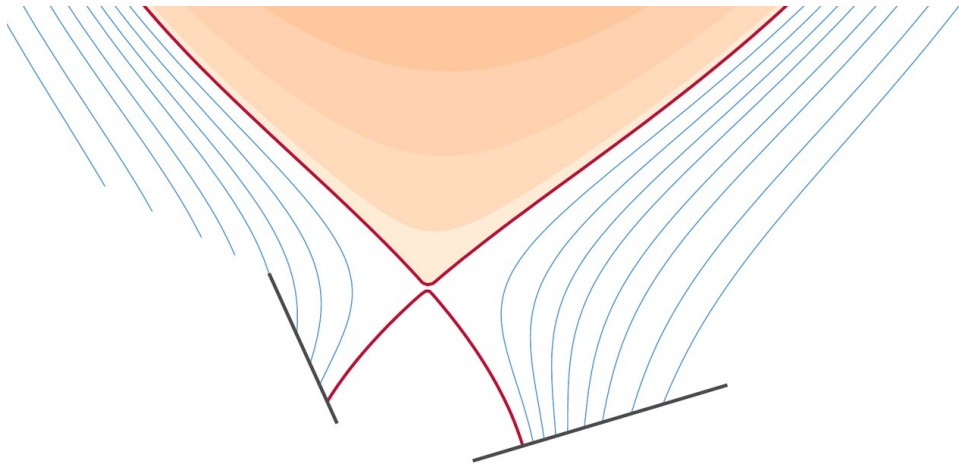
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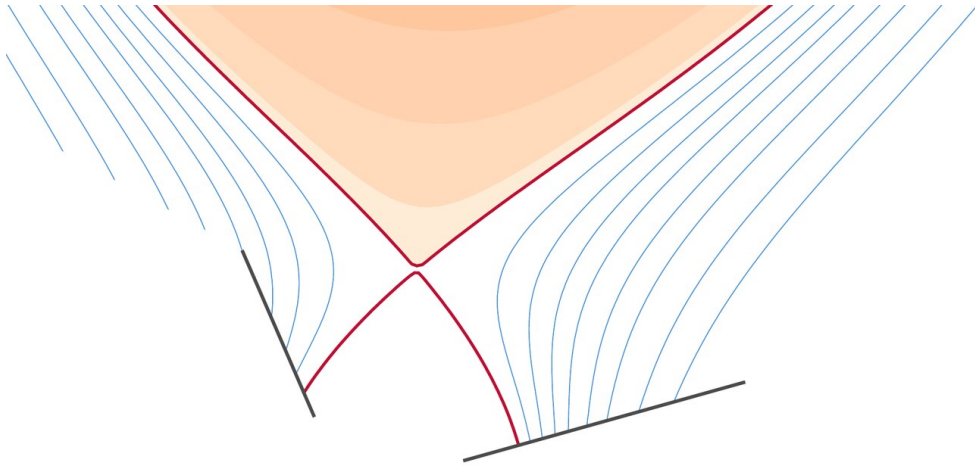
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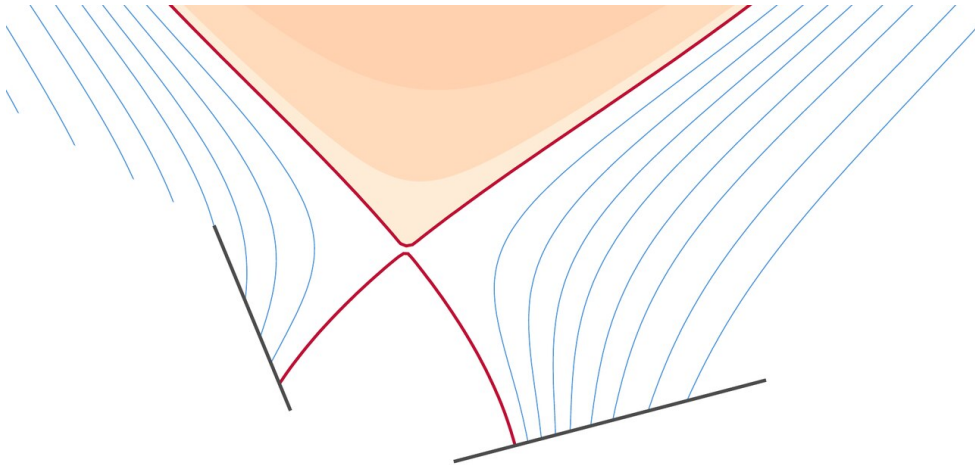
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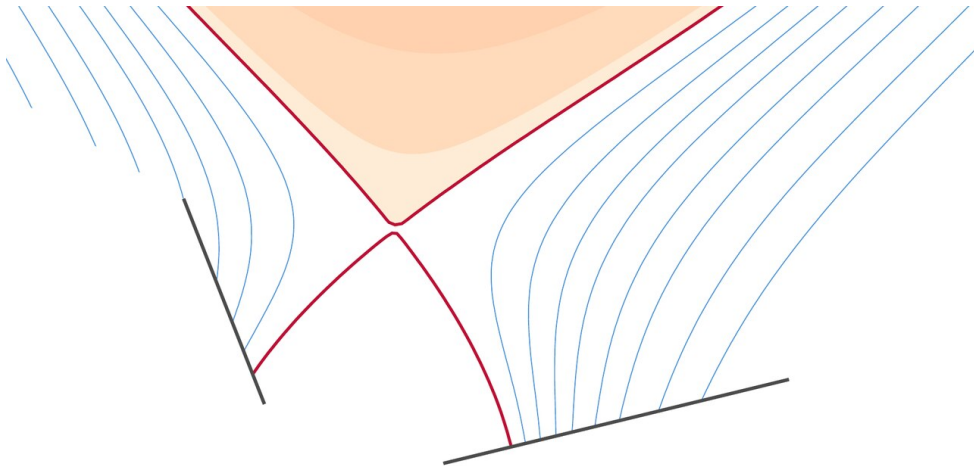
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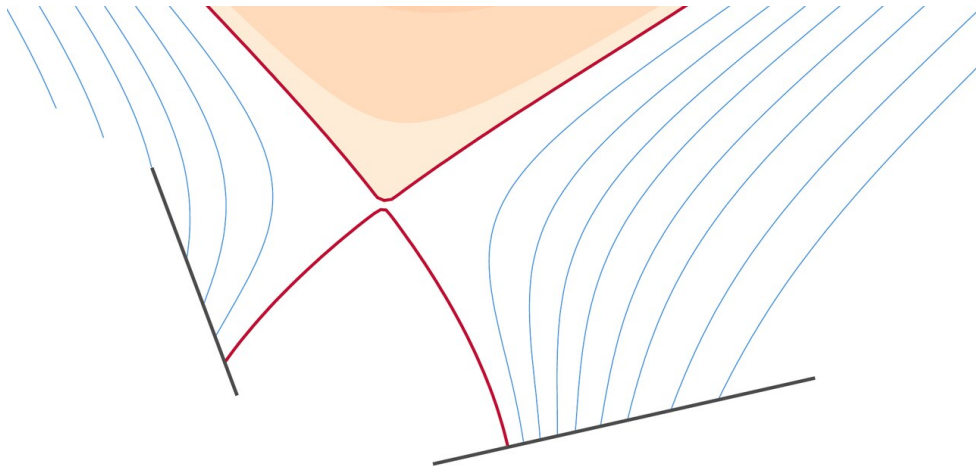
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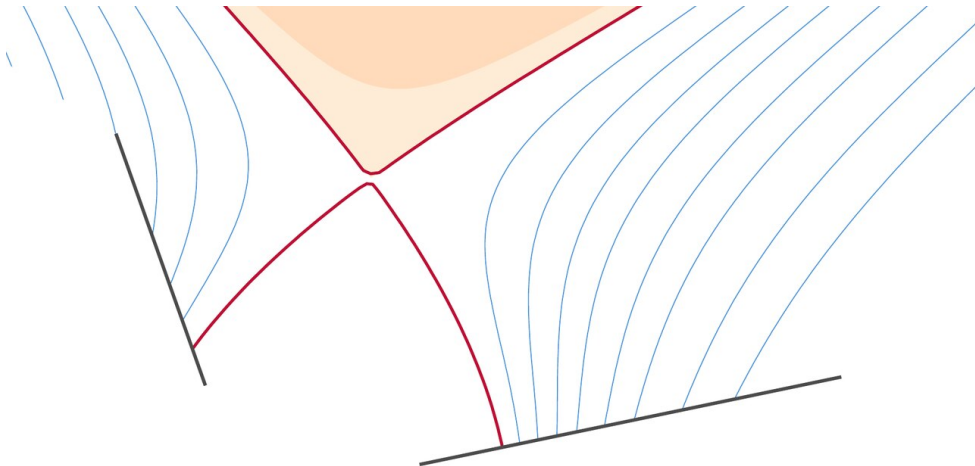
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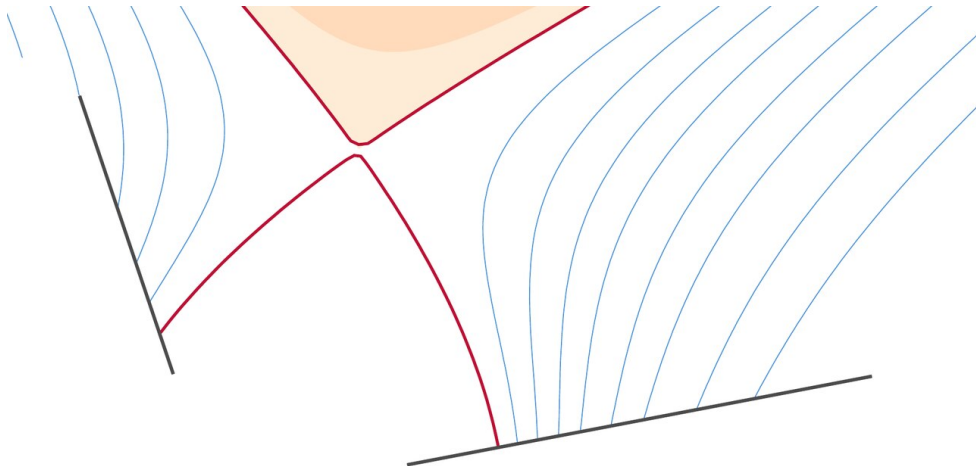
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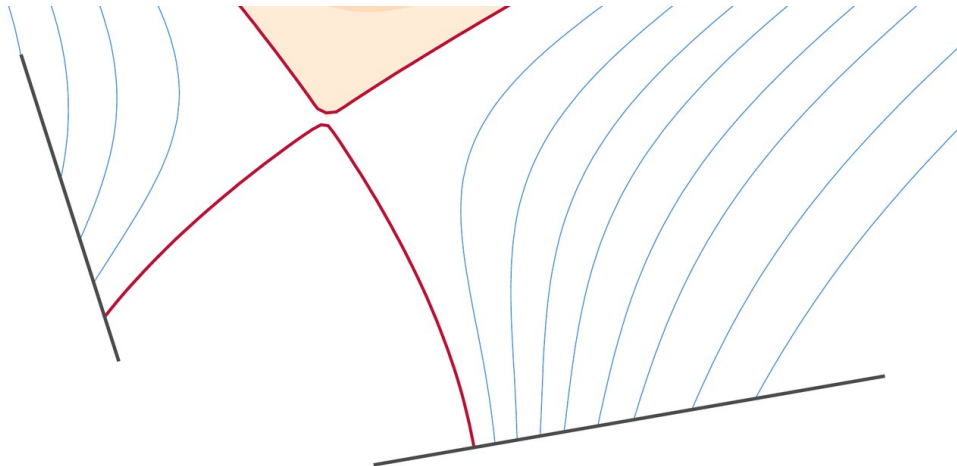
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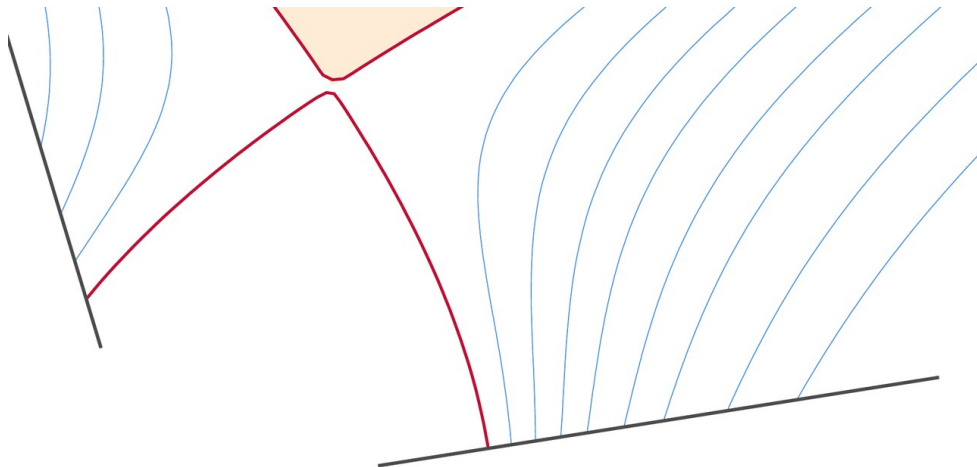
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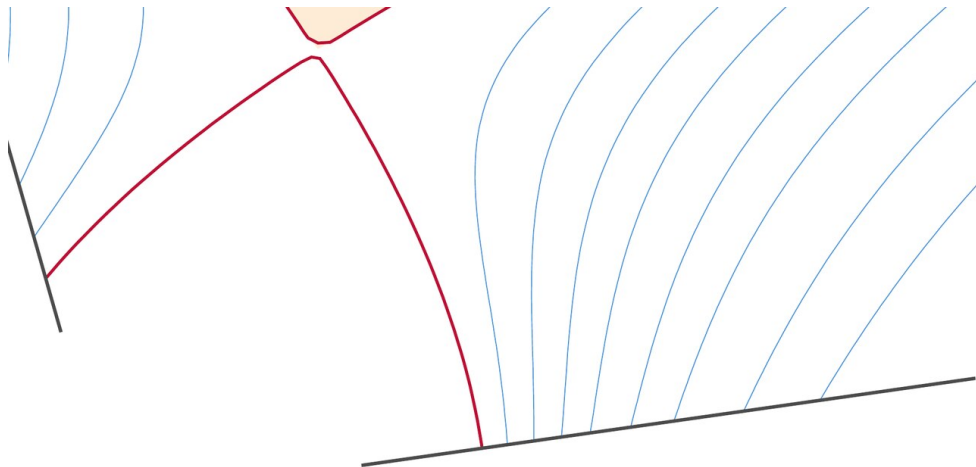
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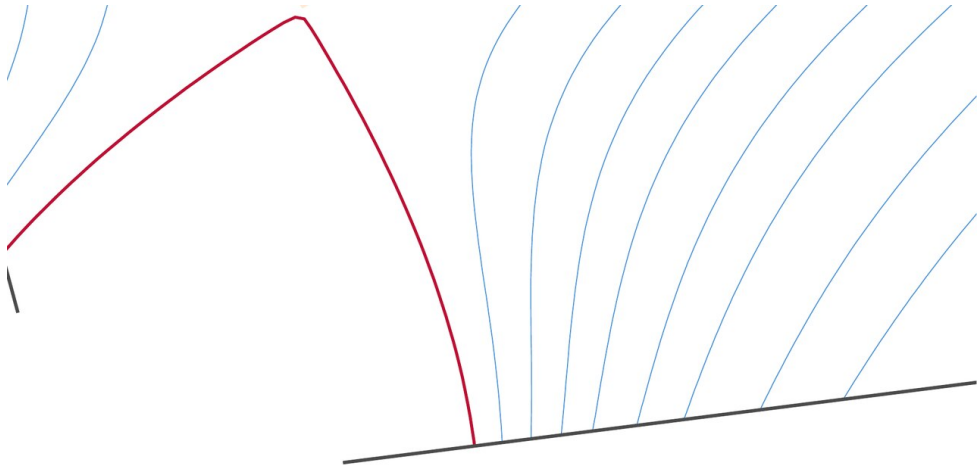
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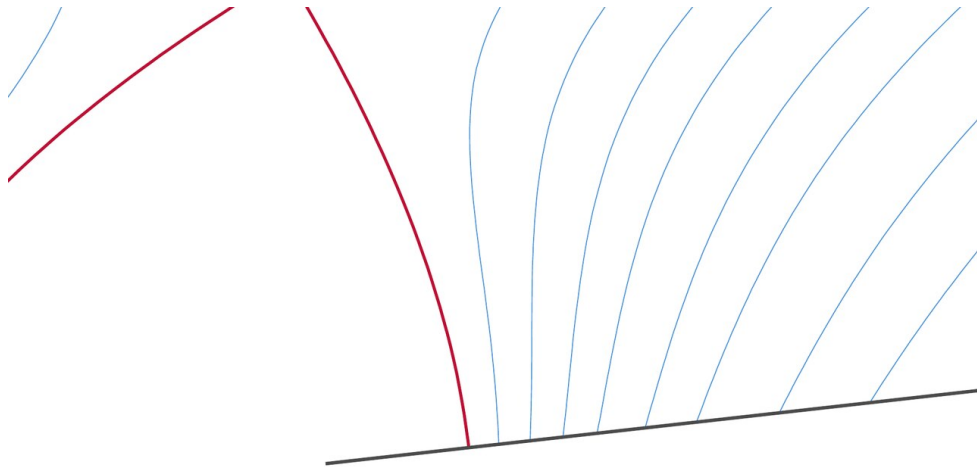
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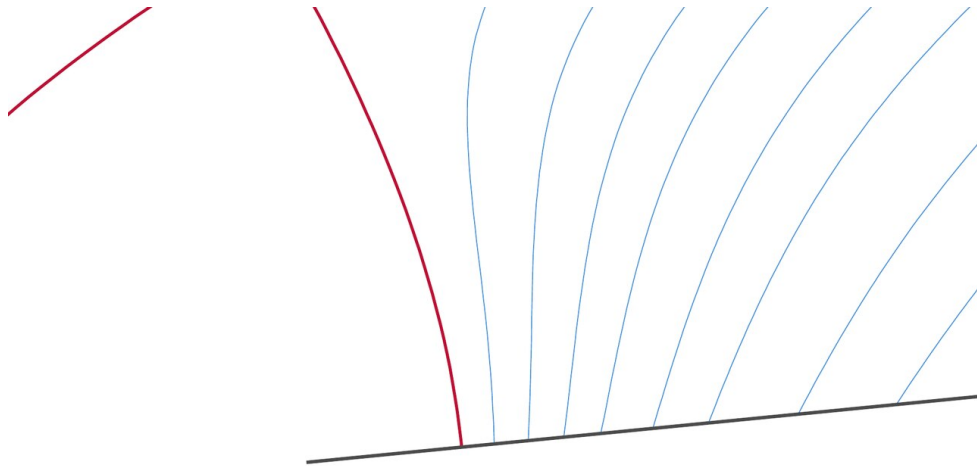
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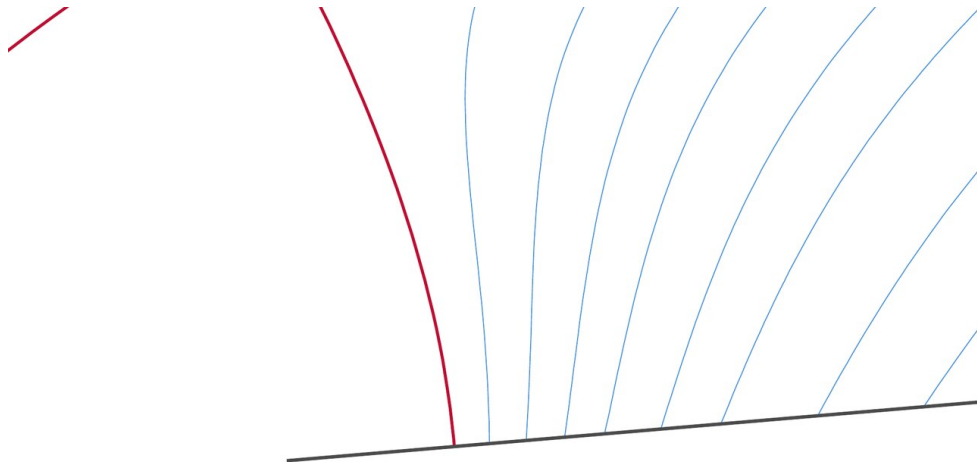
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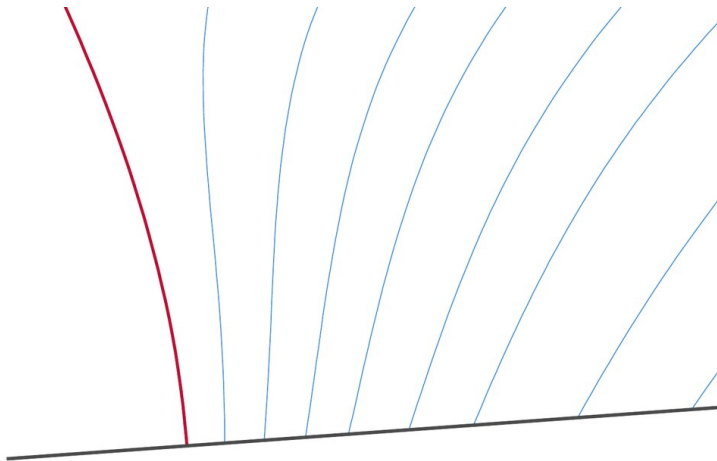
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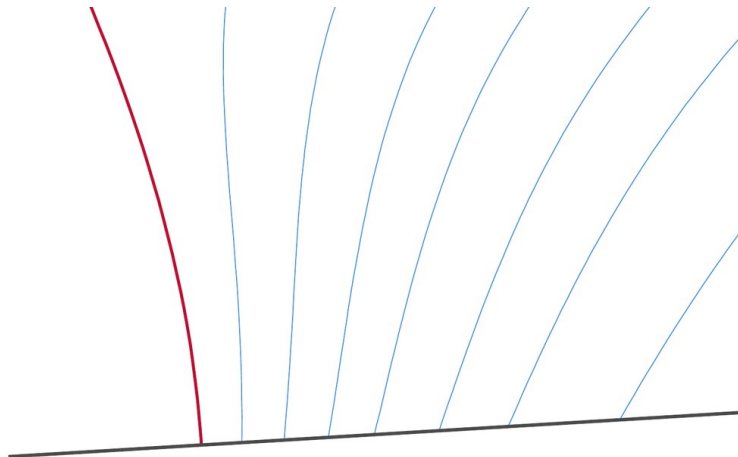
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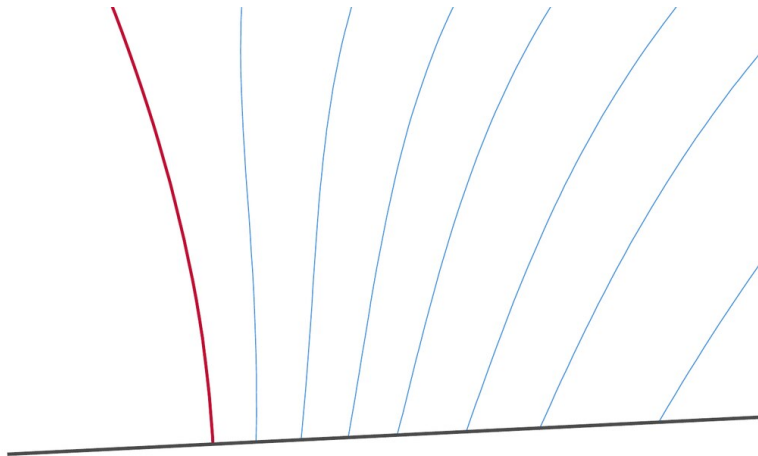
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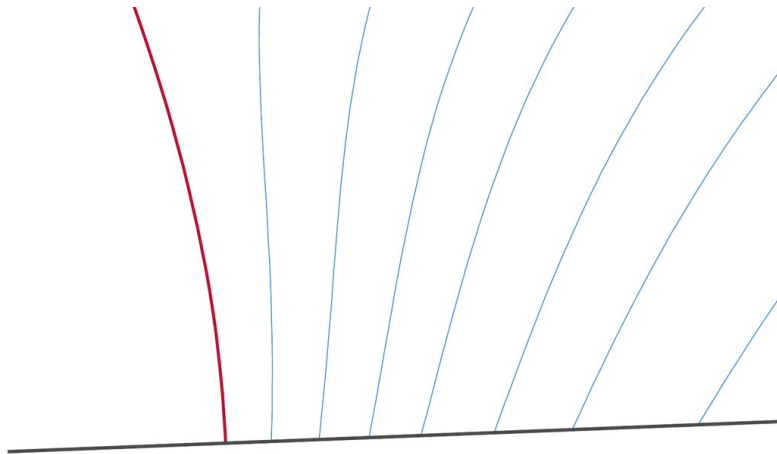
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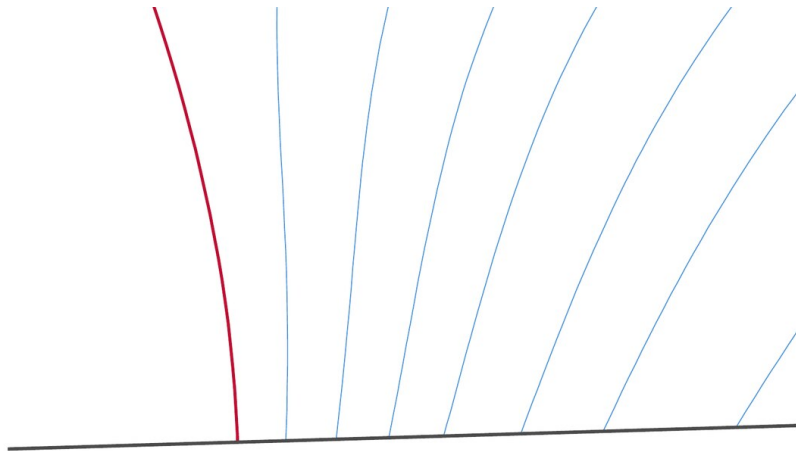
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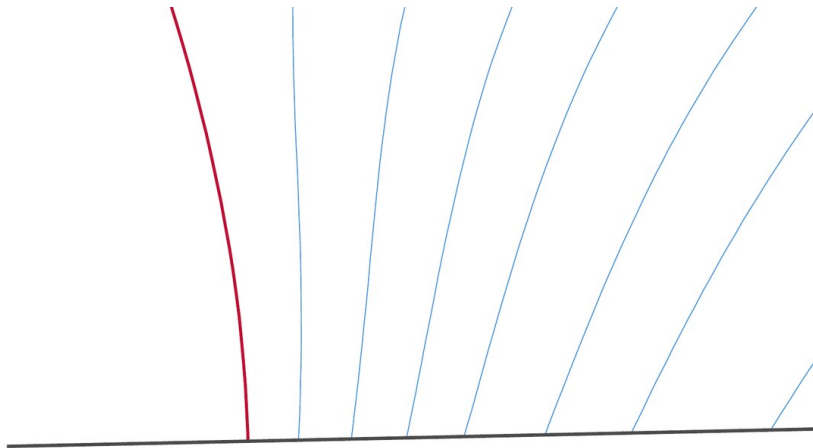
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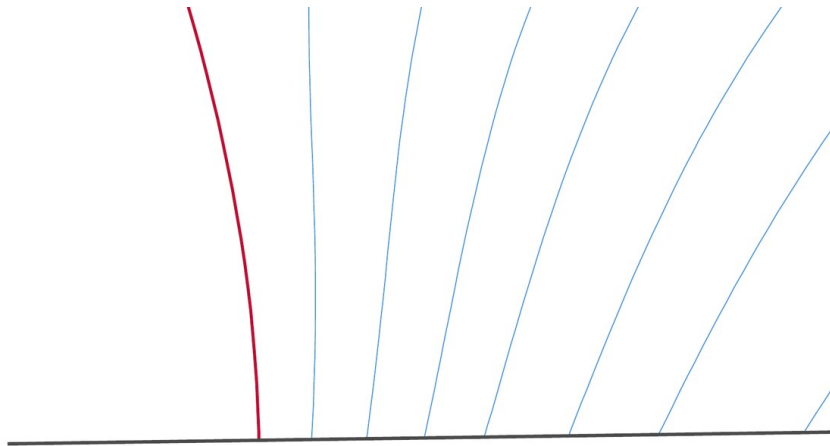
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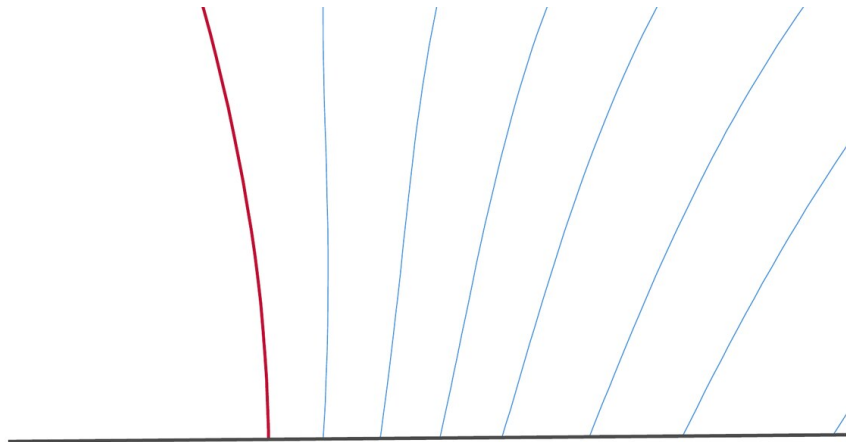
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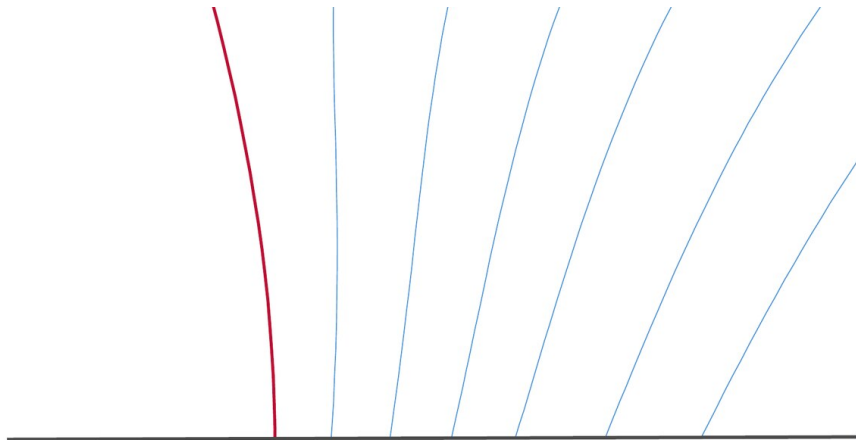
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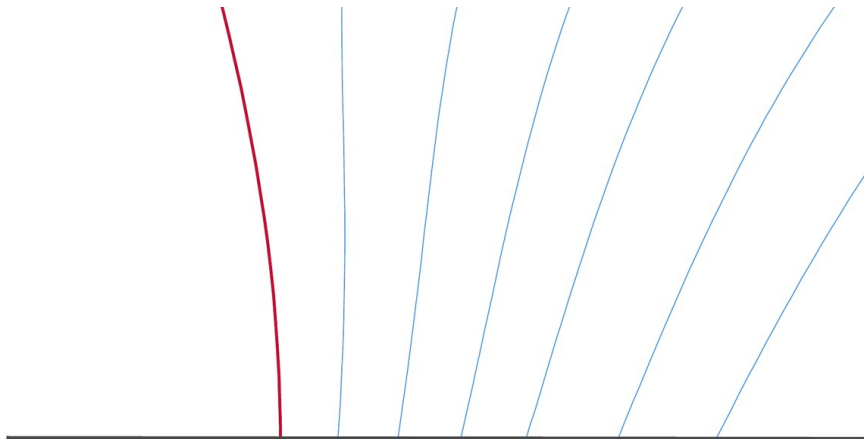
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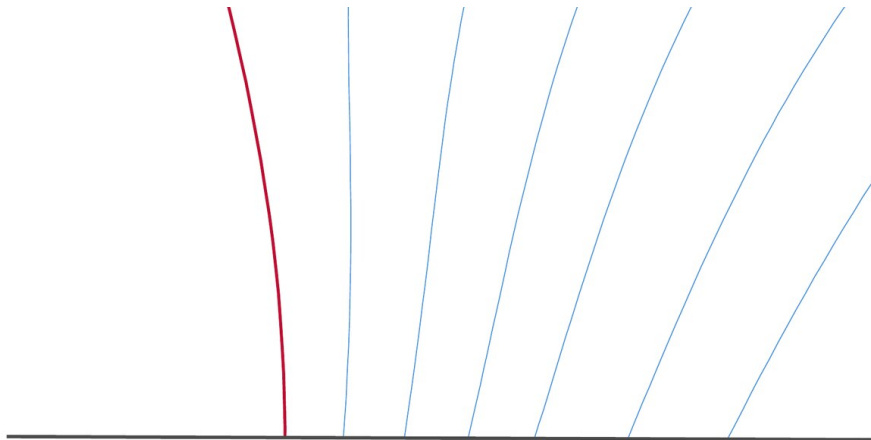
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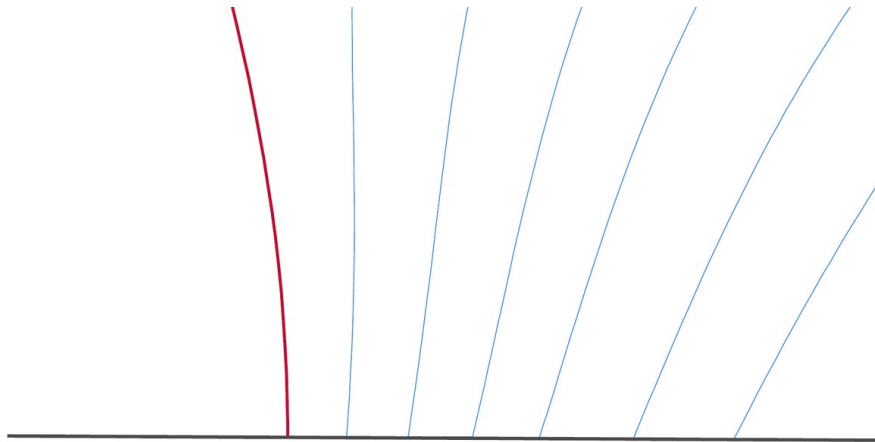
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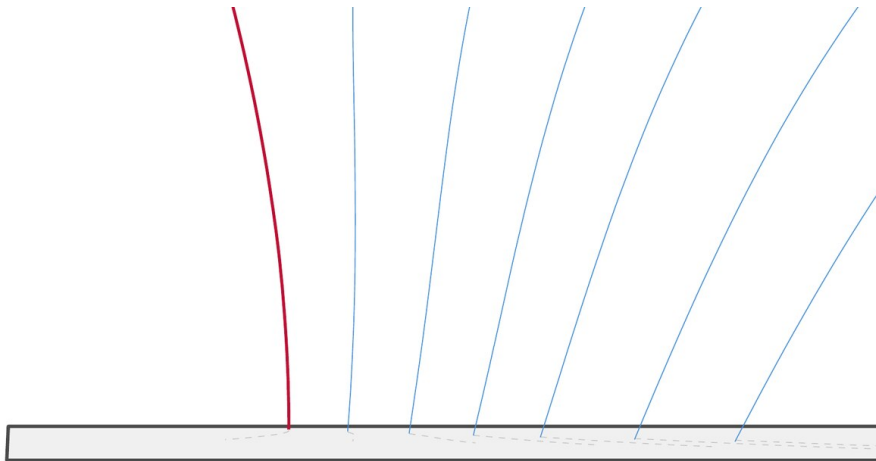
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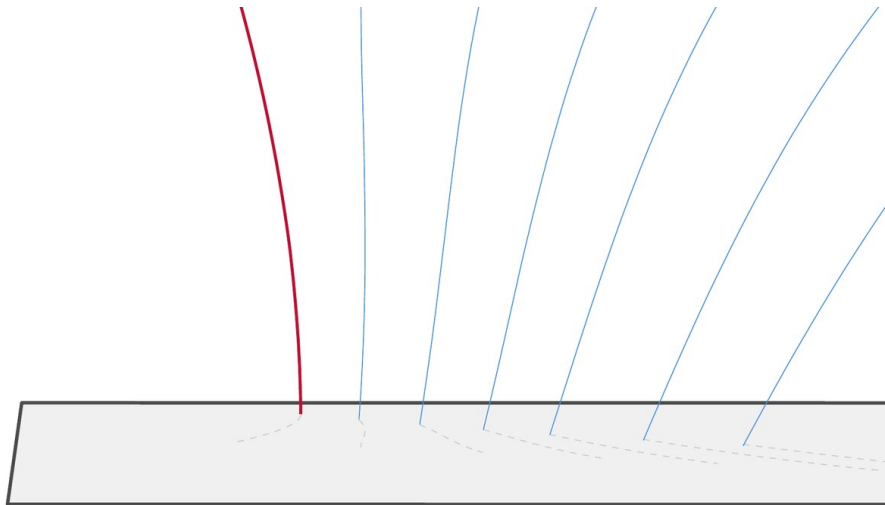
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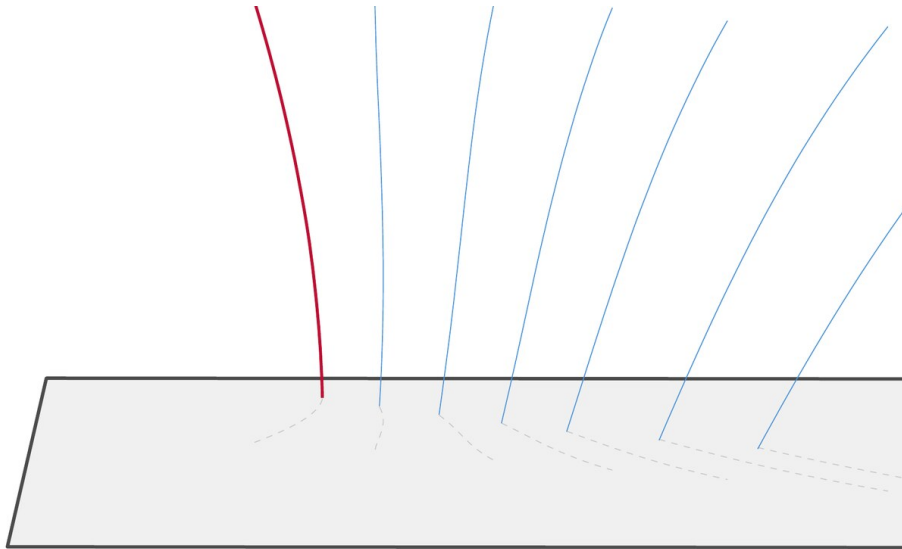
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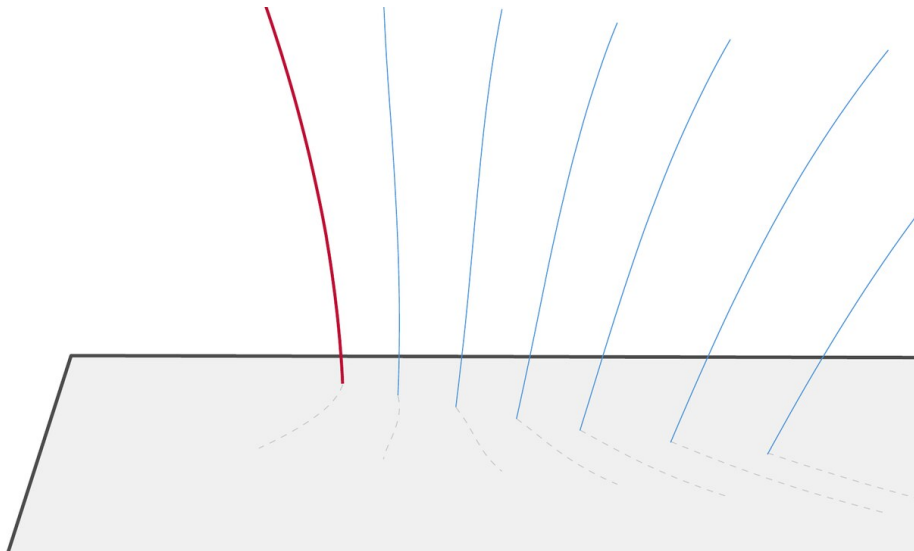
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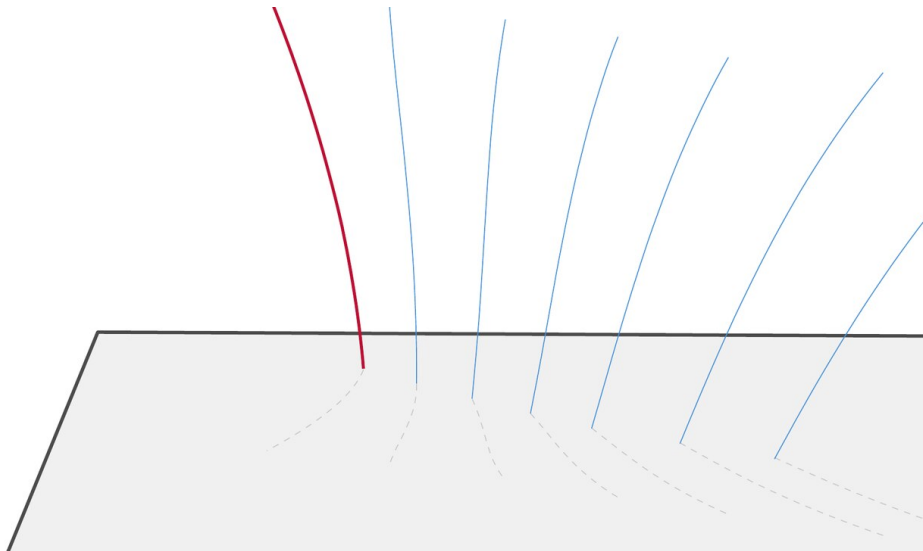
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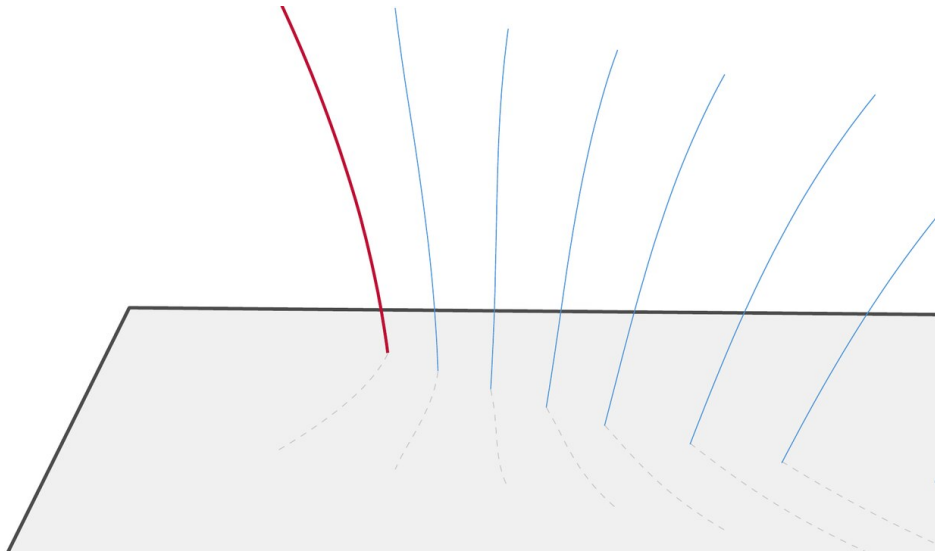
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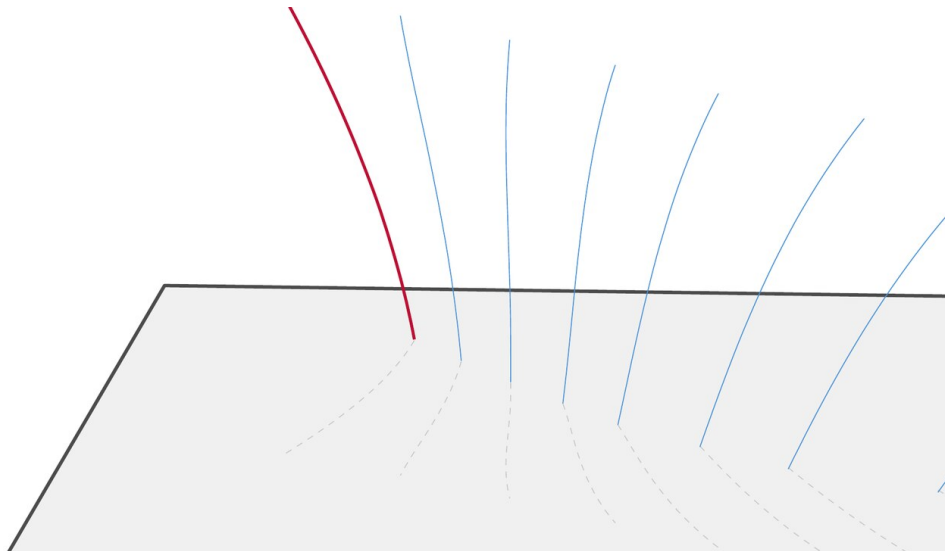
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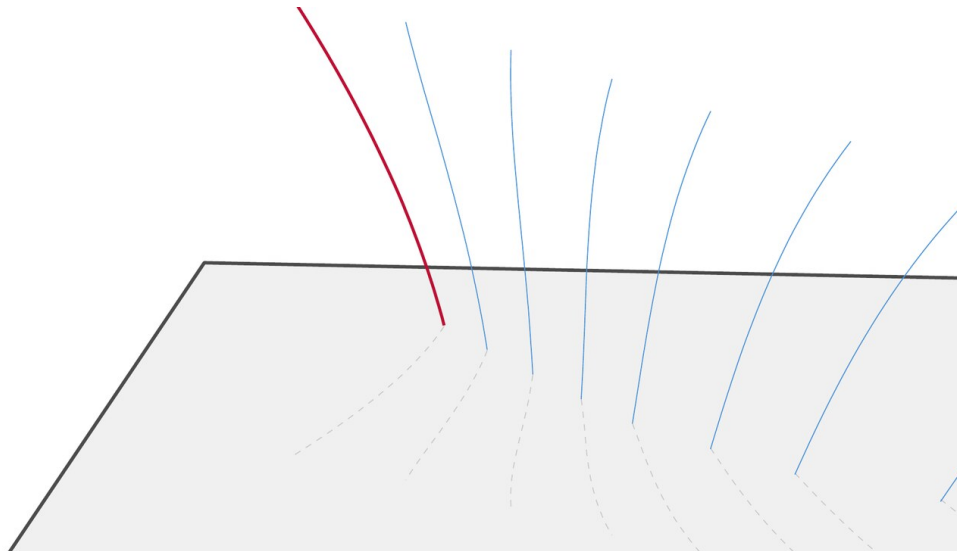
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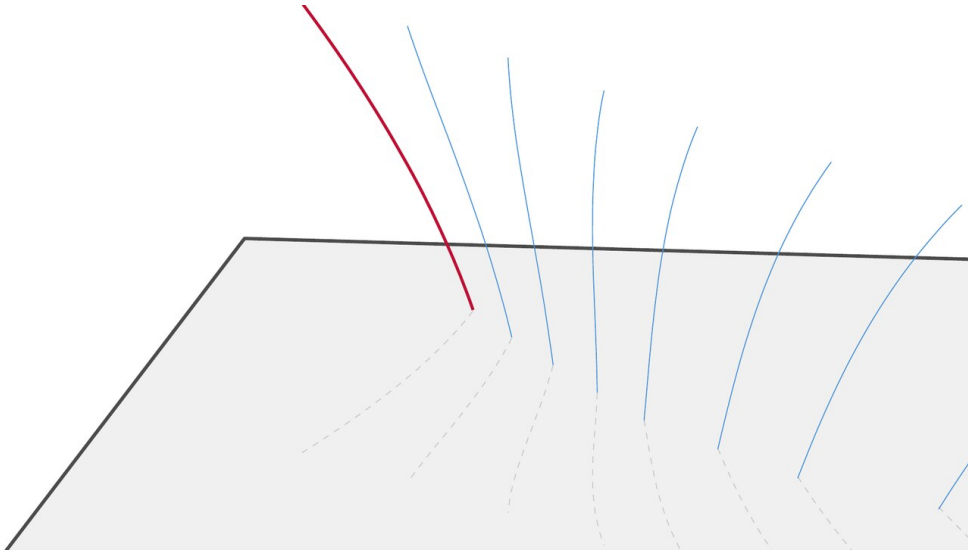
Boundary layers: where fluid SOL approximations break down



