Influence of Downstream Waves on Impinging SBLI

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Timothy Missing, Holger Babinsky

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NWTF

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Harding Distinguished Postgraduate Scholars Programme

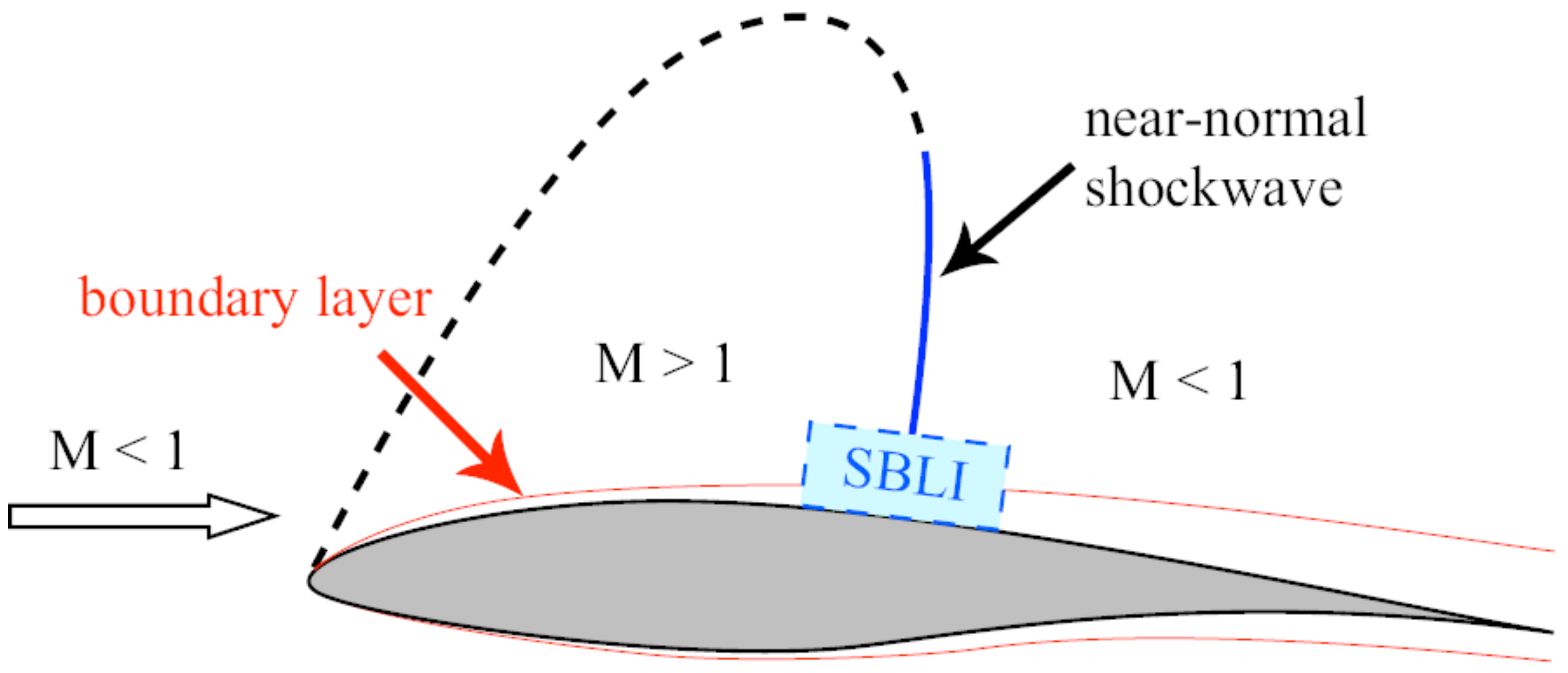
Shock-Boundary Layer Interactions

Widely observed in high-speed wall-bounded flow fields

Occur in many systems - supersonic intakes and transonic airfoils

Associated with flow separation and losses

https://www.heritageconcorde.com/air-in-take-system



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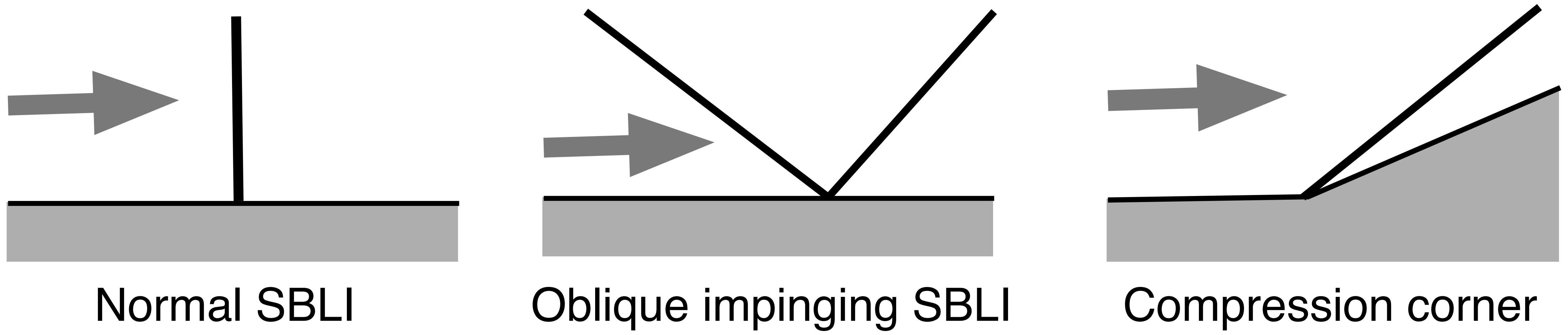

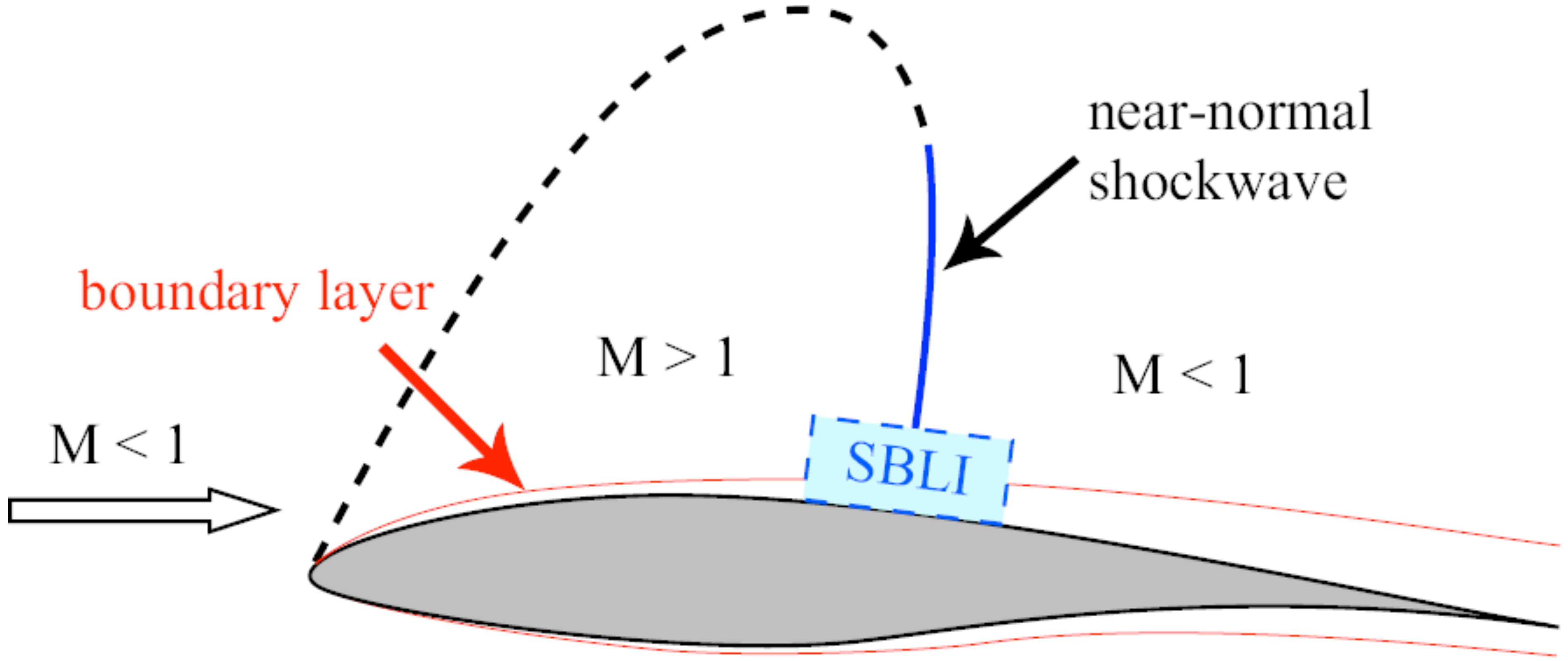

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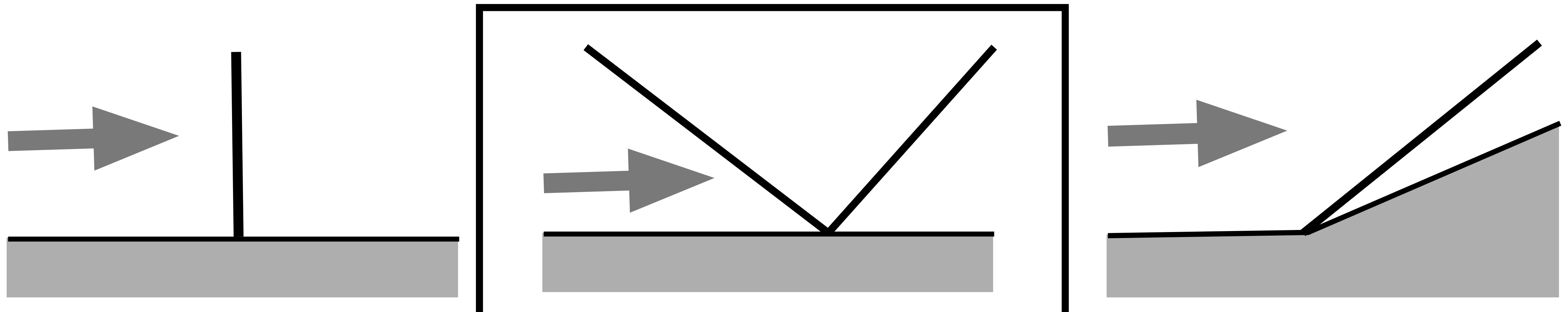
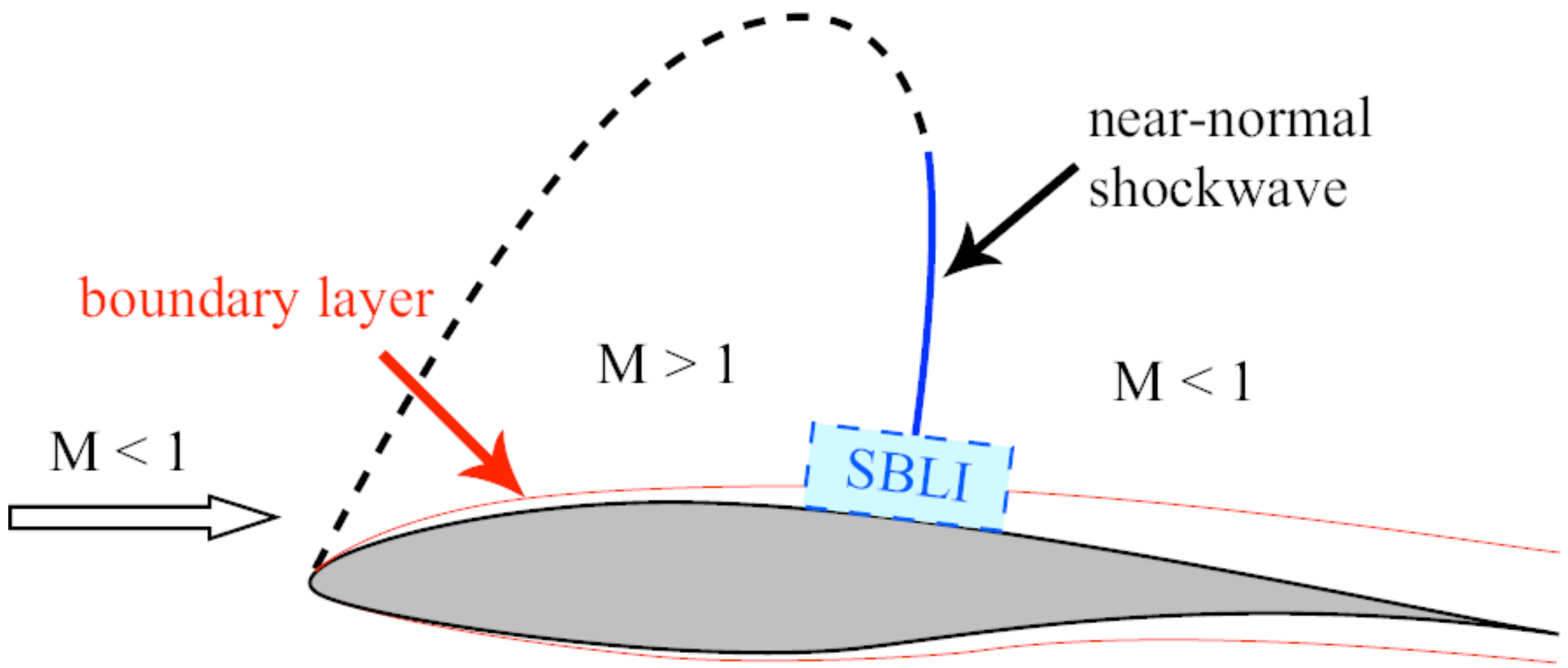
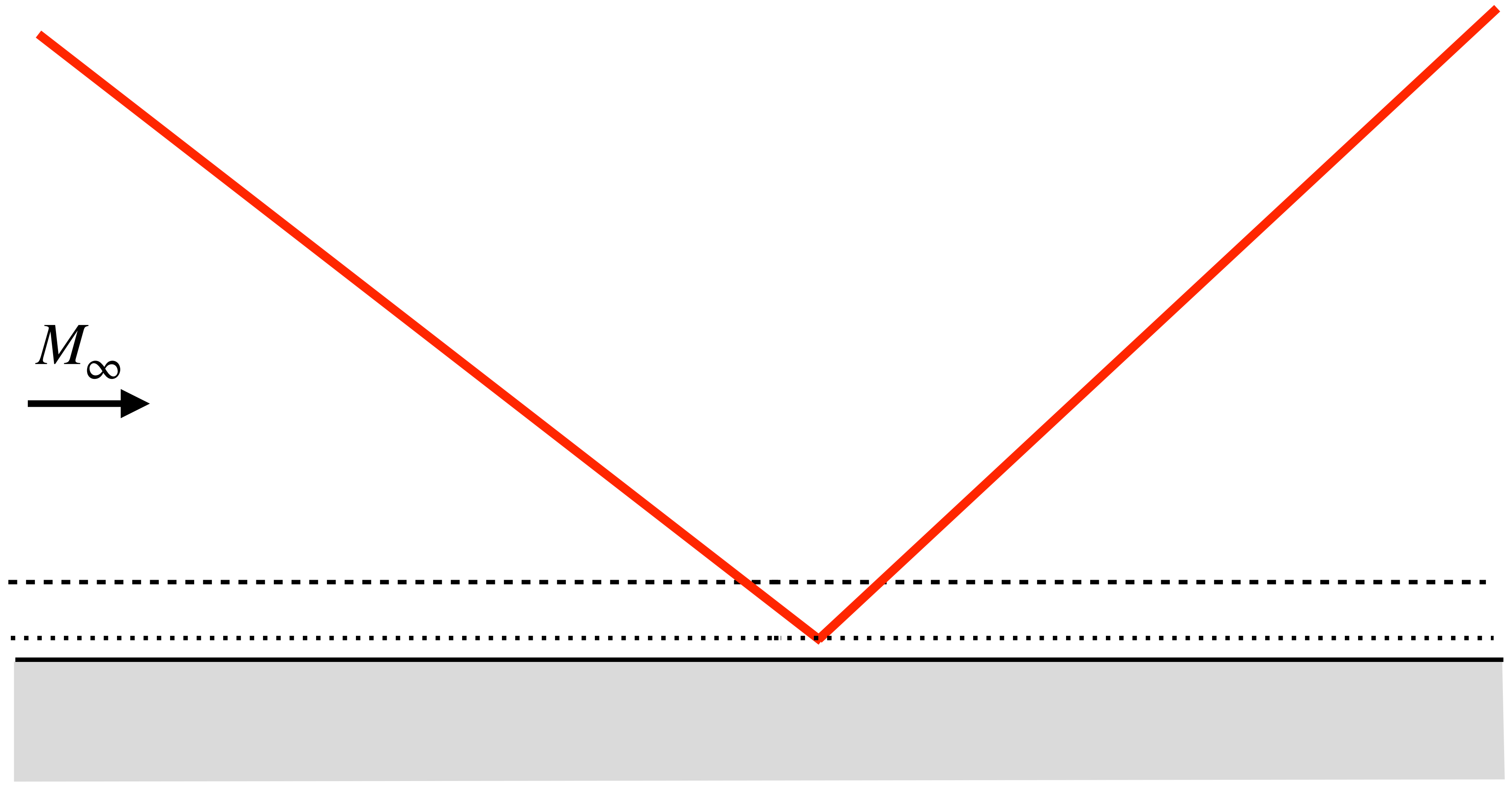


Normal SBLI | Oblique impinging SBLI | Compression corner

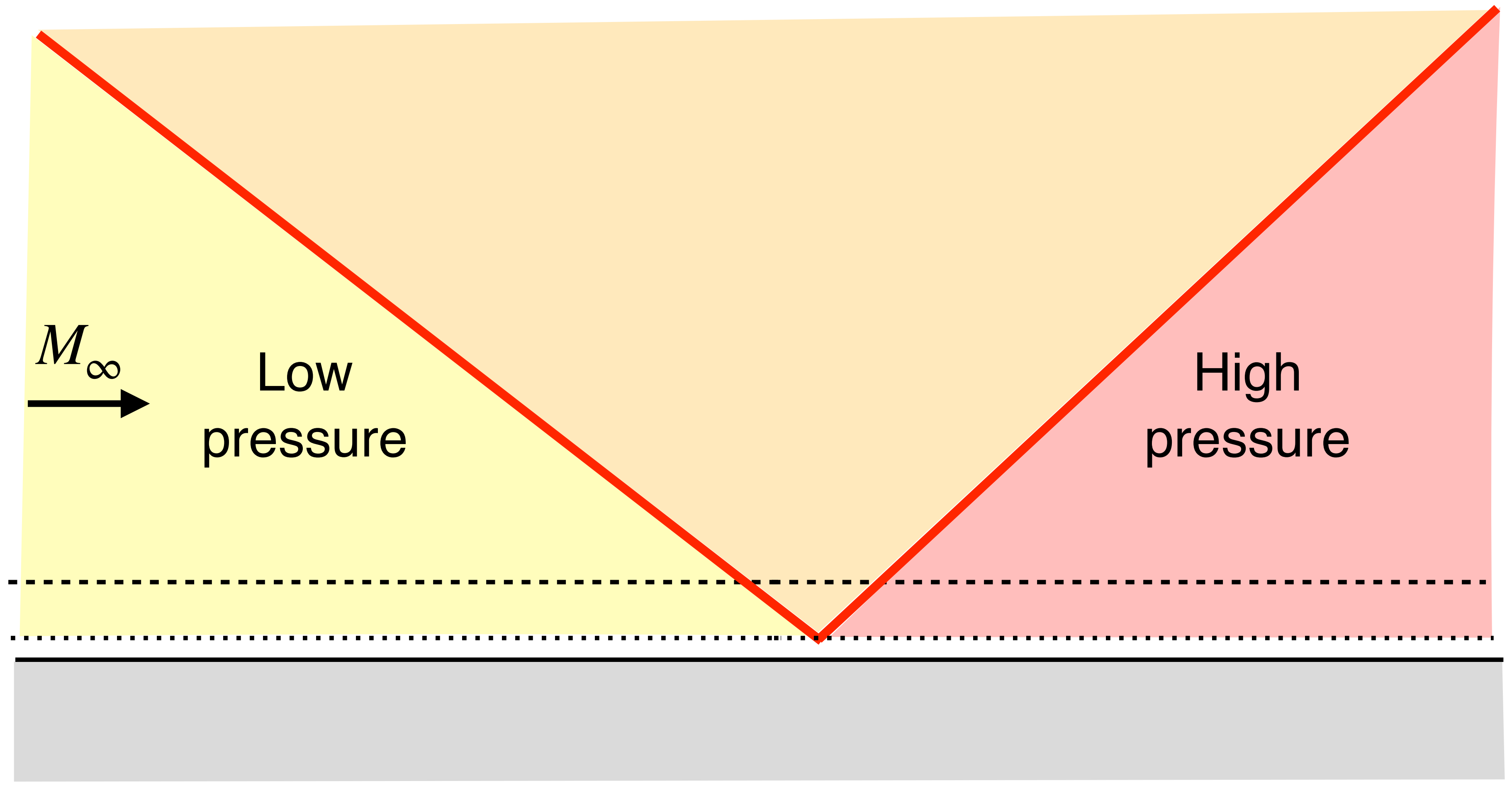


Oblique SBLI



Oblique SBLI

Adverse pressure gradient imposed by the shock



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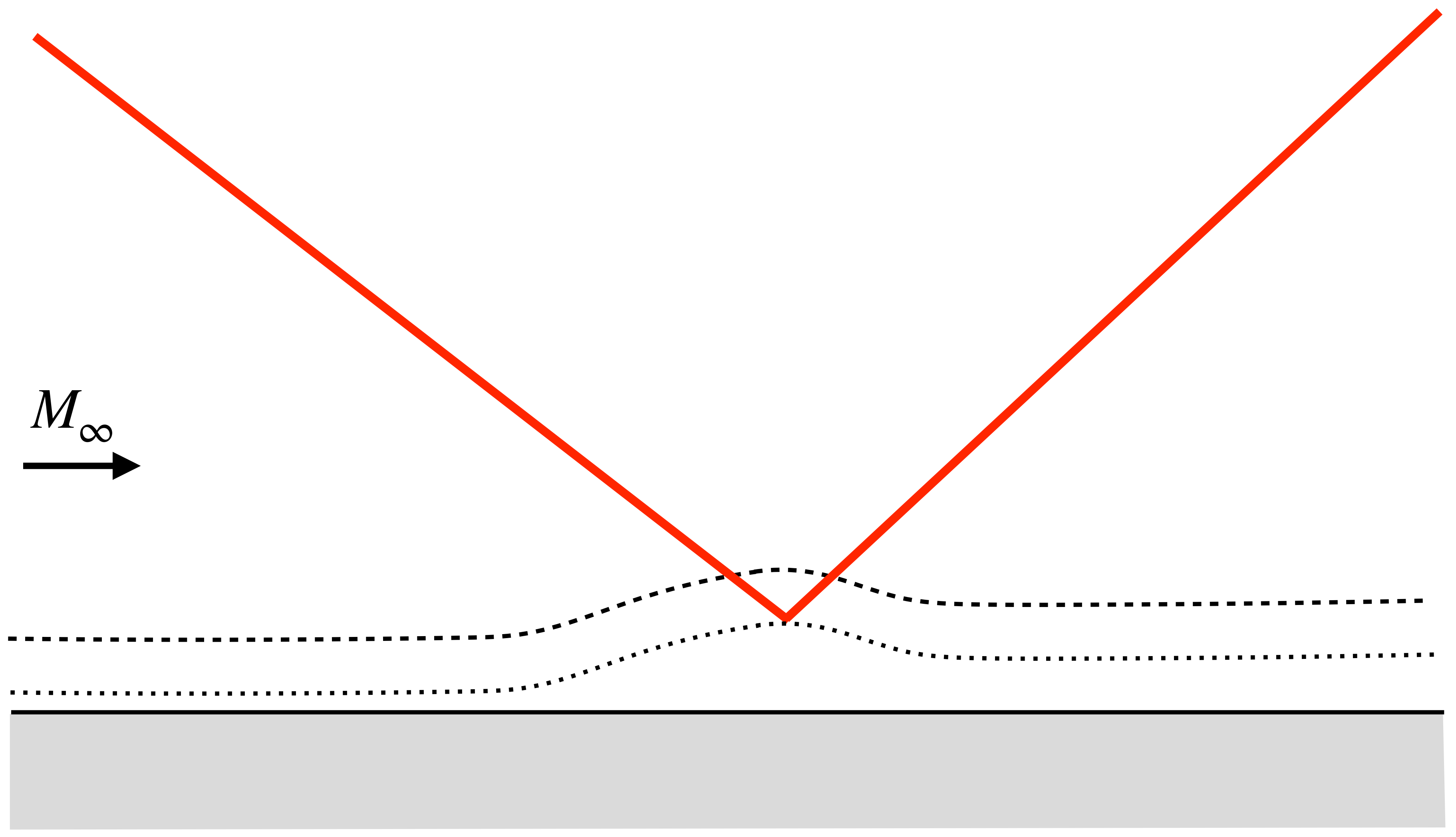
Boundary layer thickens ahead of shock



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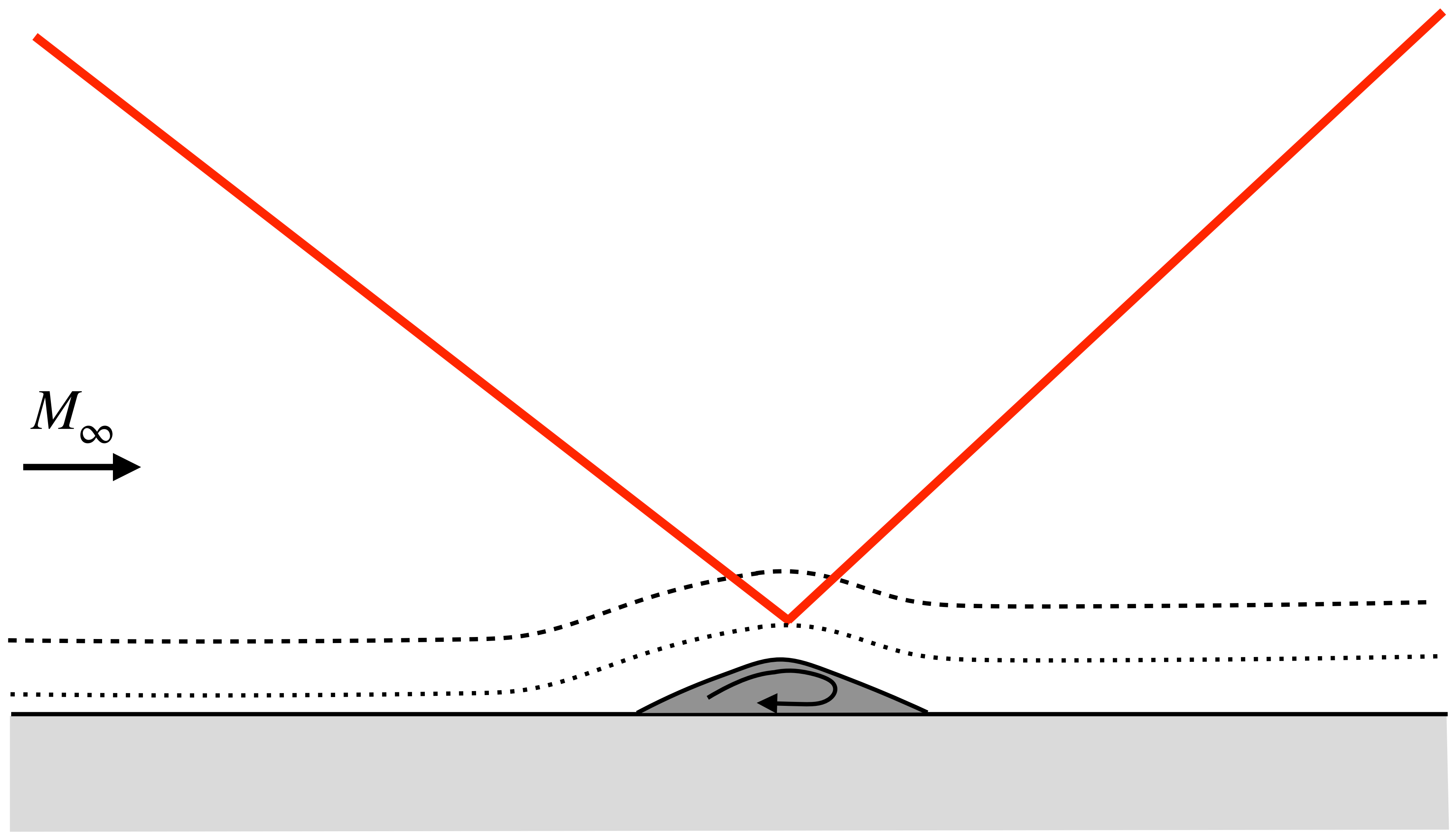