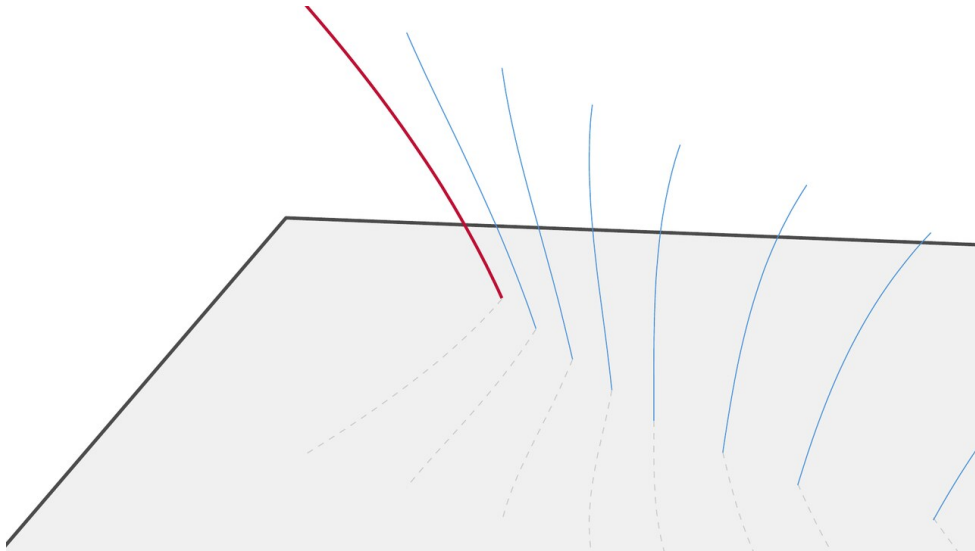
Boundary layers: where fluid SOL approximations break down



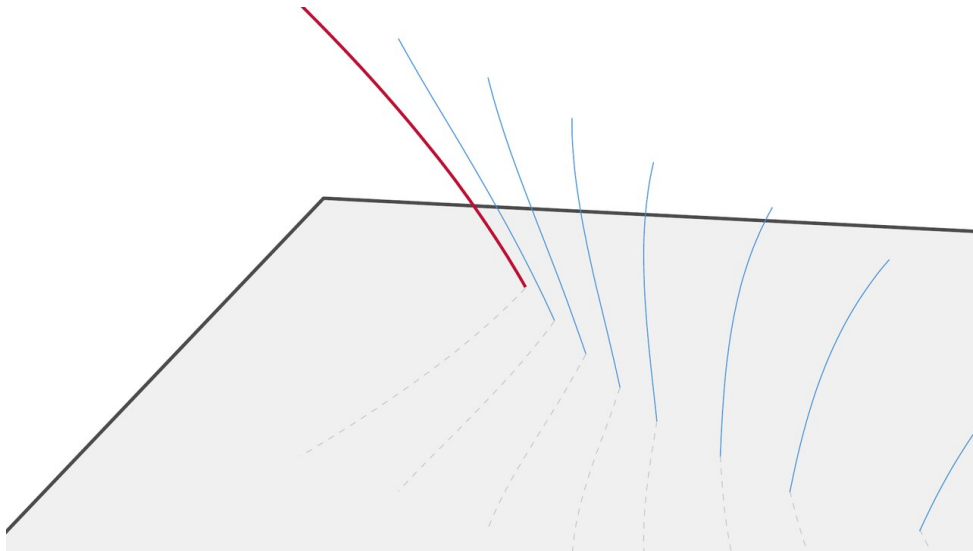
Boundary layers: where fluid SOL approximations break down



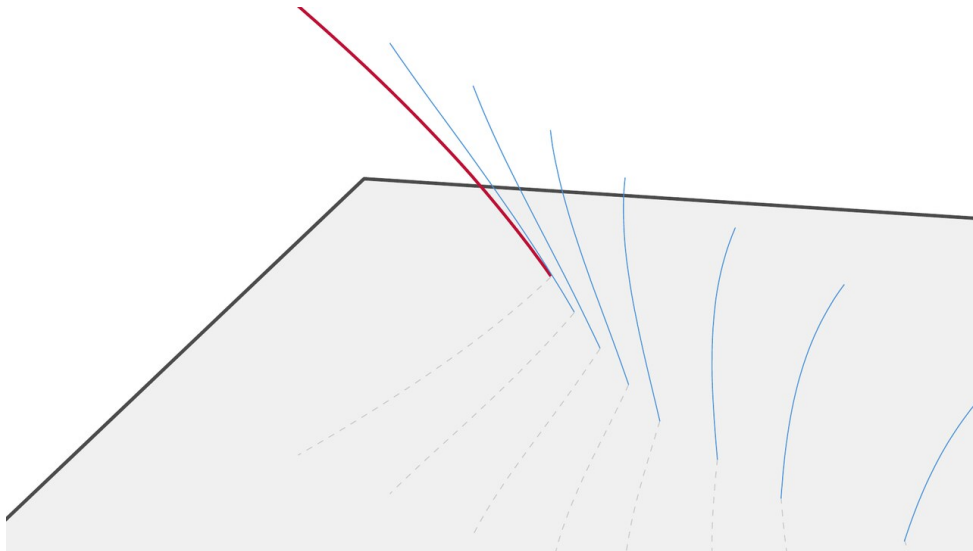
Boundary layers: where fluid SOL approximations break down



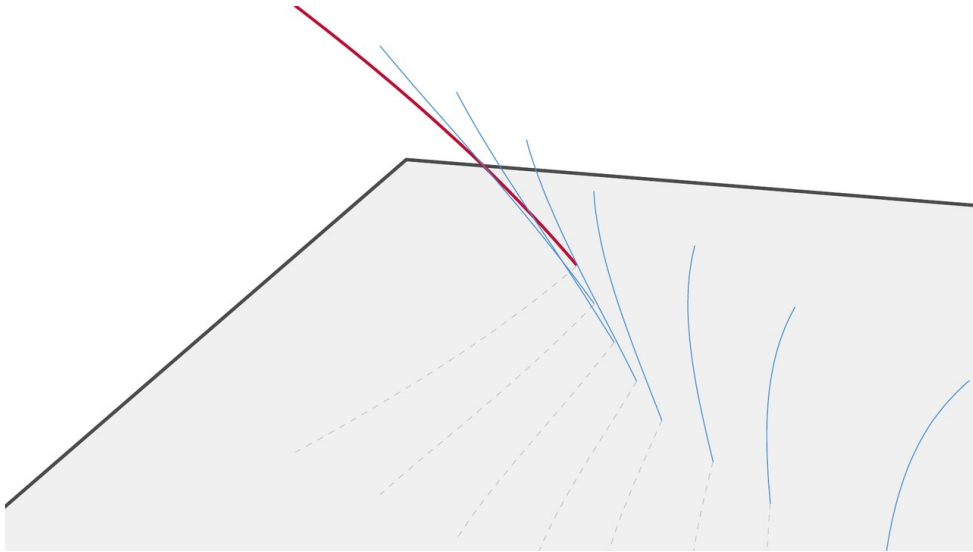
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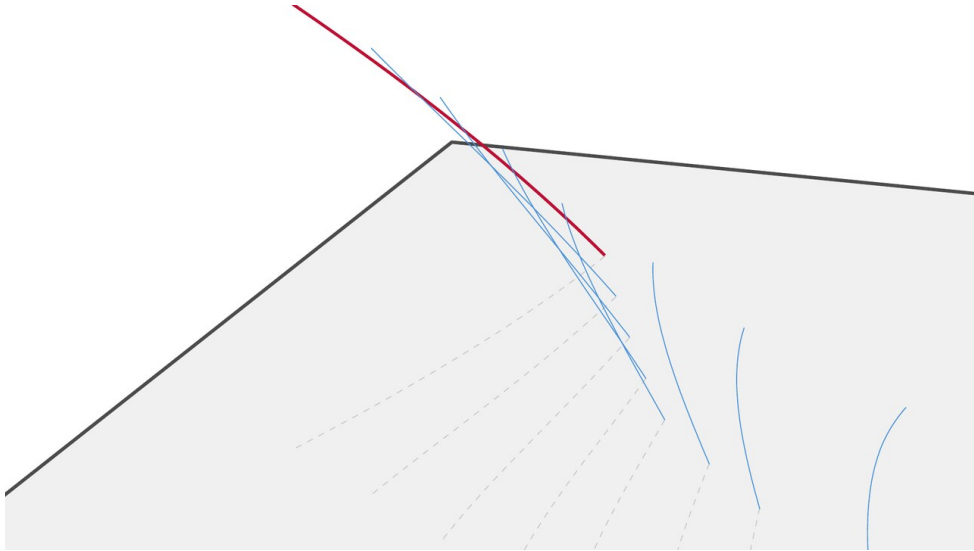
Boundary layers: where fluid SOL approximations break down



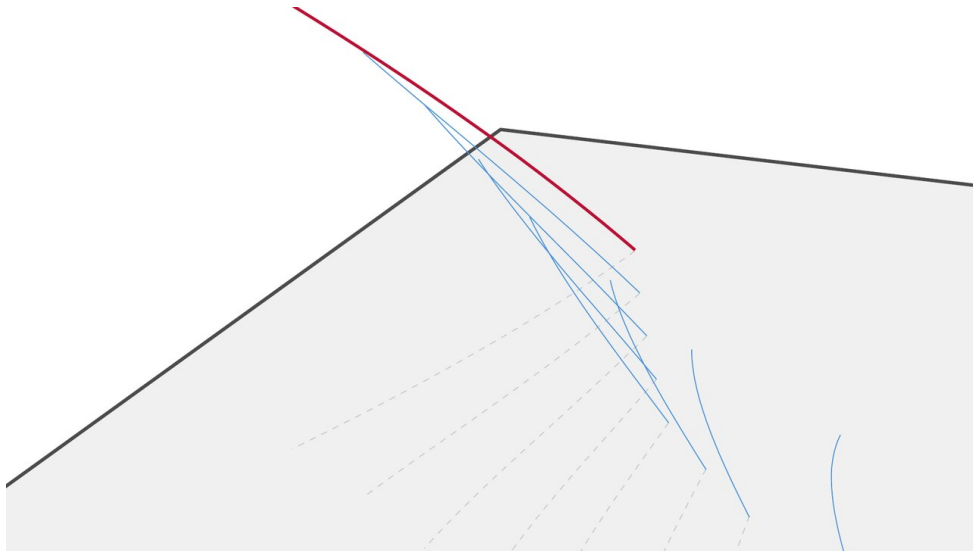
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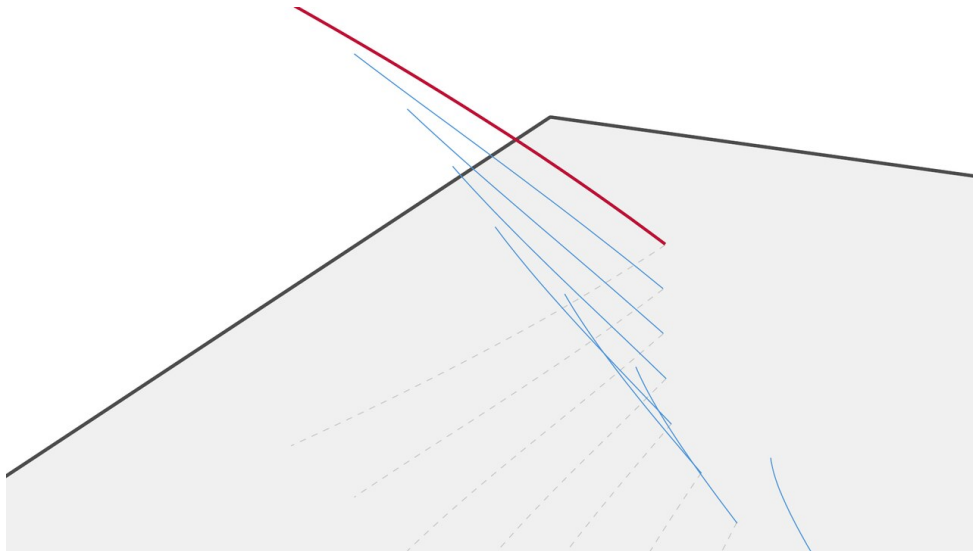
Boundary layers: where fluid SOL approximations break down



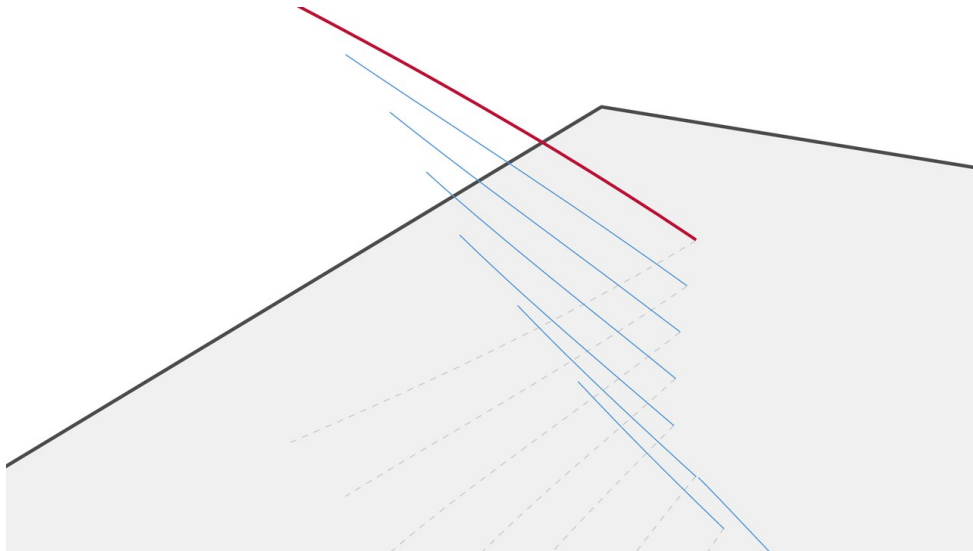
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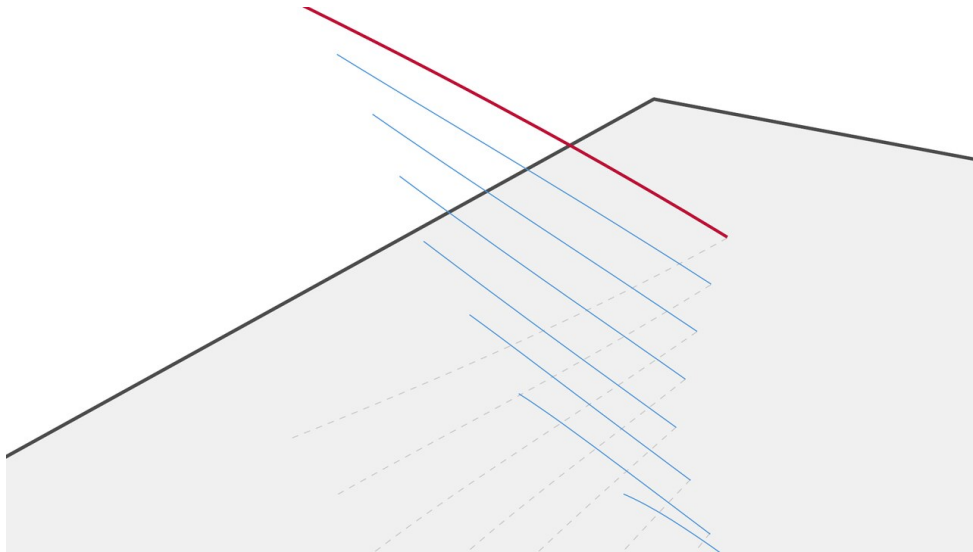
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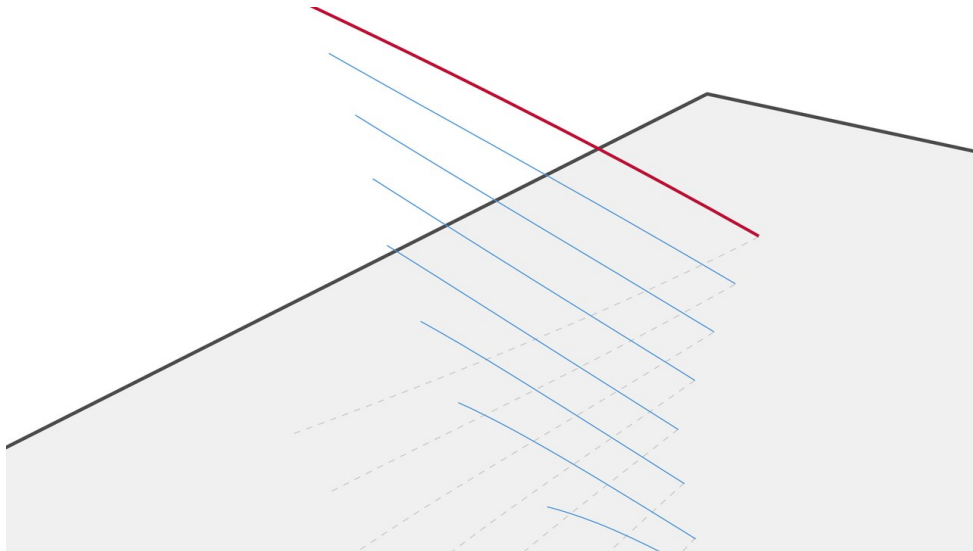
Boundary layers: where fluid SOL approximations break down