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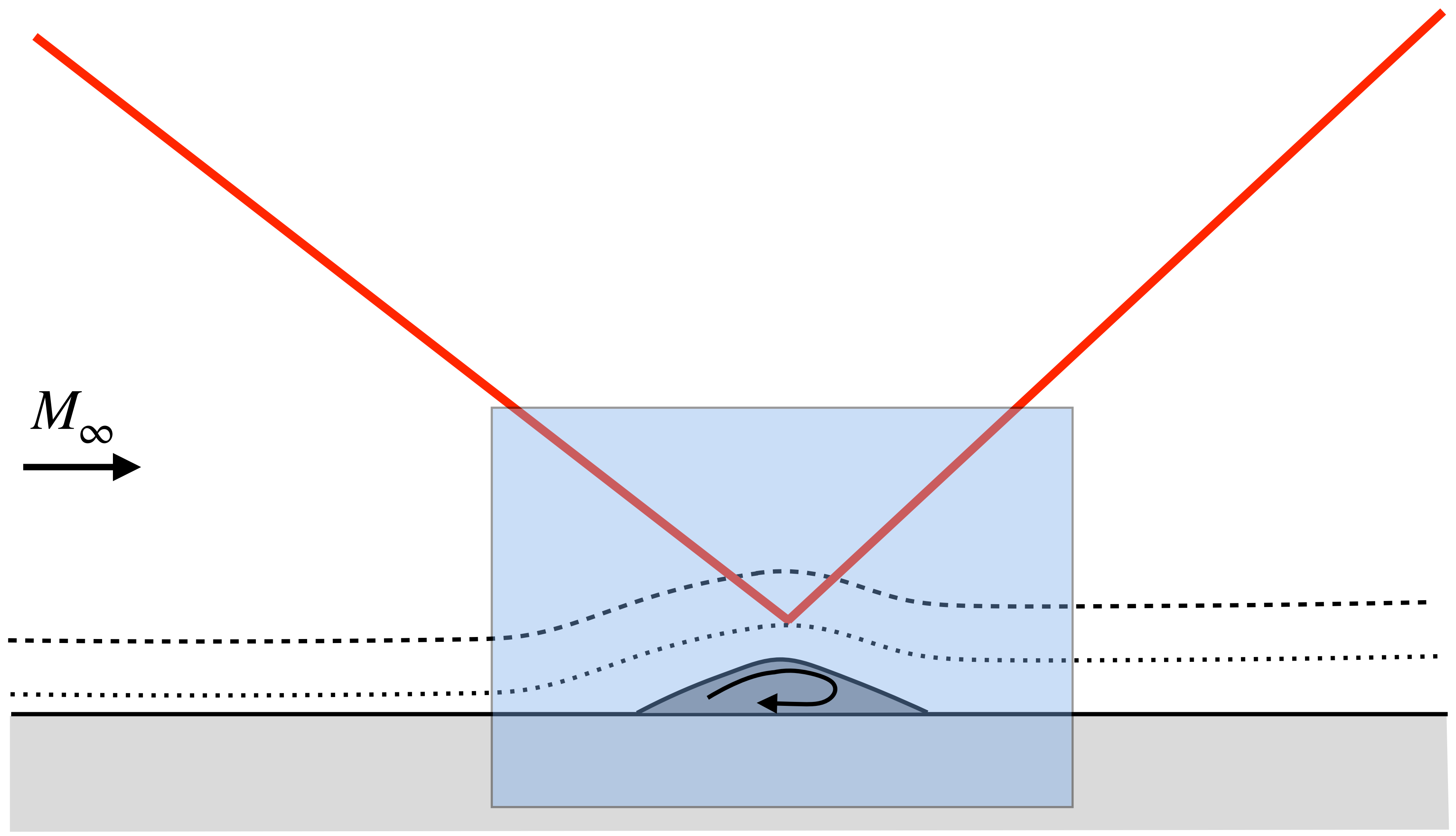

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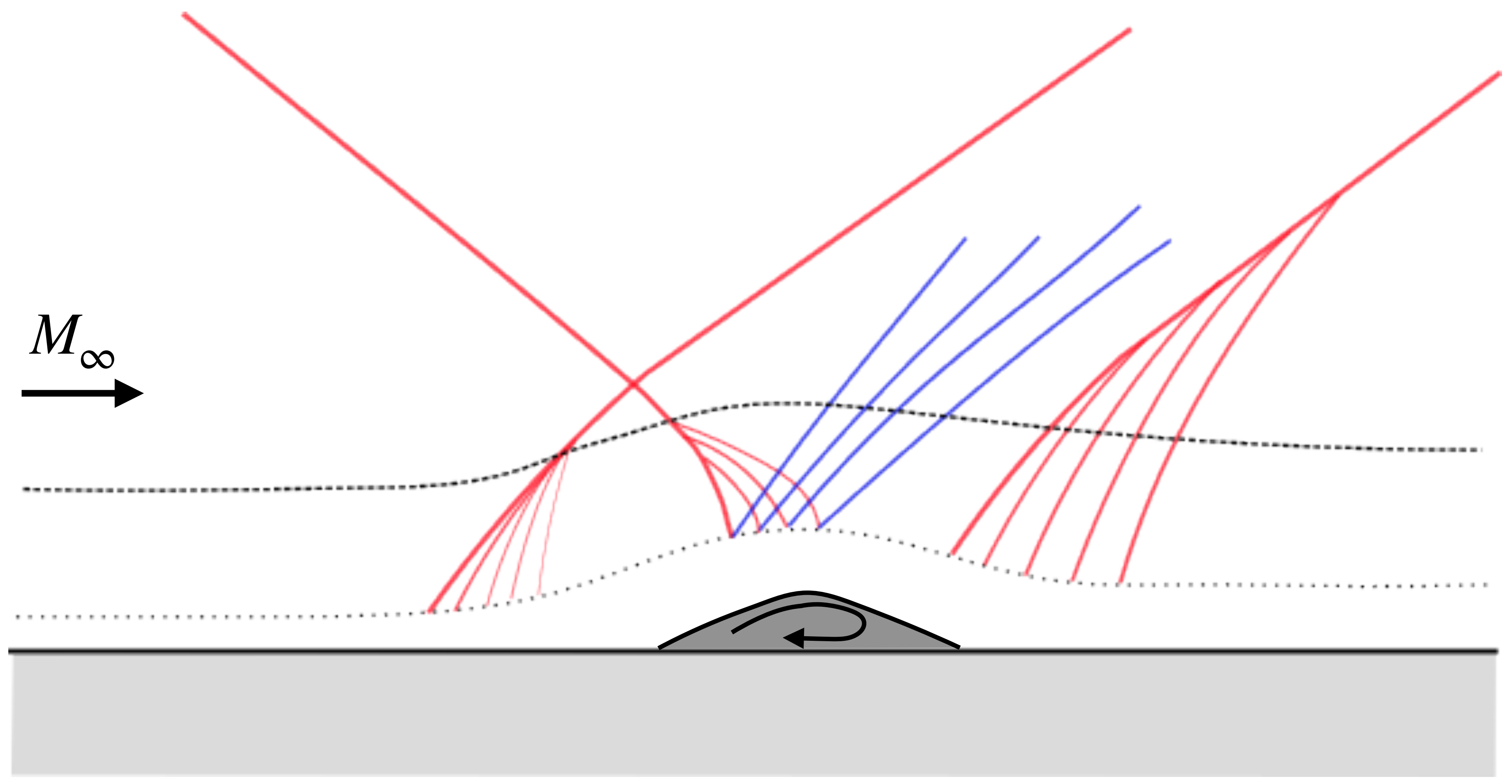

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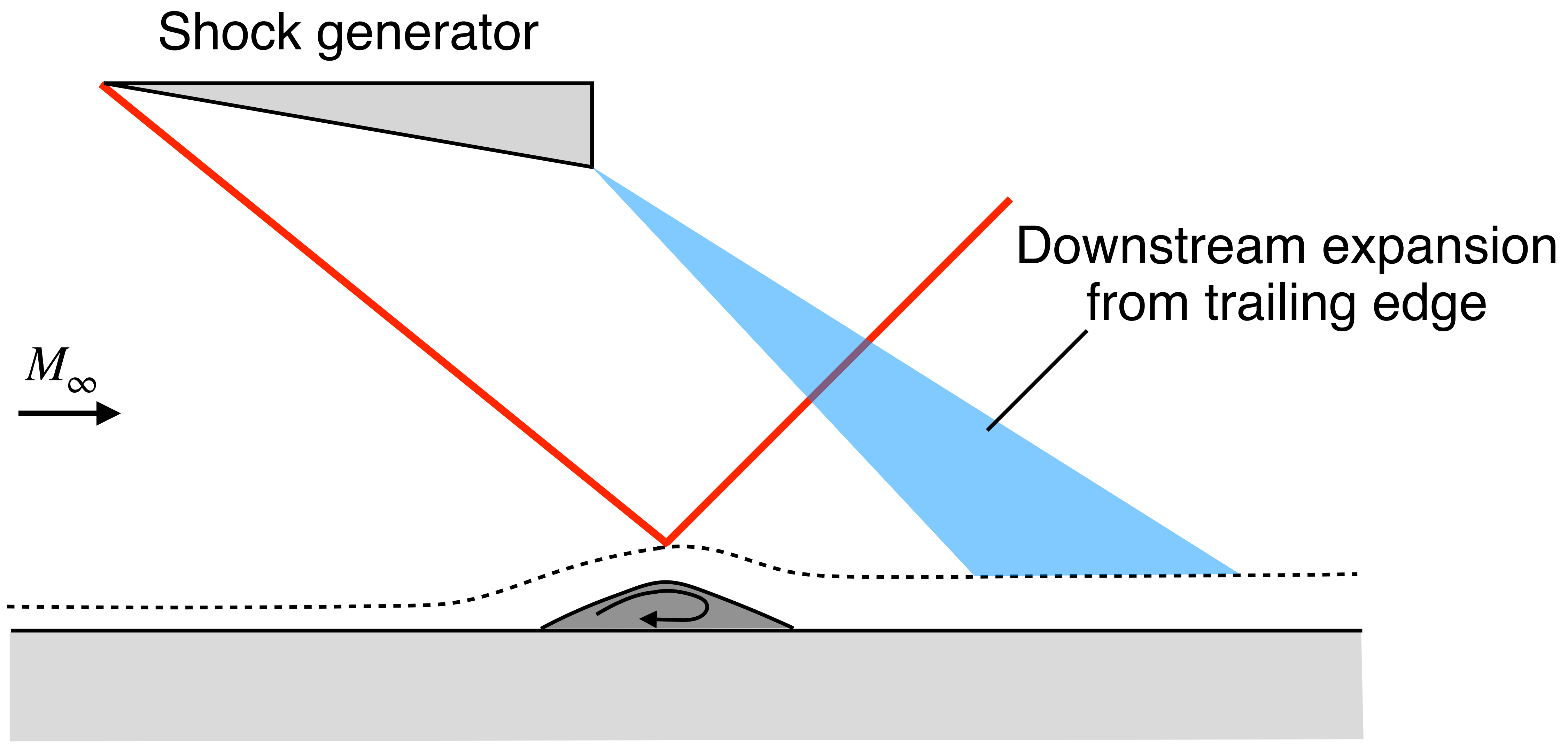
Typical experiments introduce additional expansion



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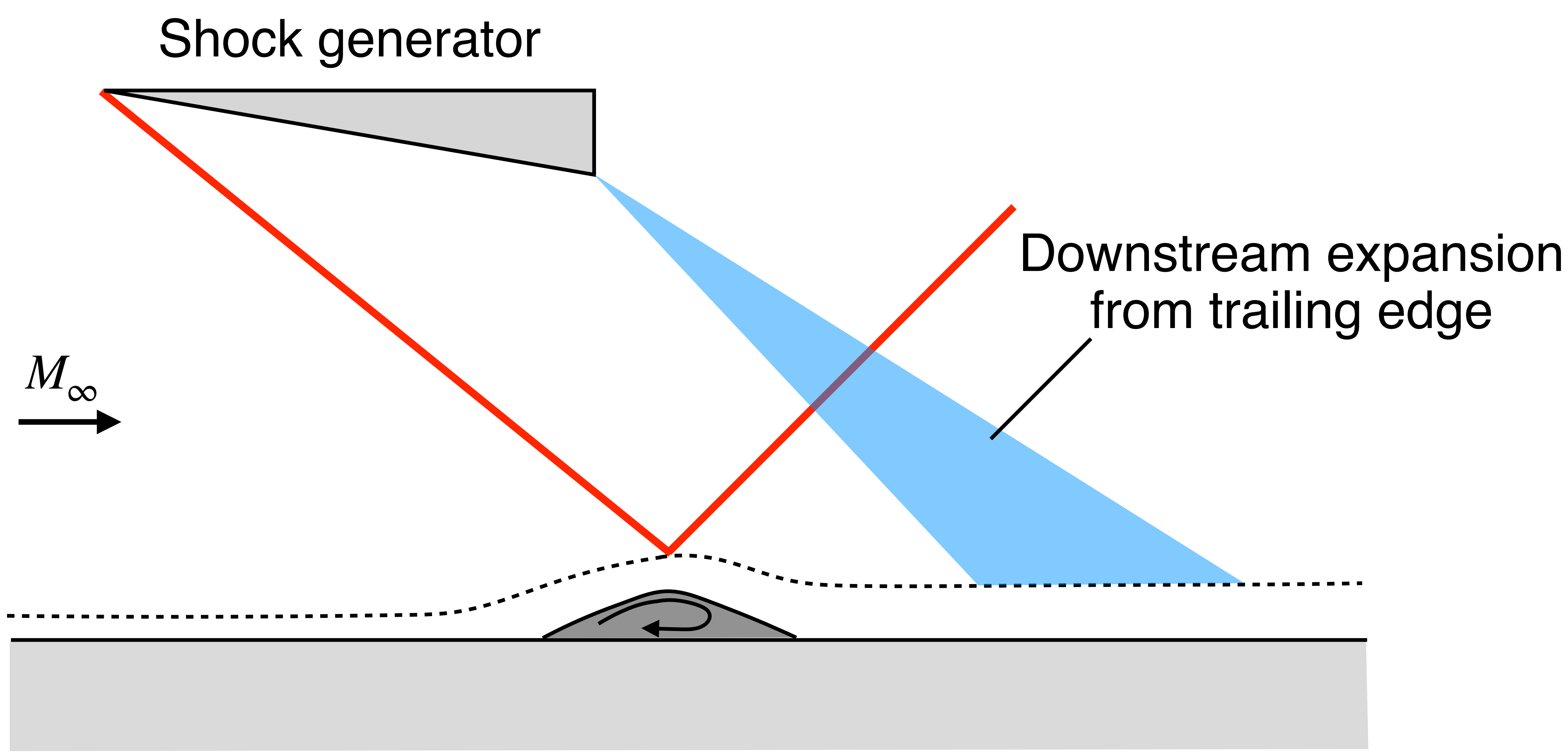

Downstream waves are generally ignored - **Is this valid?**

Downstream waves in literature

Grossman and Bruce, 2018 [1]:

Separation size reduces with decreasing distance D

Effect observed for D up to $11\delta_i$

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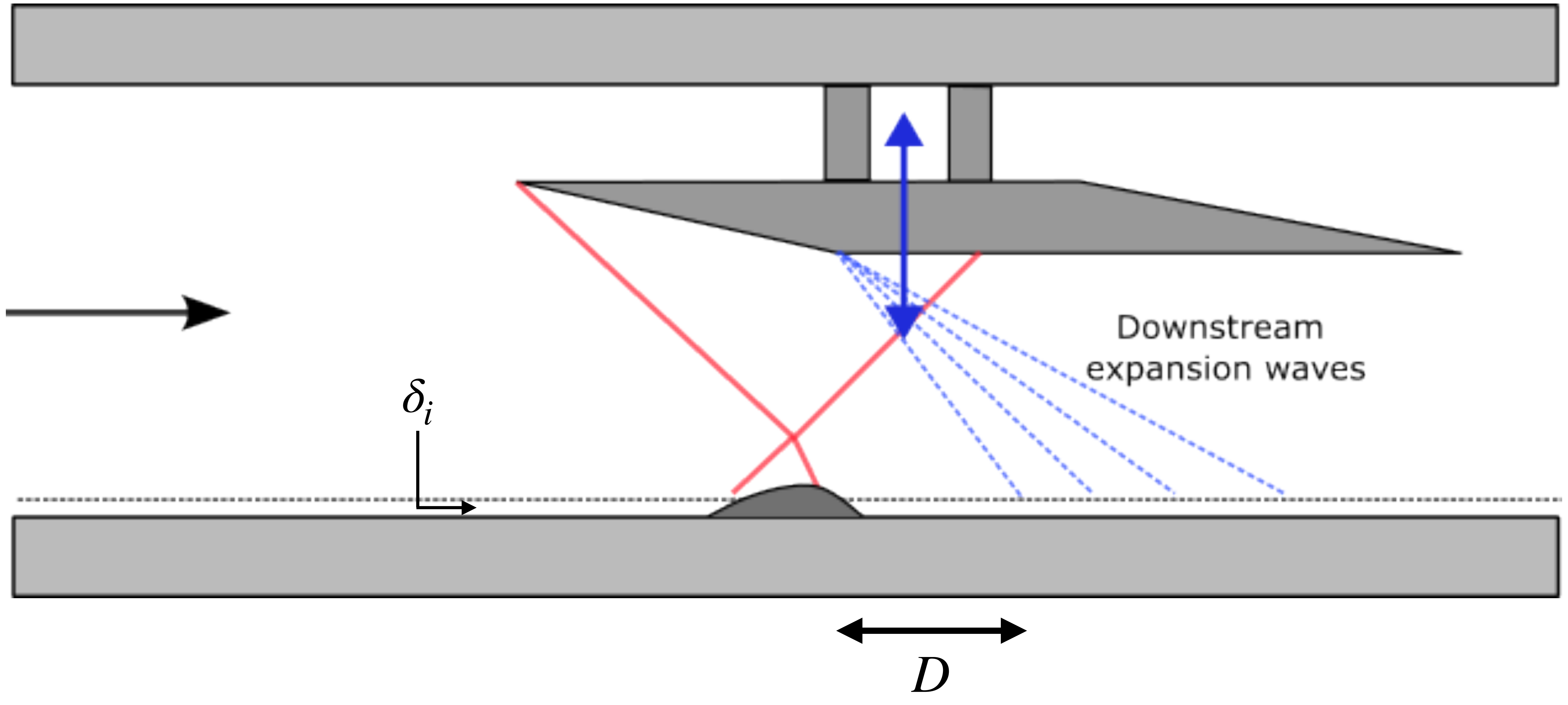

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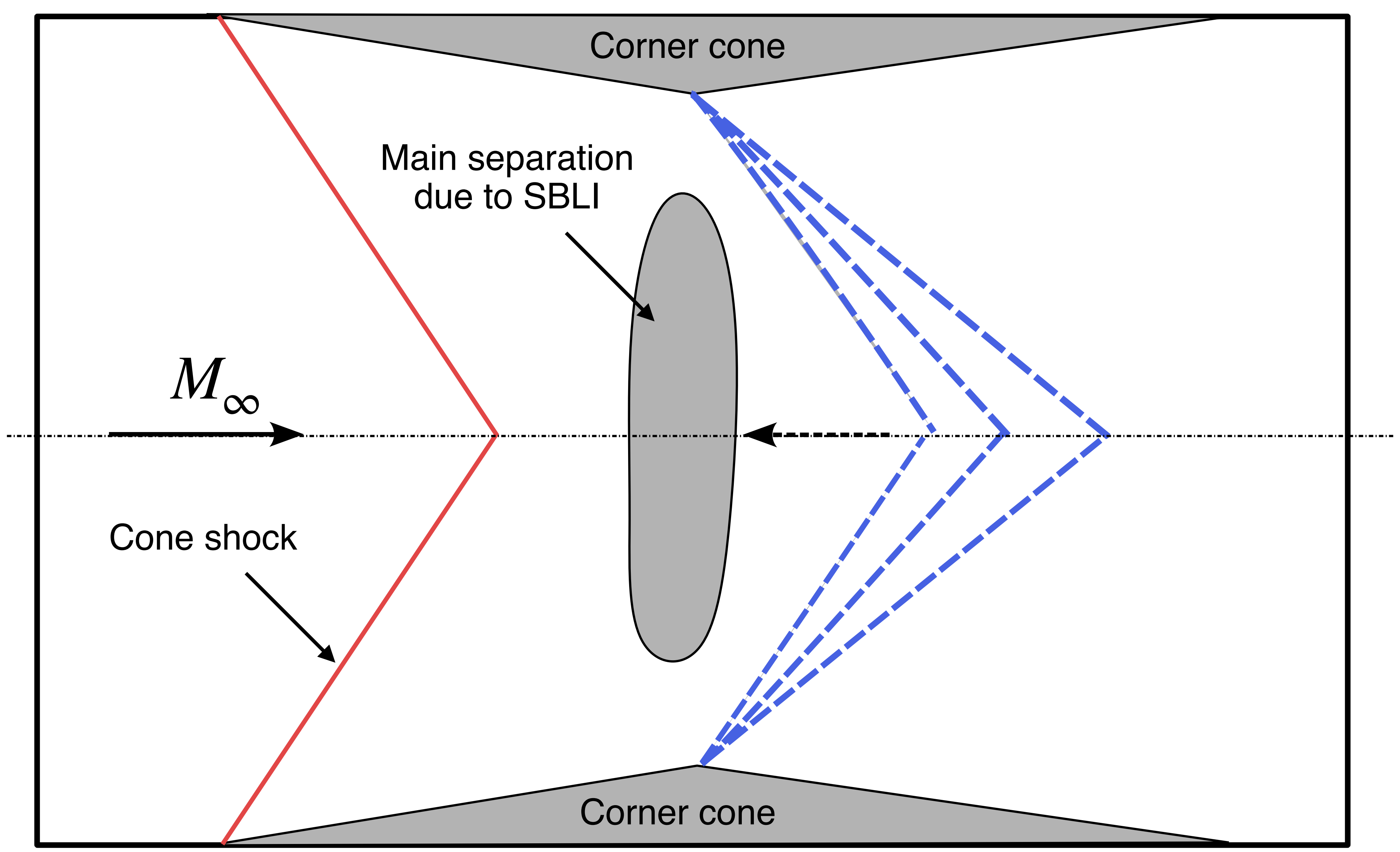
Missing and Babinsky, 2023 [2]:

Use of corner cones to study the effect of corner separation



Downstream waves in literature

Missing and Babinsky, 2023 [2]:

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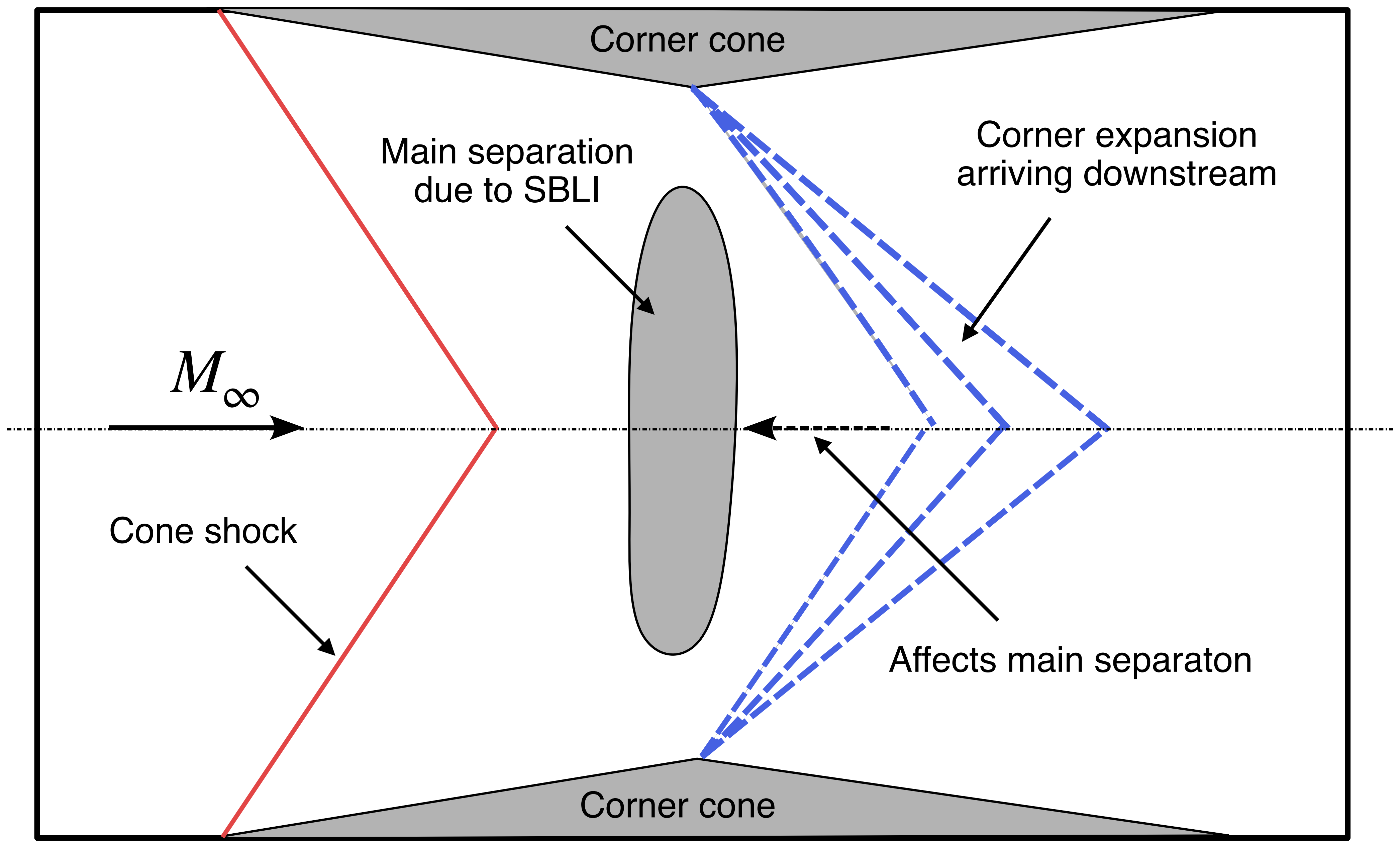
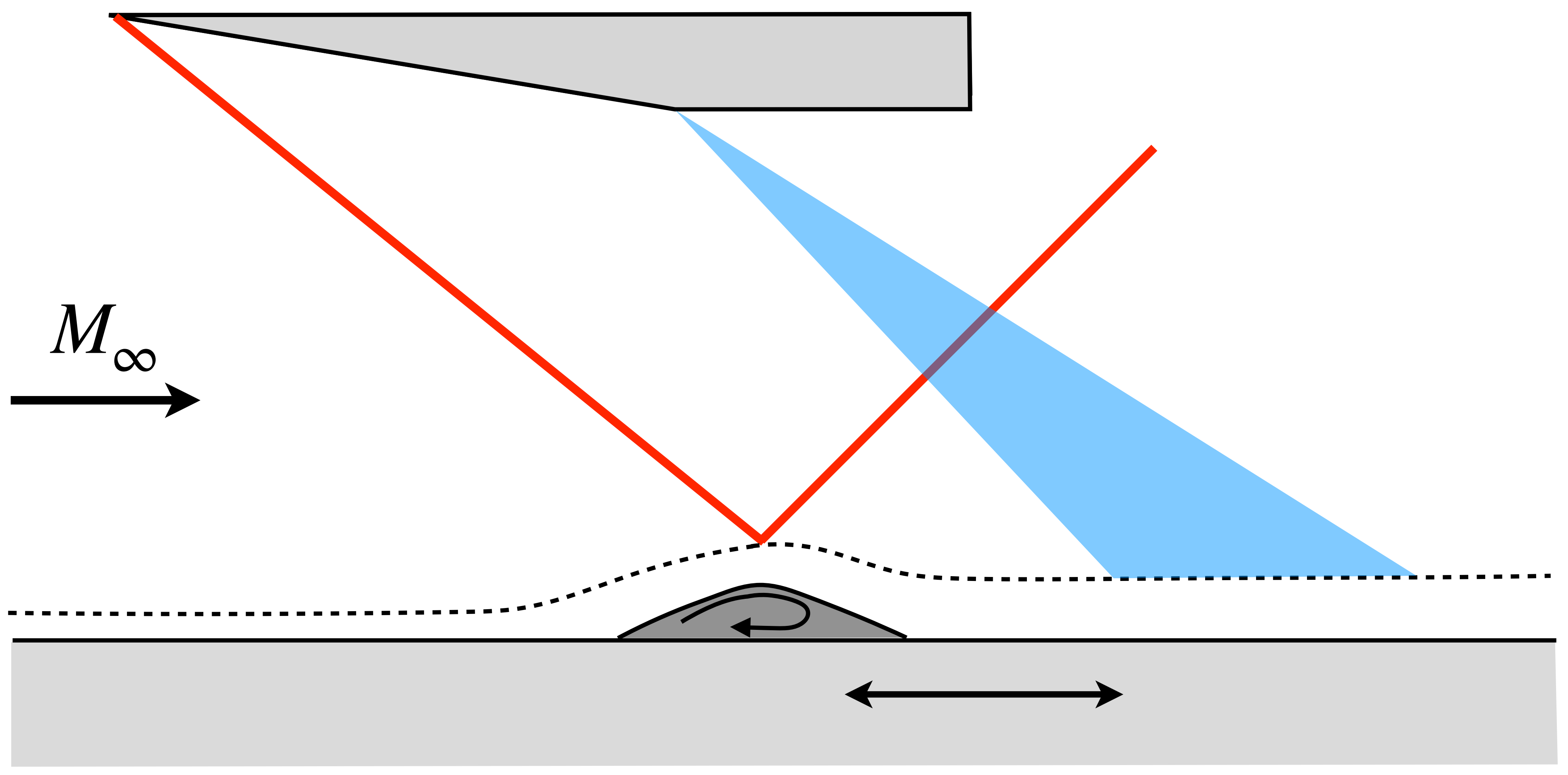
Downstream expansion influenced the primary SBLI



Key Questions

Are downstream waves important?

Do these factors play significant roles?