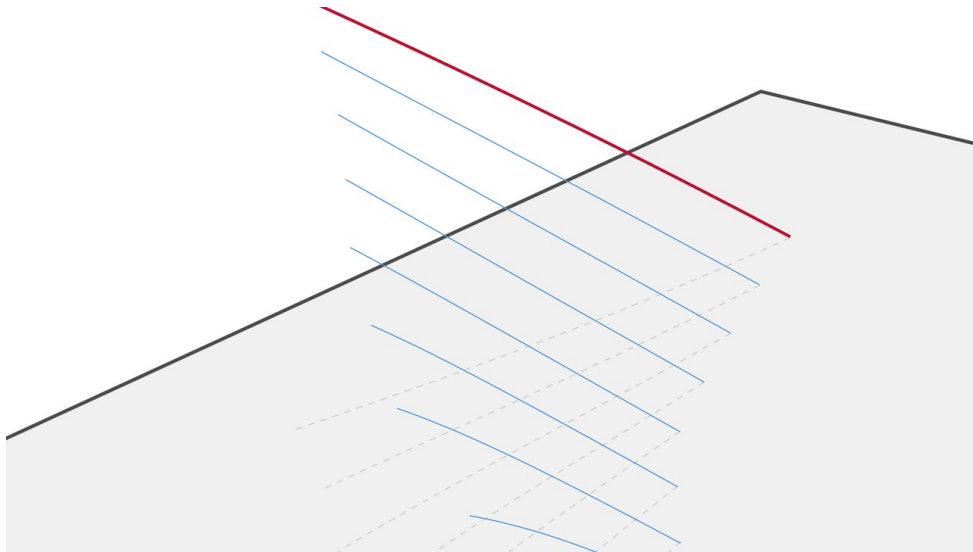
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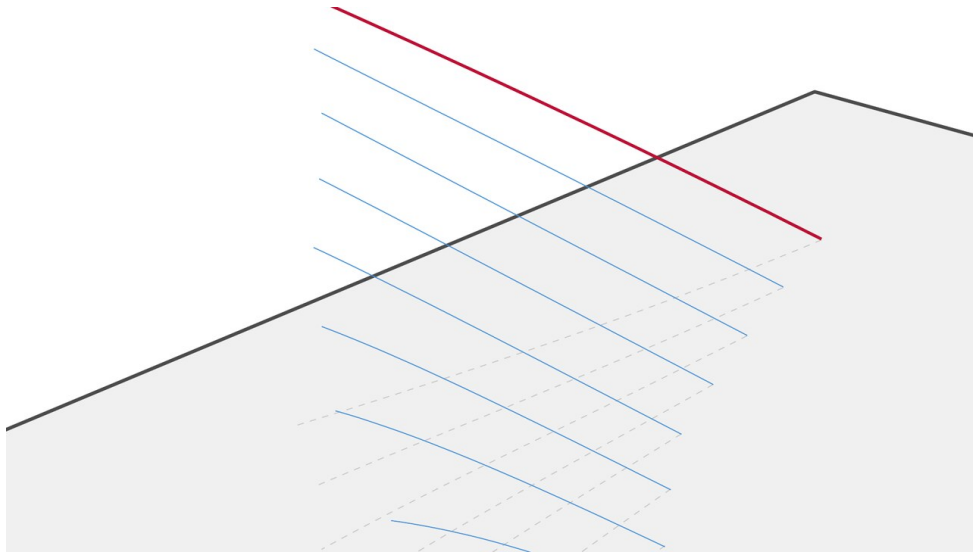
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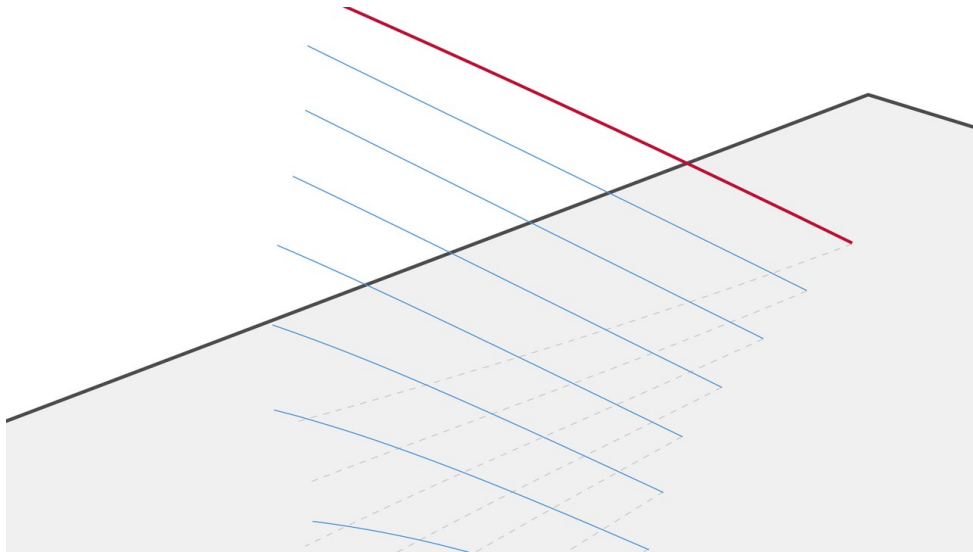
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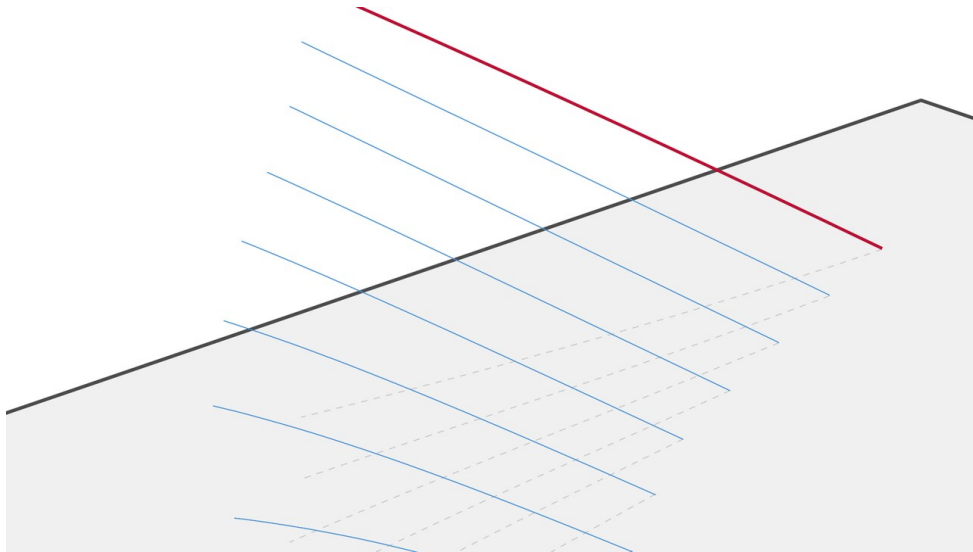
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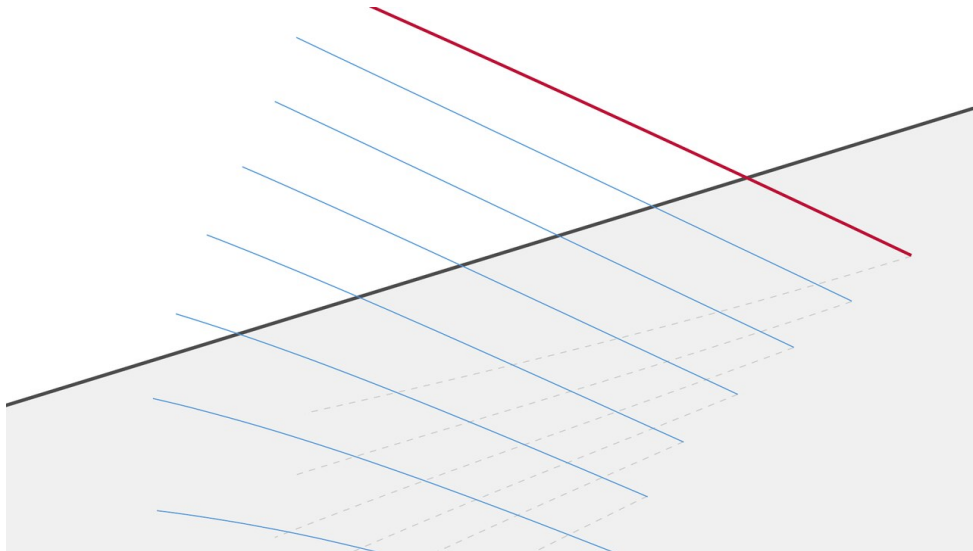
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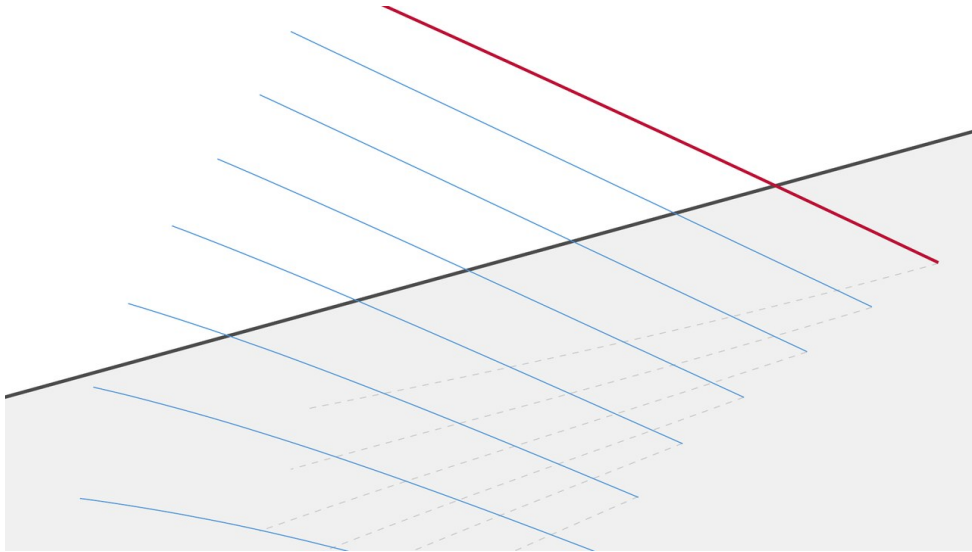
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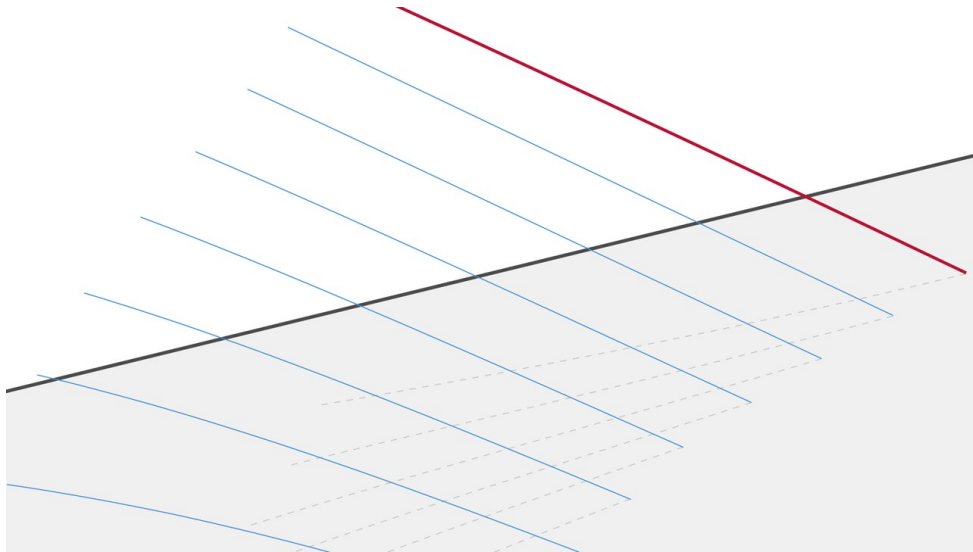
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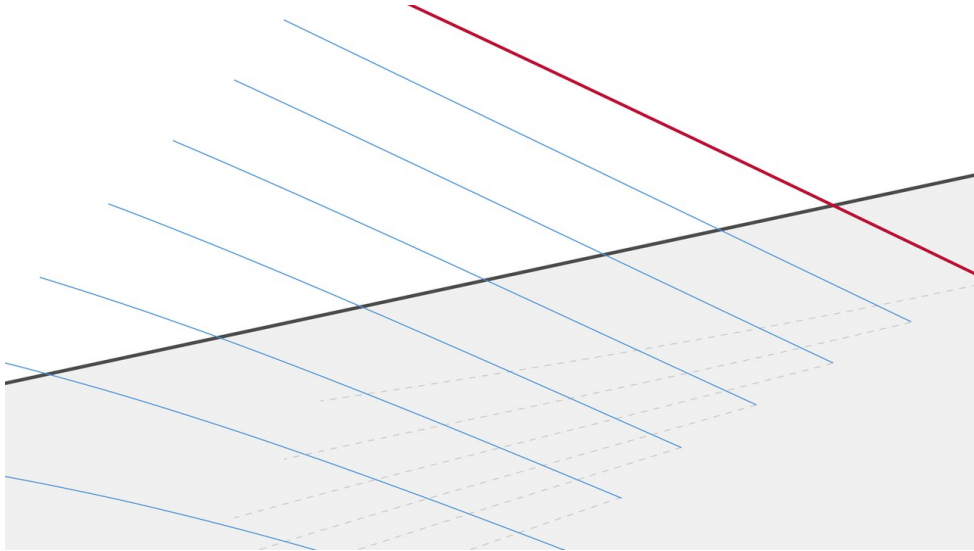
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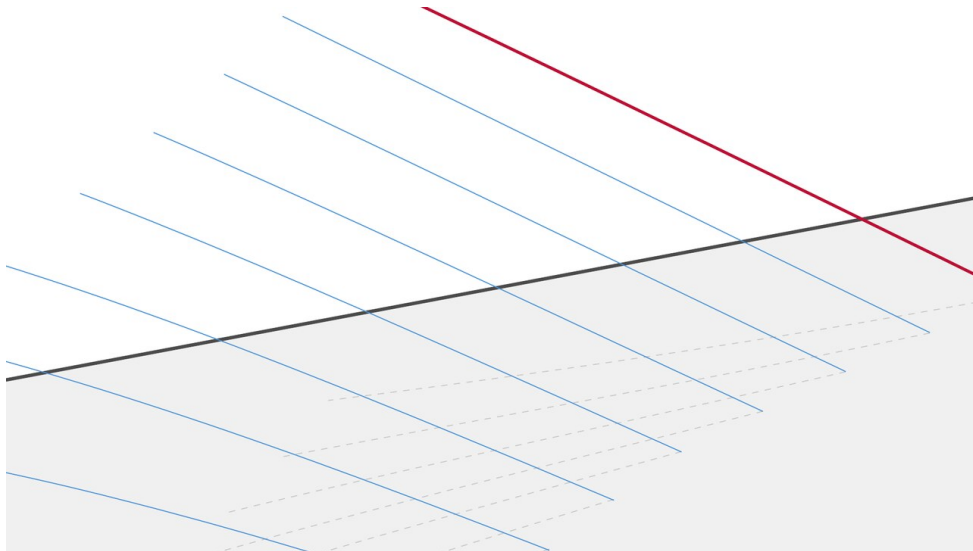
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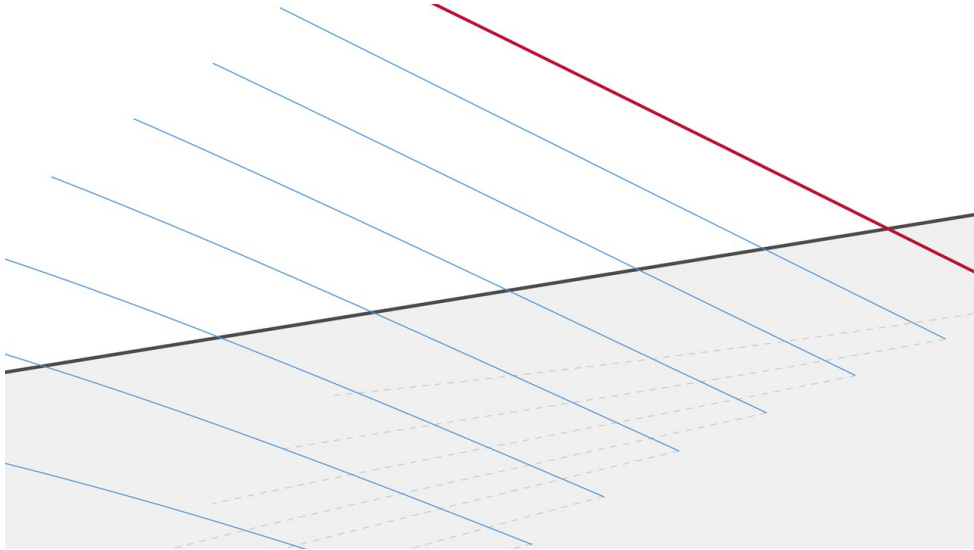
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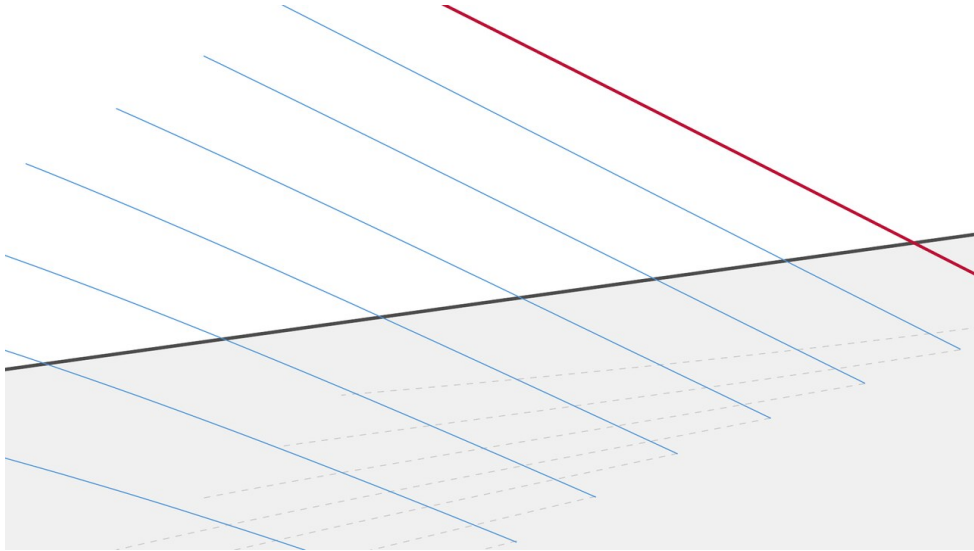
Boundary layers: where fluid SOL approximations break down



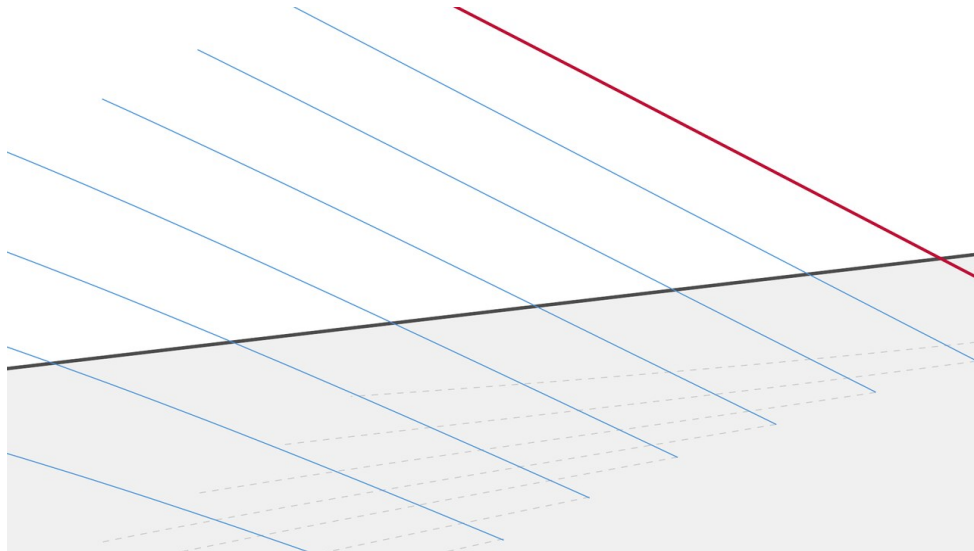
Boundary layers: where fluid SOL approximations break down



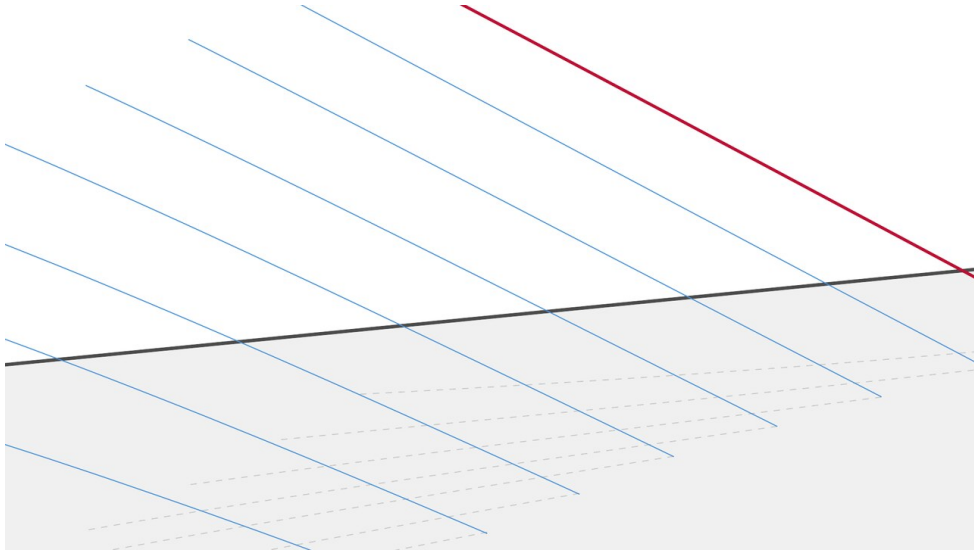
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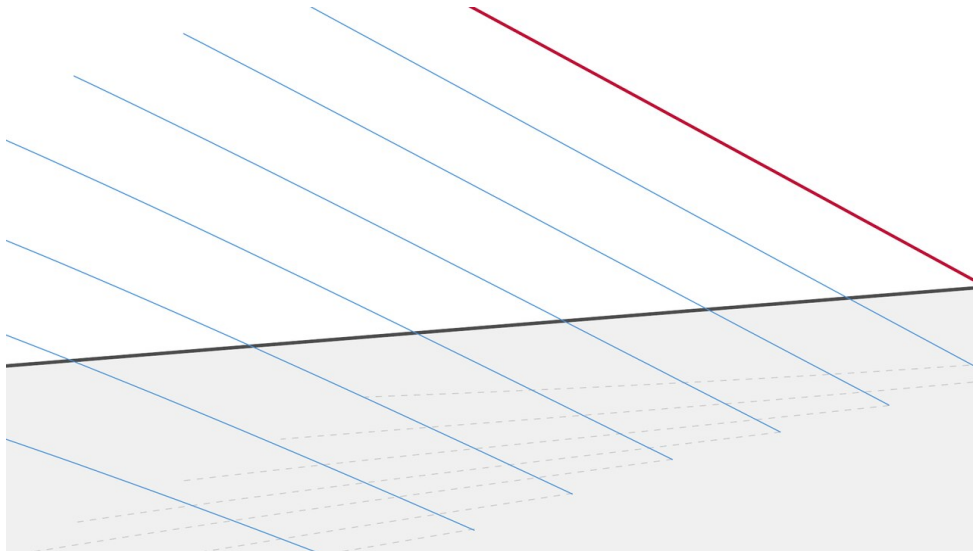
Boundary layers: where fluid SOL approximations break down



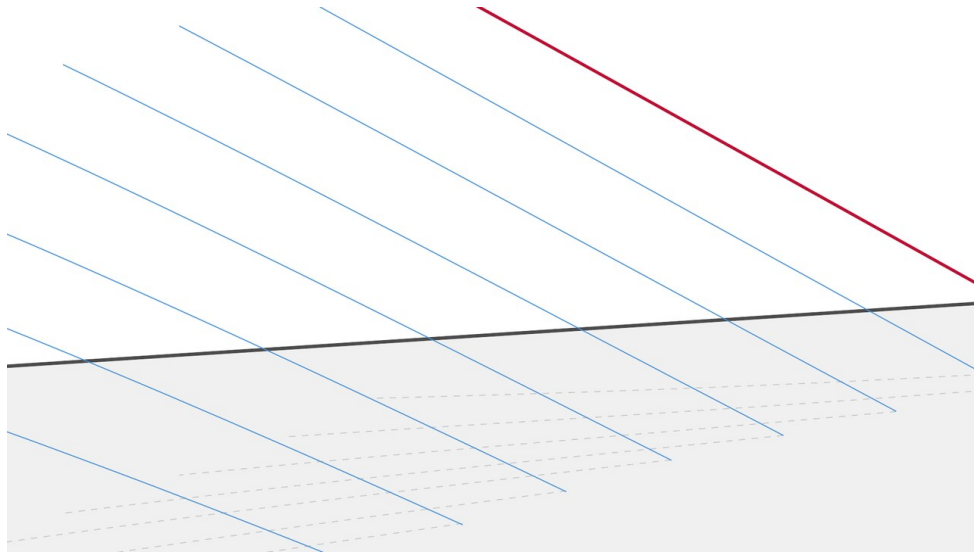
Boundary layers: where fluid SOL approximations break down



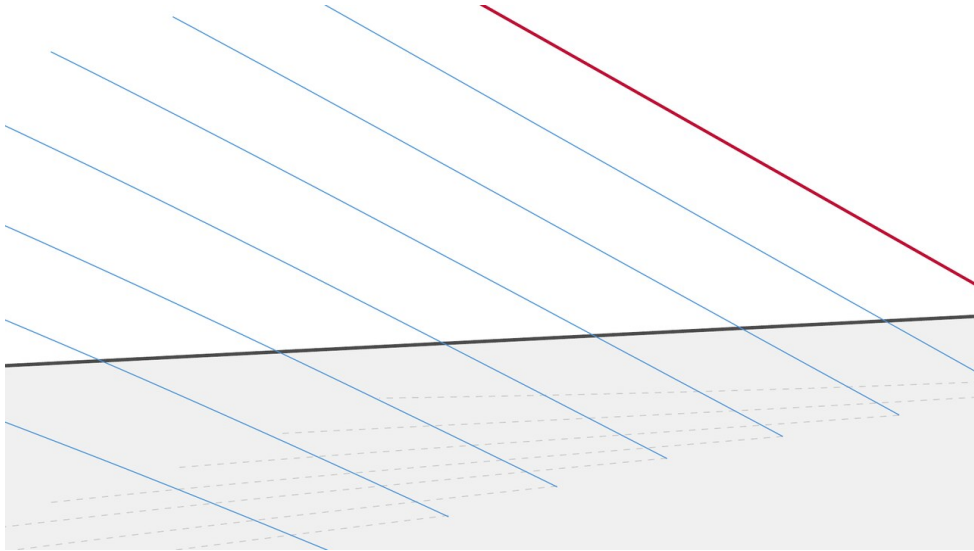
Boundary layers: where fluid SOL approximations break down



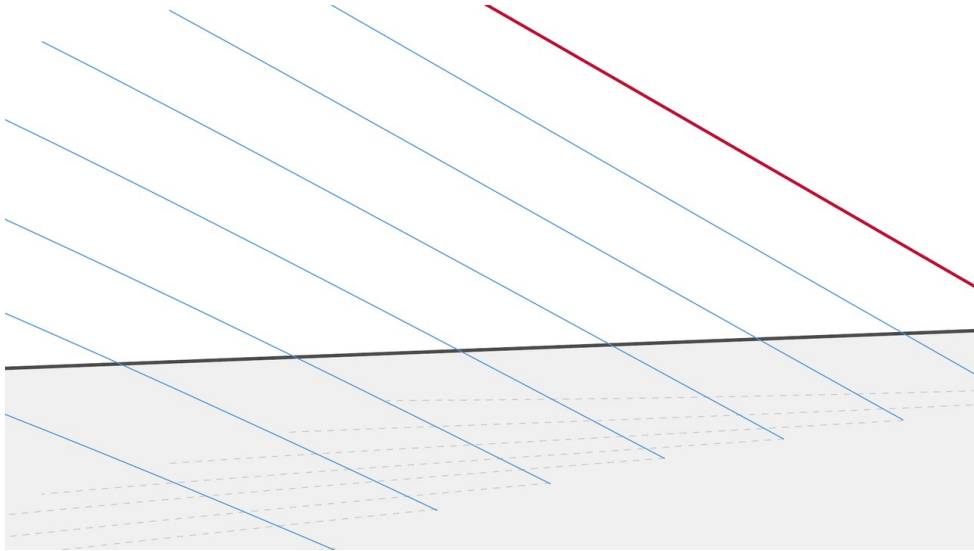
Boundary layers: where fluid SOL approximations break down



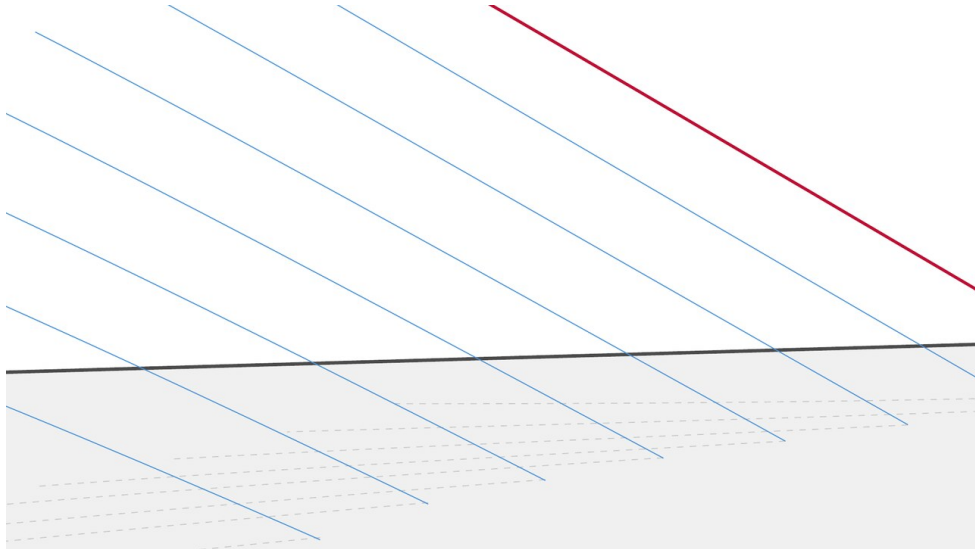
Boundary layers: where fluid SOL approximations break down



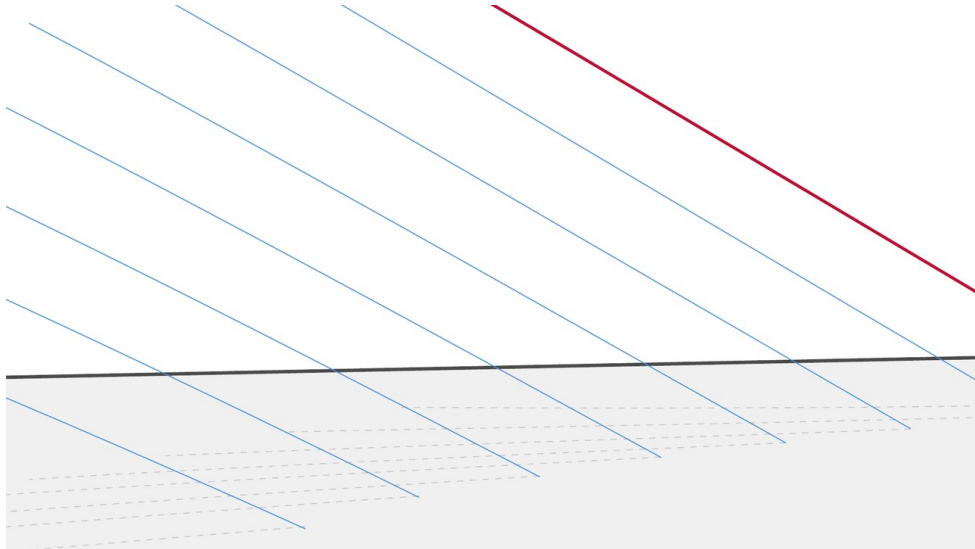
Boundary layers: where fluid SOL approximations break down



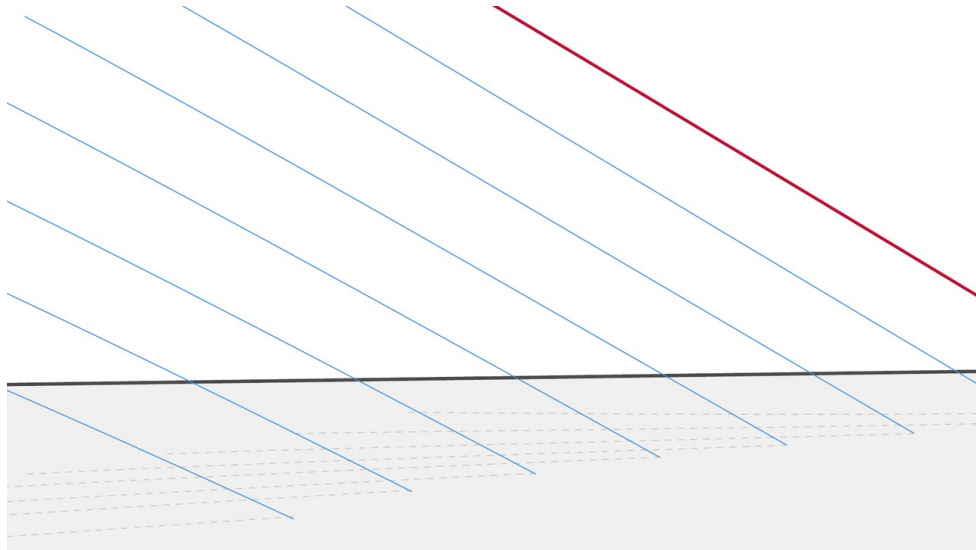
Boundary layers: where fluid SOL approximations break down



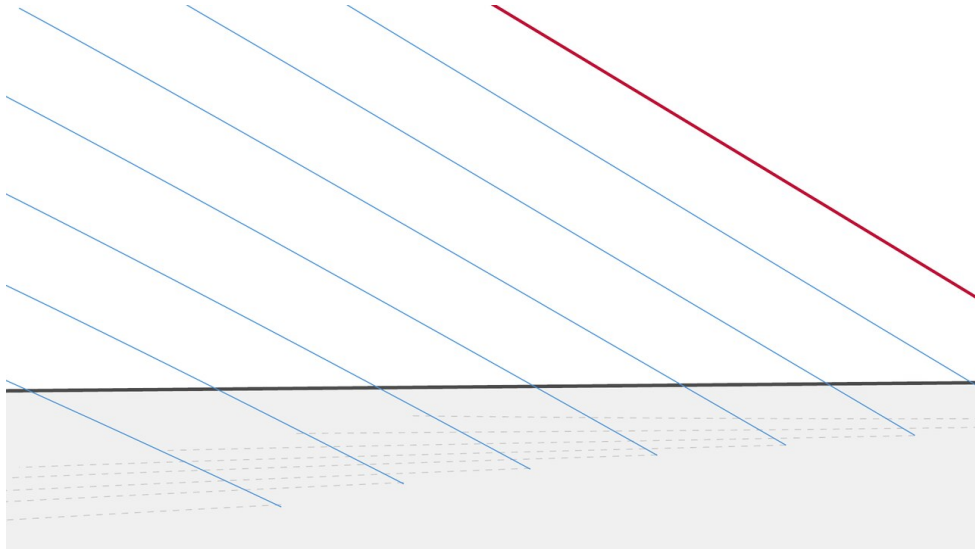
Boundary layers: where fluid SOL approximations break down



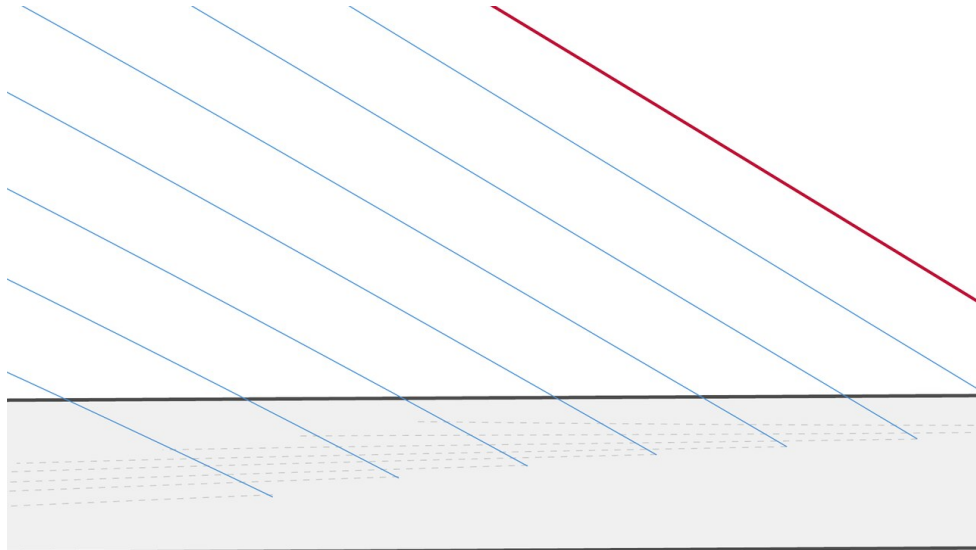
Boundary layers: where fluid SOL approximations break down



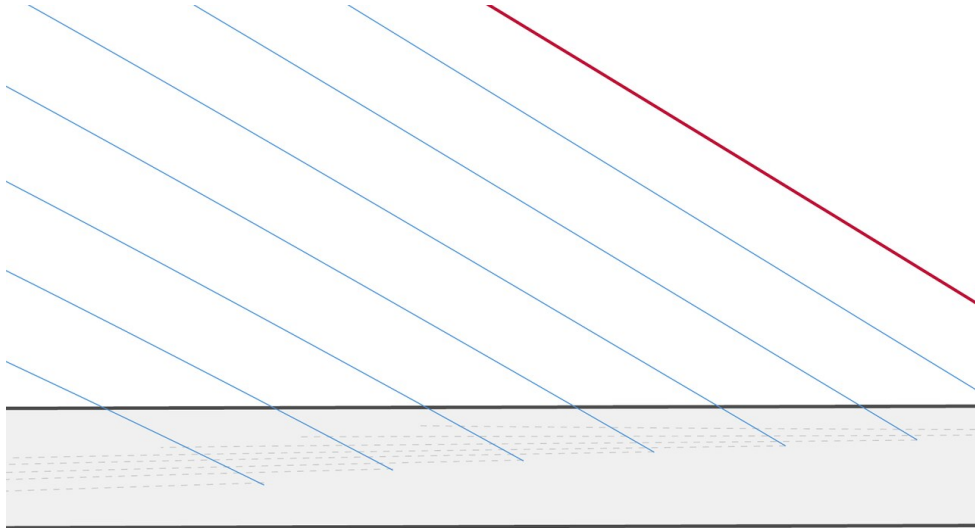
Boundary layers: where fluid SOL approximations break down



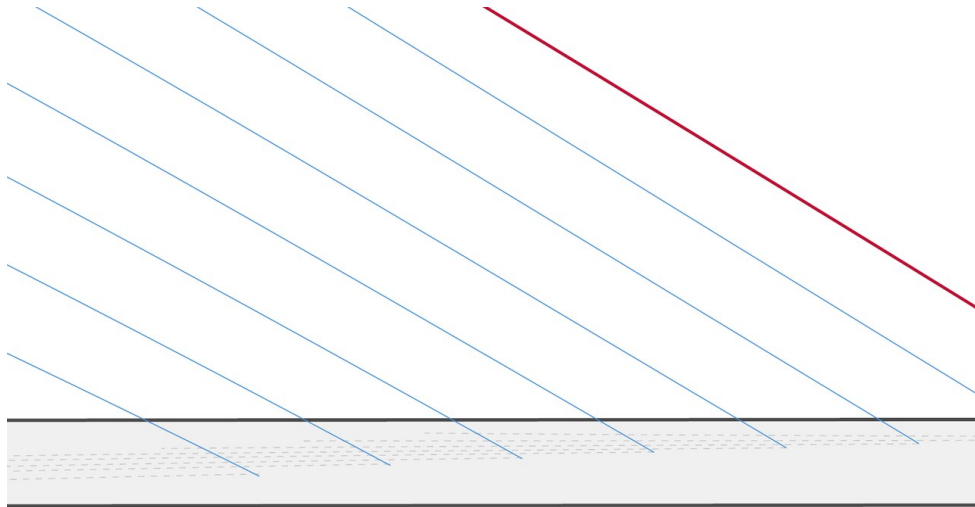
Boundary layers: where fluid SOL approximations break down



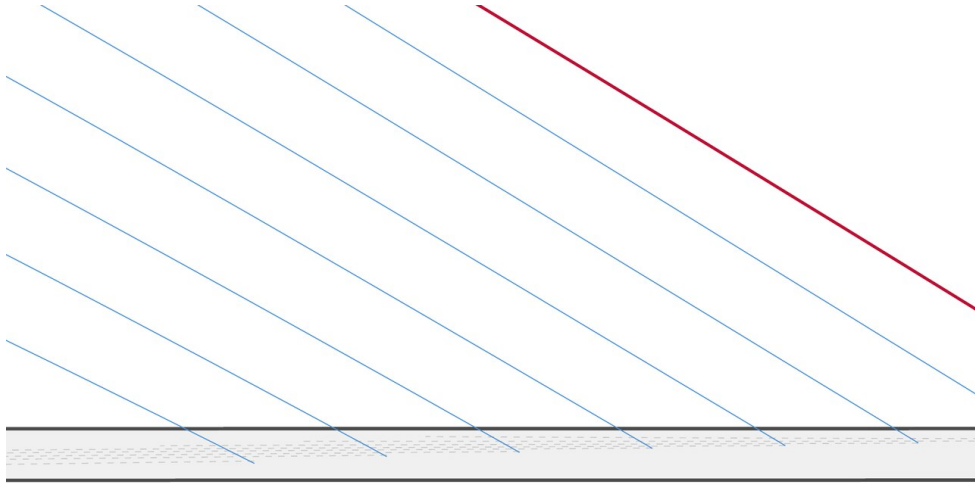
Boundary layers: where fluid SOL approximations break down



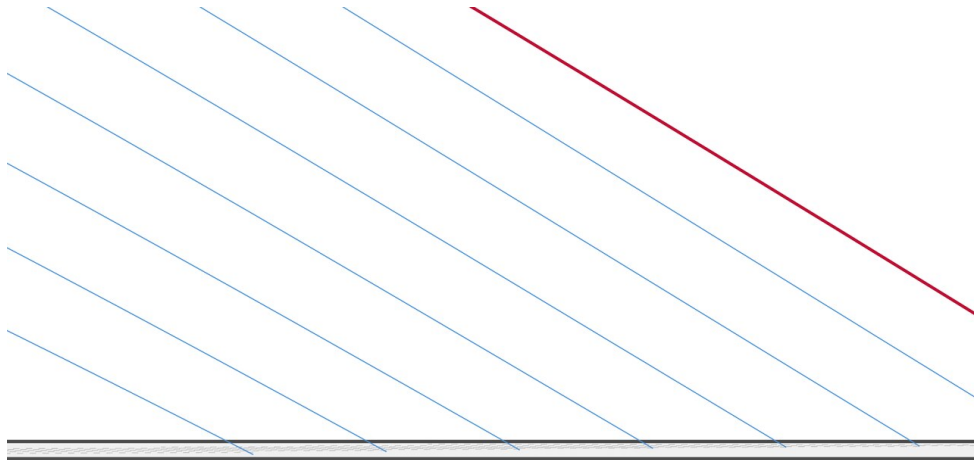
Boundary layers: where fluid SOL approximations break down



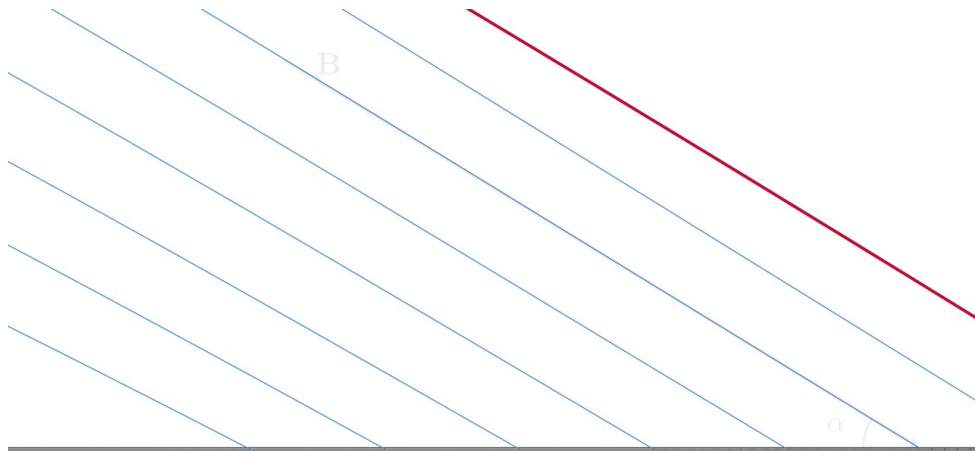
Boundary layers: where fluid SOL approximations break down



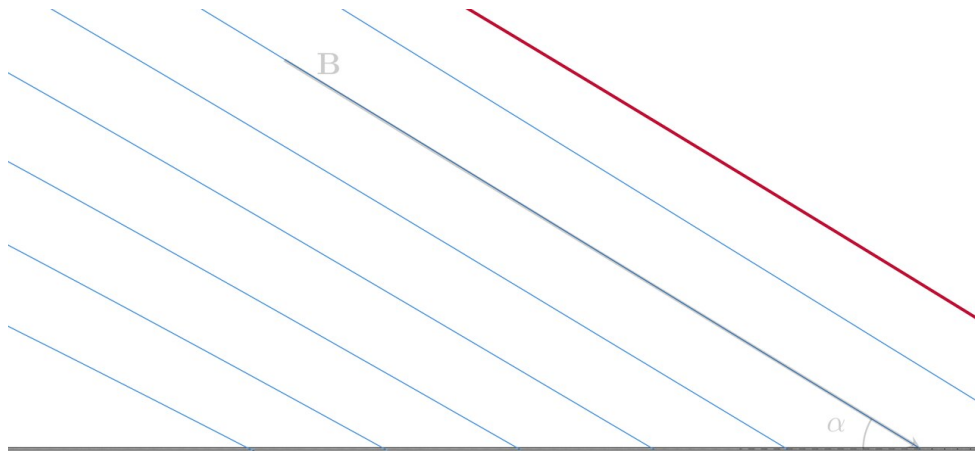
Boundary layers: where fluid SOL approximations break down



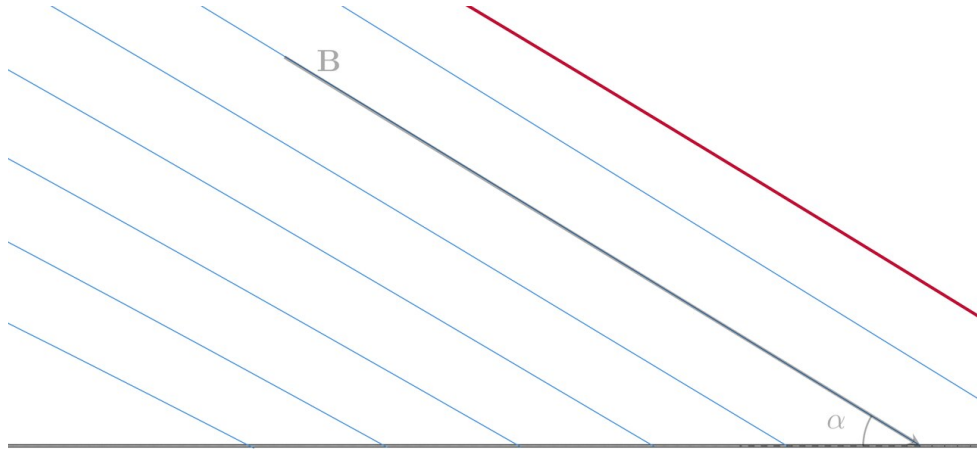
Boundary layers: where fluid SOL approximations break down



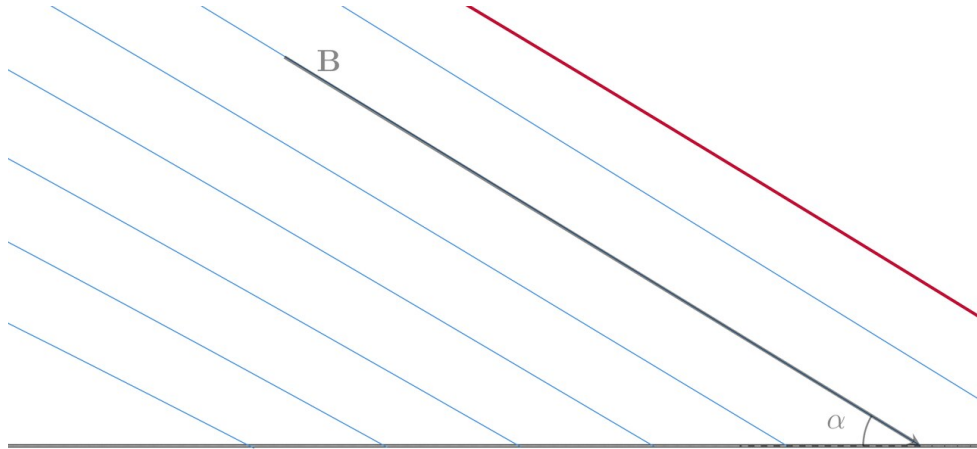
Boundary layers: where fluid SOL approximations break down



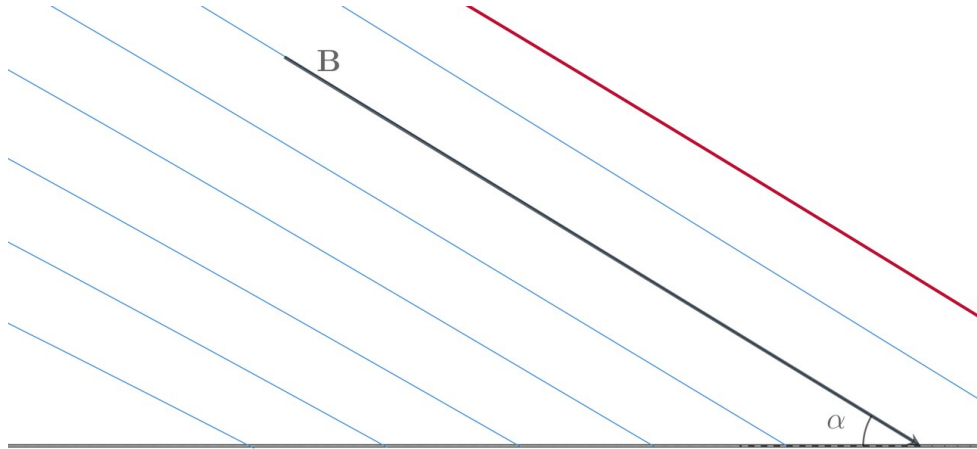
Boundary layers: where fluid SOL approximations break down