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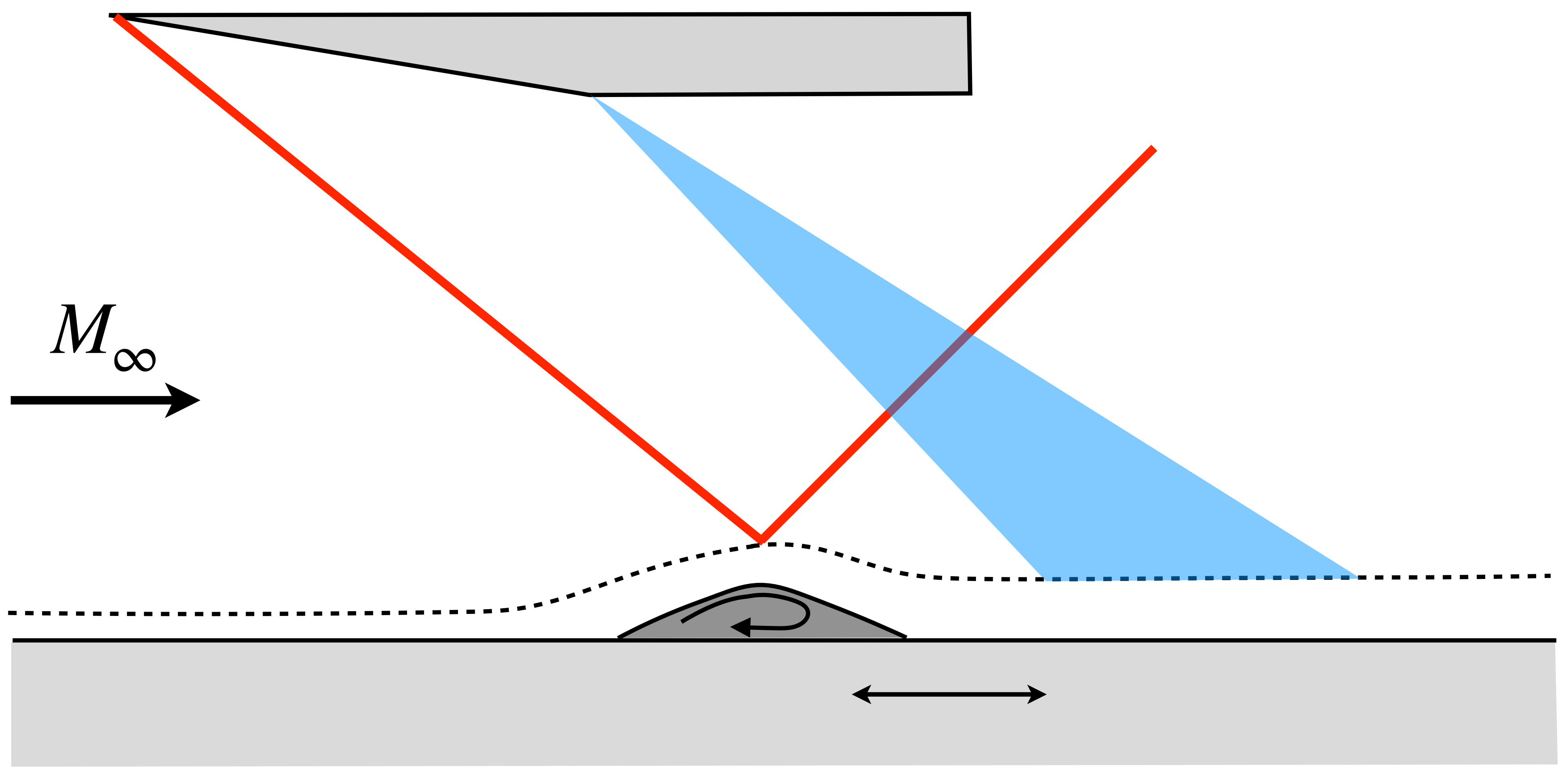

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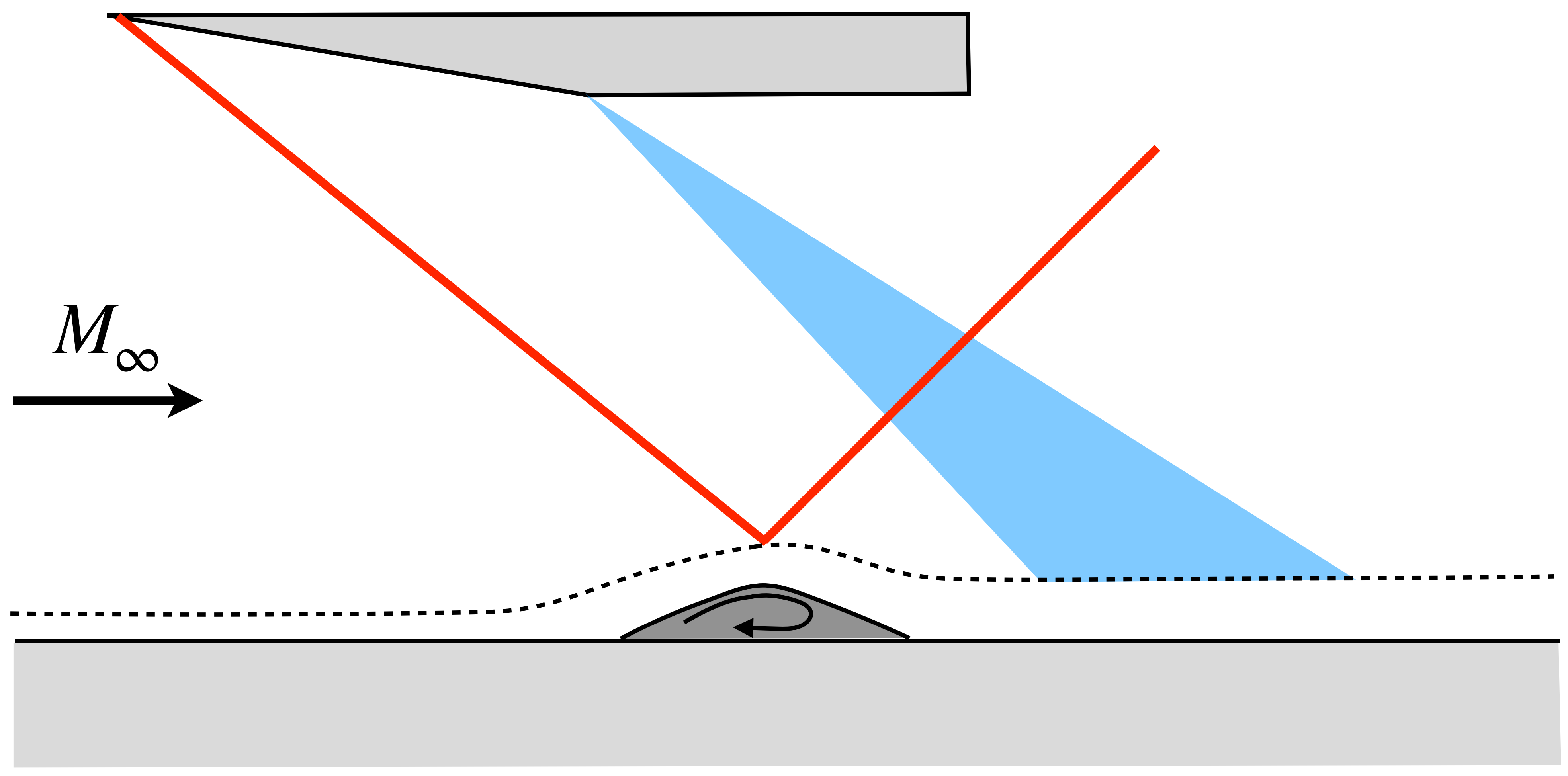

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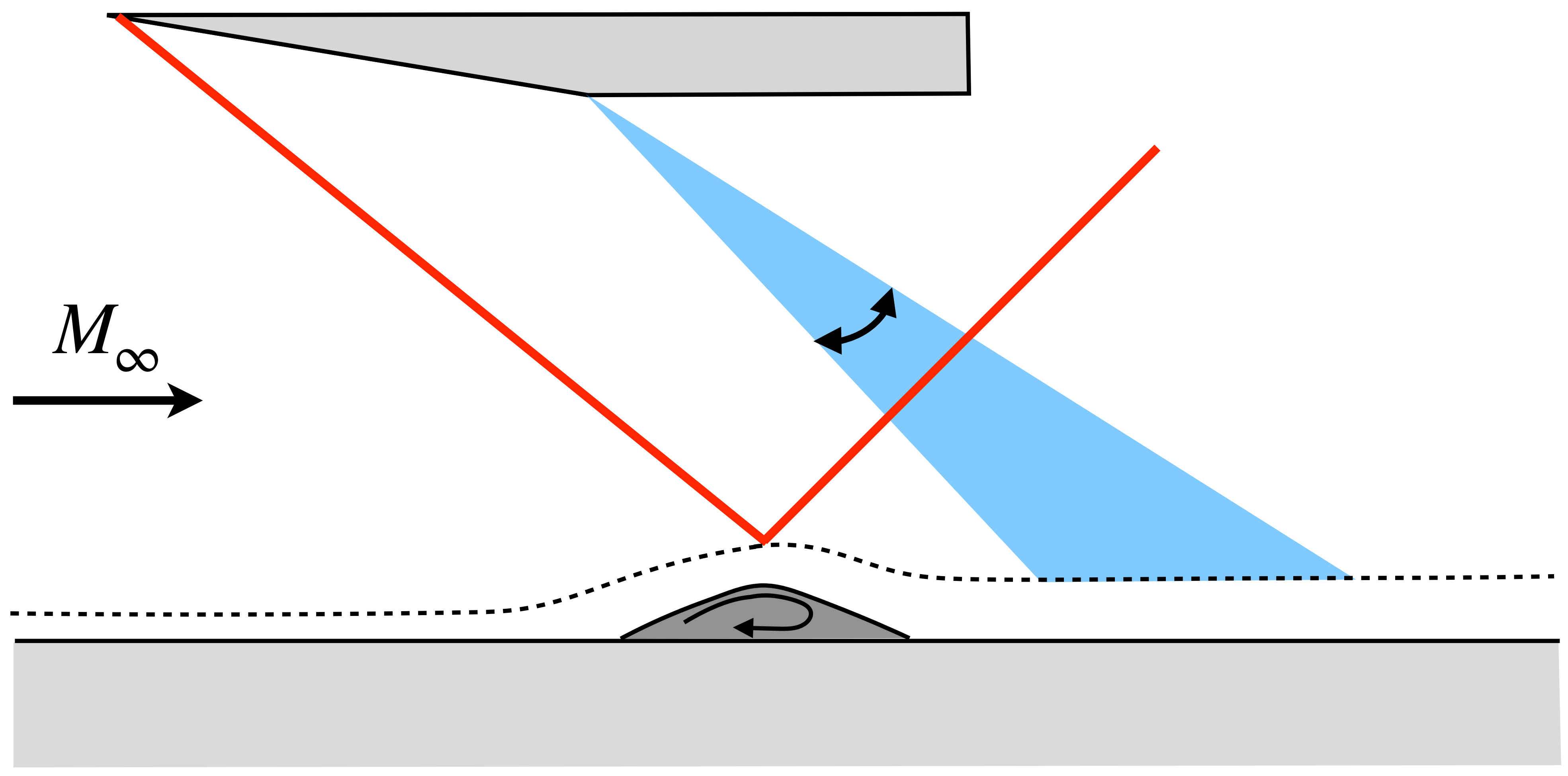

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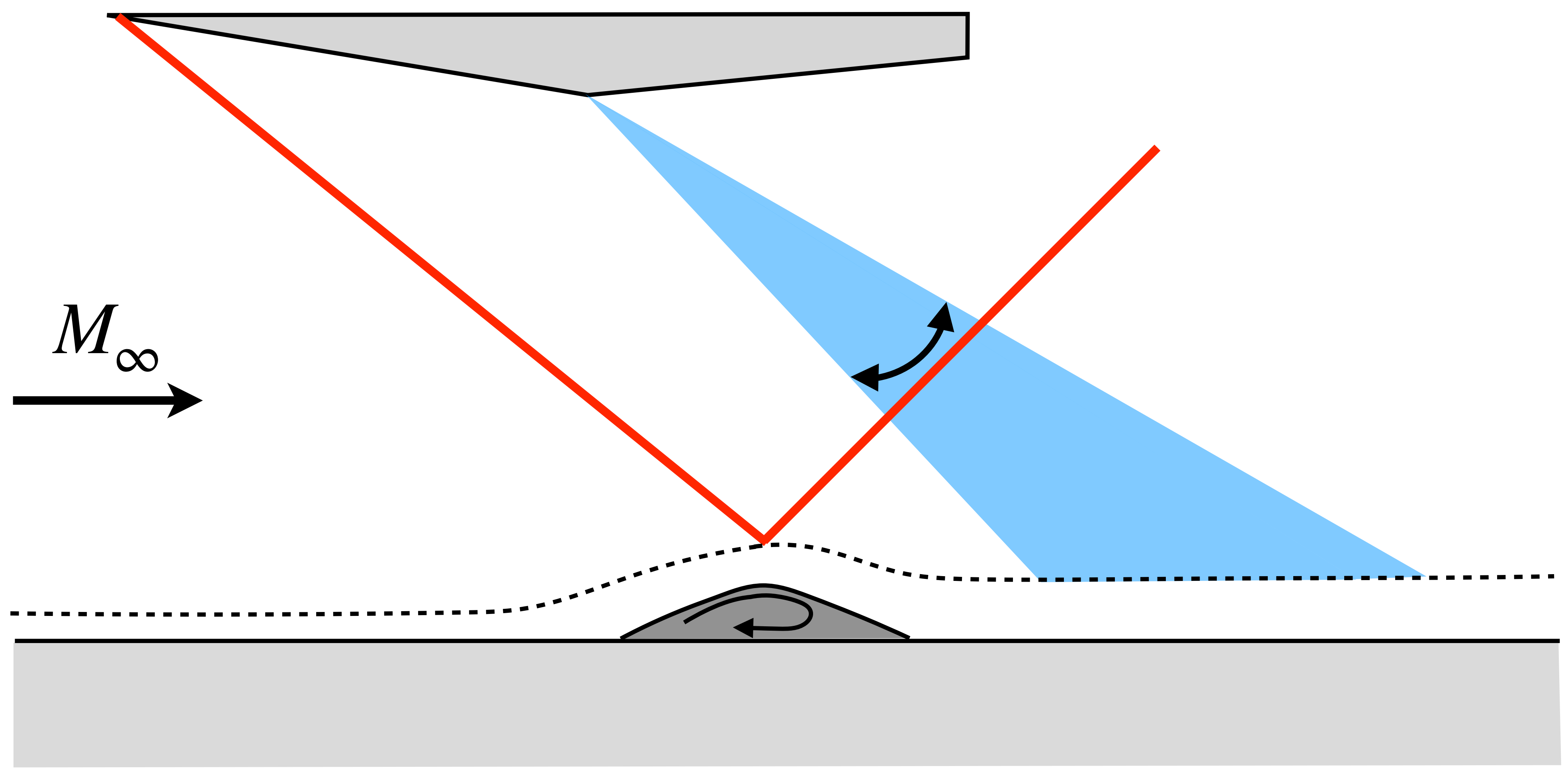

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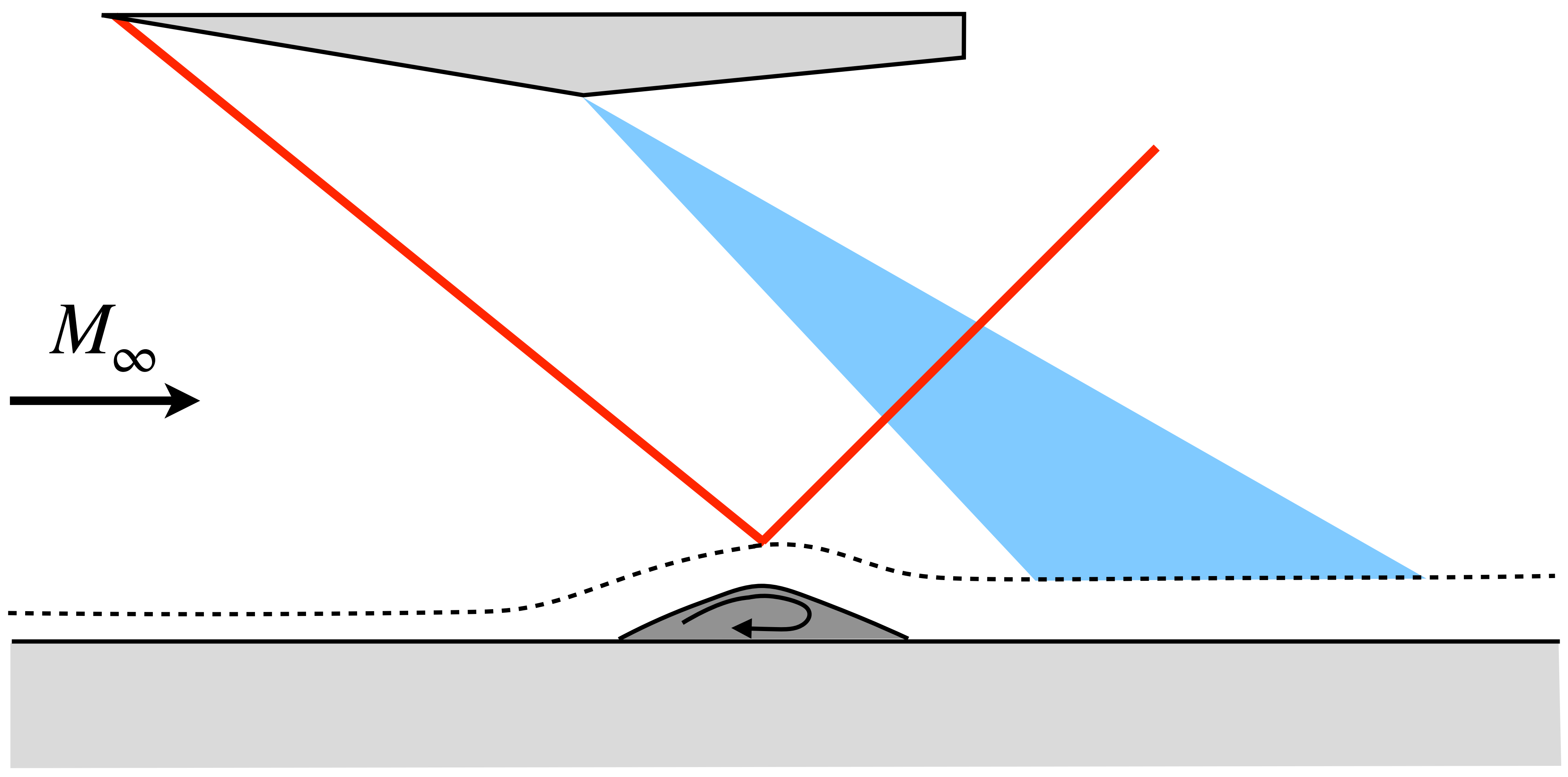

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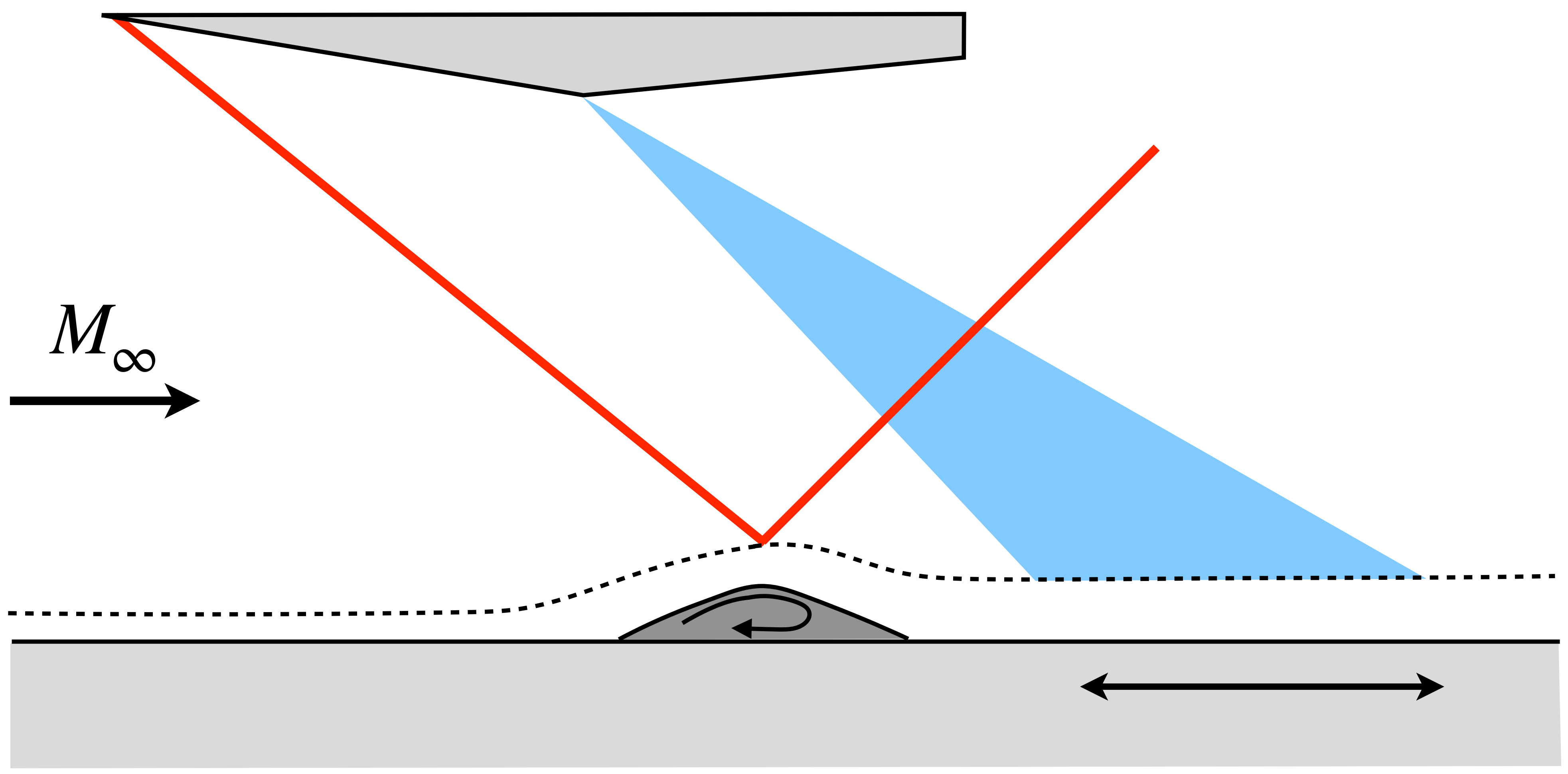

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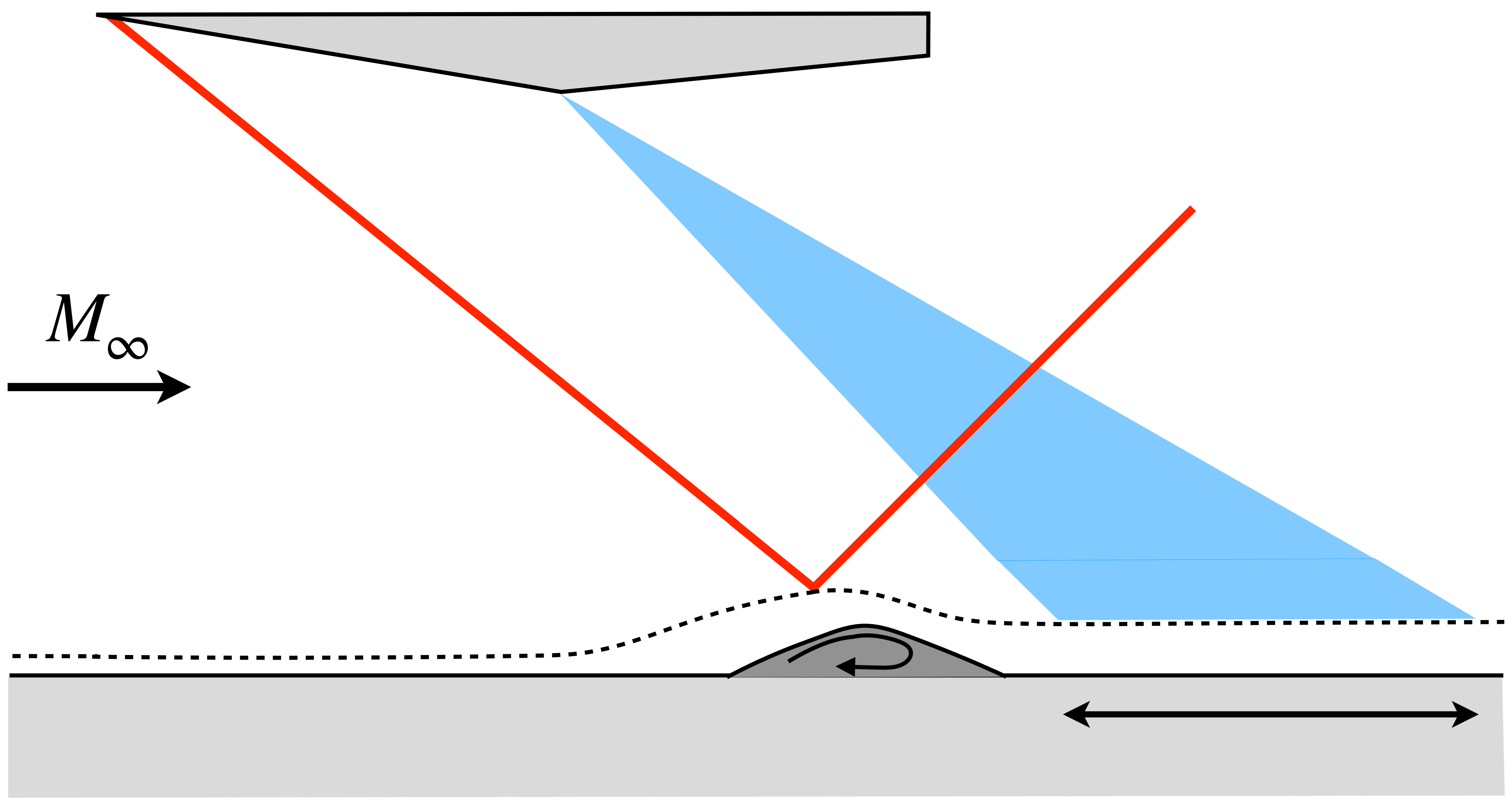

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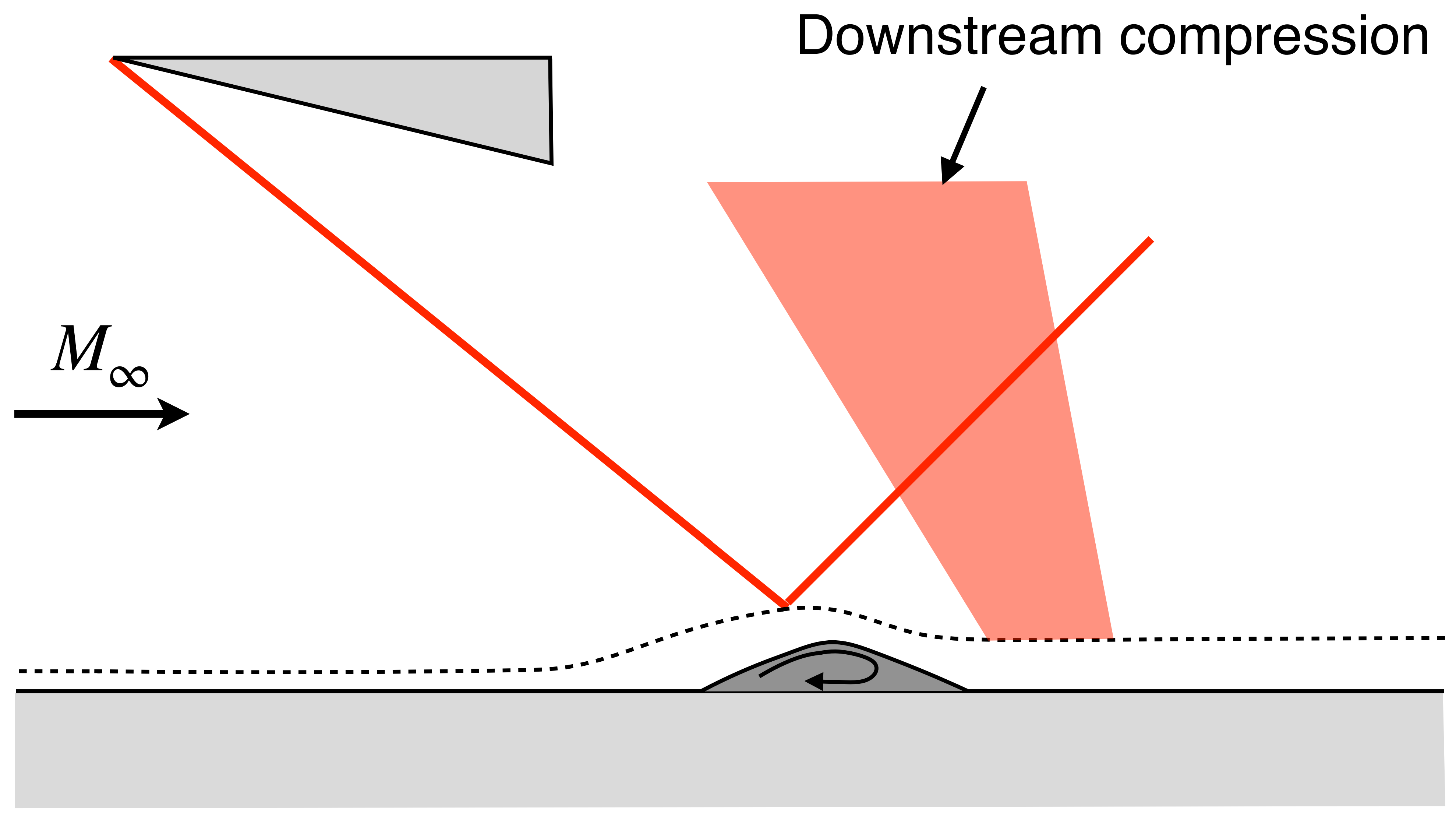

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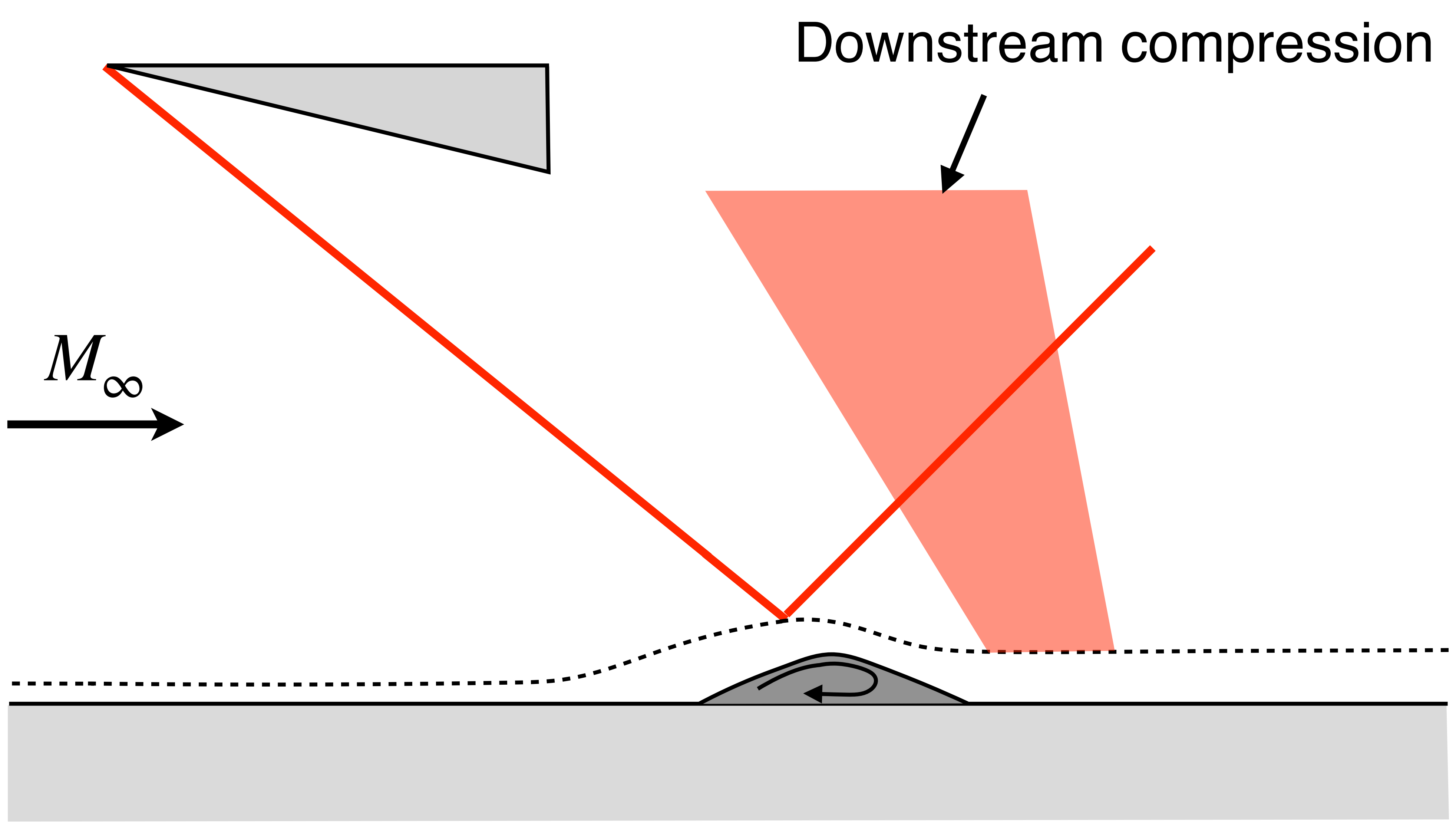
What is the underlying mechanism?