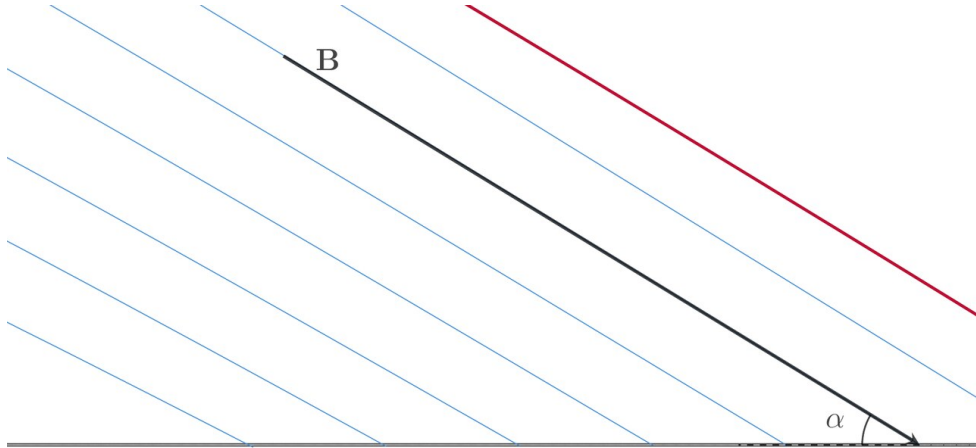
Boundary layers: where fluid SOL approximations break down



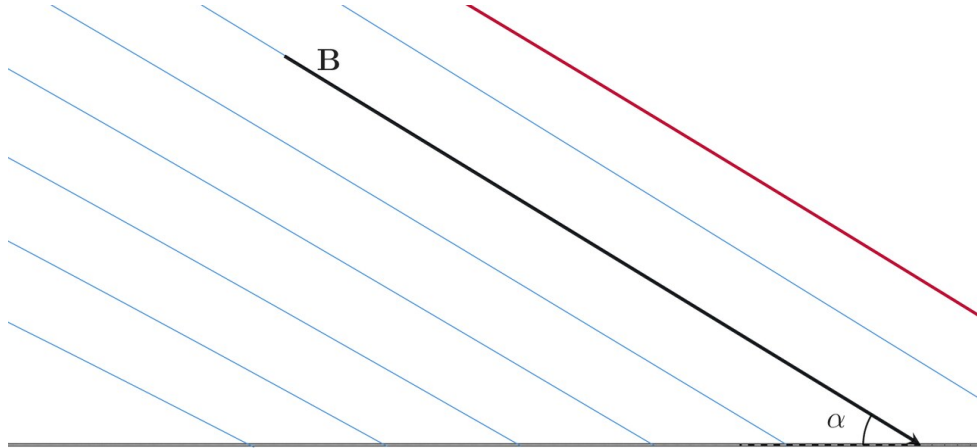
Boundary layers: where fluid SOL approximations break down



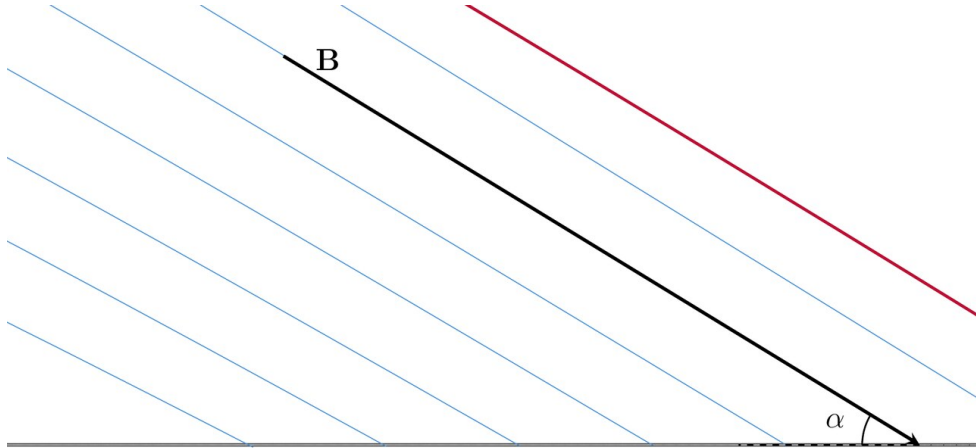
Boundary layers: where fluid SOL approximations break down



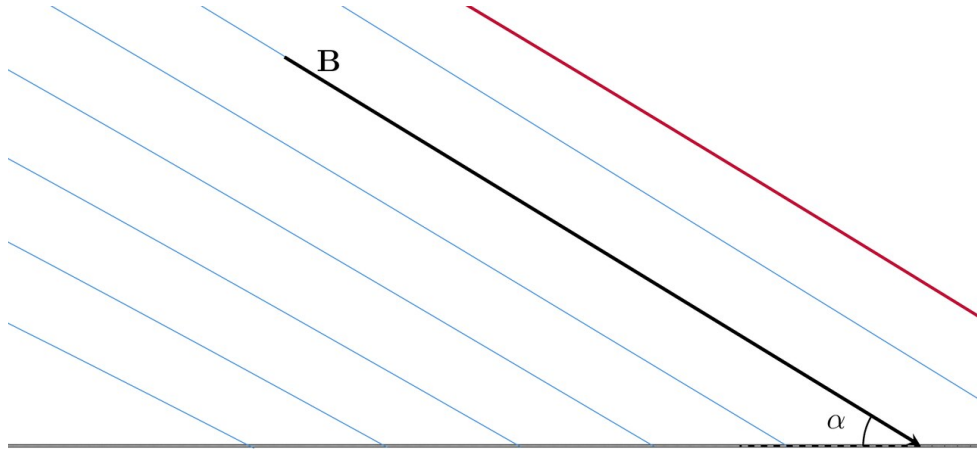
Boundary layers: where fluid SOL approximations break down



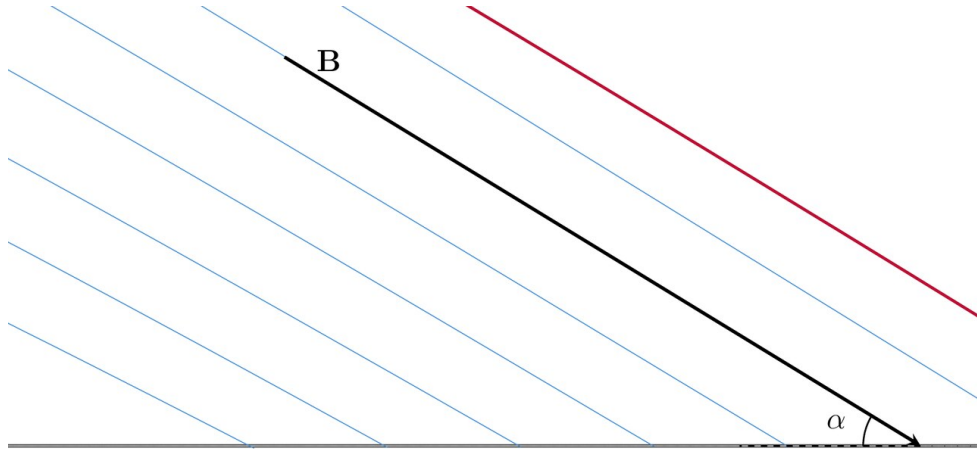
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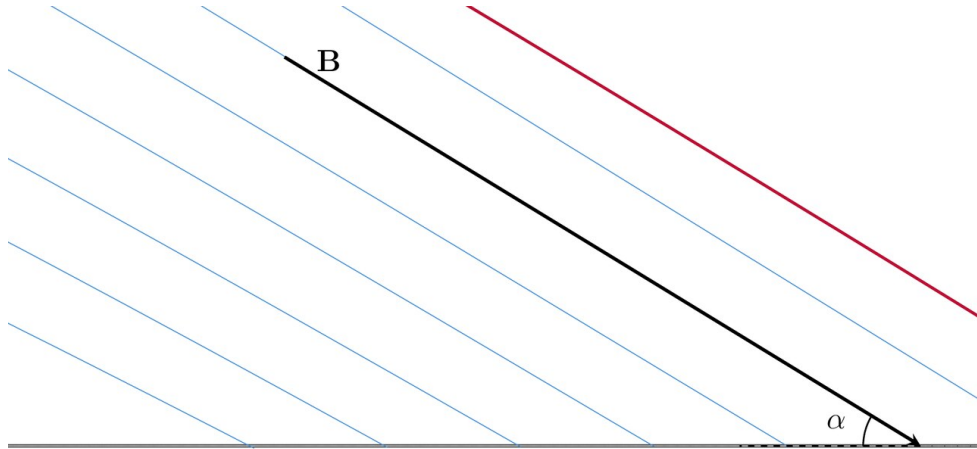
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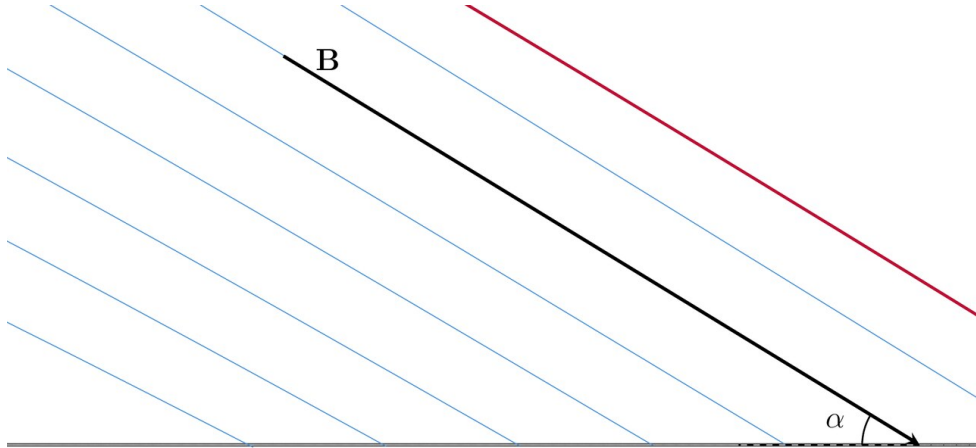
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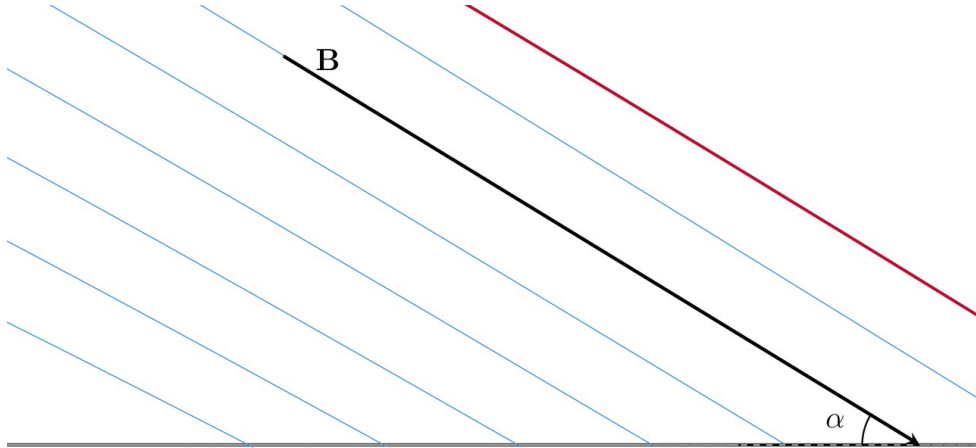
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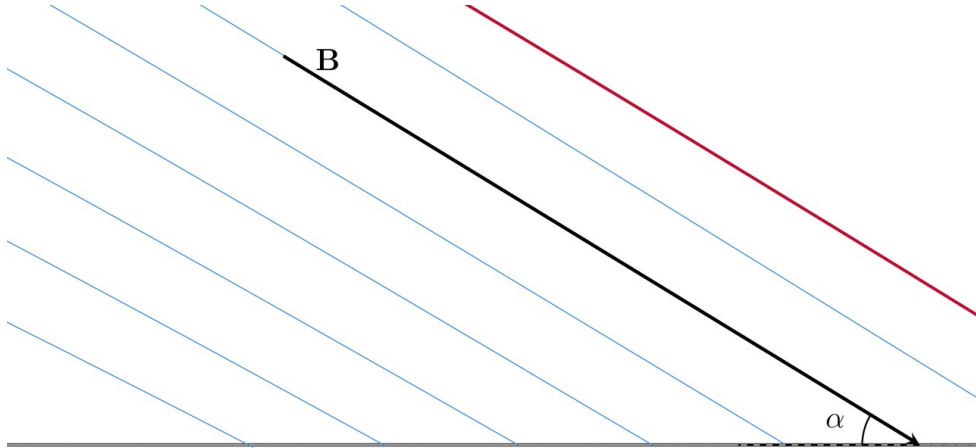
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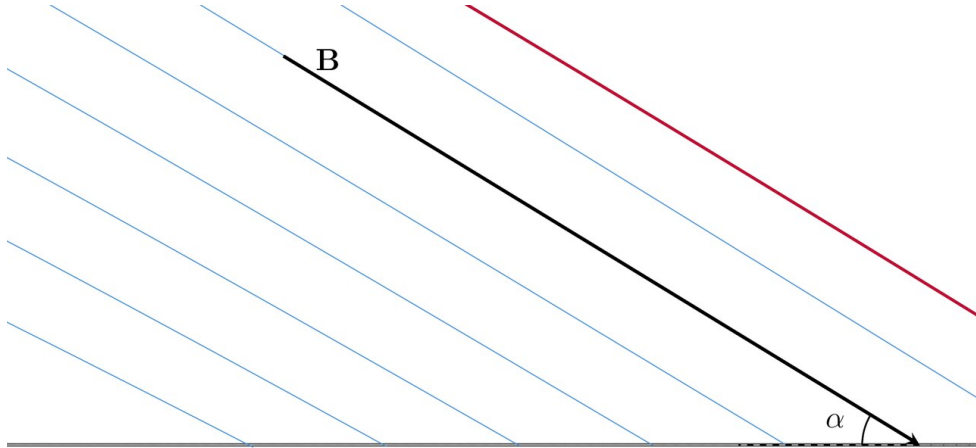
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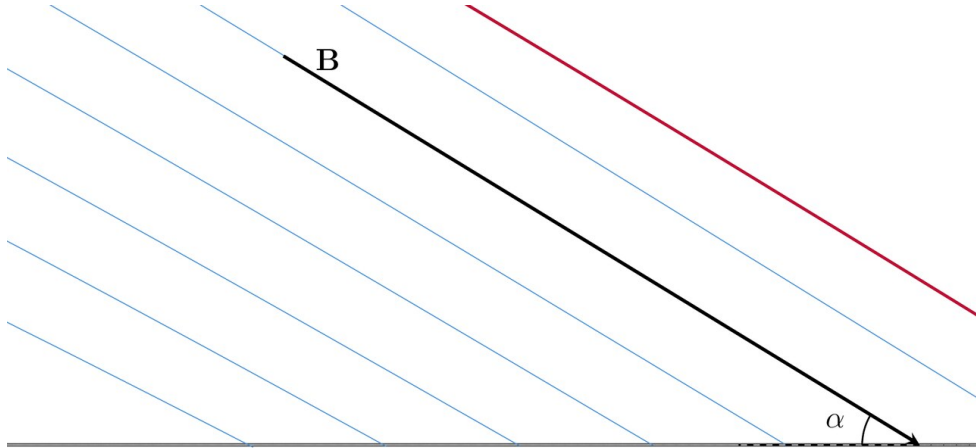
Boundary layers: where fluid SOL approximations break down



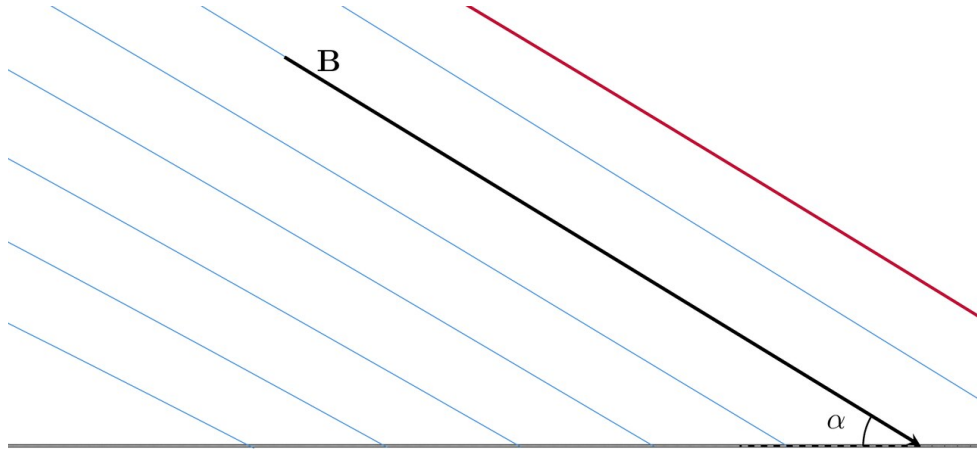
Boundary layers: where fluid SOL approximations break down