Test Facilities at Cambridge

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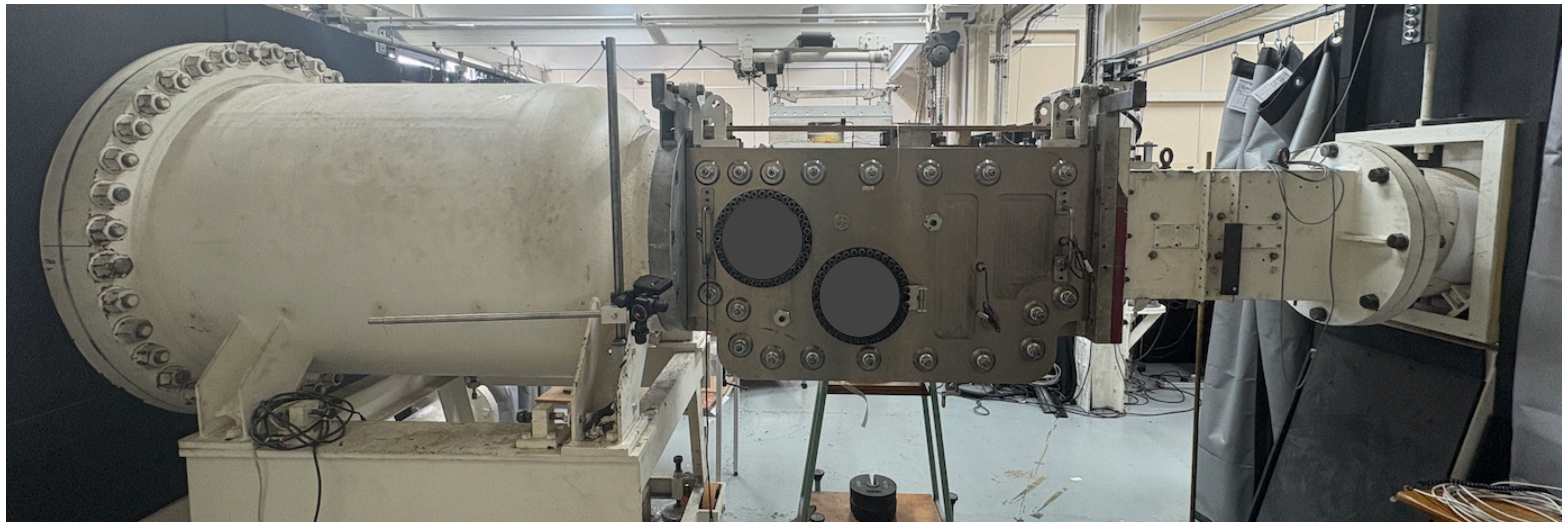
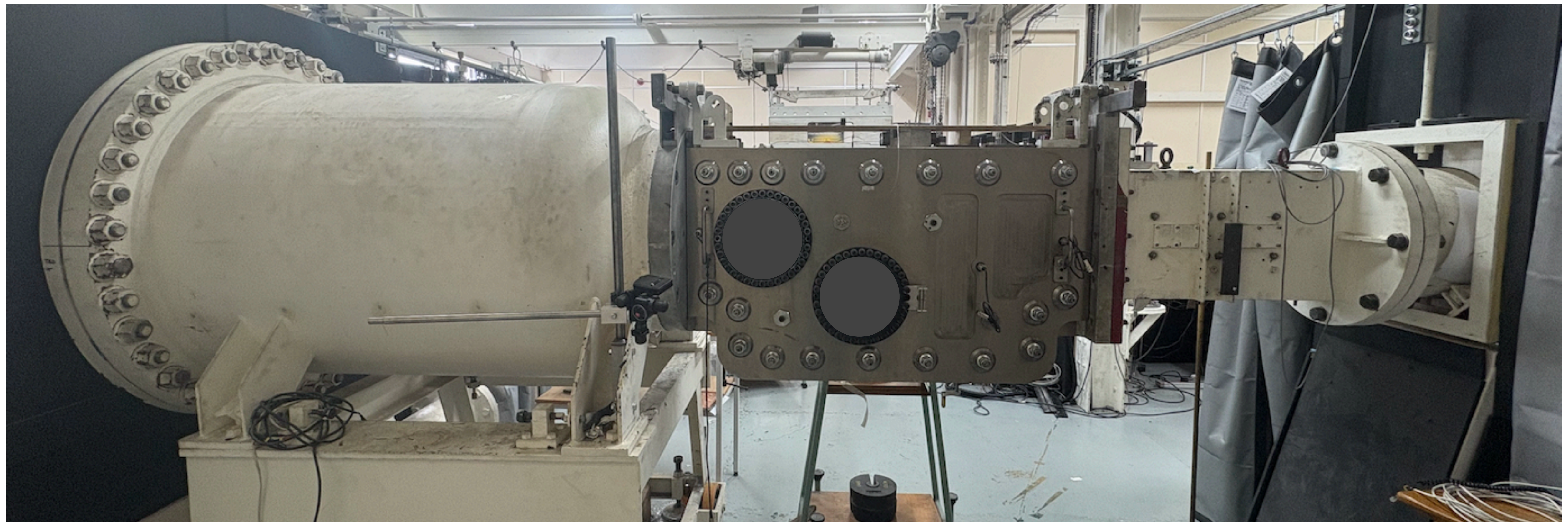


Intake studies at transonic Mach numbers

Test Facilities at Cambridge



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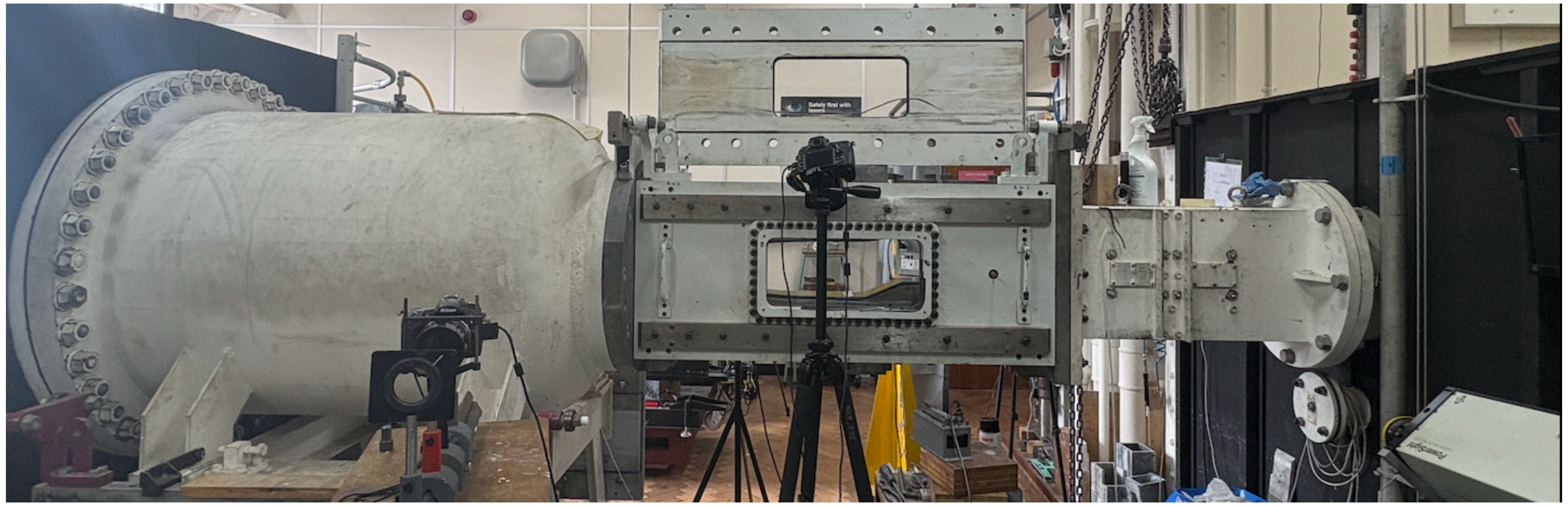
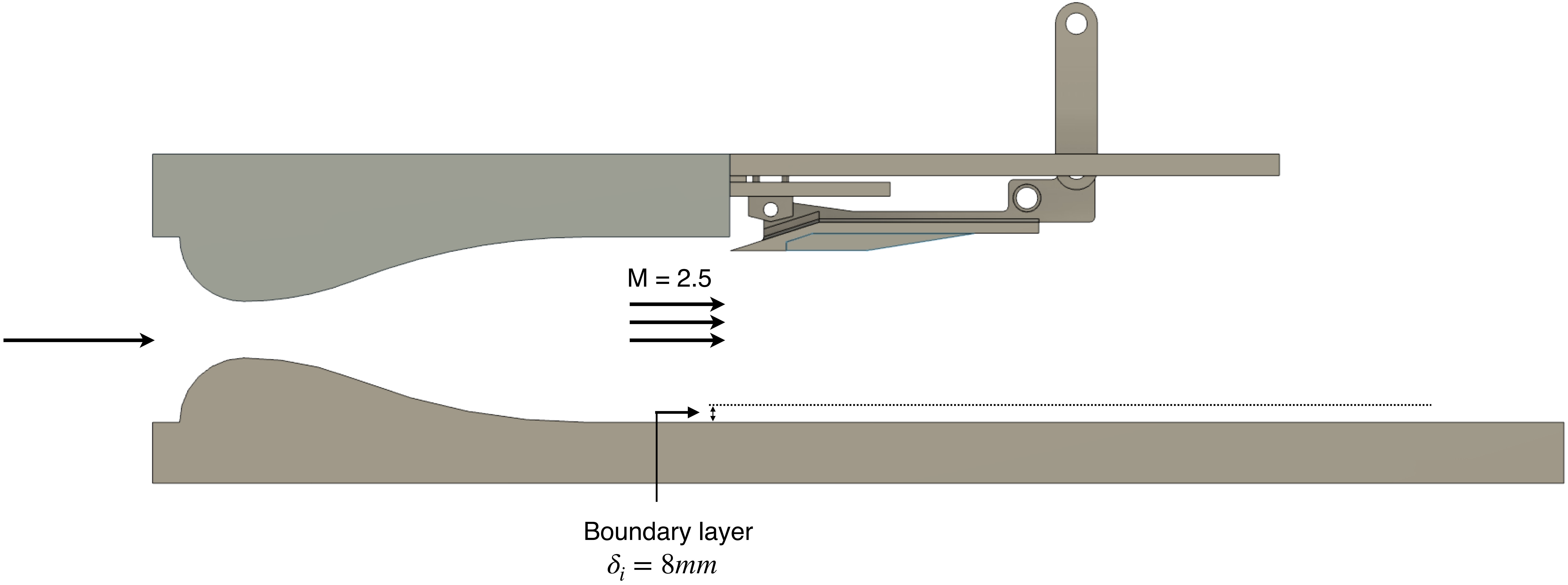


Fundamental SBLI and flow control studies upto M = 3.5

Experimental Setup

Experimental Setup



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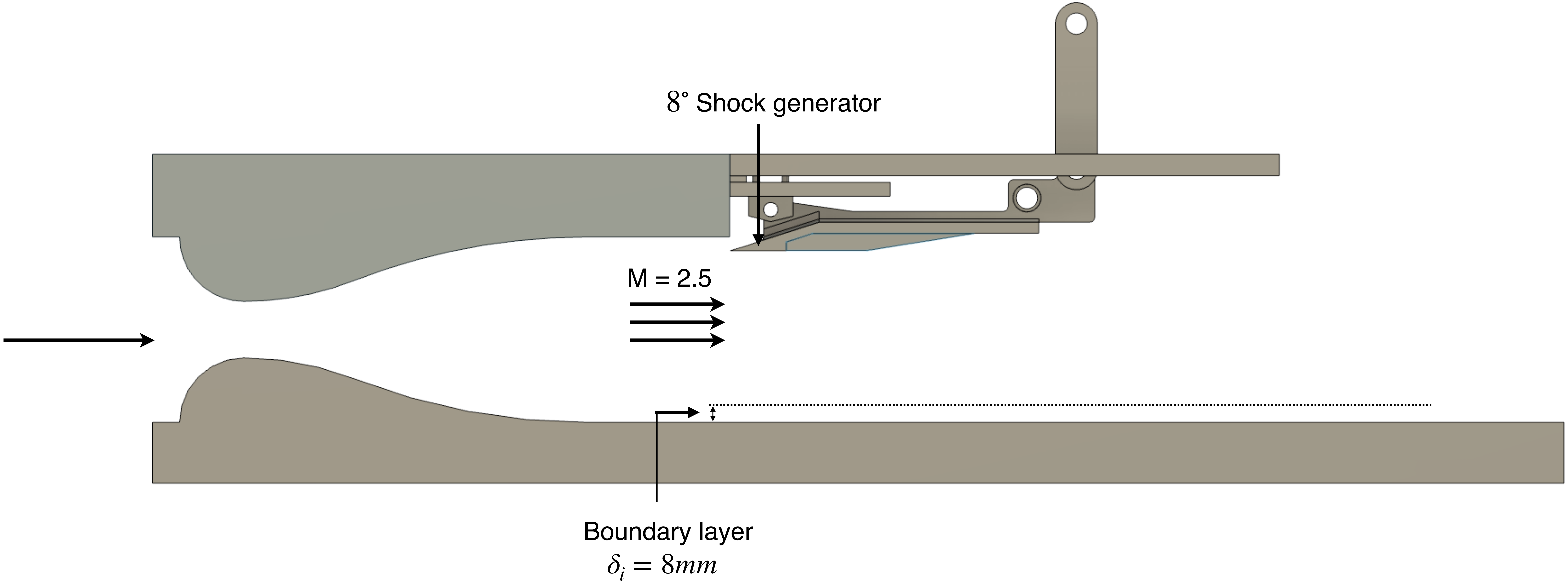

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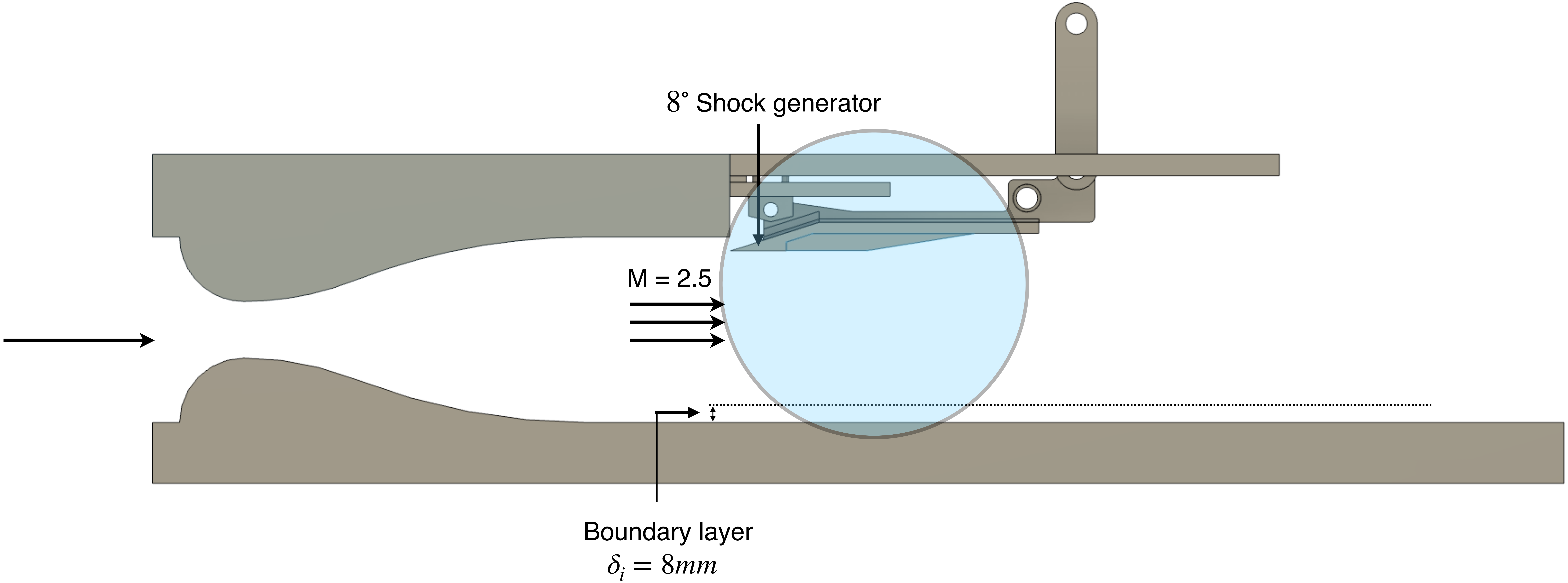

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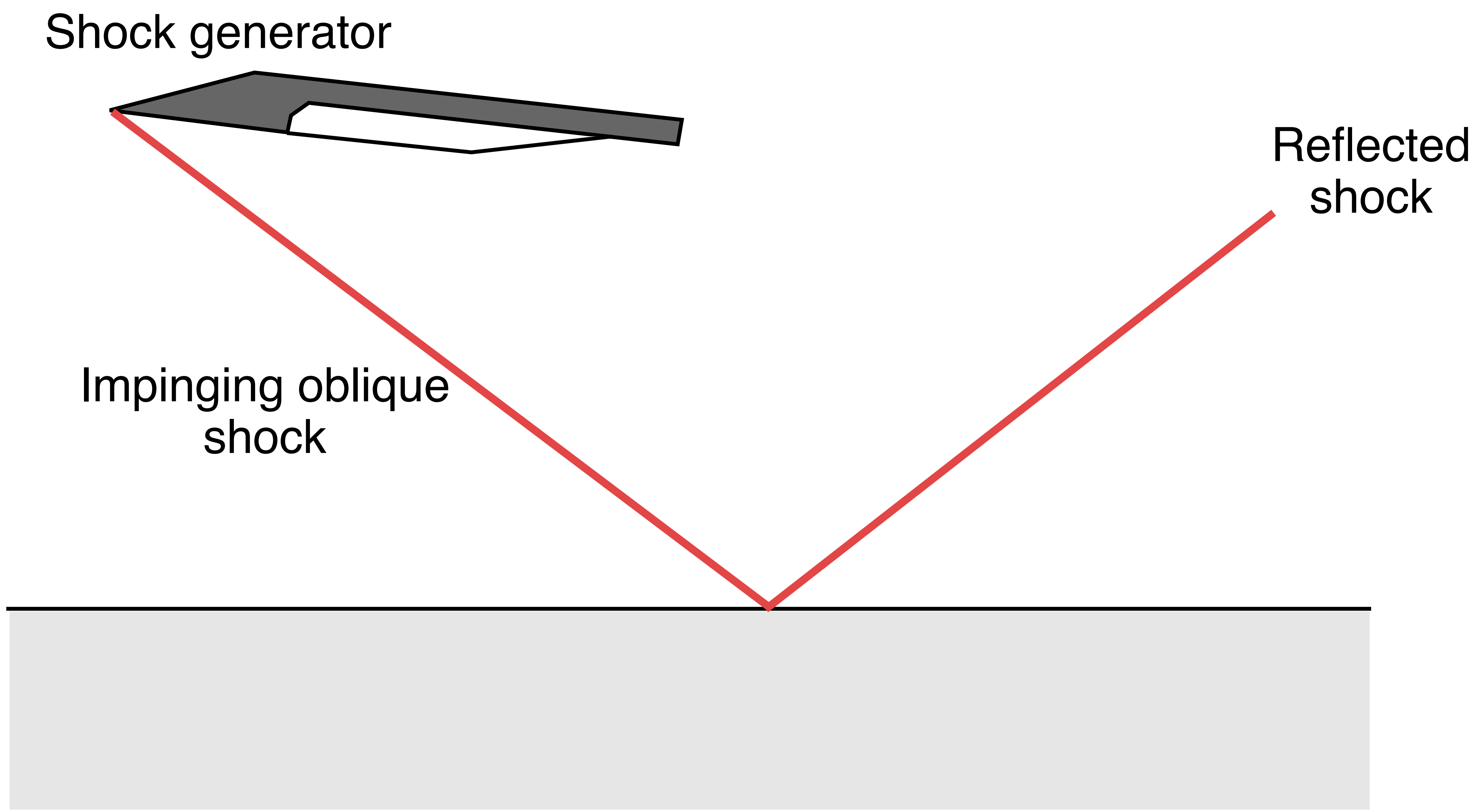

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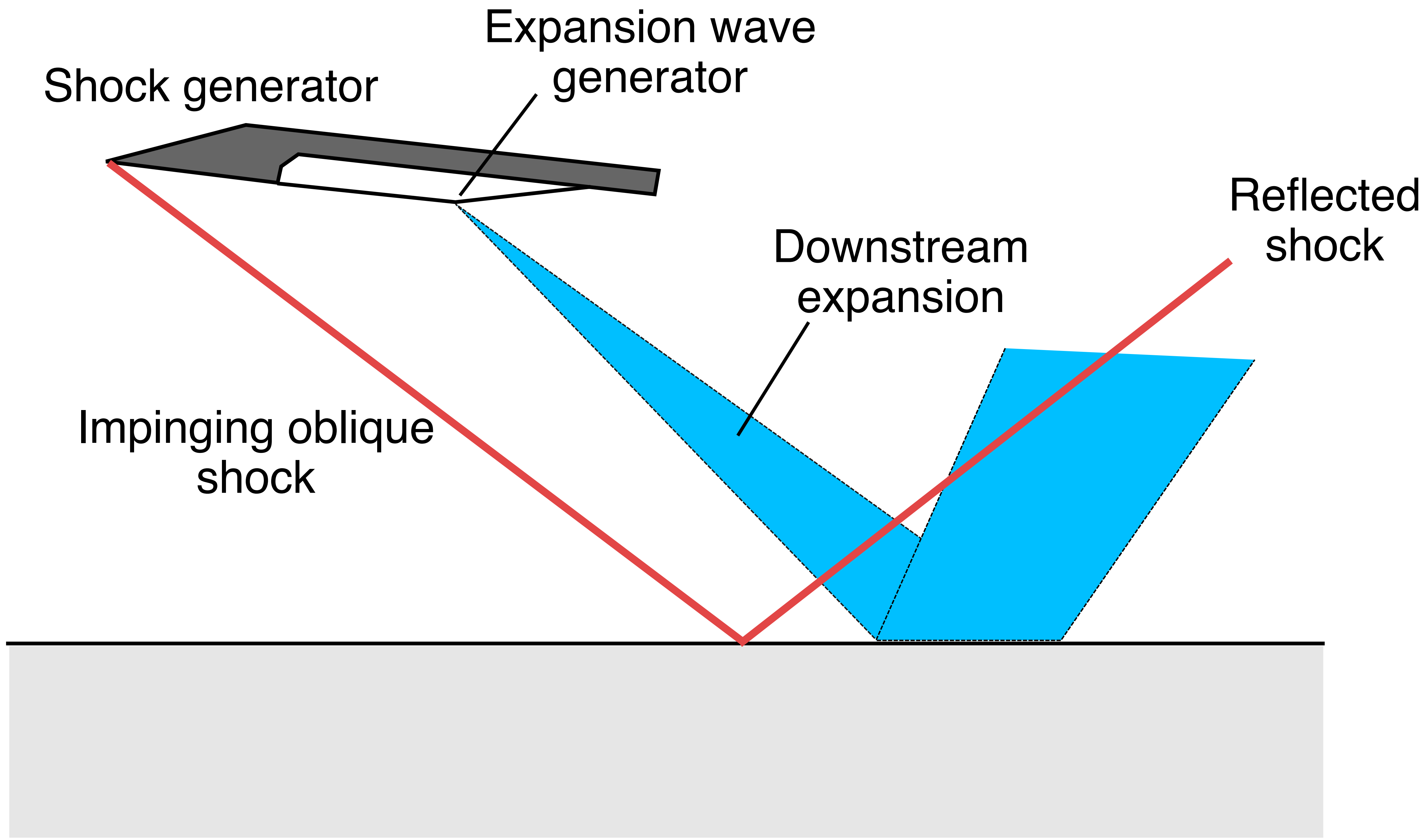
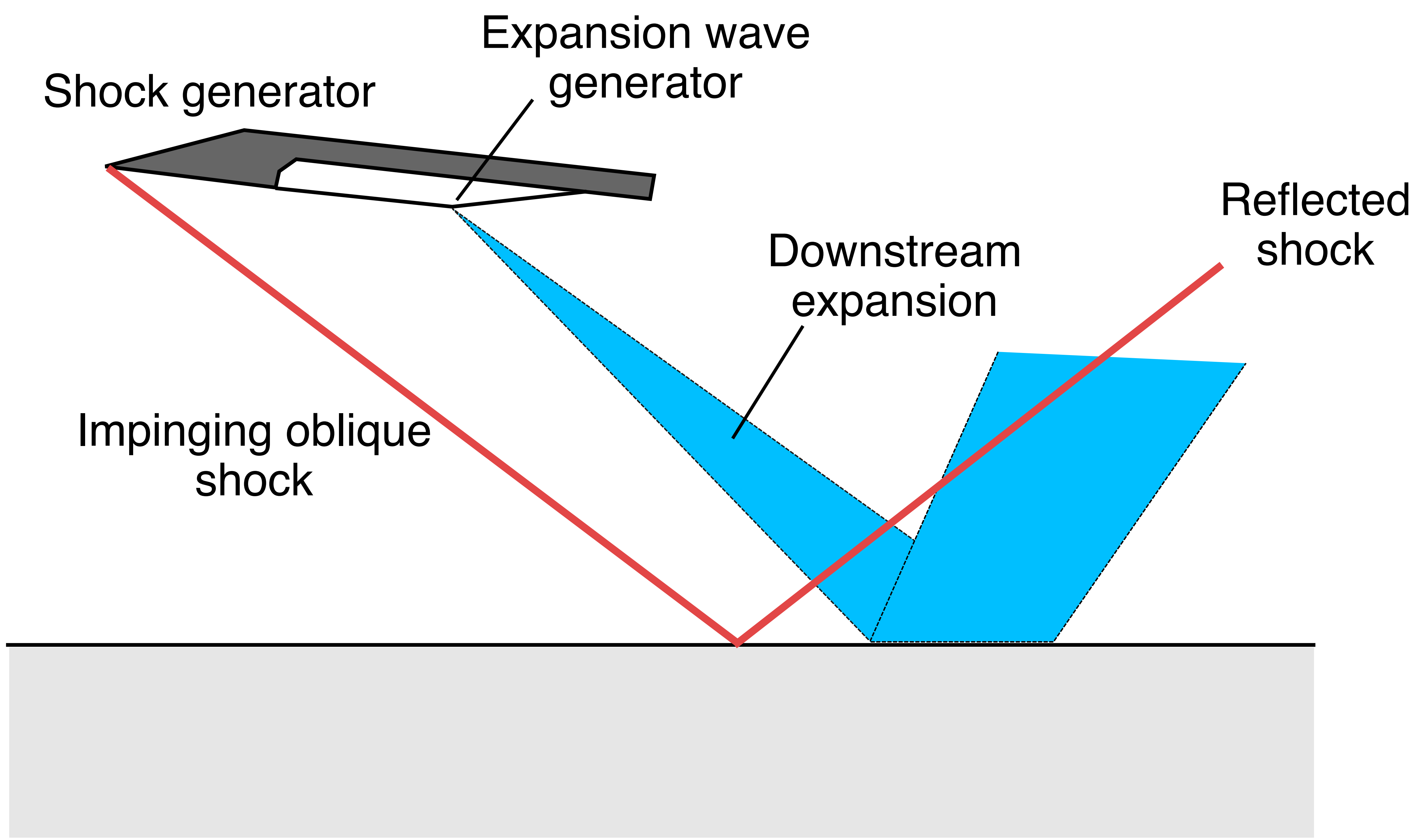

Expansion wave
generator
Shock generator
Reflected
shock
Downstream
expansion
Impinging oblique
shock

Setup



Variables:

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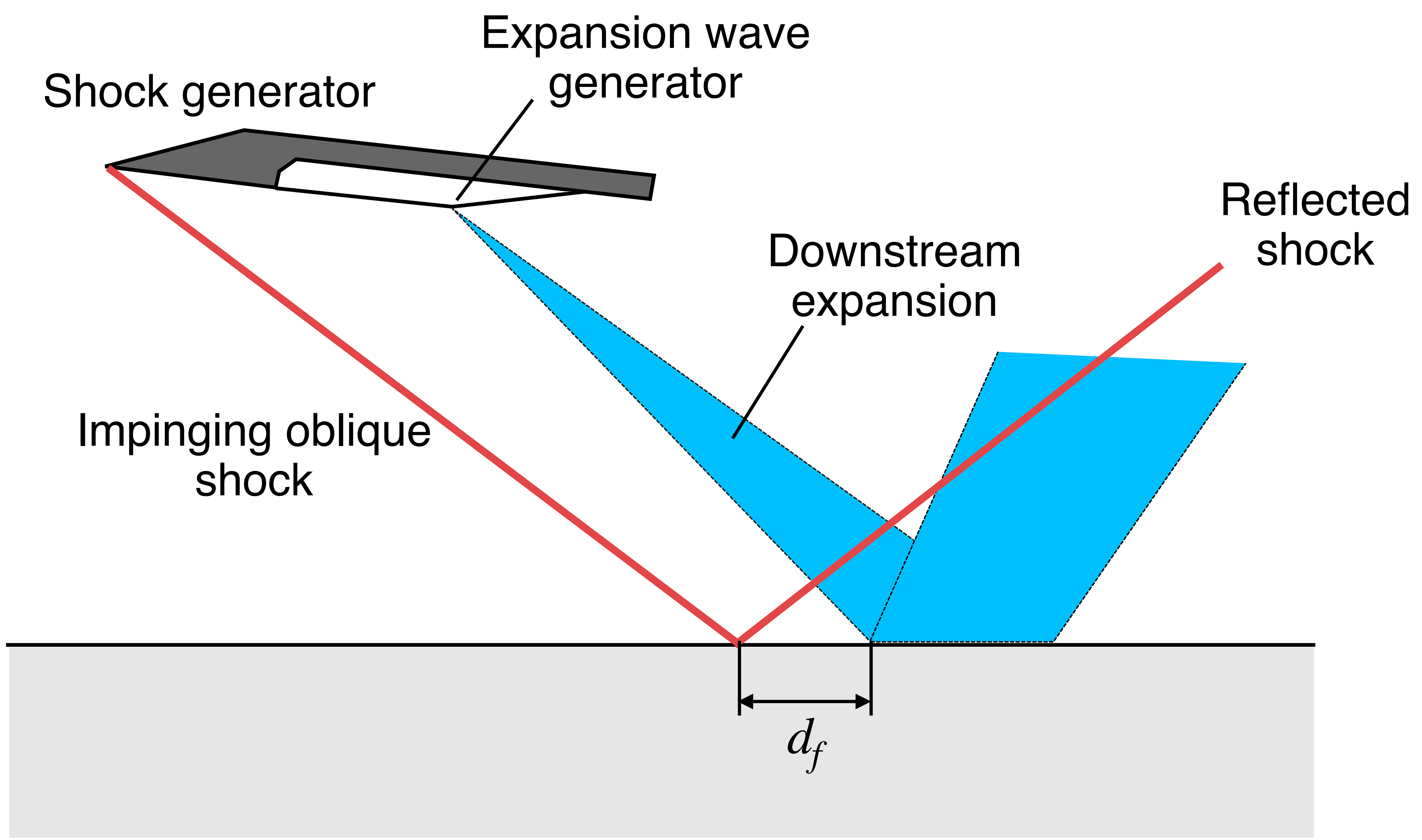

Variables: $\overline{d_f} = d_f / \delta_i$

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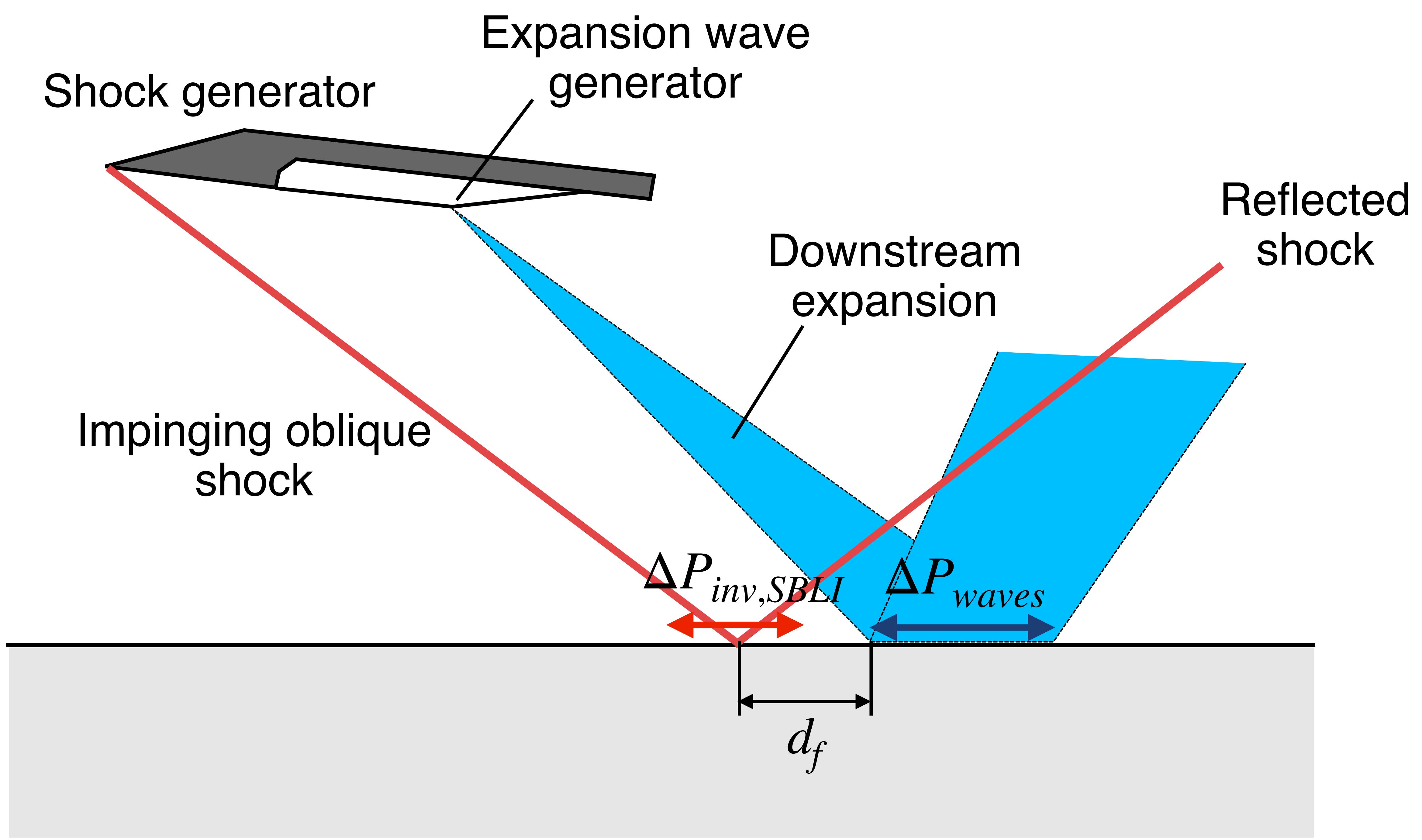

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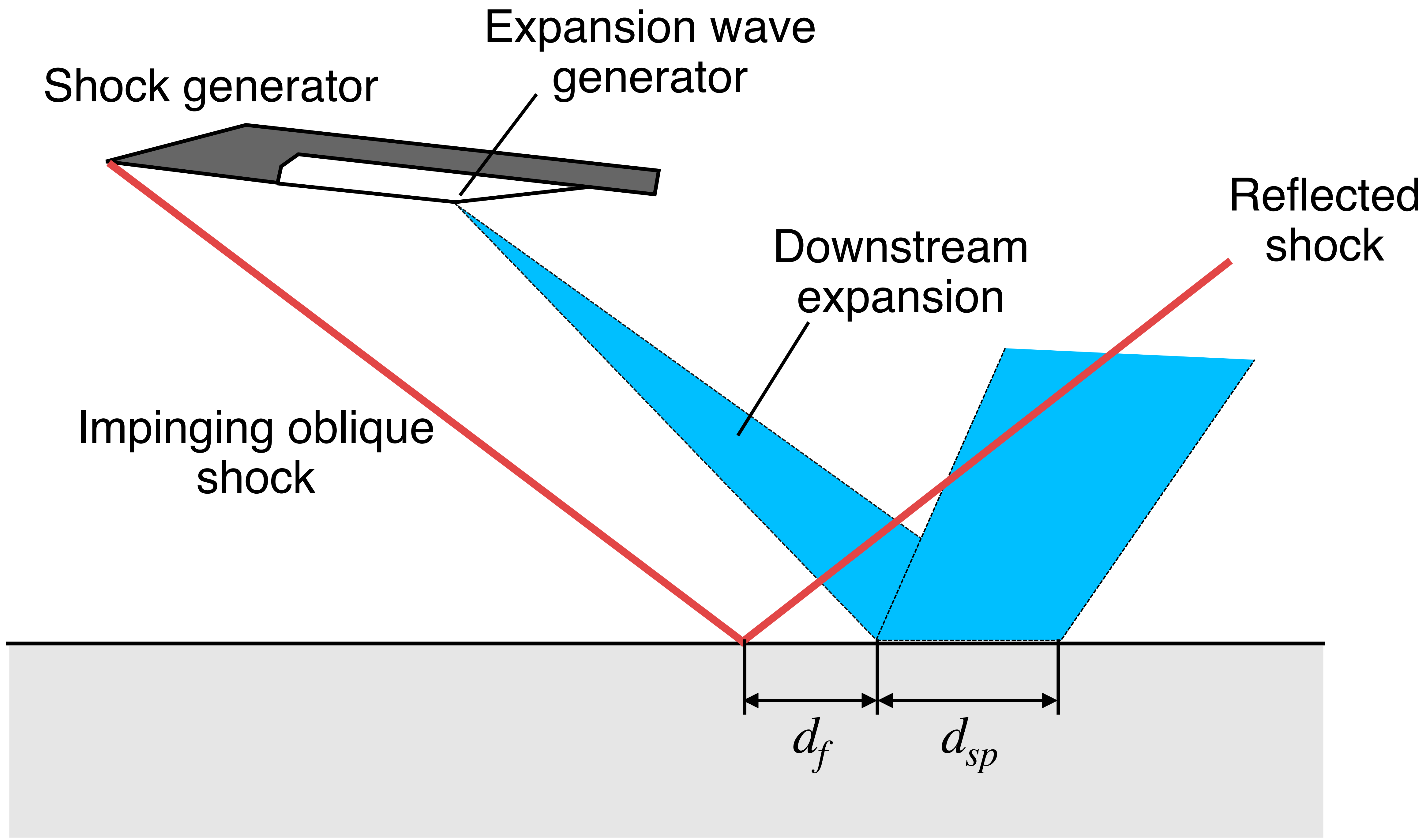

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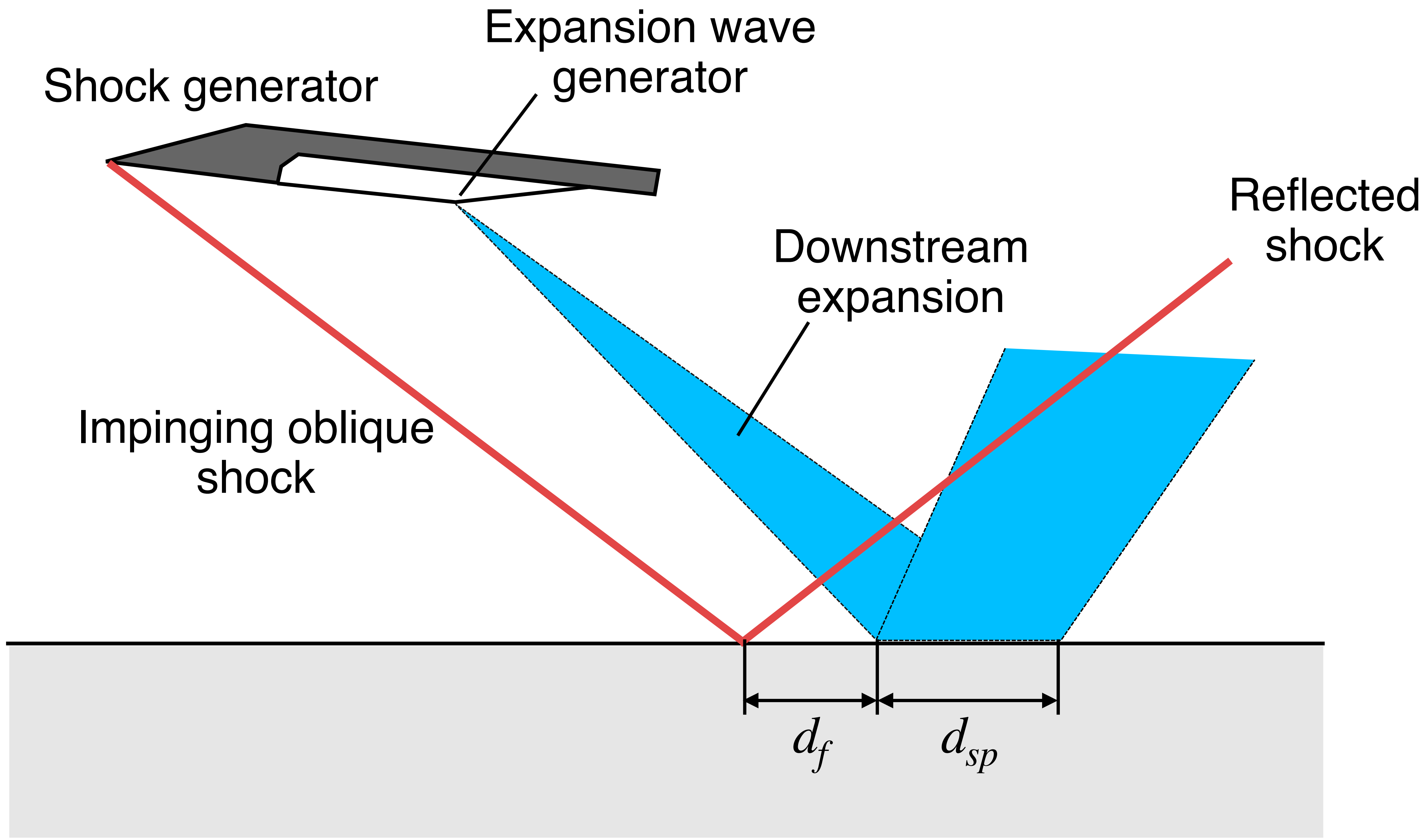

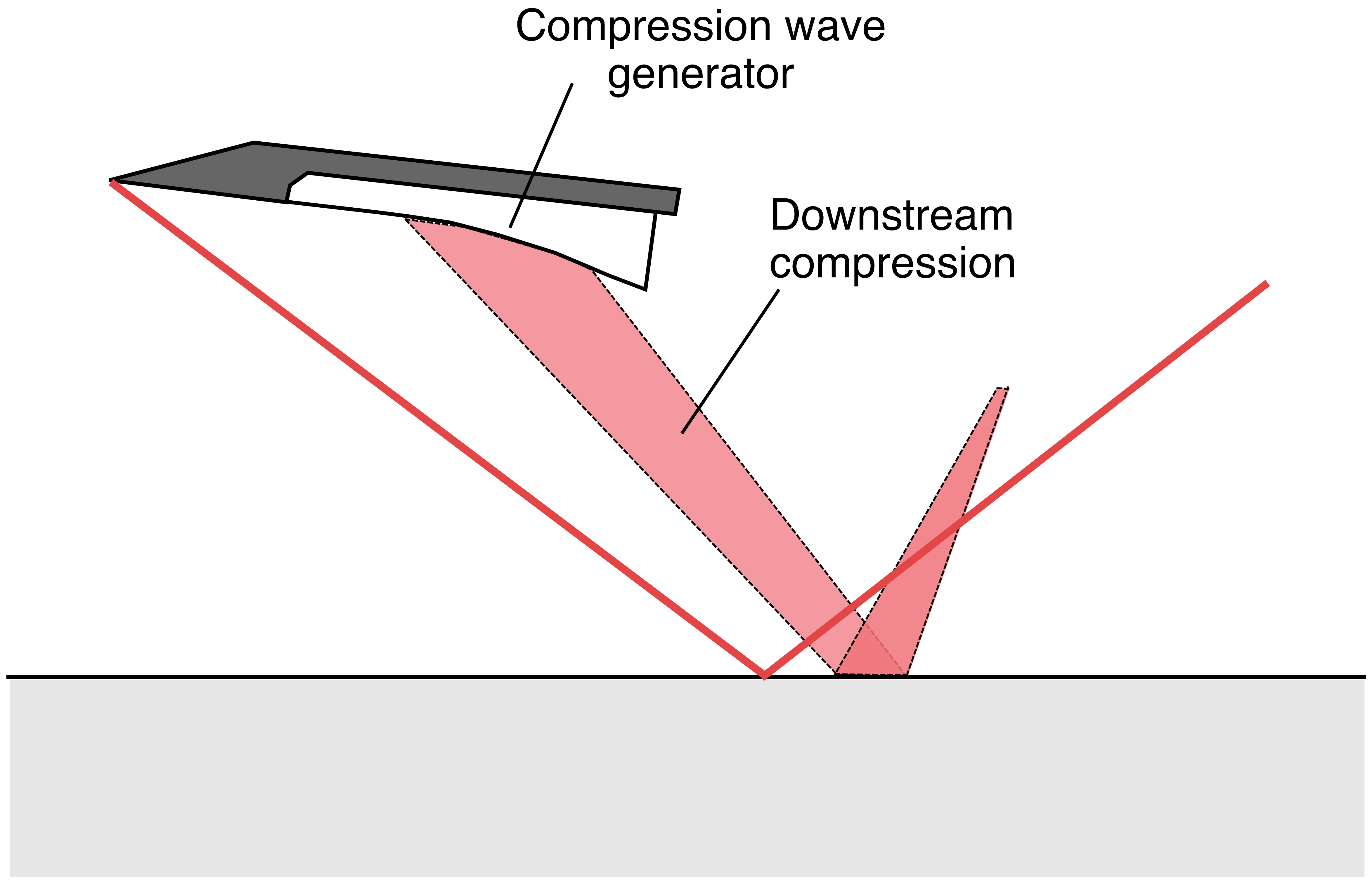

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$$\overline{dp/dx} = \overline{\Delta P}/(d_{sp}/\delta_i)$$

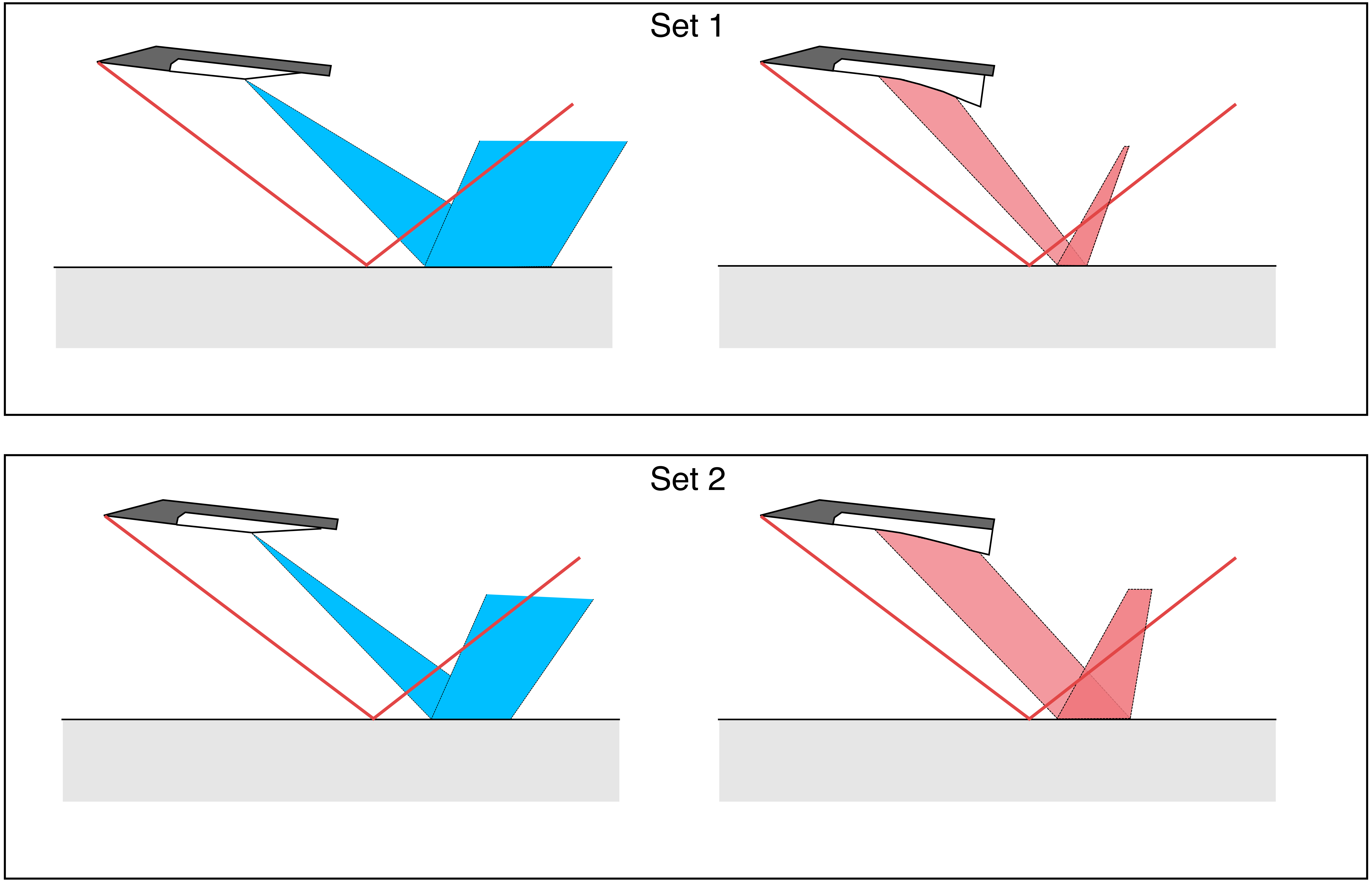
Setup

Setup

Set 1

Set 2

Setup



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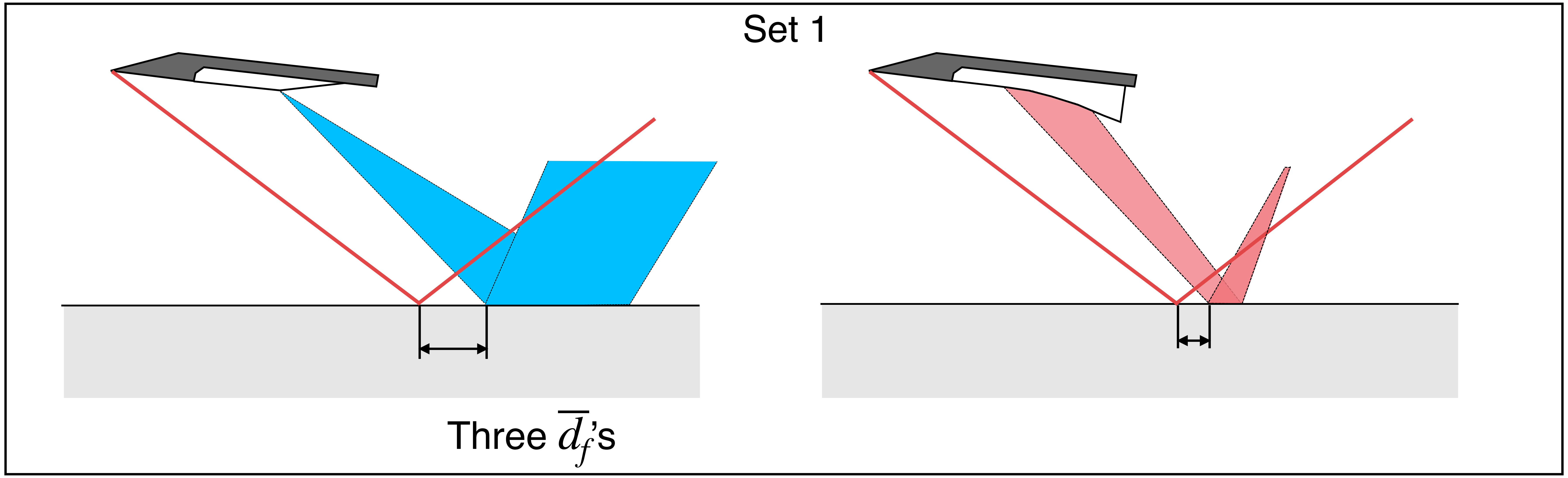

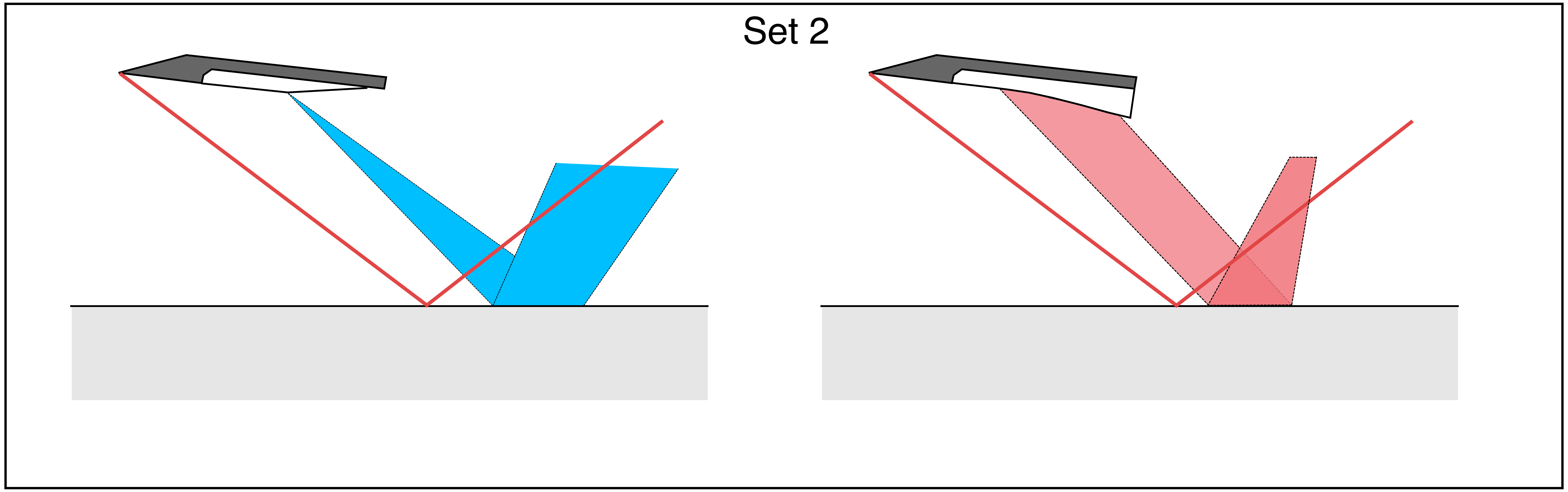

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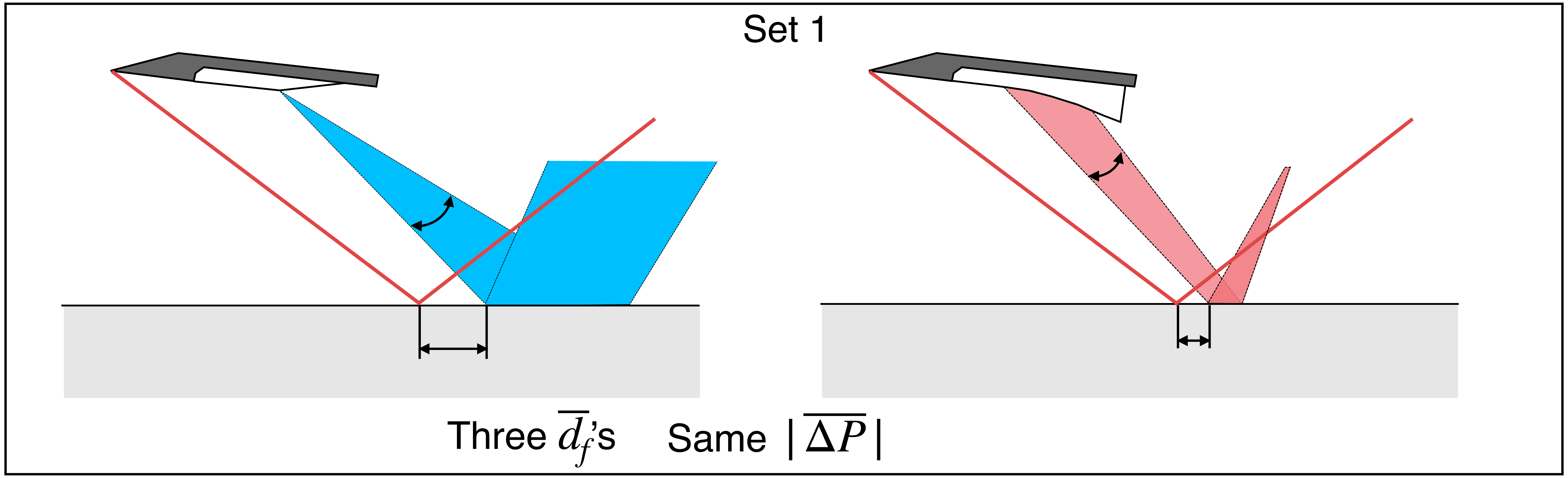