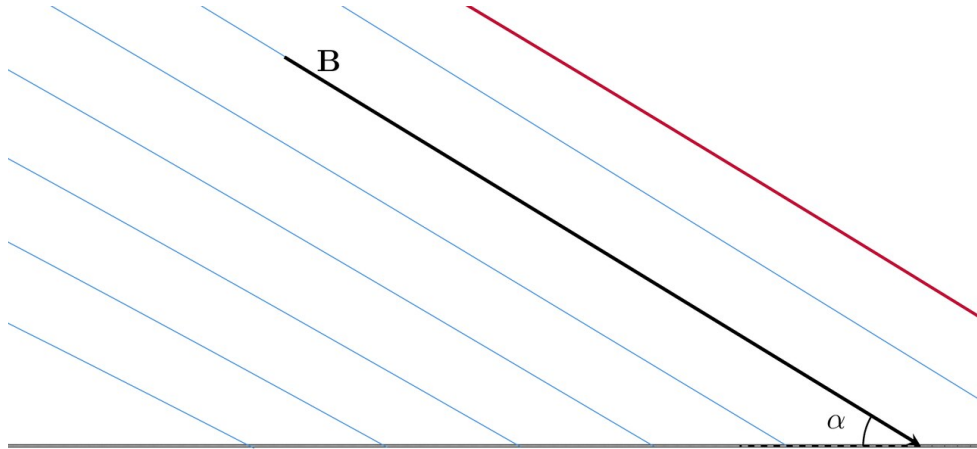
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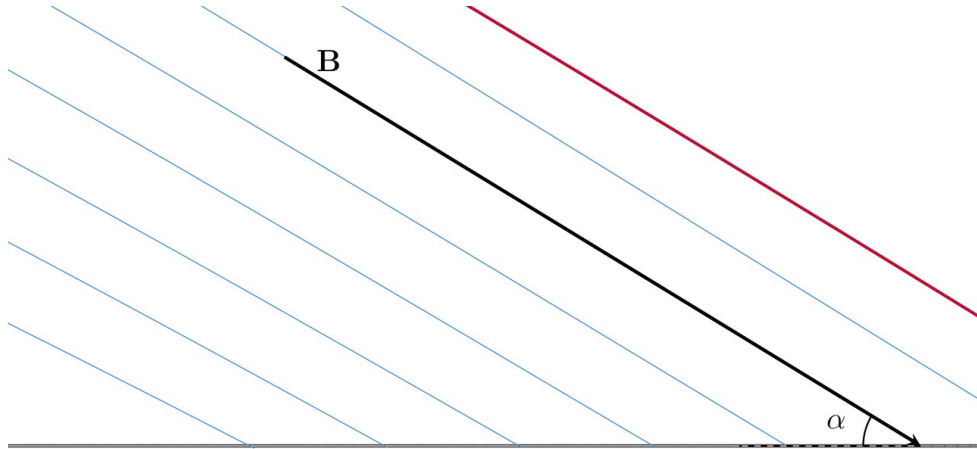
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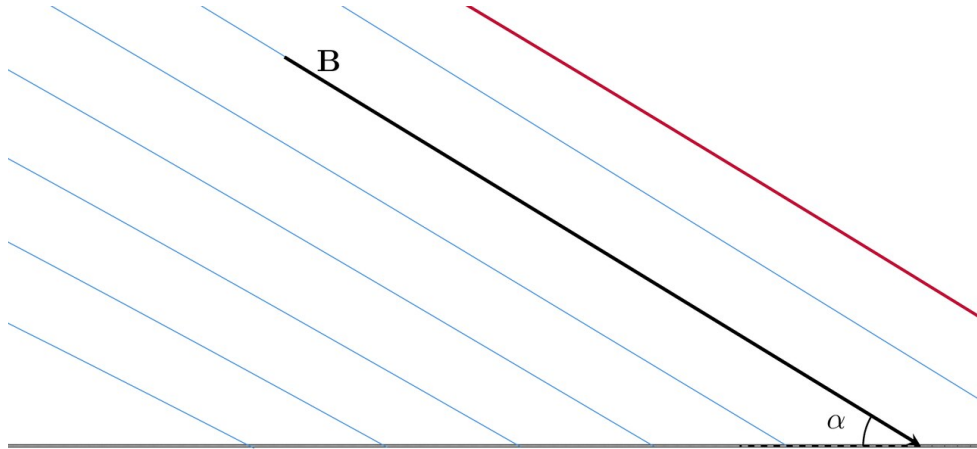
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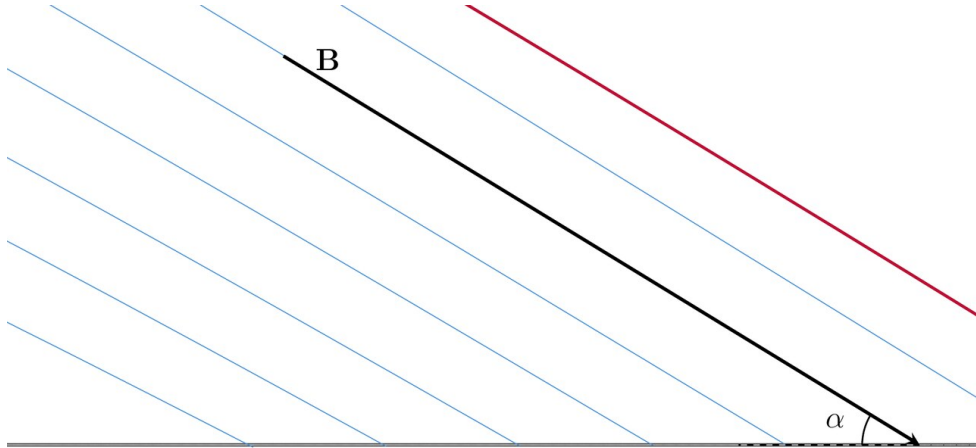
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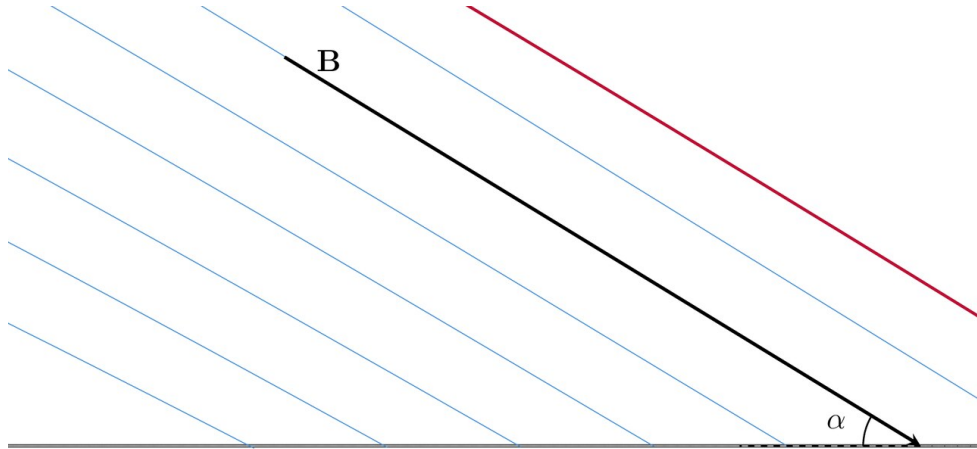
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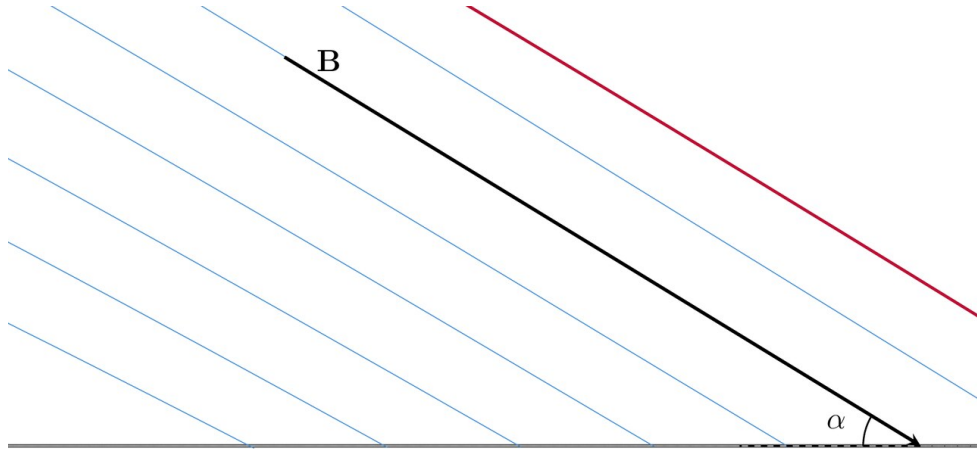
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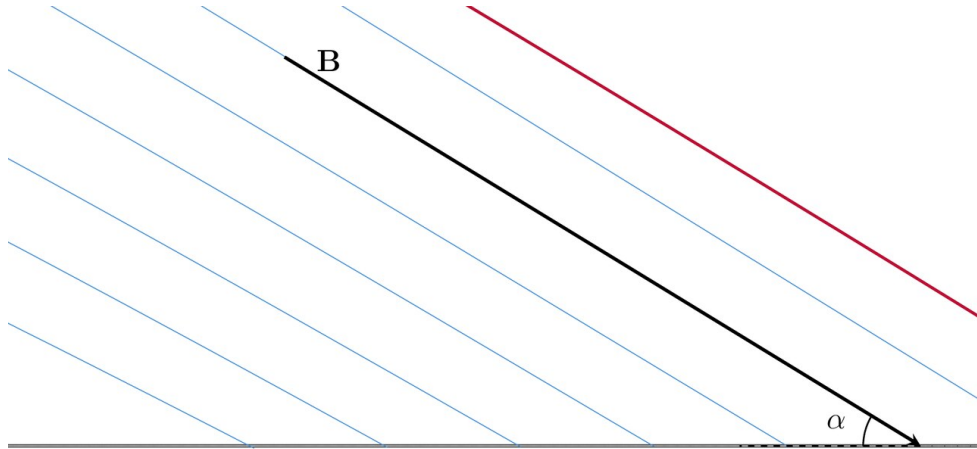
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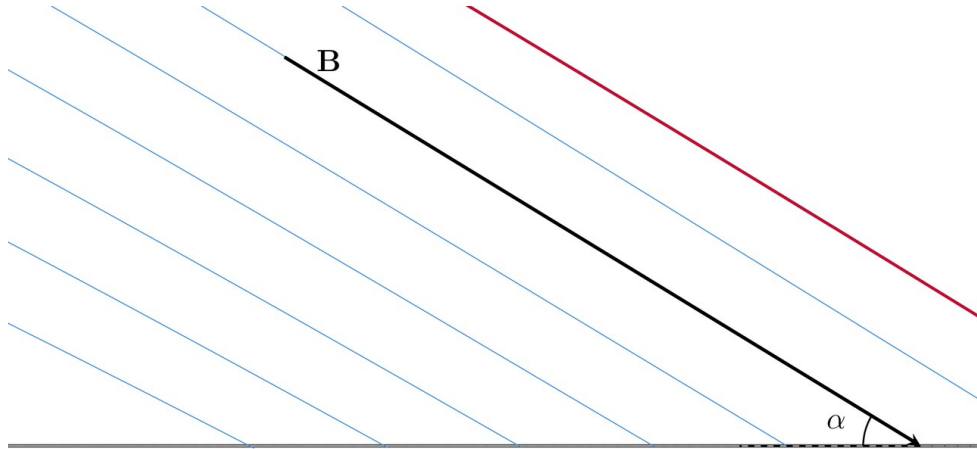
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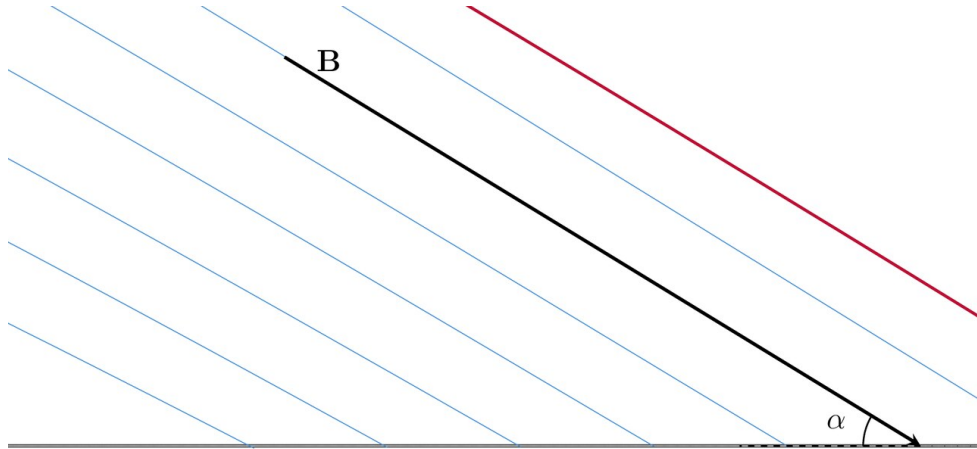
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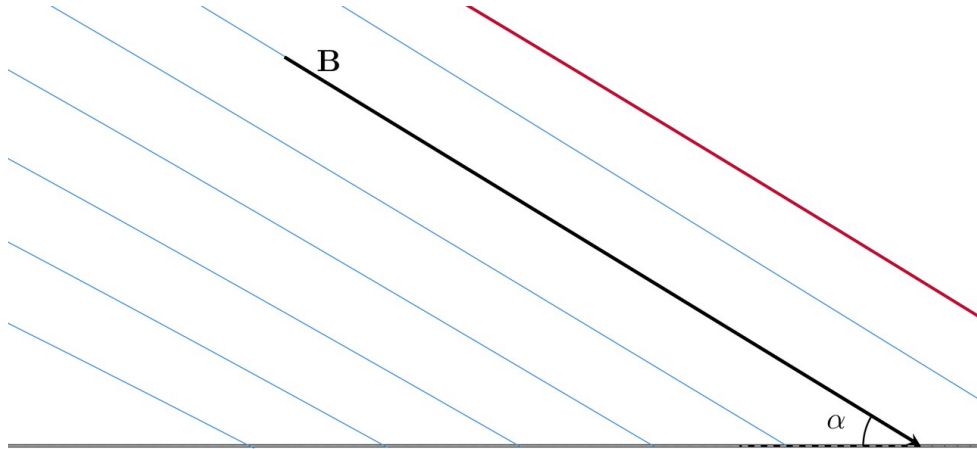
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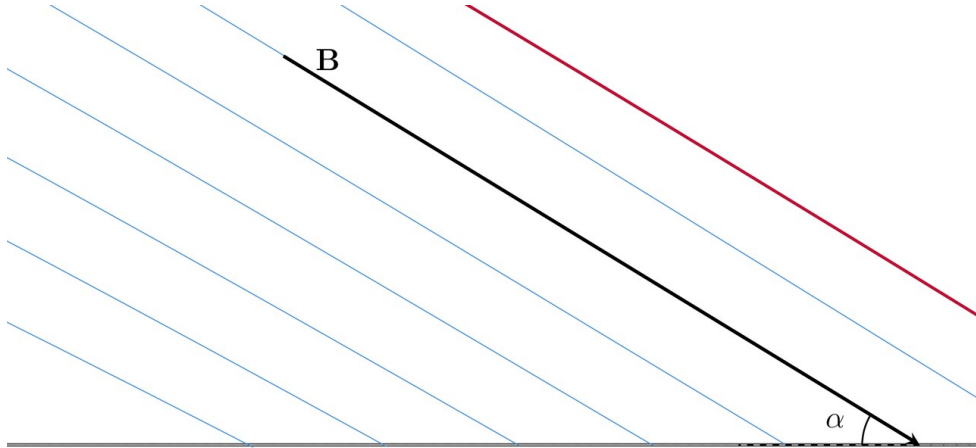
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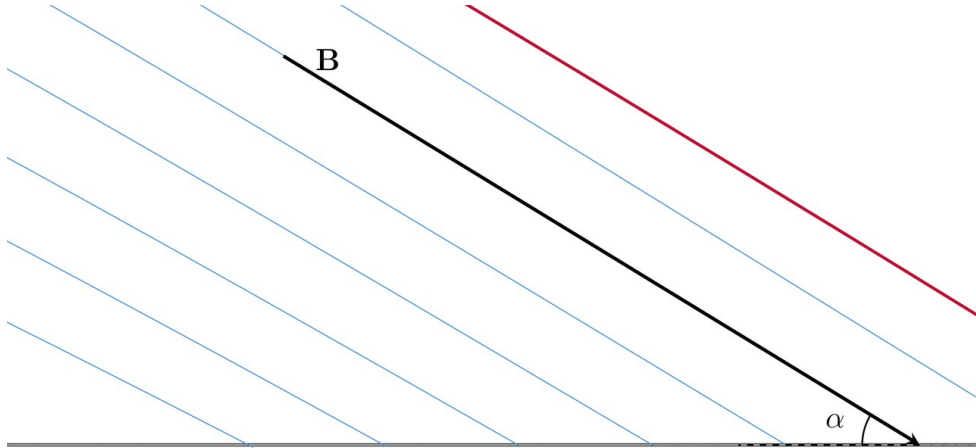
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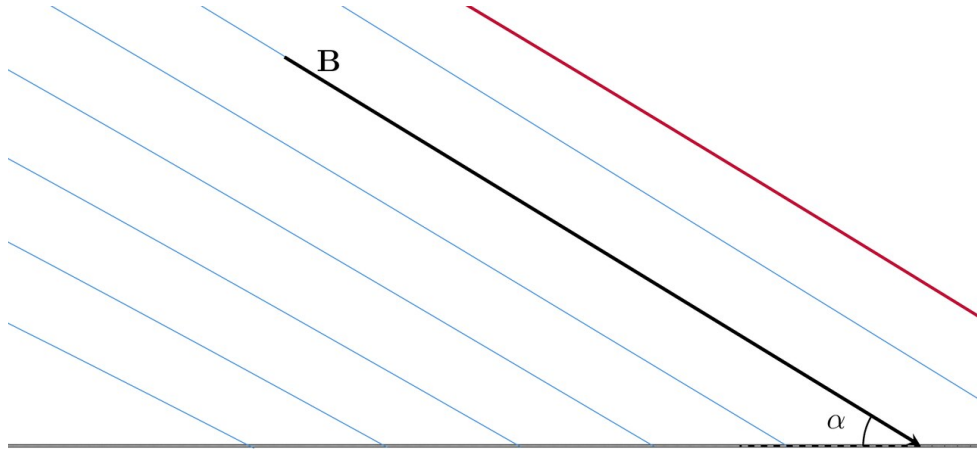
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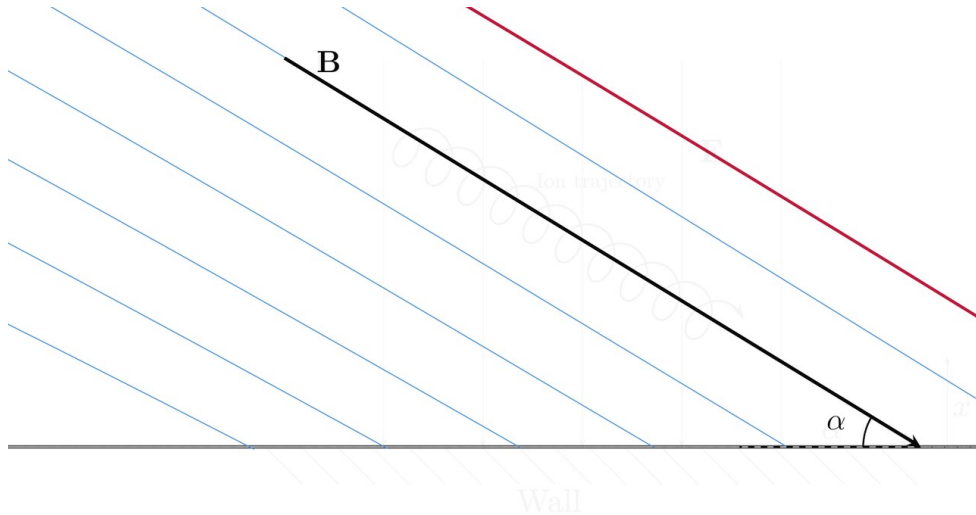
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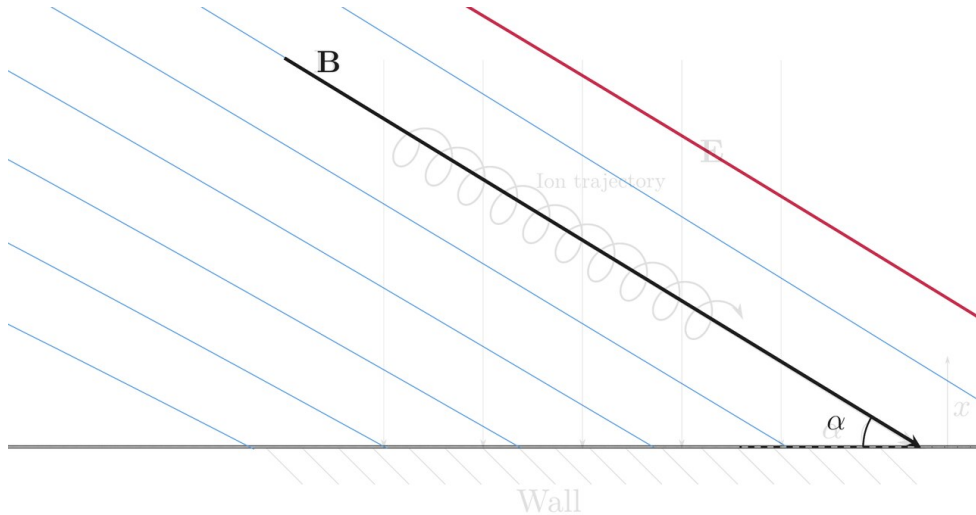
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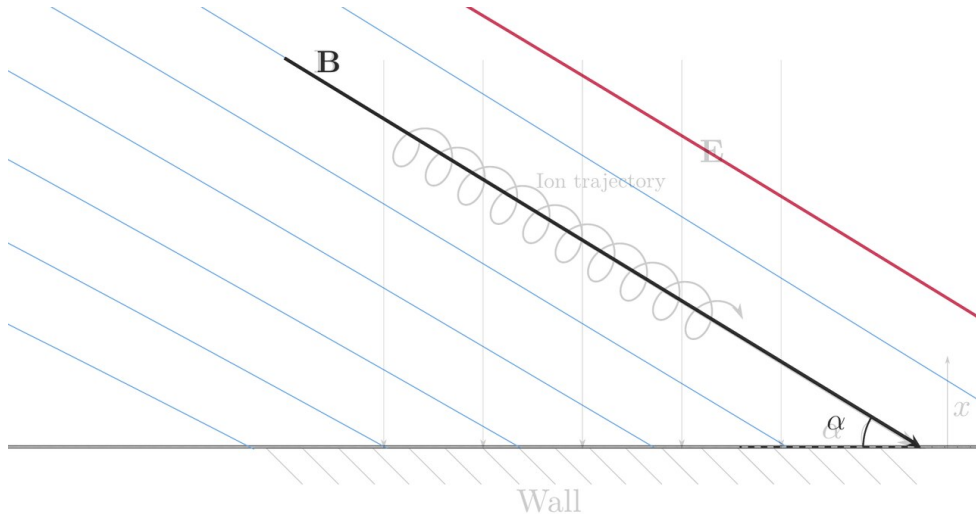
Boundary layers: where fluid SOL approximations break down



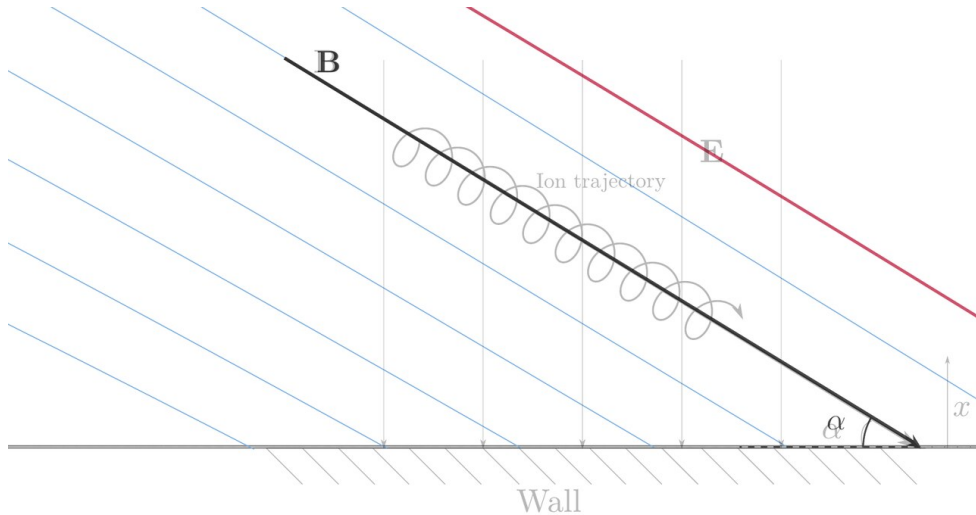
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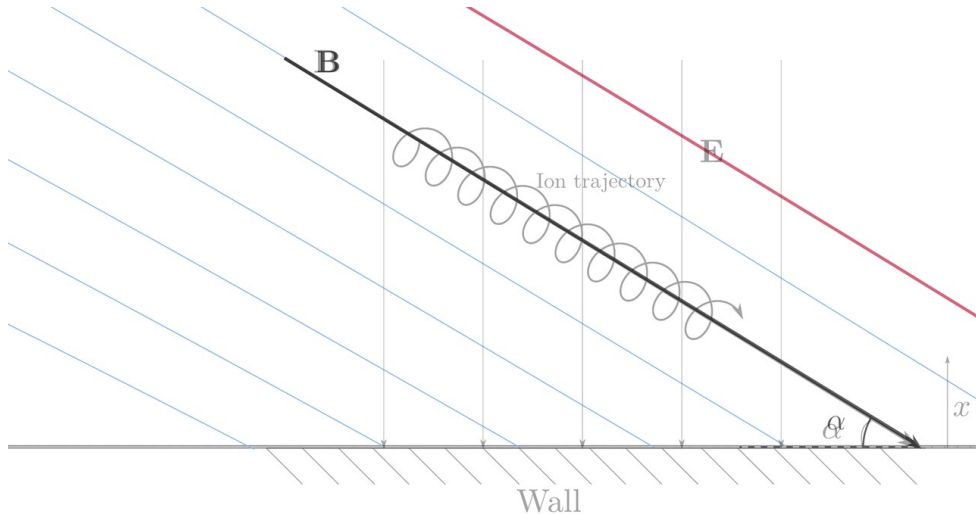
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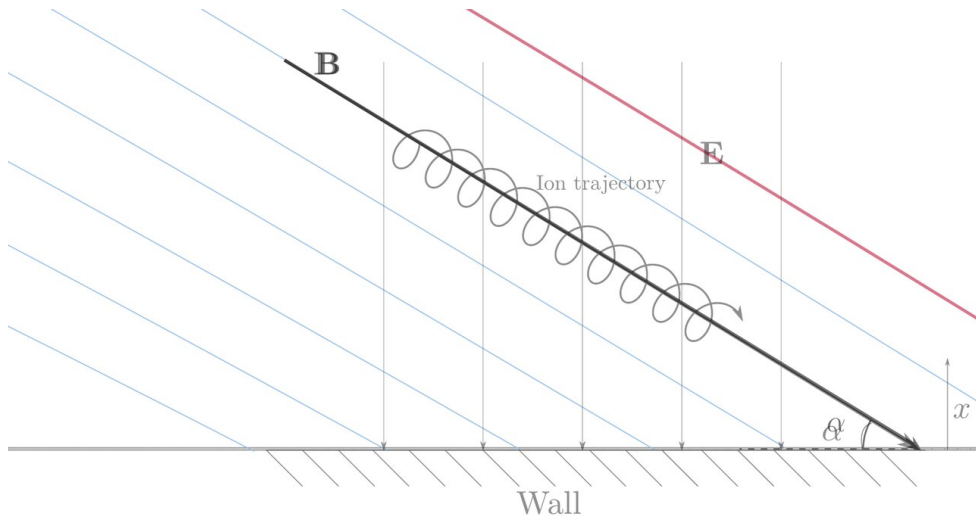
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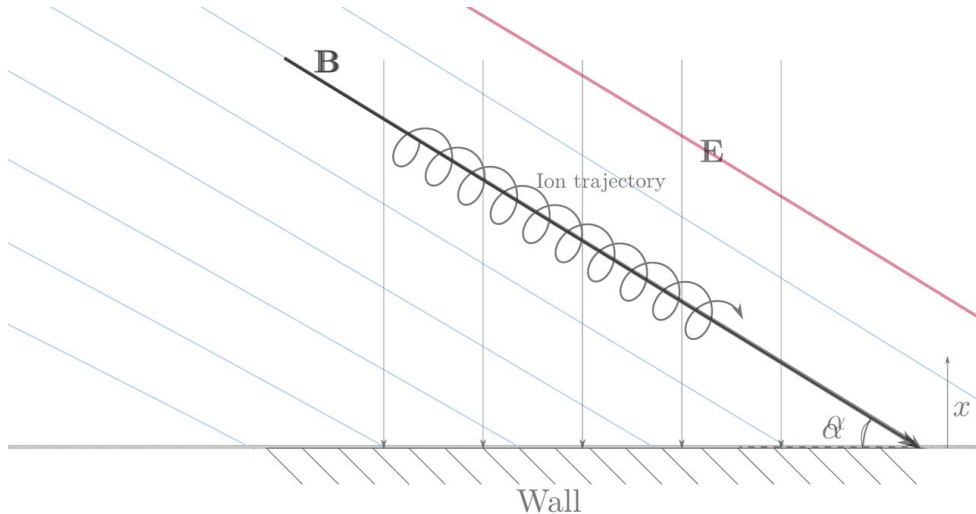
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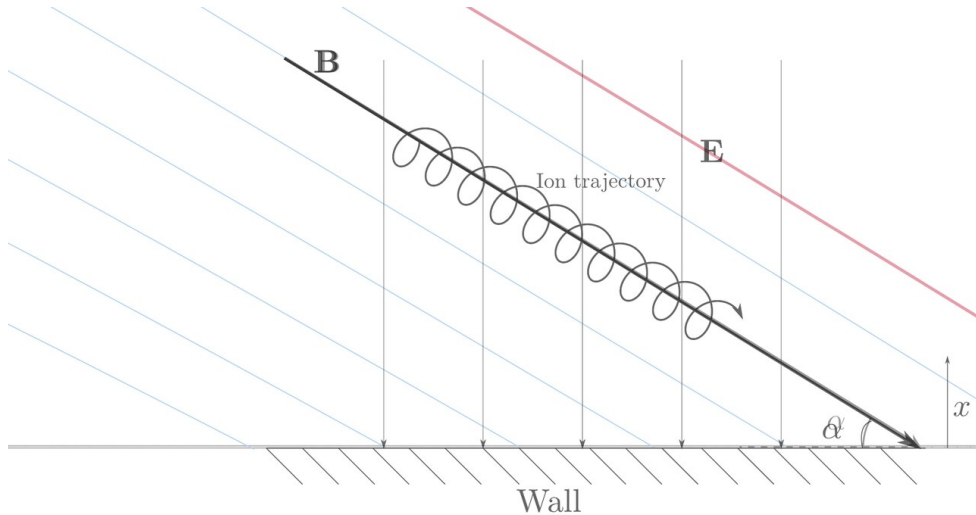
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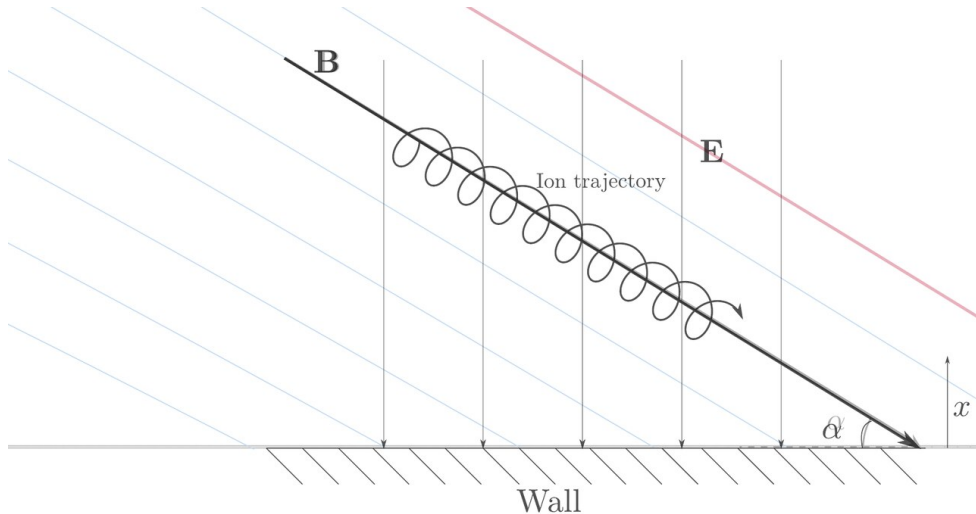
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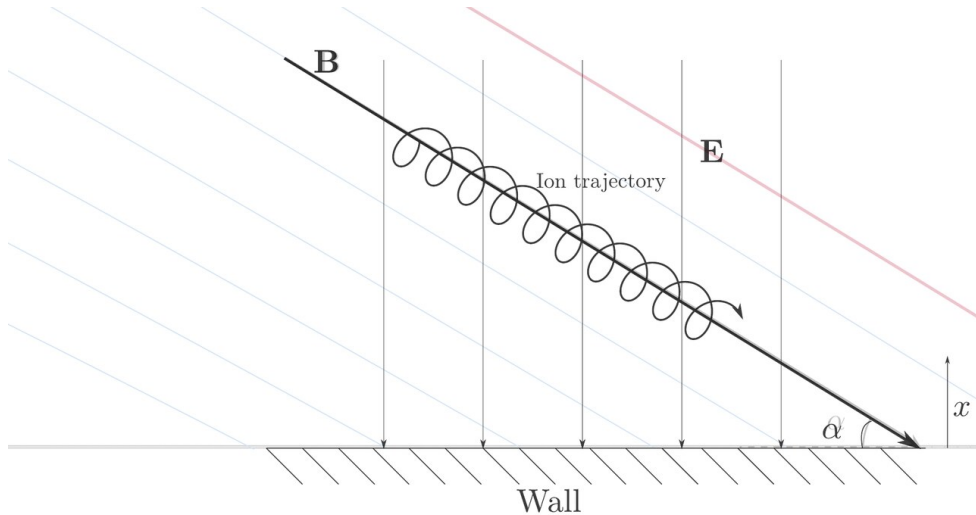
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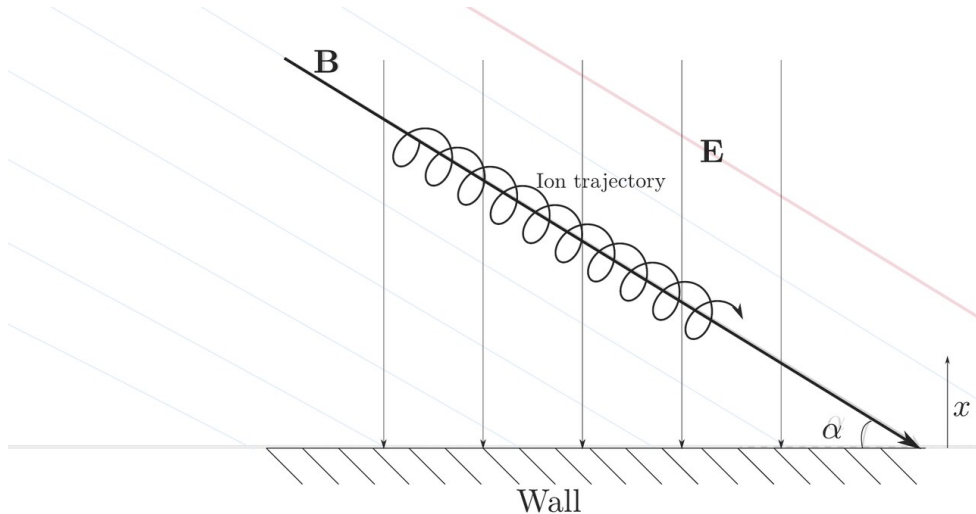
Boundary layers: where fluid SOL approximations break down