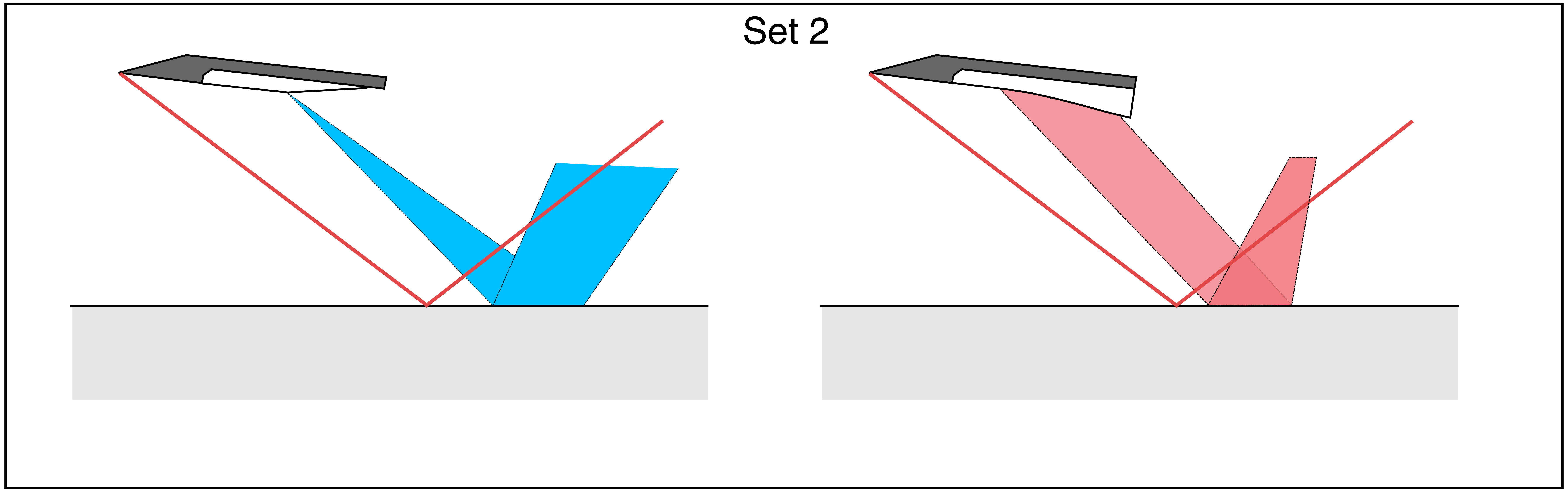

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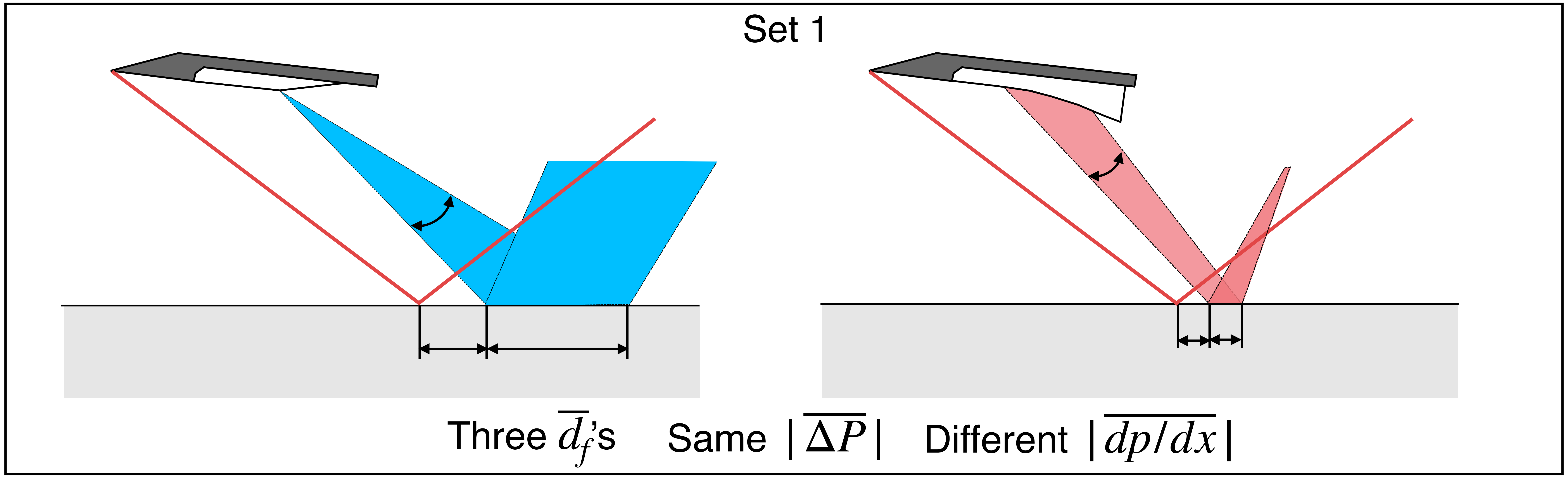
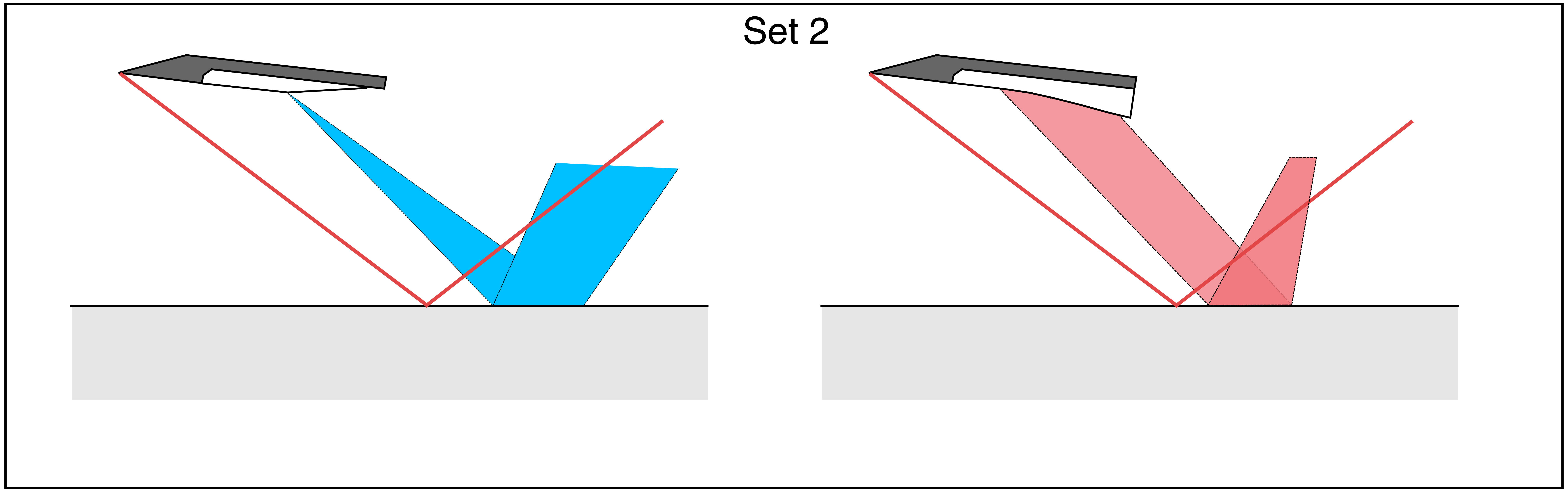

Set 1
Three $\overline{d_f}$'s
Same $|\overline{\Delta P}|$
Different $|\overline{dp/dx}|$


Set 2

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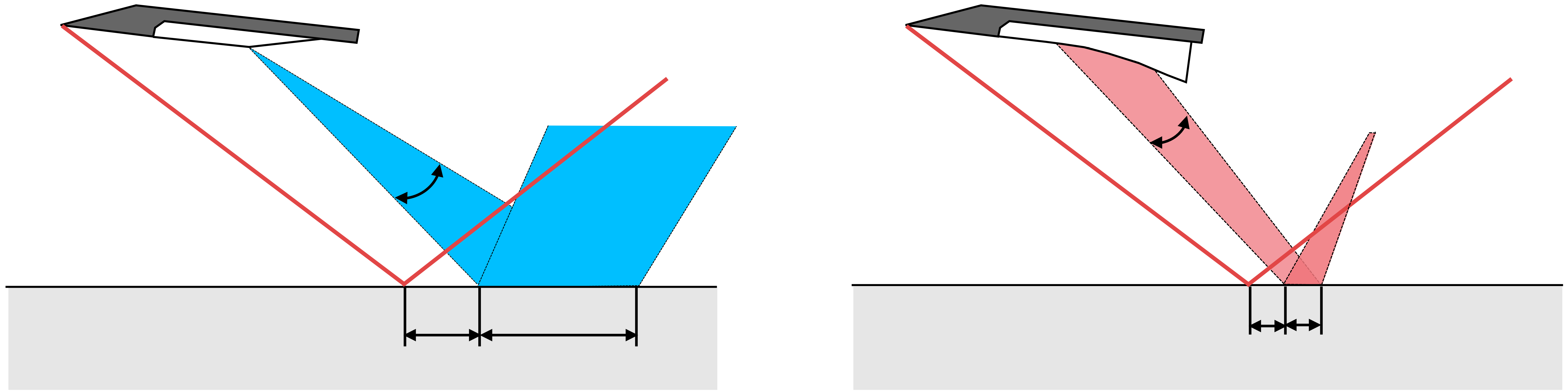
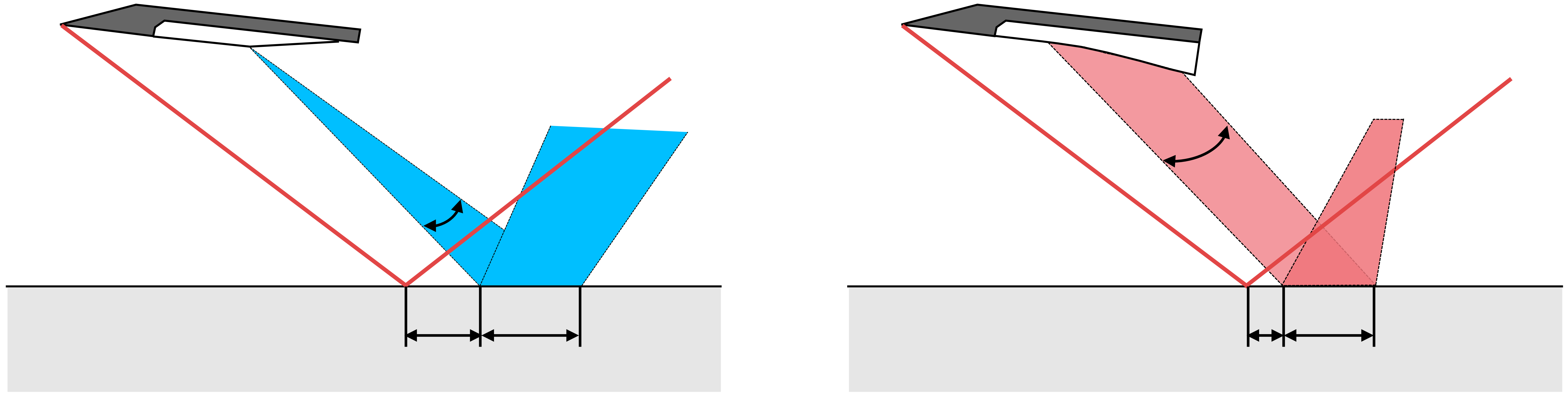


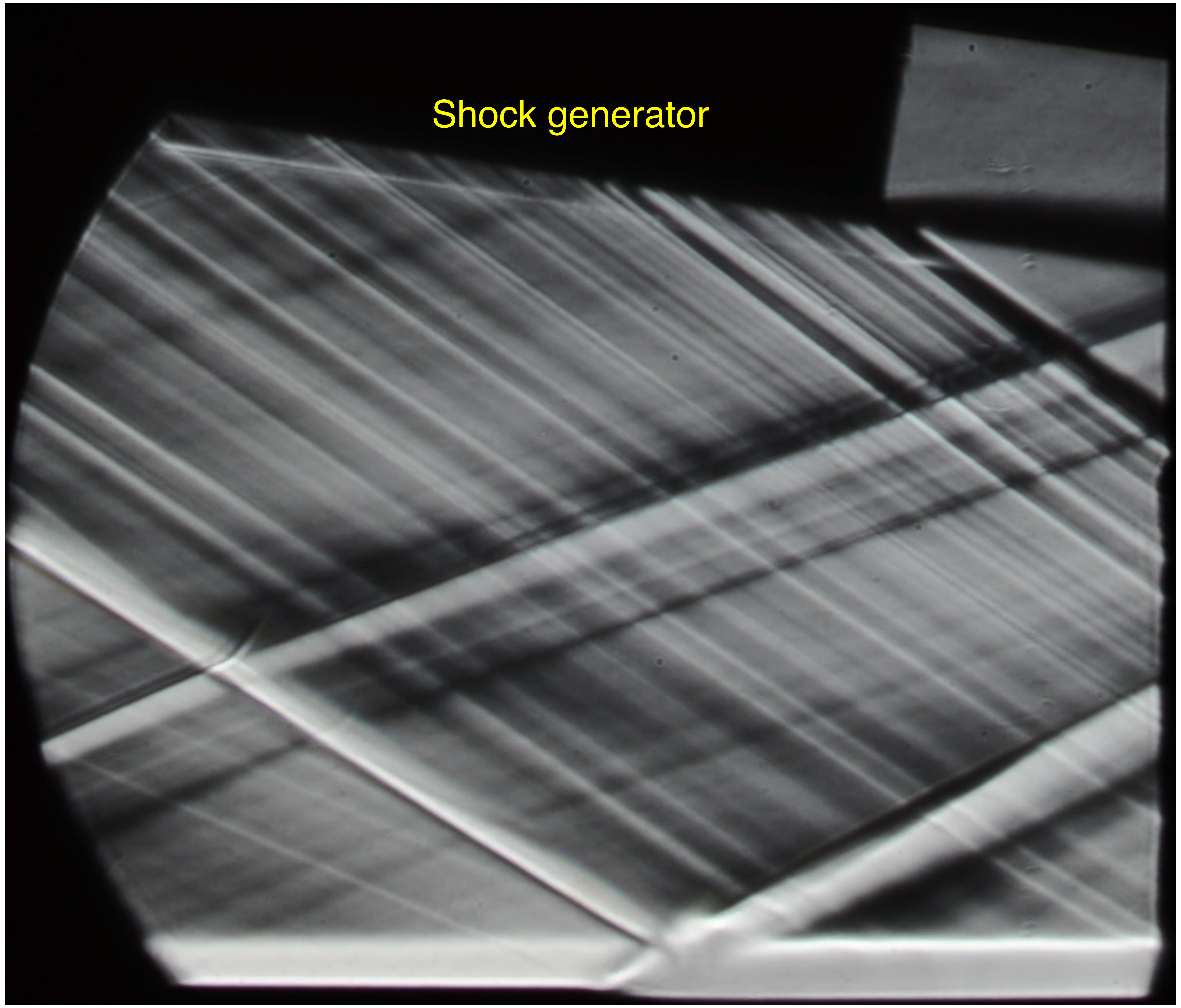
Three $\overline{d_f}$'s   Same $|\overline{\Delta P}|$ Different $|\overline{dp/dx}|$

Set 2



Three $\overline{d_f}$'s   Same $|\overline{\Delta P}|$ Same $|\overline{dp/dx}|$

Baseline flowfield



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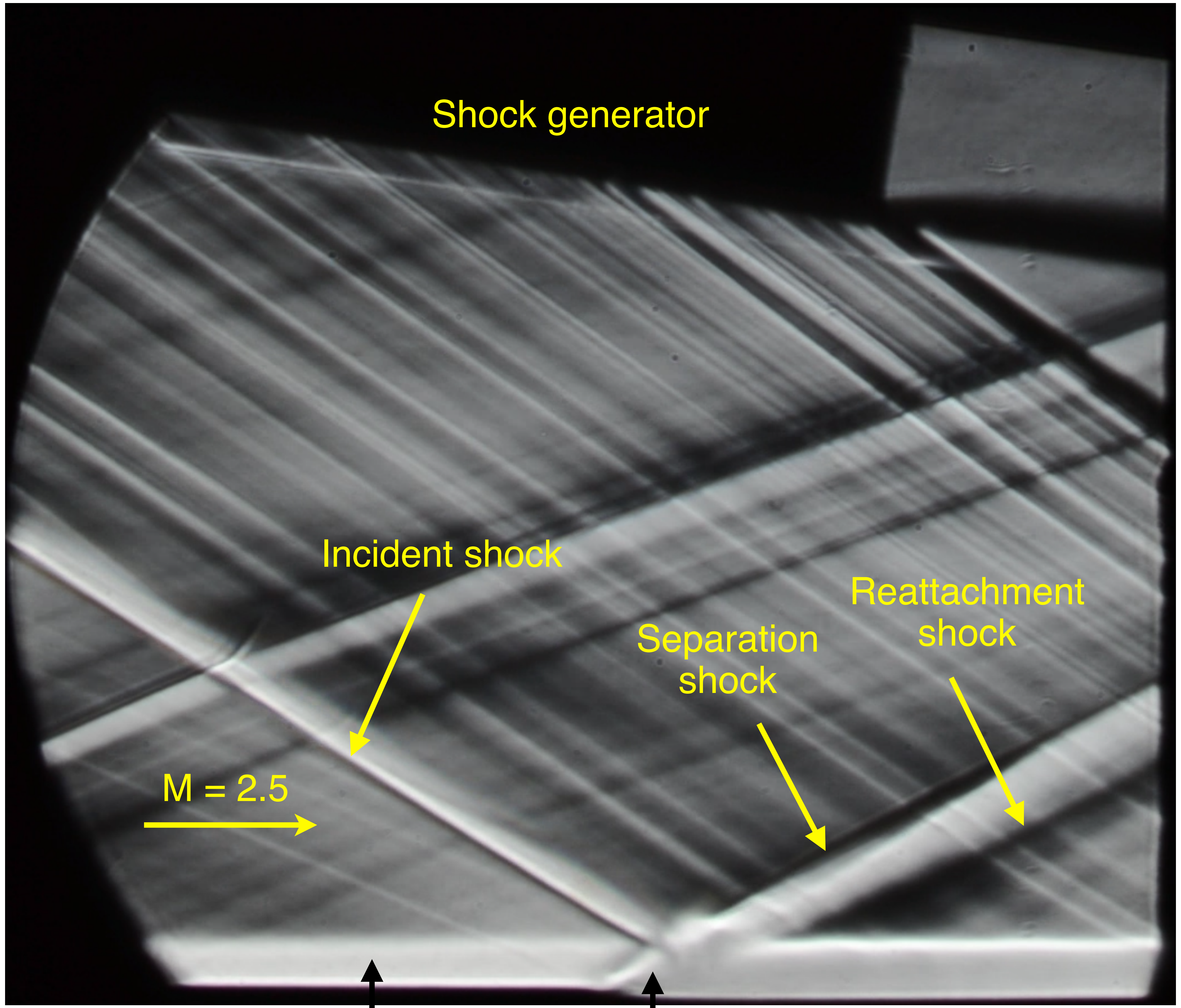

Incoming boundary layer

Separation bubble

Baseline flowfield

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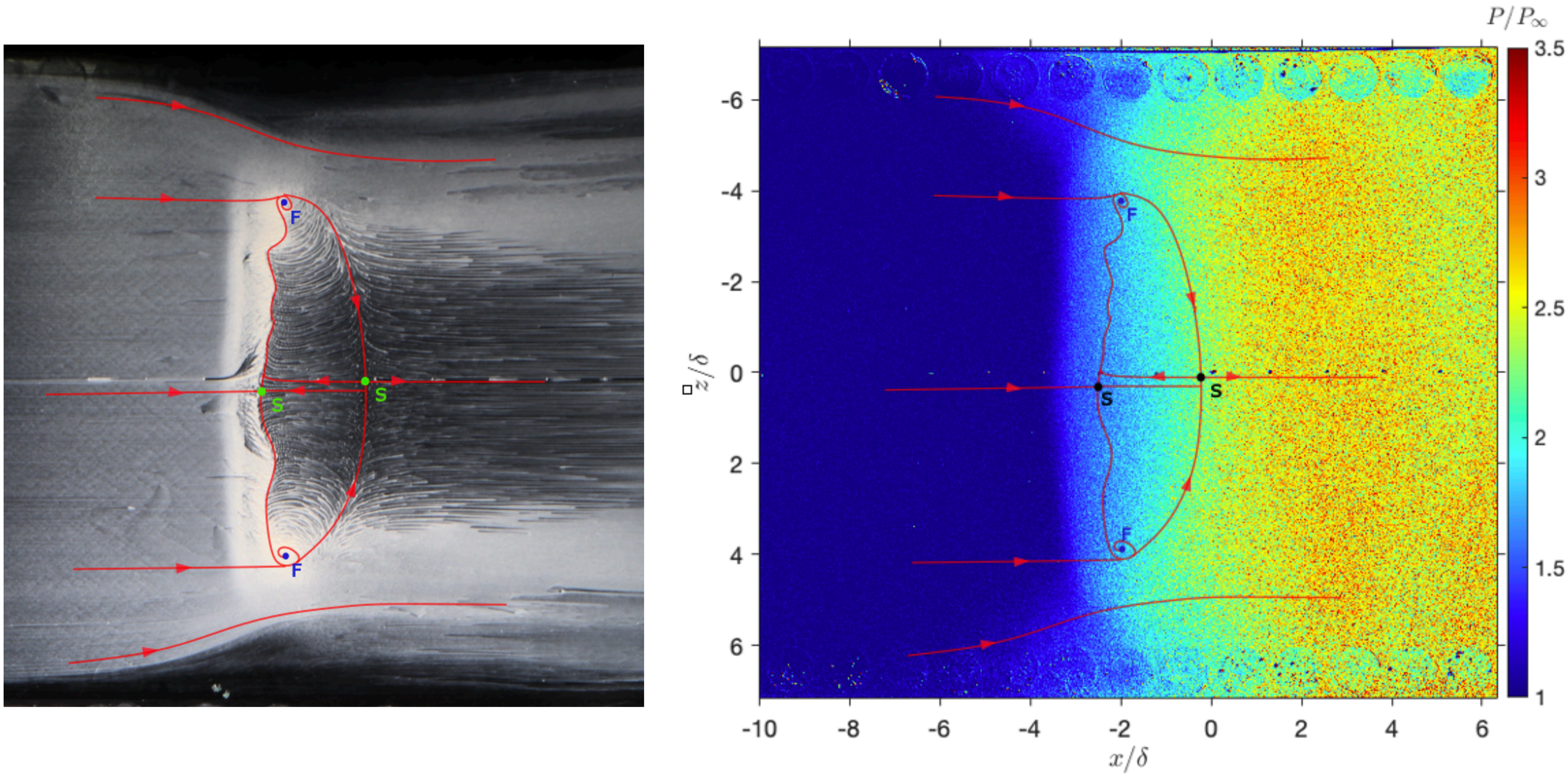

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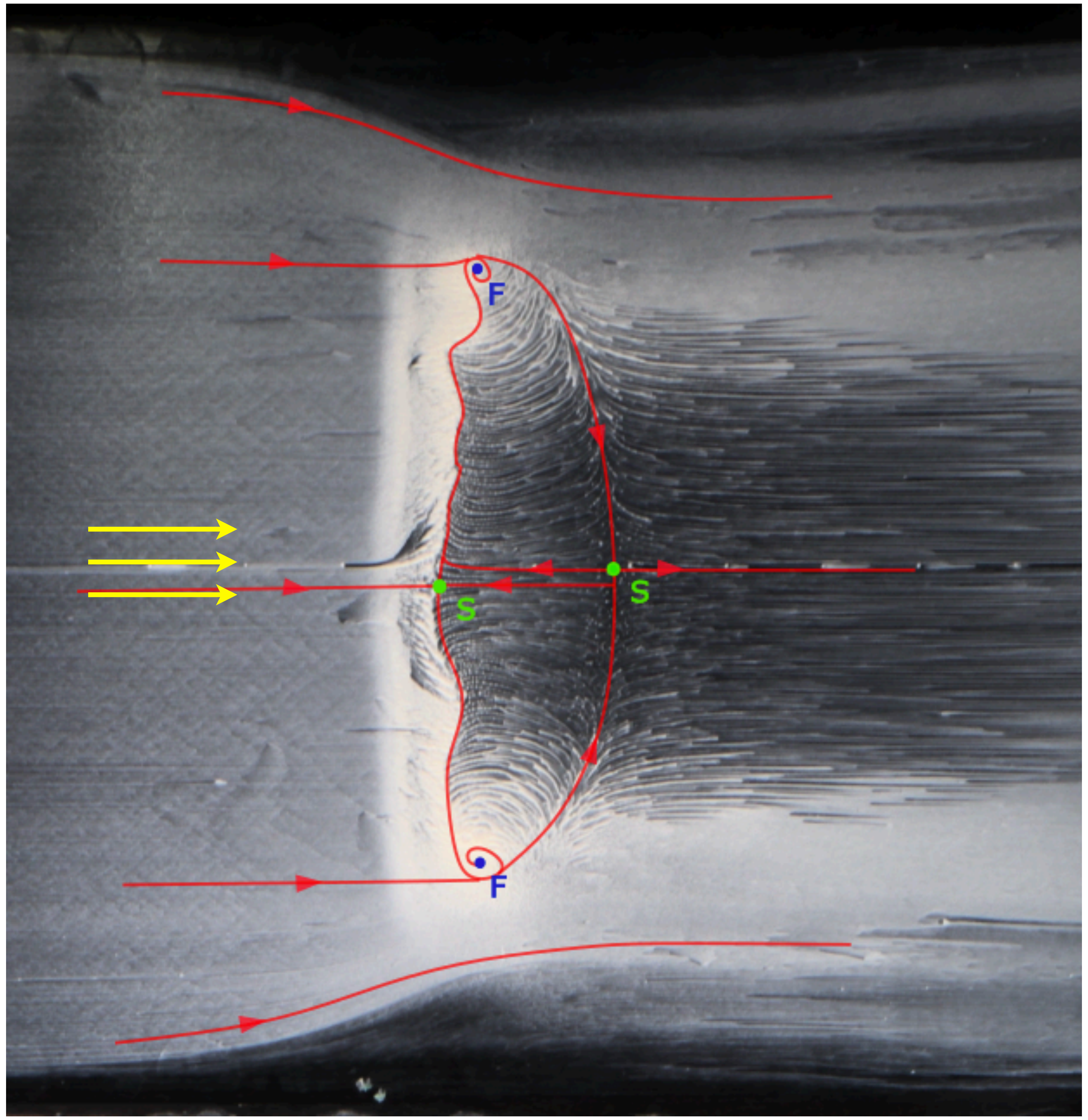

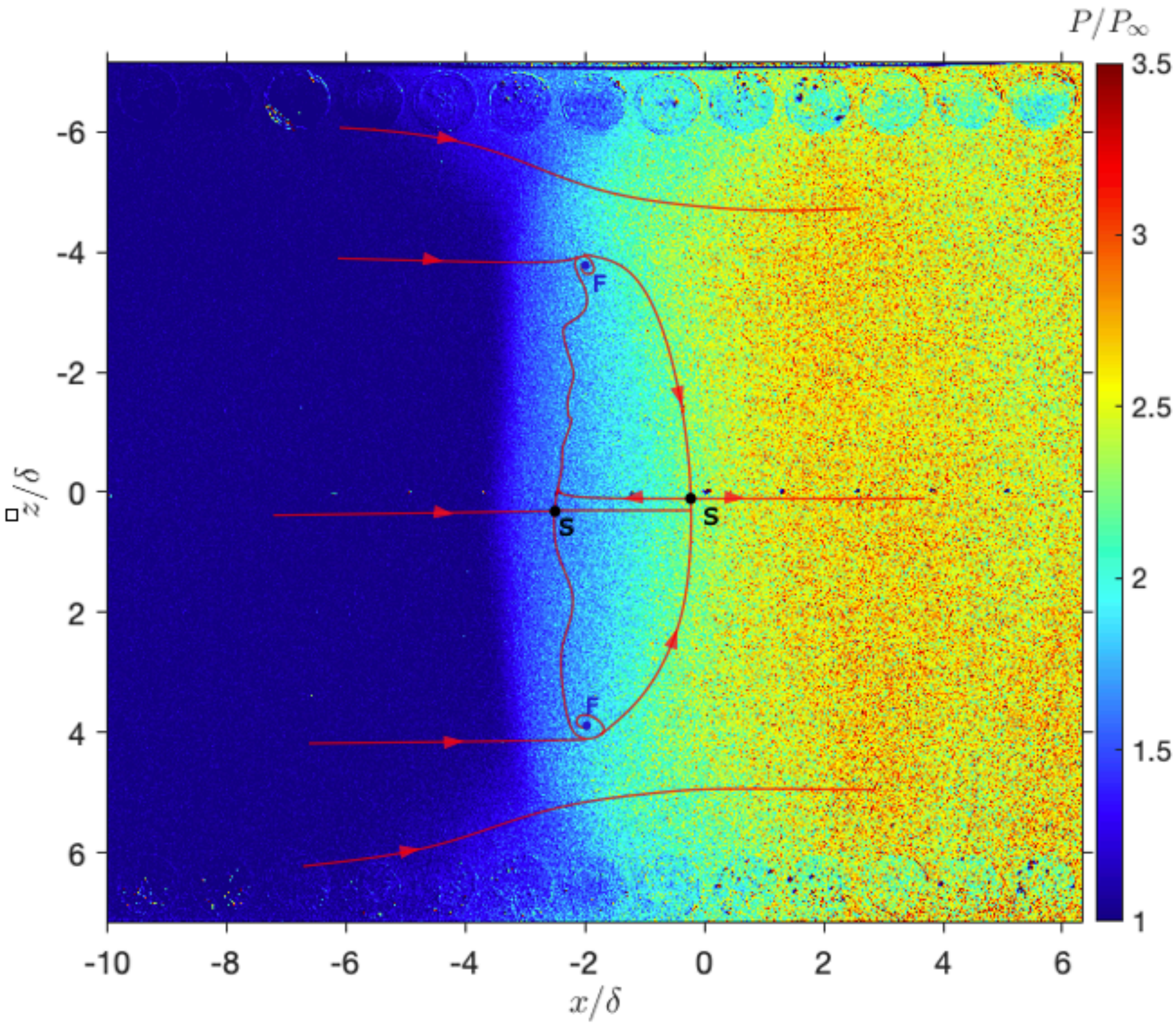

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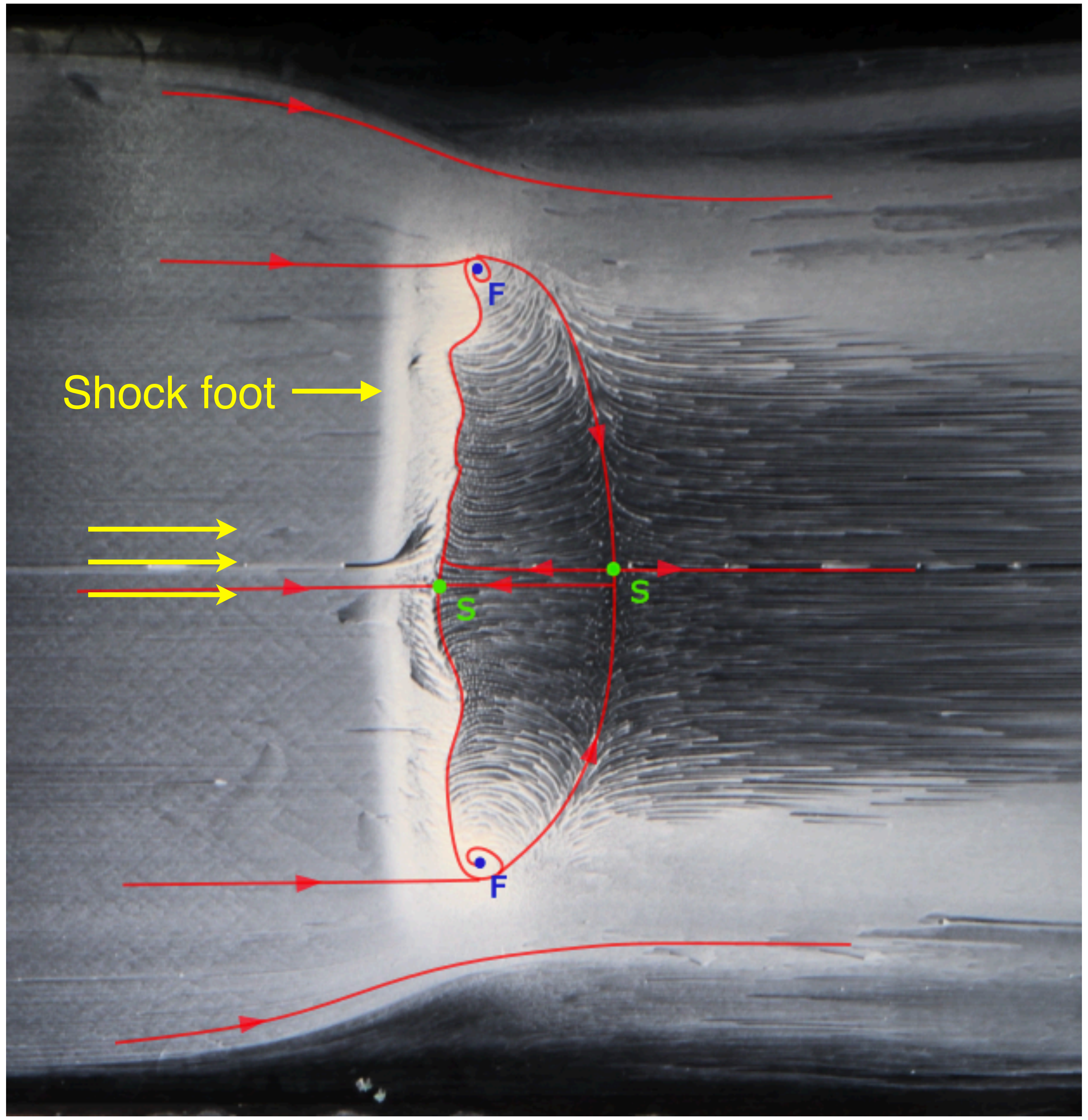