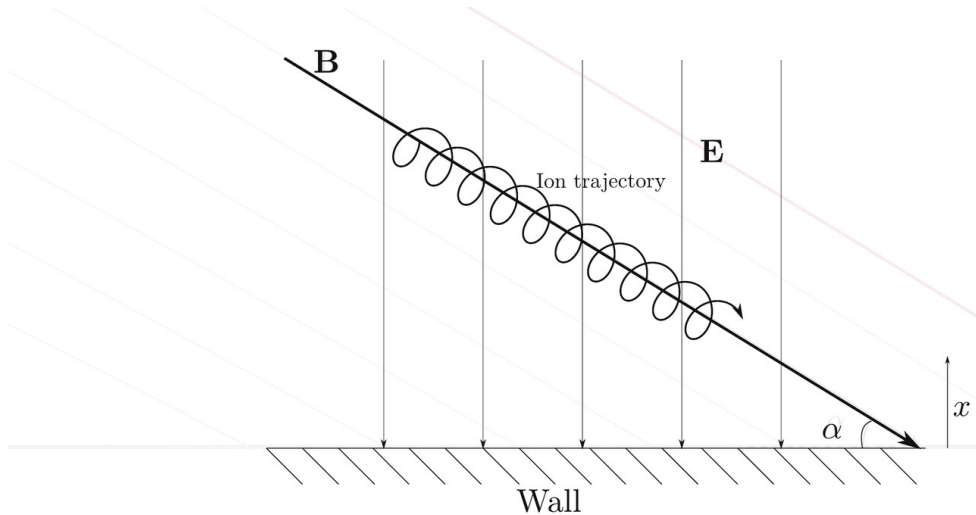
Boundary layers: where fluid SOL approximations break down



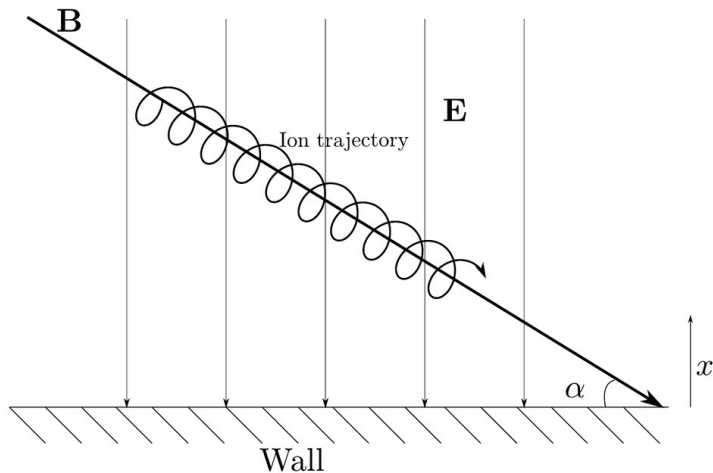
Boundary layers: where fluid SOL approximations break down



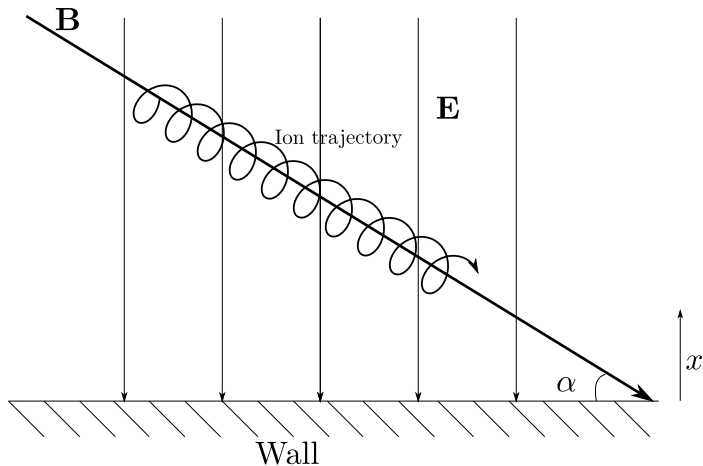
Boundary layers: where fluid SOL approximations break down



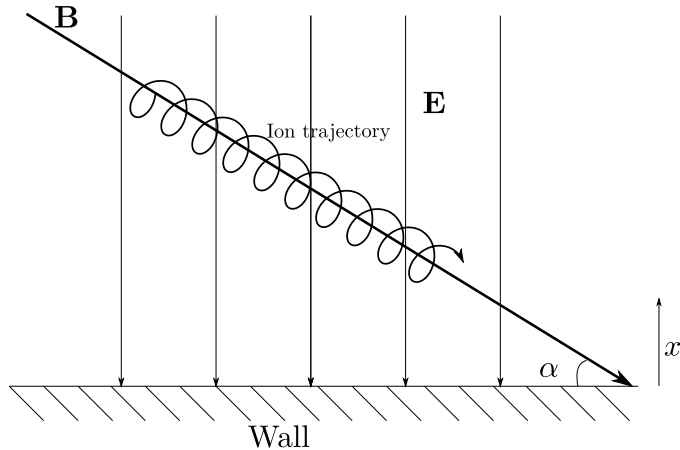
Boundary layers: where fluid SOL approximations break down



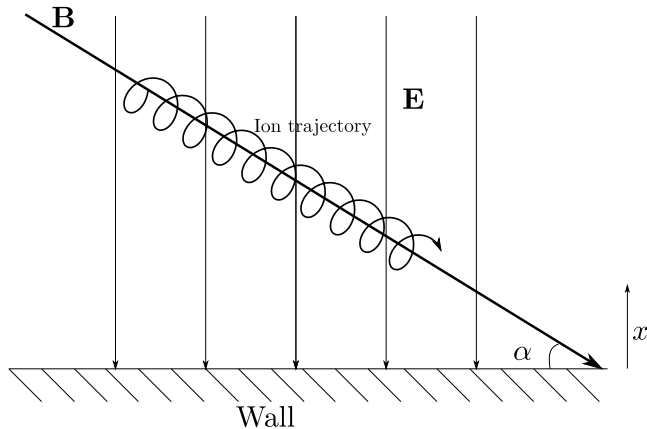
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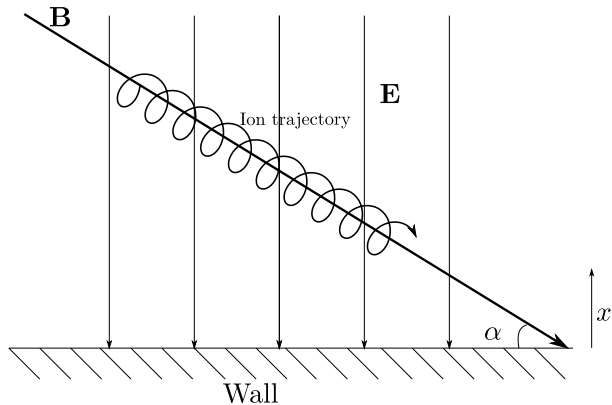
Boundary layers: where fluid SOL approximations break down



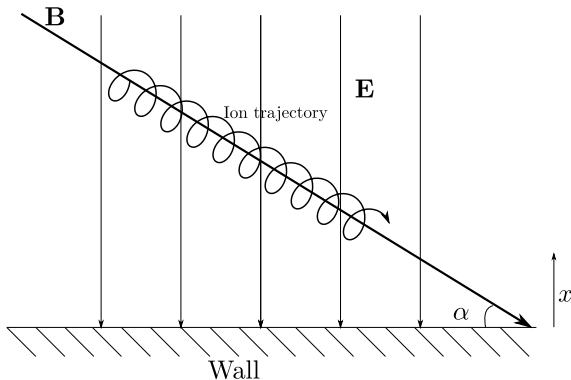
Boundary layers: where fluid SOL approximations break down



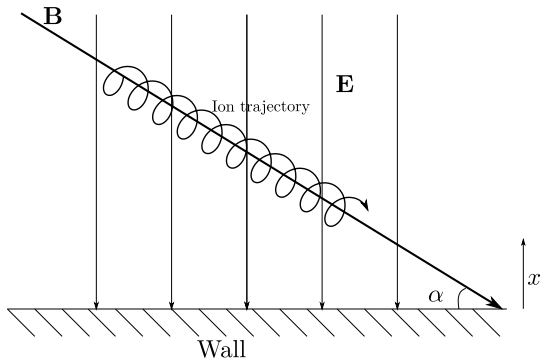
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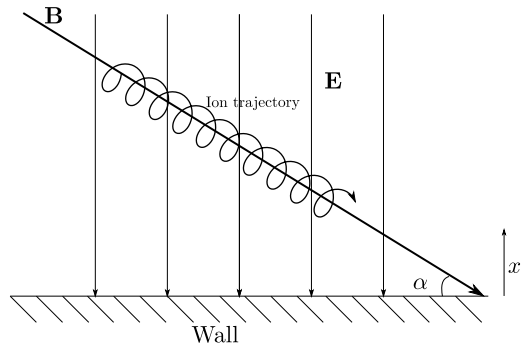
Boundary layers: where fluid SOL approximations break down



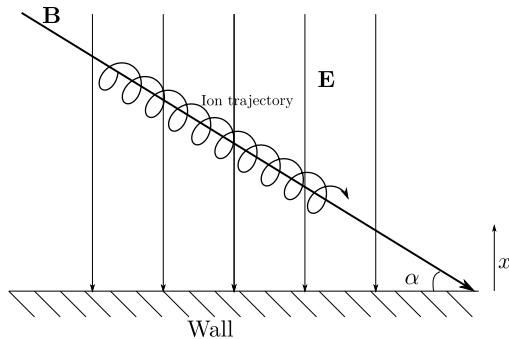
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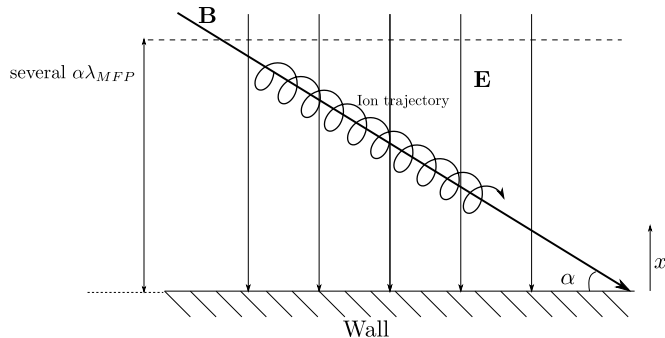
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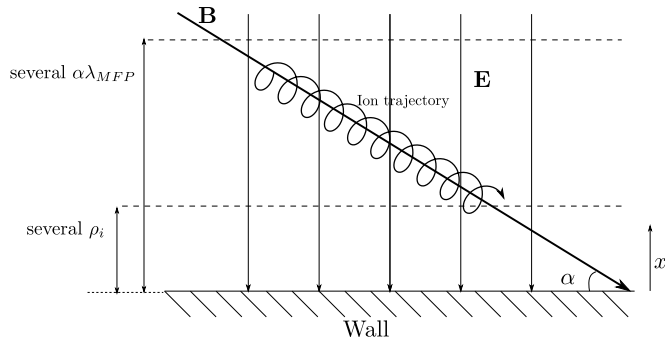
Boundary layers: where fluid SOL approximations break down



Towards the wall, length scales shrink and fluid SOL approximations break down:

- **Collisional layer** $\sim \lambda_{MFP} \sin \alpha \sim 0.5 \text{ m}$: *high collisionality* breaks **this work**

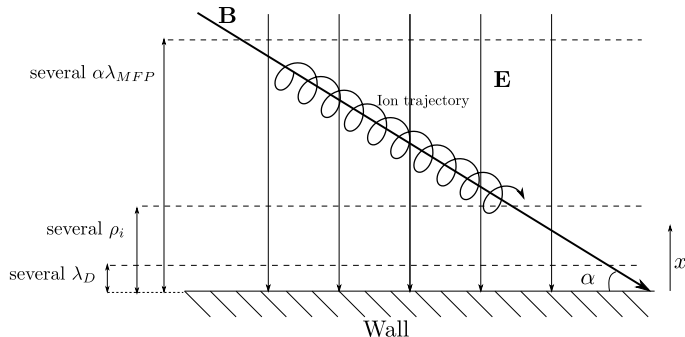
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- **Magnetic presheath (MP)** $\sim \rho_i \sim 0.7$ mm: *circular gyro-orbits* break (collisionless)
- **Debye sheath** $\sim \lambda_D \sim 0.02$ mm: *quasineutrality* breaks (shielding of the negatively charged wall)

Why fluid cannot connect directly to the magnetic presheath

Ions entering the MP must satisfy the **kinetic**

Chodura condition:

- ▶ no ions leave the wall: $f_{MPE}(v_{\parallel} \leq 0) = 0$
- ▶ few slow ions:

$$\frac{Z^2 T_e}{m_i} \int d^3 \mathbf{v} \frac{f_{MPE}}{v_{\parallel}^2} \leq n_{e,MPE}$$

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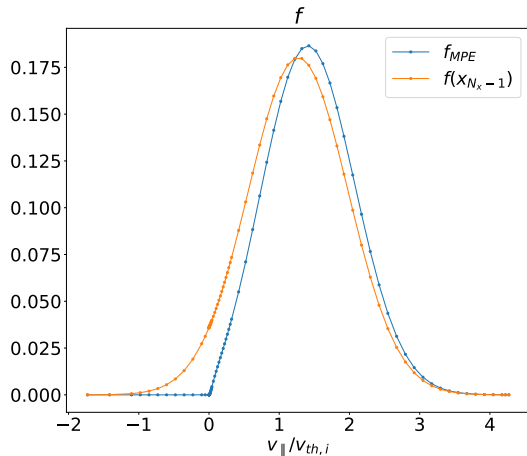
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A Maxwellian has $f(v_{\parallel}=0) \neq 0 \Rightarrow$ integral **diverges**.

$\Rightarrow$ Need a kinetic, collisional layer with full Fokker-Planck ion-ion collisions



Maxwellian far from the wall vs. f at the MPE
(CLOVER)

Model (CLOVER) and key result

Drift kinetic ions, Boltzmann electrons, quasineutral:

$$-v_{\parallel} \sin \alpha \frac{\partial f}{\partial x} + \frac{Ze}{m_i} \sin \alpha \frac{\partial \phi}{\partial x} \frac{\partial f}{\partial v_{\parallel}} = C_{ii}[f, f]$$

$$n_i = \int f d^3\mathbf{v} = n_{i\infty} e^{e(\phi - \phi_{\infty})/T_e}$$

- ▶ $x \rightarrow \infty$: Maxwellian $x = 0$: $f(v_{\parallel} \leq 0) = 0$
- ▶ Semi-Lagrangian (tracing characteristics), finite elements; the discretised collision operator conserves particle number, momentum and energy exactly

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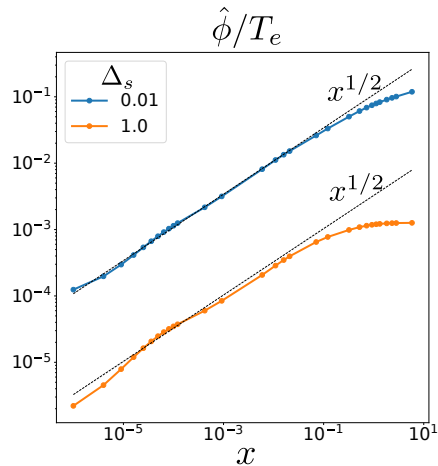
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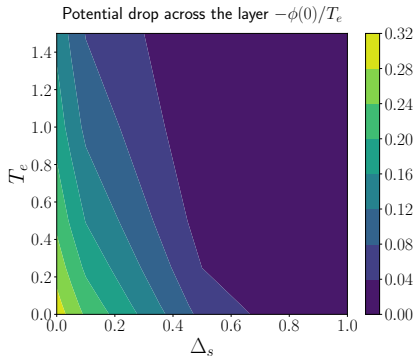
Near the MPE: $\hat{\phi} \propto \sqrt{x} \Rightarrow E \rightarrow \infty$

$\Rightarrow$ The layer itself enforces the Chodura condition



Results

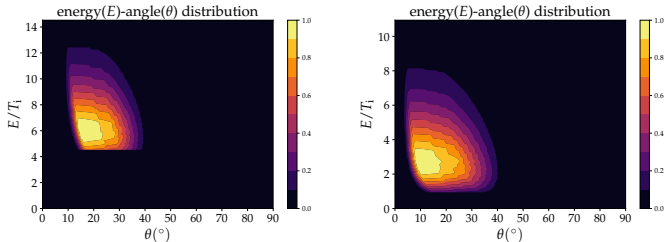
Potential drop across the layer



Largest for slow incoming flow (small
 $\Delta_s = u_{\parallel\infty}/c_s - 1$)

Challenge: resolving the Chodura condition numerically needs very fine x and $v_{\parallel}$ grids.

Ions at the wall (CLOVER $\rightarrow$ GYRAZE)



Energy-angle distribution, $\alpha = 3^{\circ}$
 $\Rightarrow$ **Input for sputtering yields**

Summary and next steps

Summary

- ▶ Collisional layer connects fluid SOL to the kinetic sheath
- ▶ Diverging field ($\hat{\phi} \propto \sqrt{x}$) enforces the Chodura condition
- ▶ CLOVER: given T_e and $u_{||\infty}/c_s$, find $\phi(x)$, f_{MPE} ; add GYRAZE to find f_{wall}

Potential next steps: with kinetic electrons, the framework could give fluid codes (not yet implemented)

- ▶ $u_{e||}$ closure:
 $u_{e||}/c_s = F(e\Delta\phi_{tot}/T_e, u_{i||}/c_s, T_e/T_i)$
- ▶ $q_{e||}$ without sheath heat transmission coefficients
- ▶ Split of $\Delta\phi_{tot}$ between the layers

Also: neutrals

Come and see the poster!