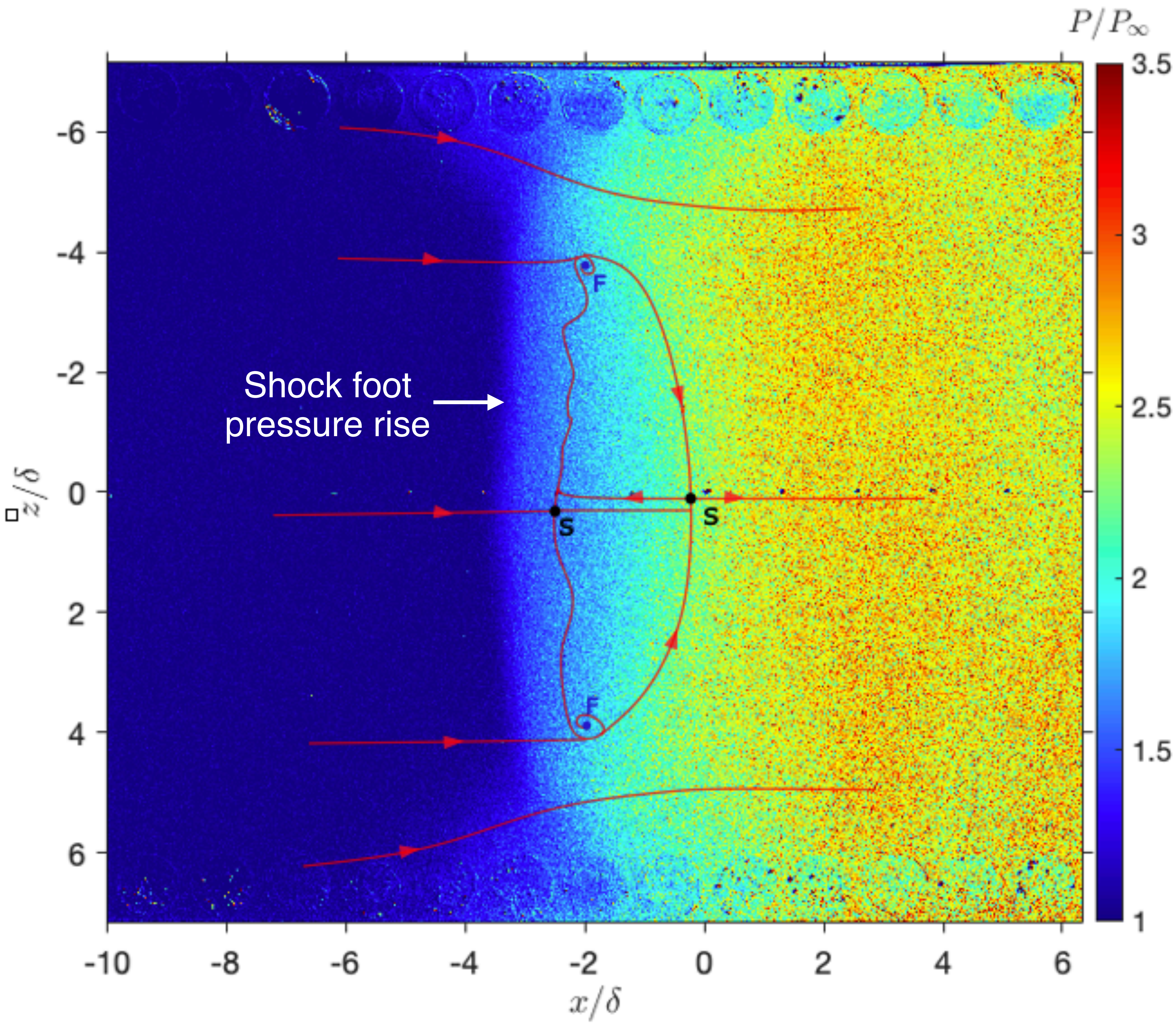

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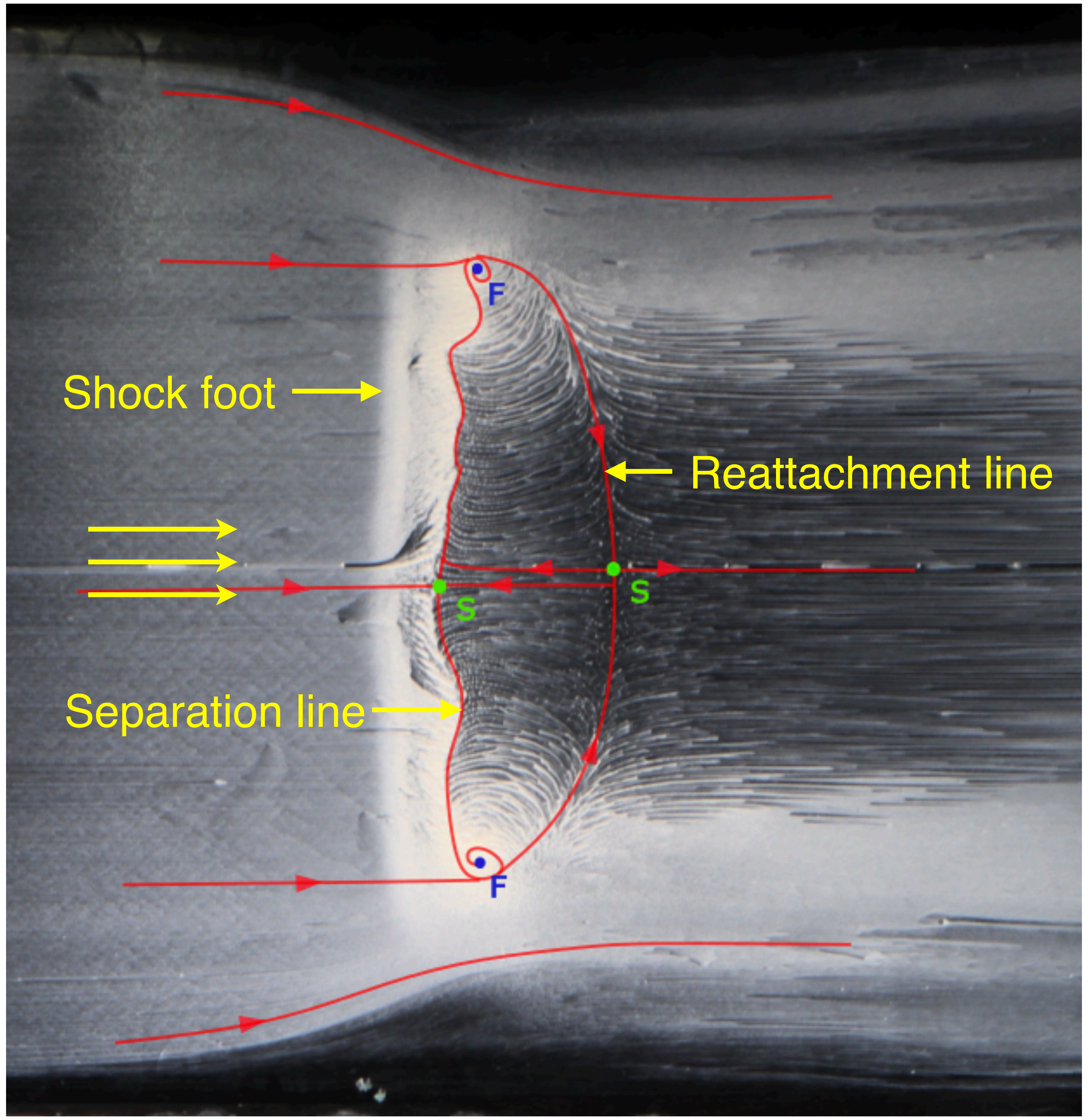

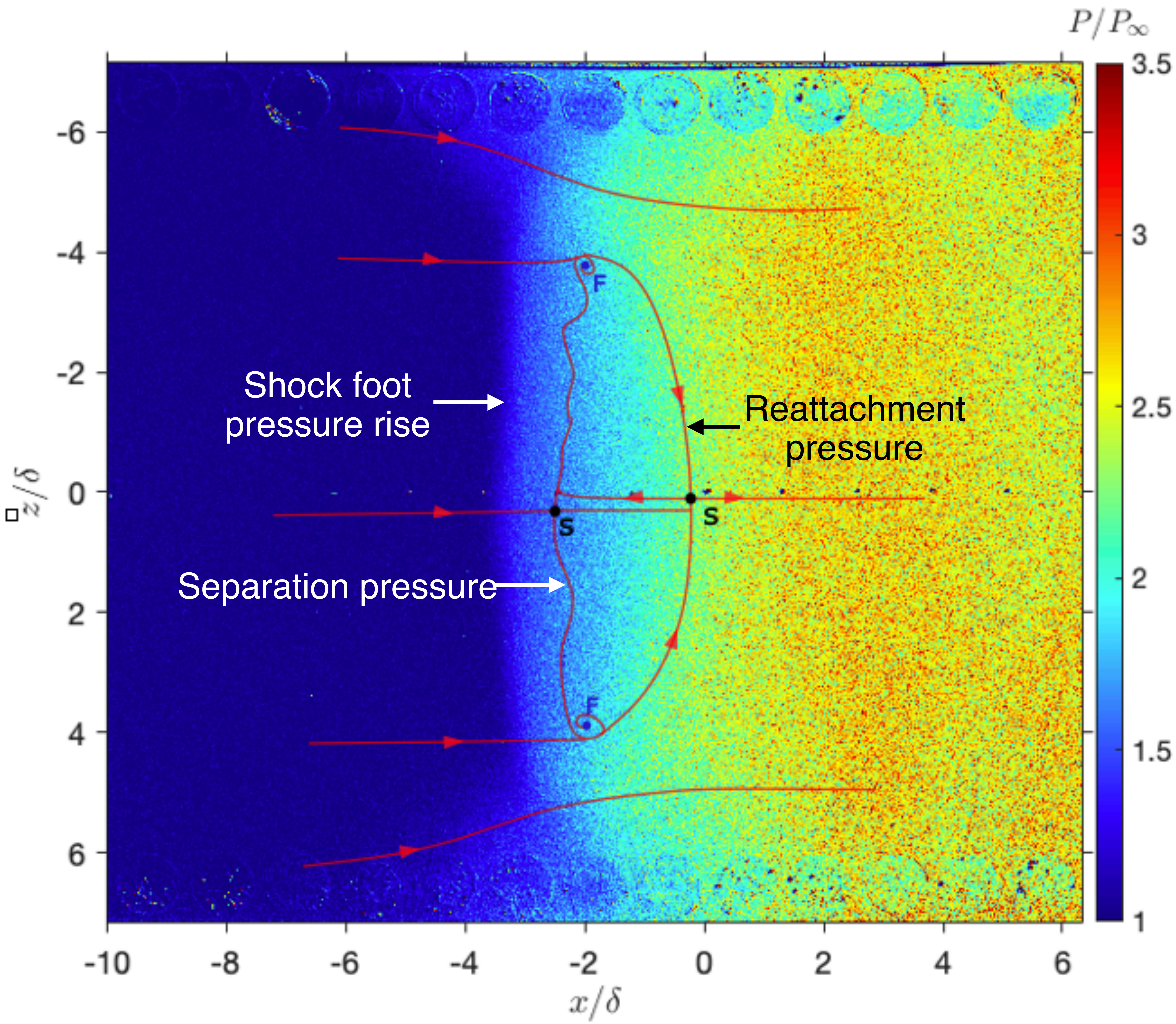

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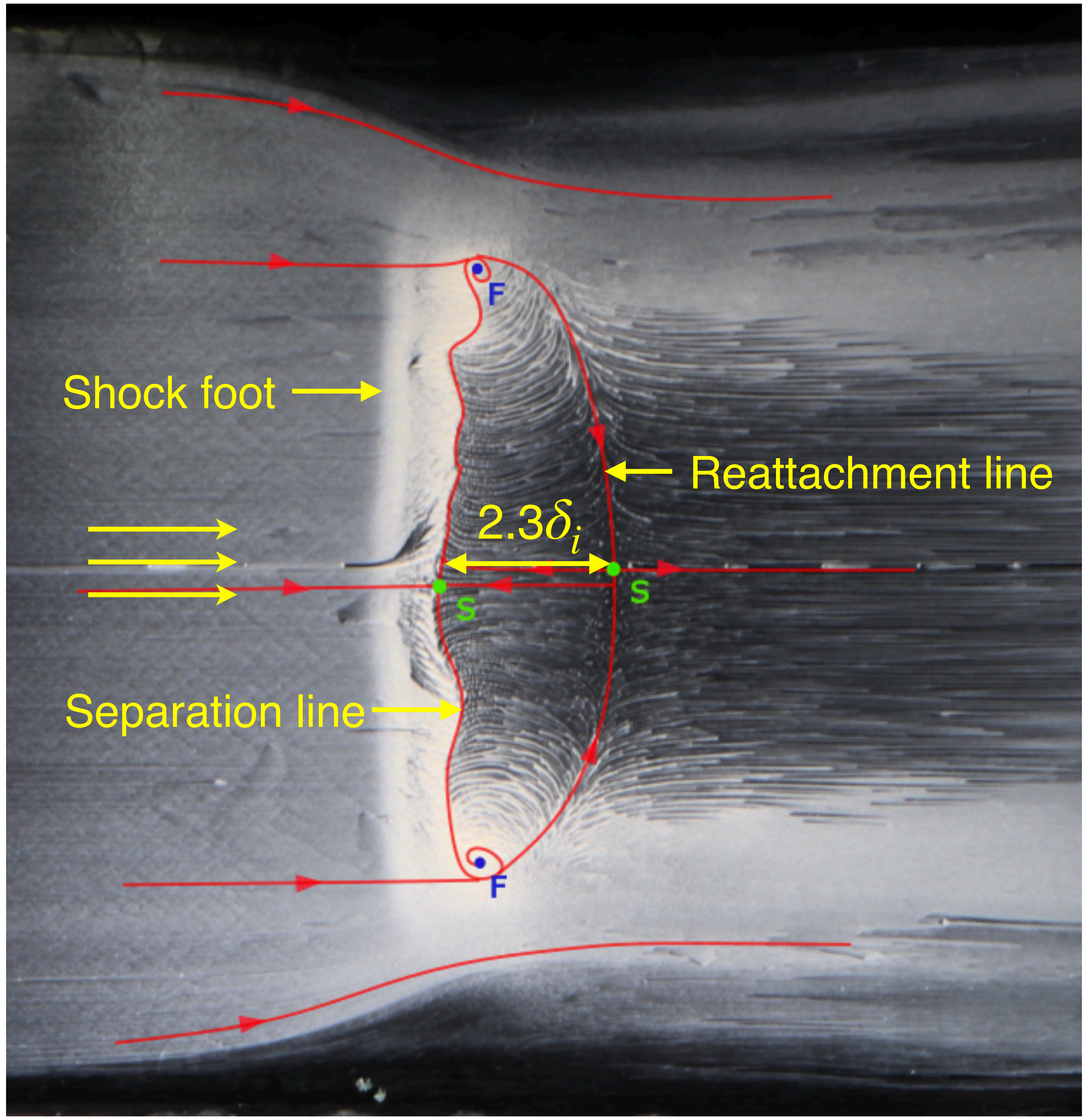

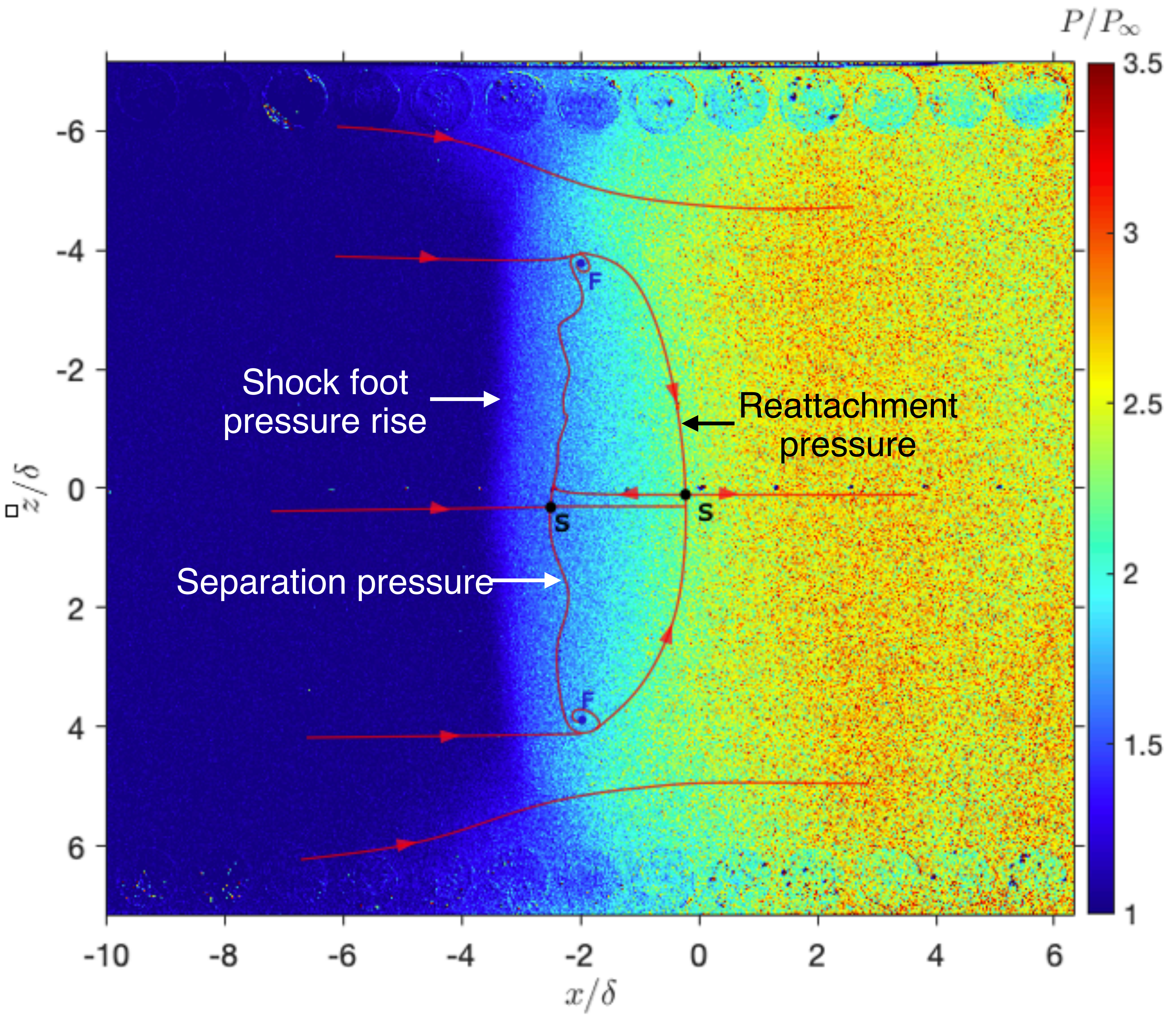

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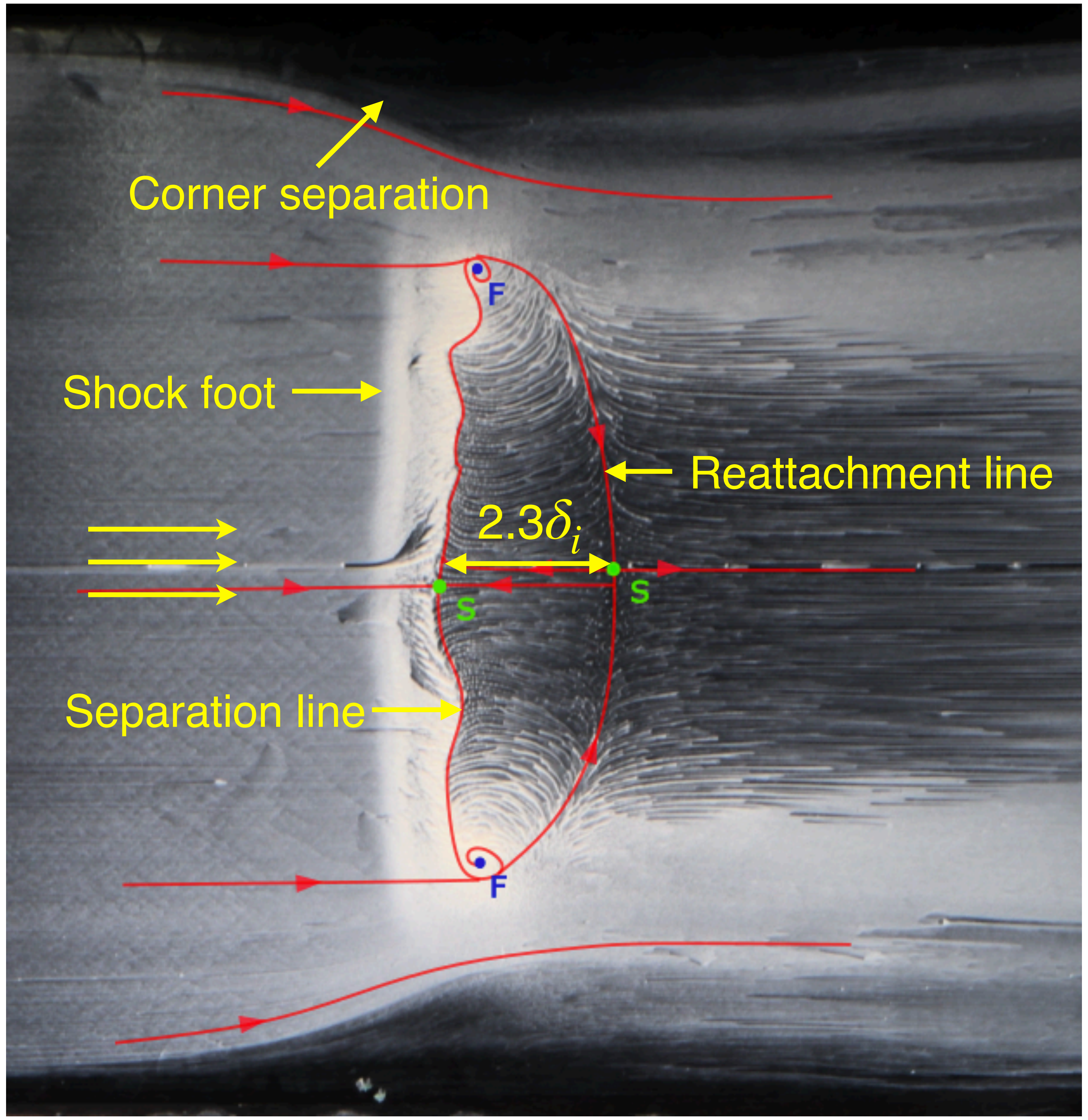

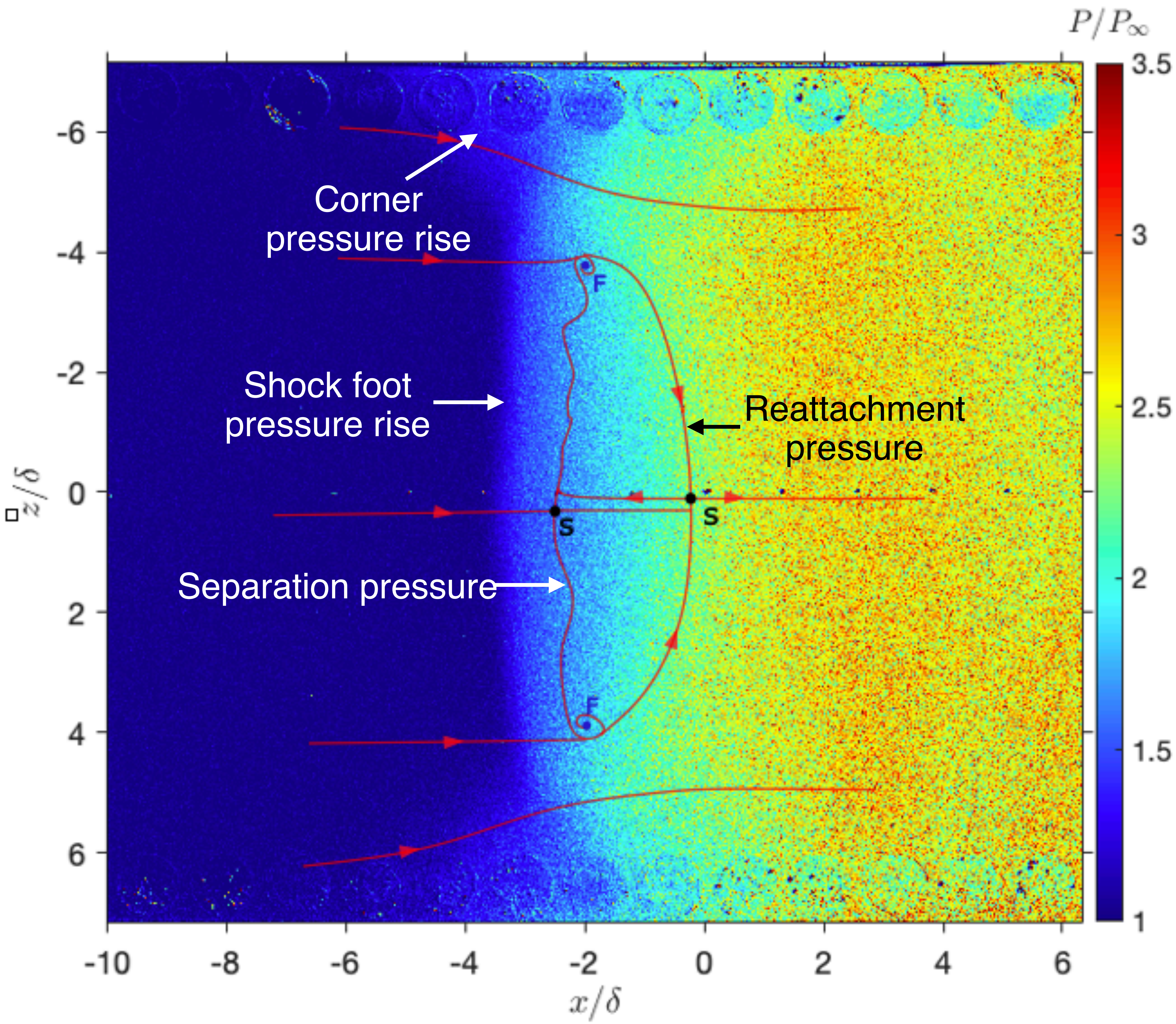

Effect of distance

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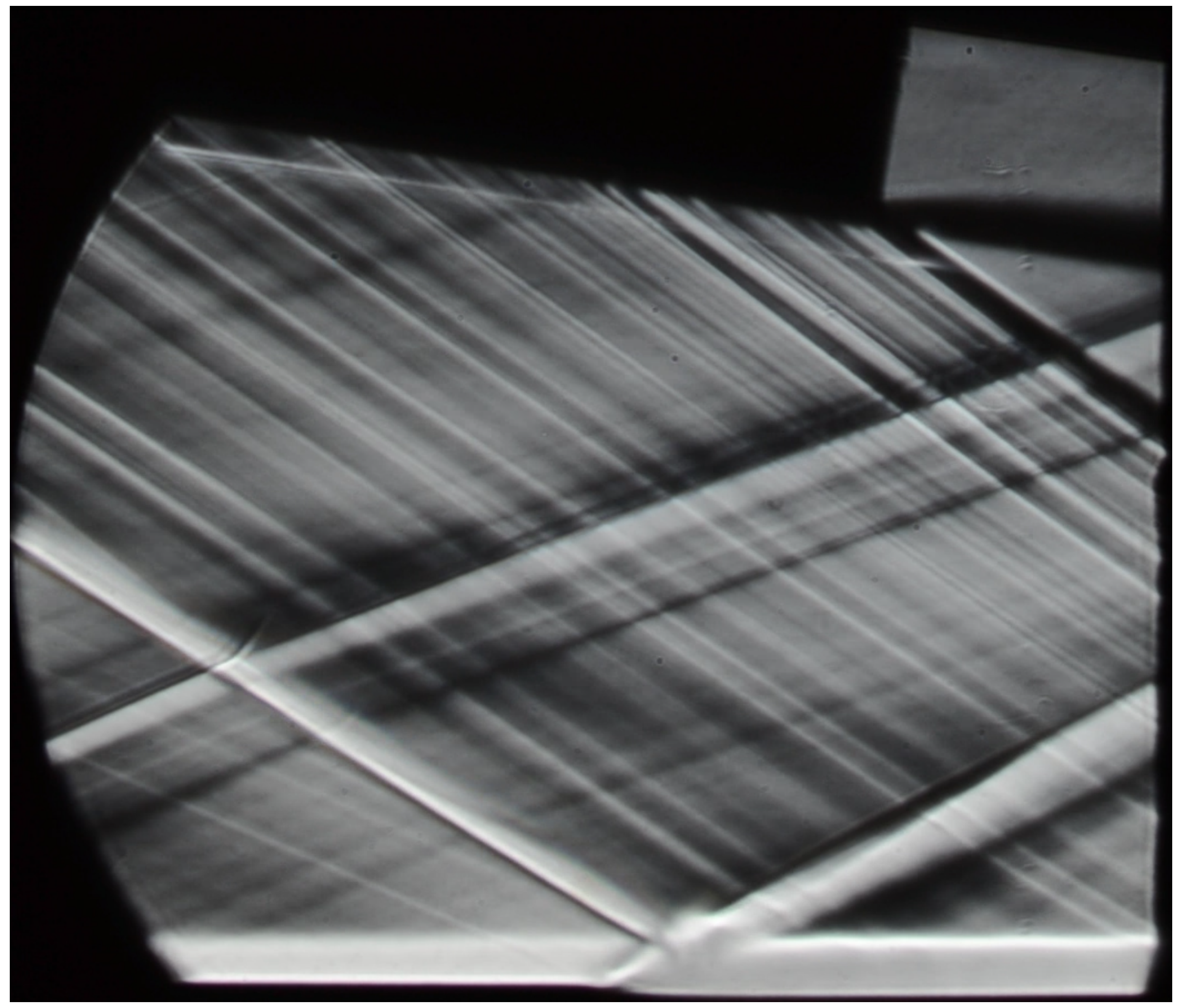
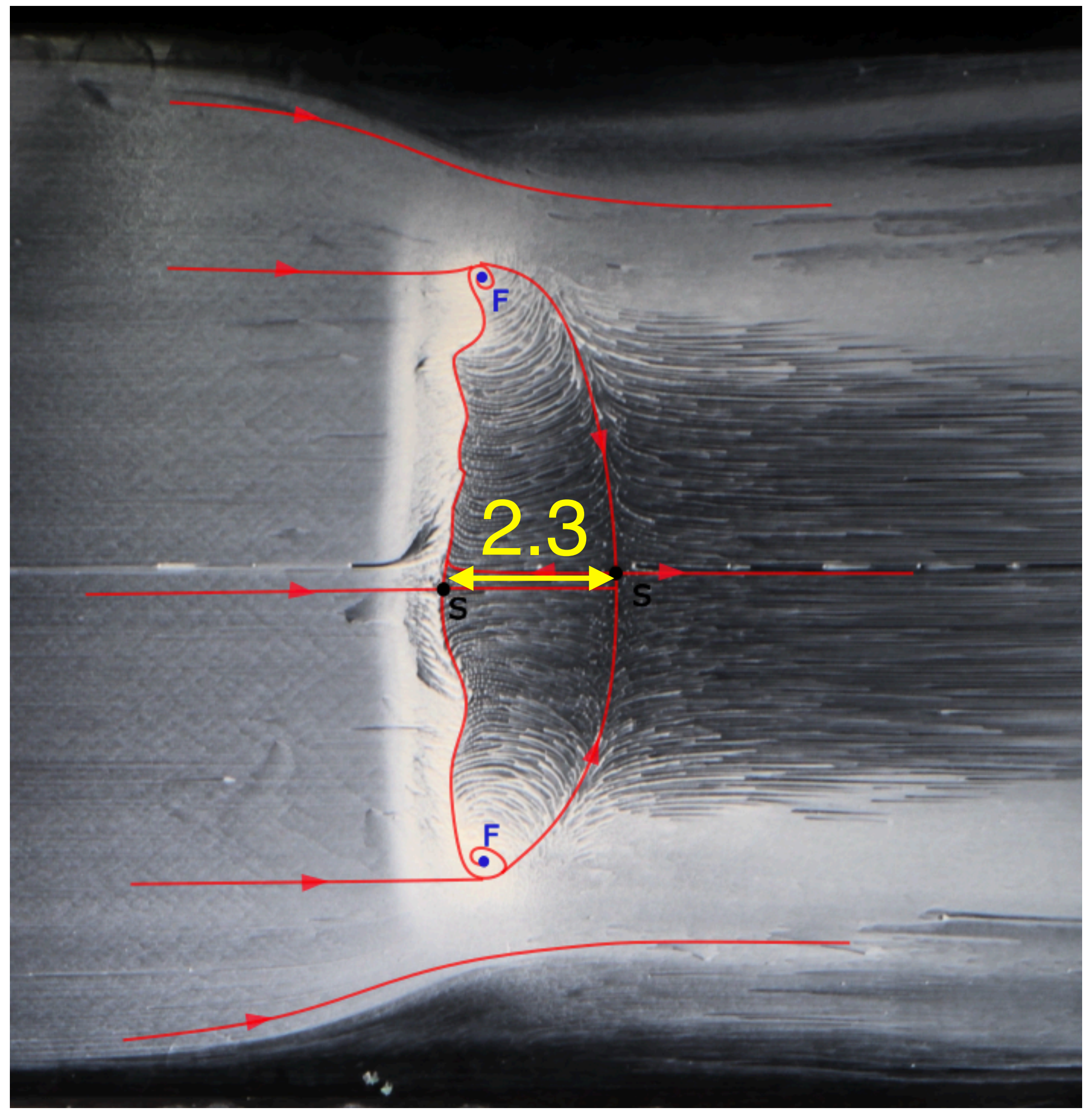
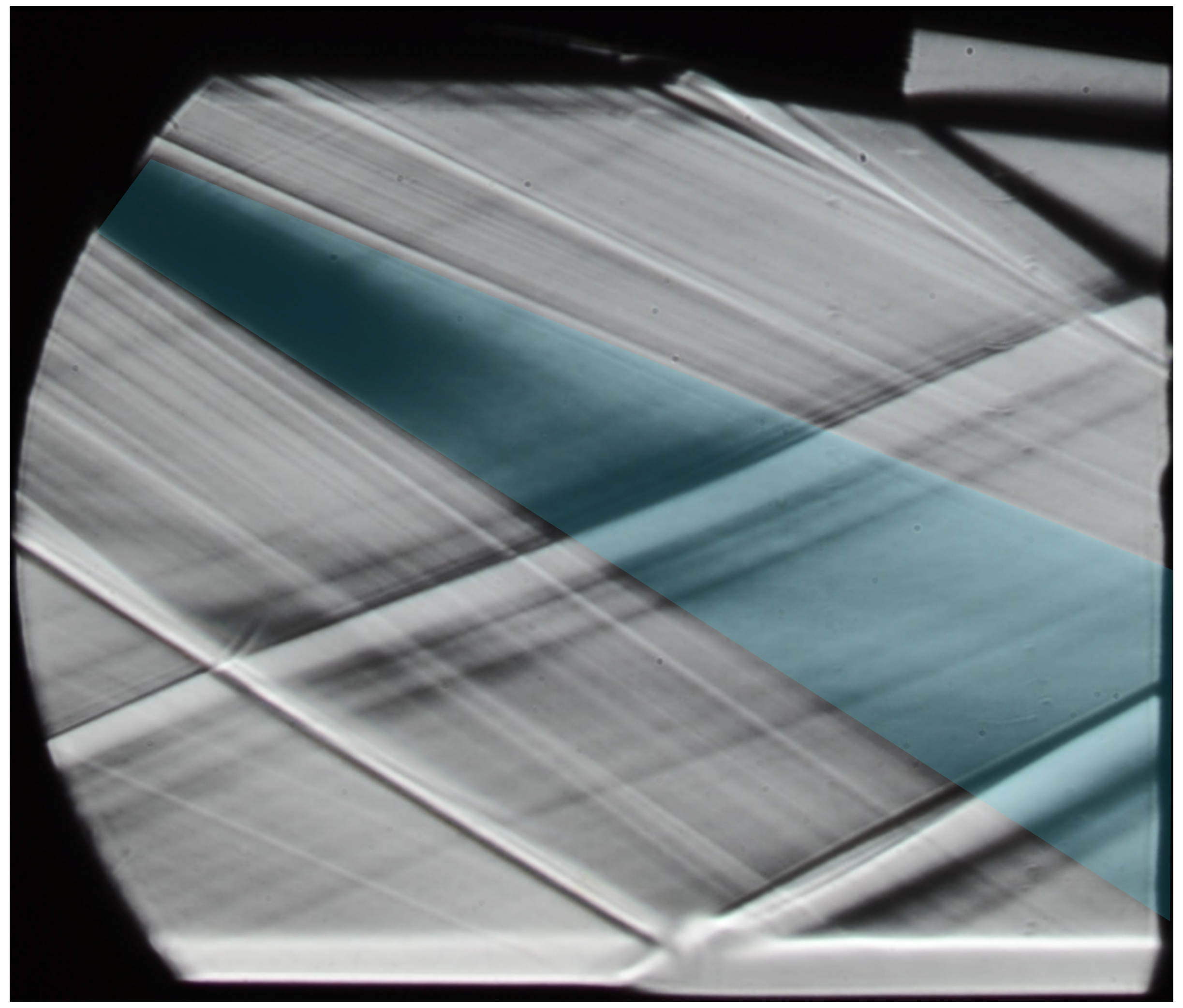


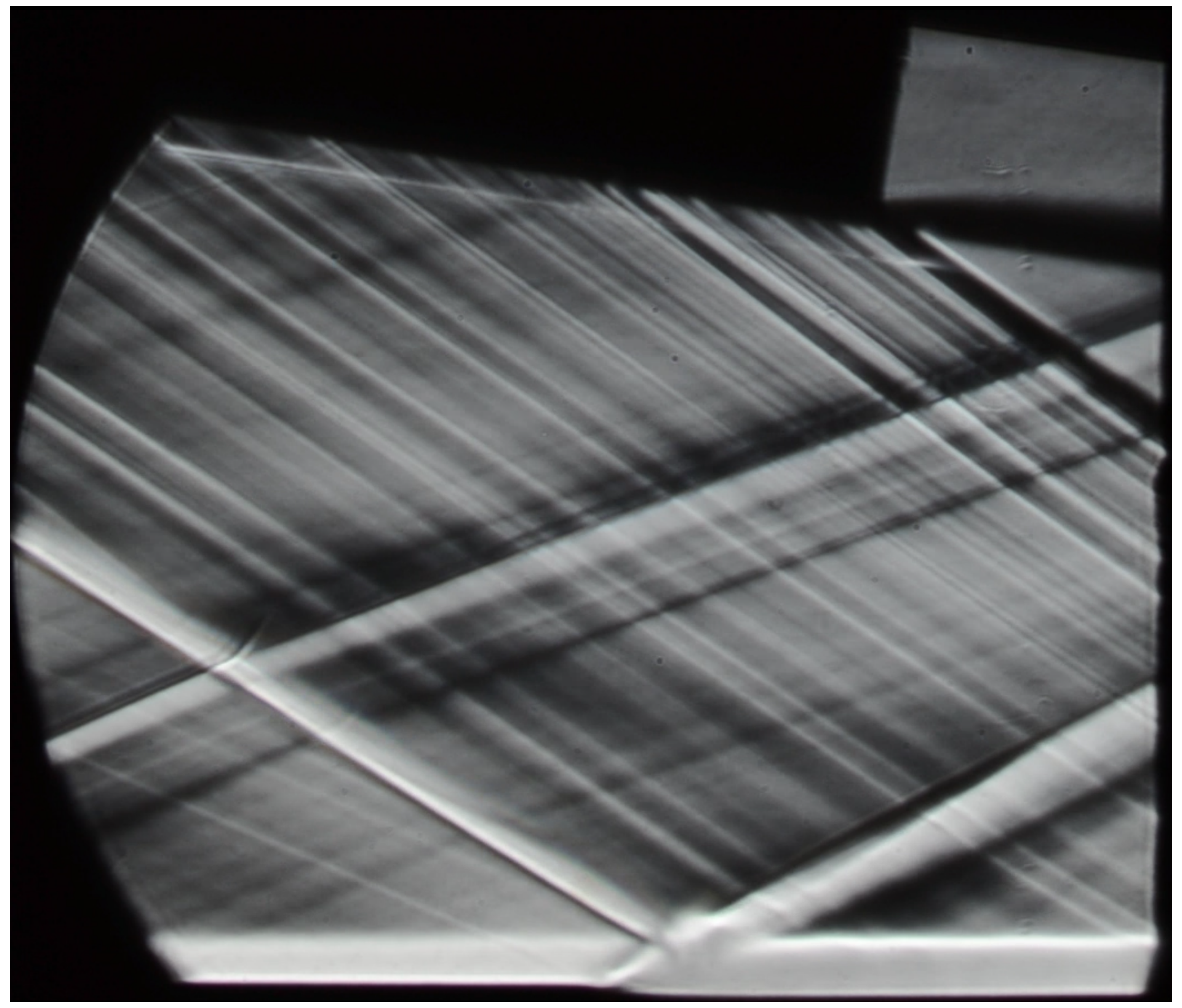
Baseline



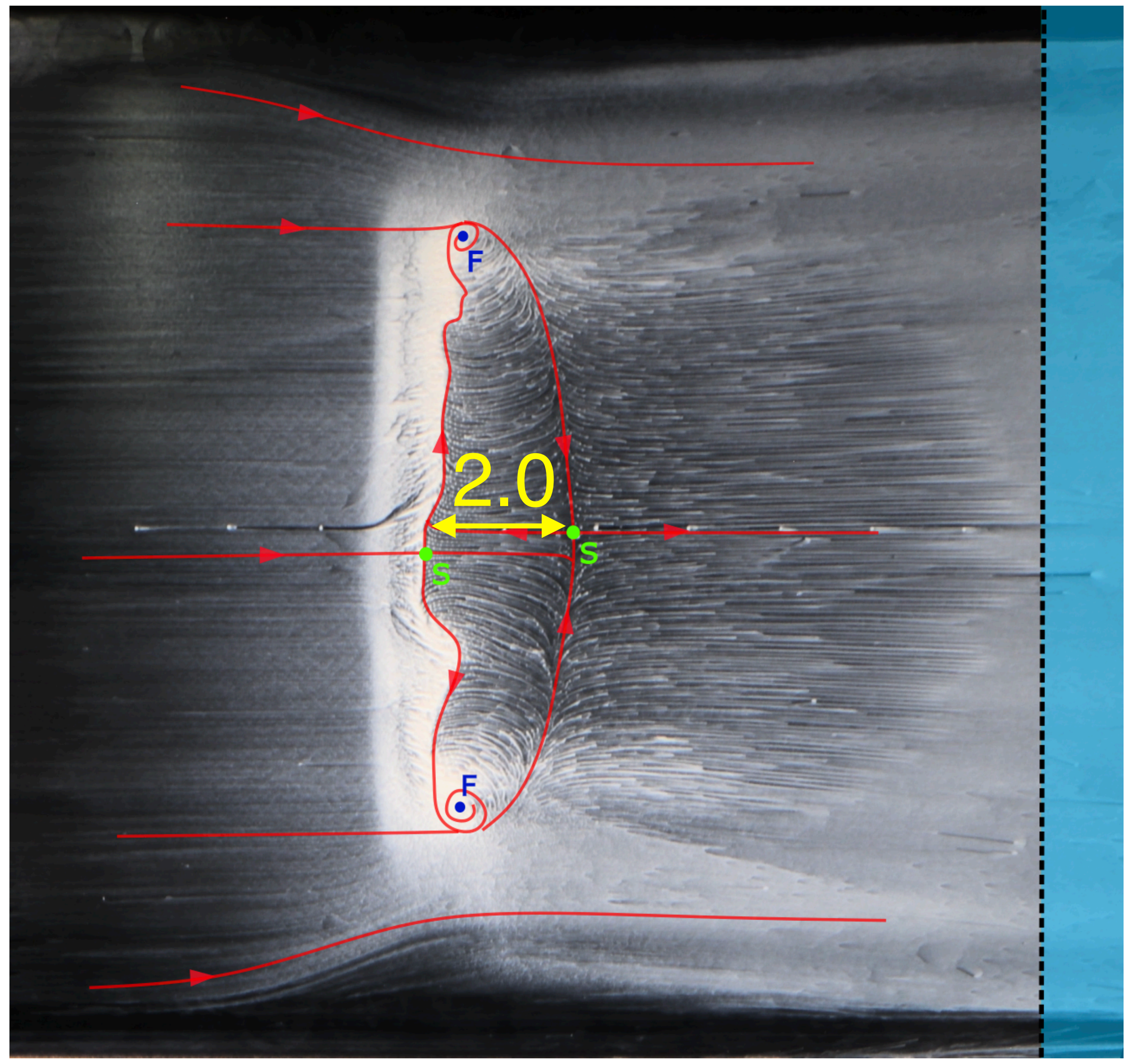
Effect of distance

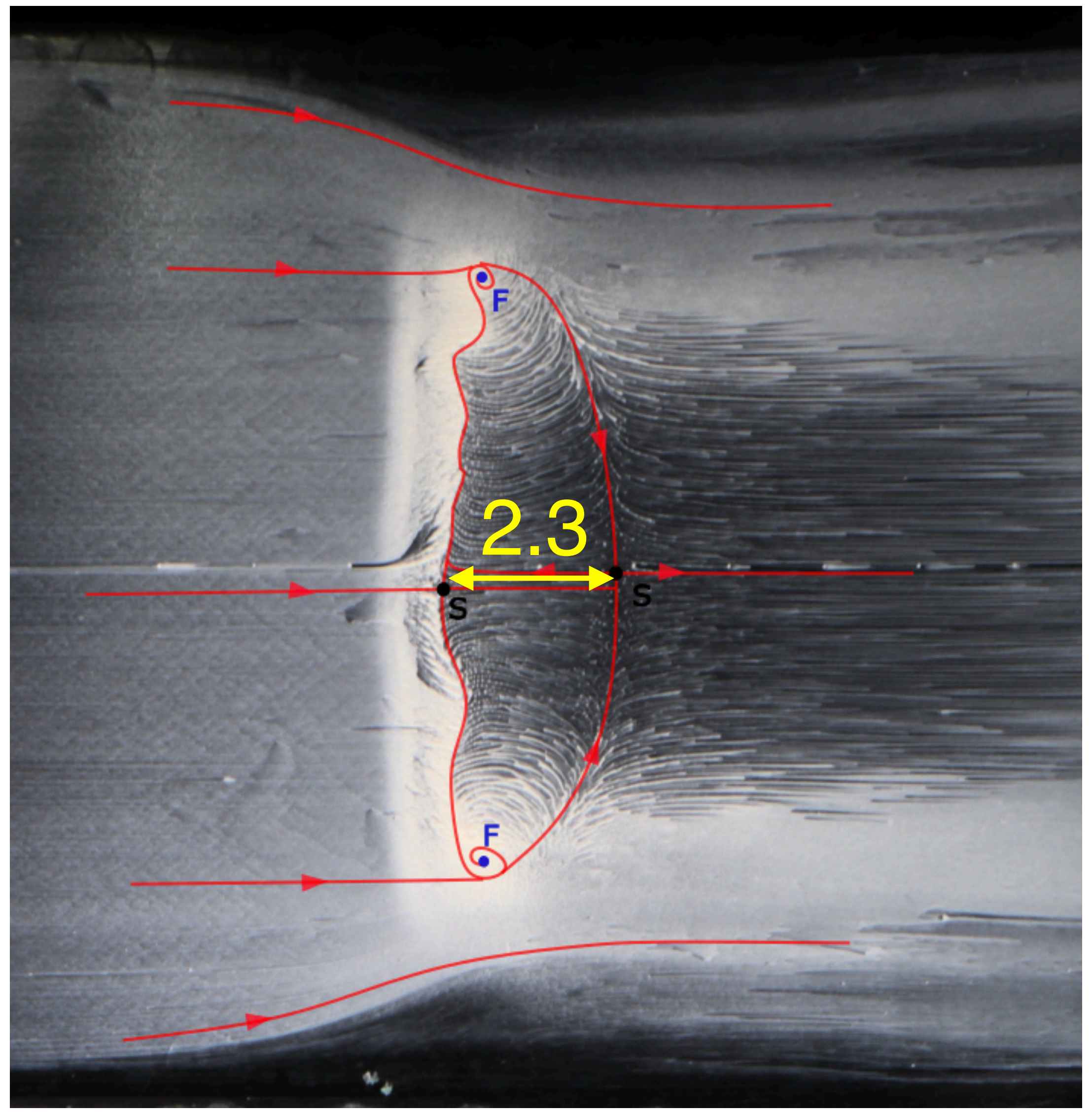


$\overline{d_f} = 6.3$



Baseline





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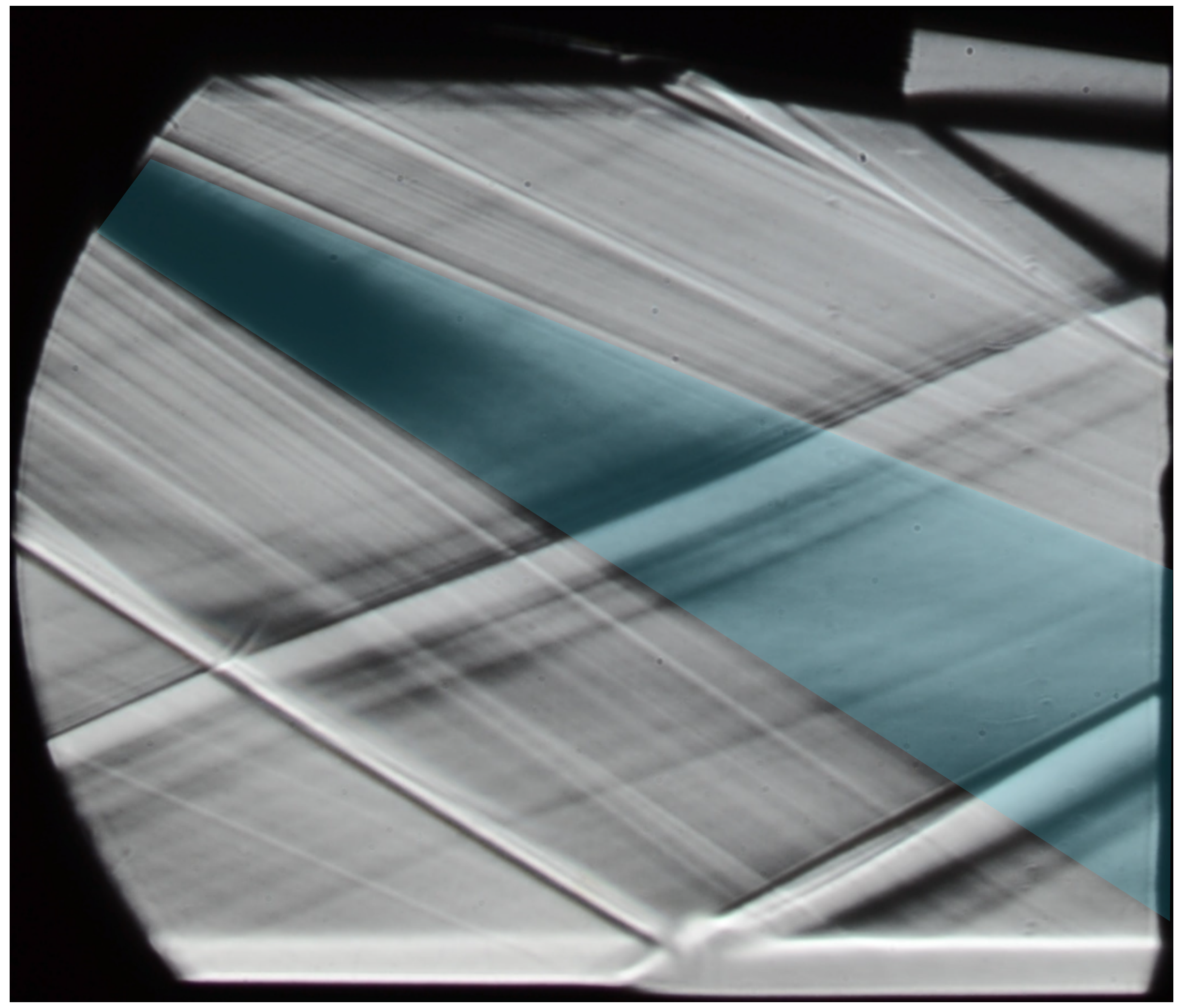

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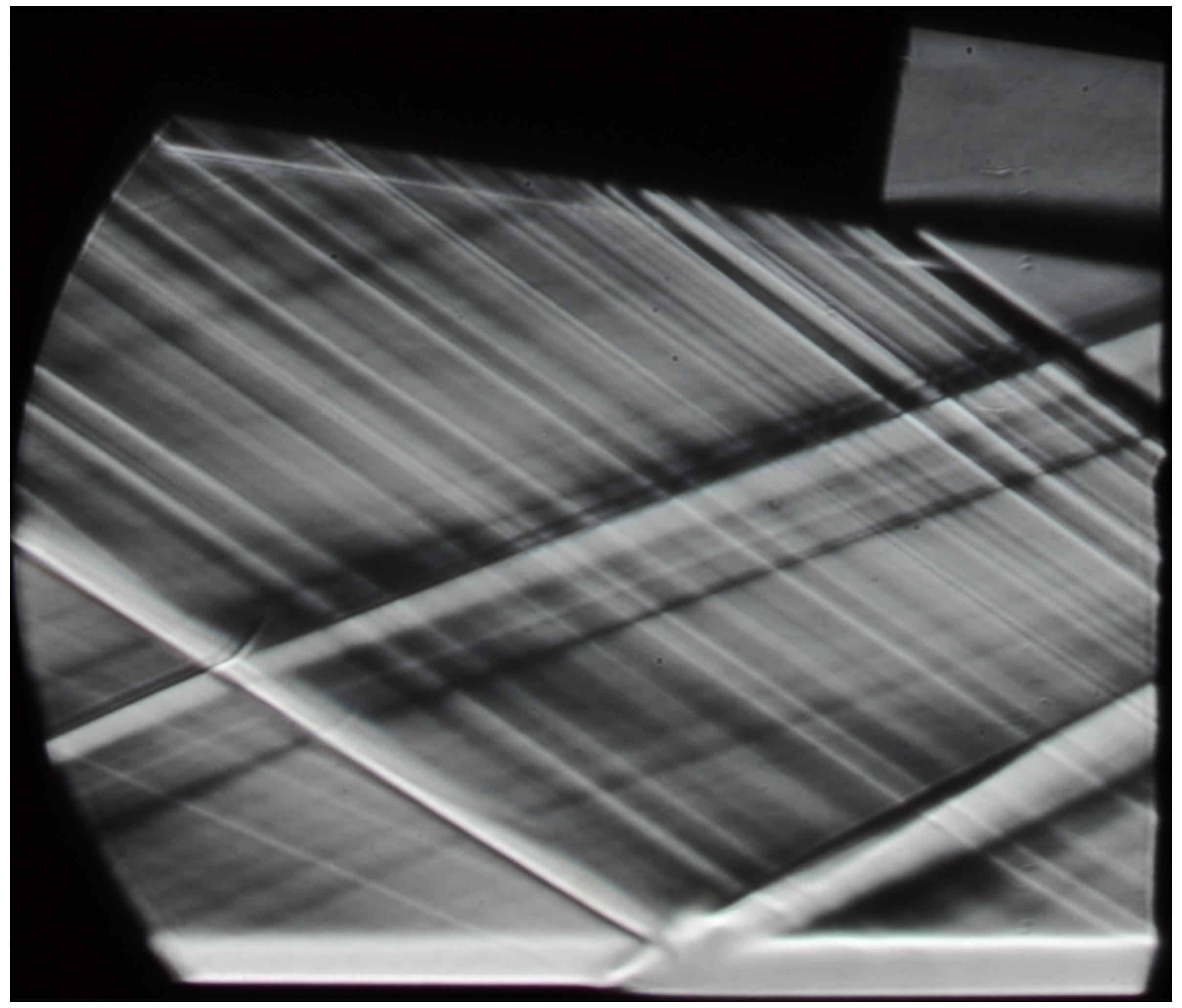

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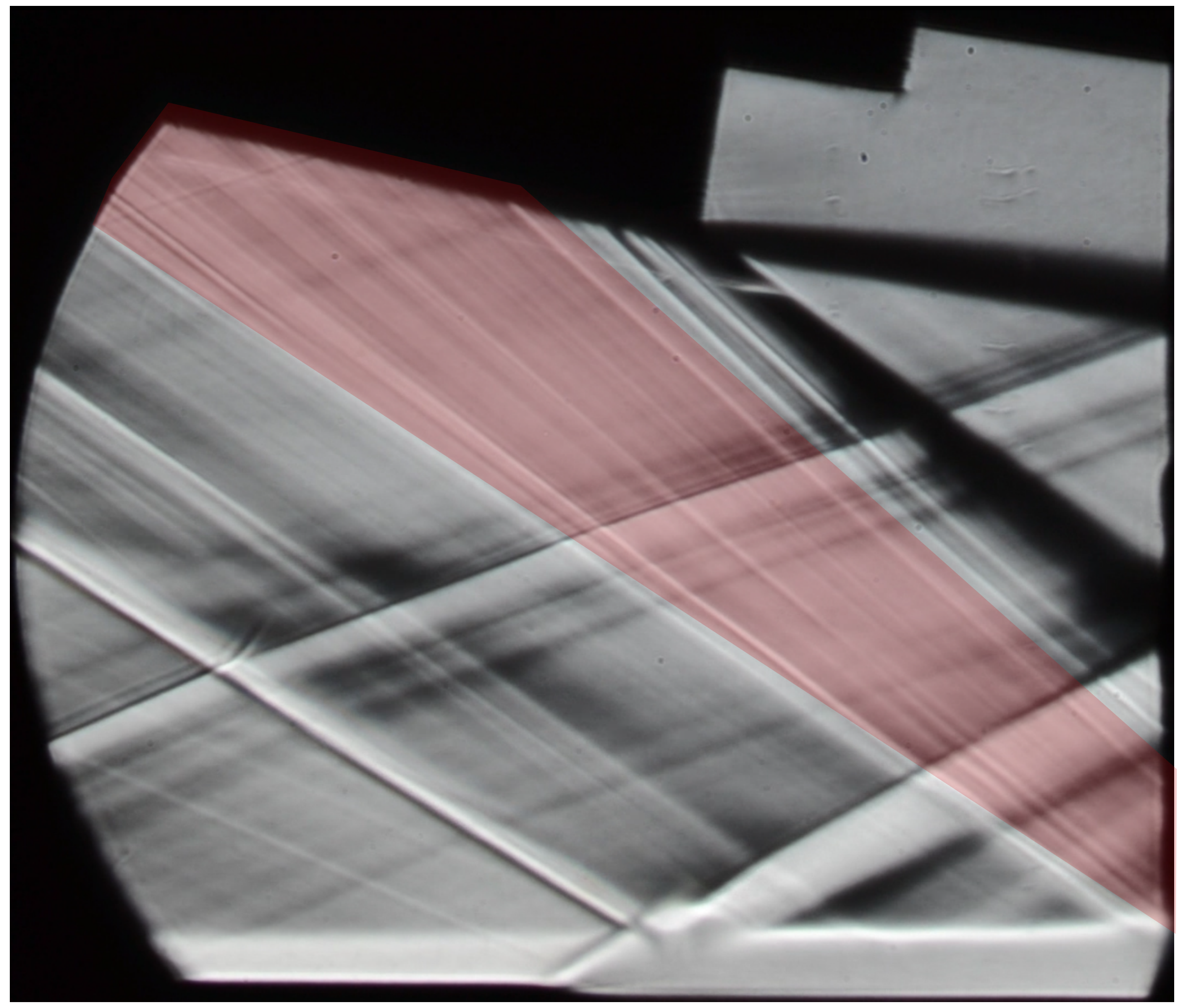

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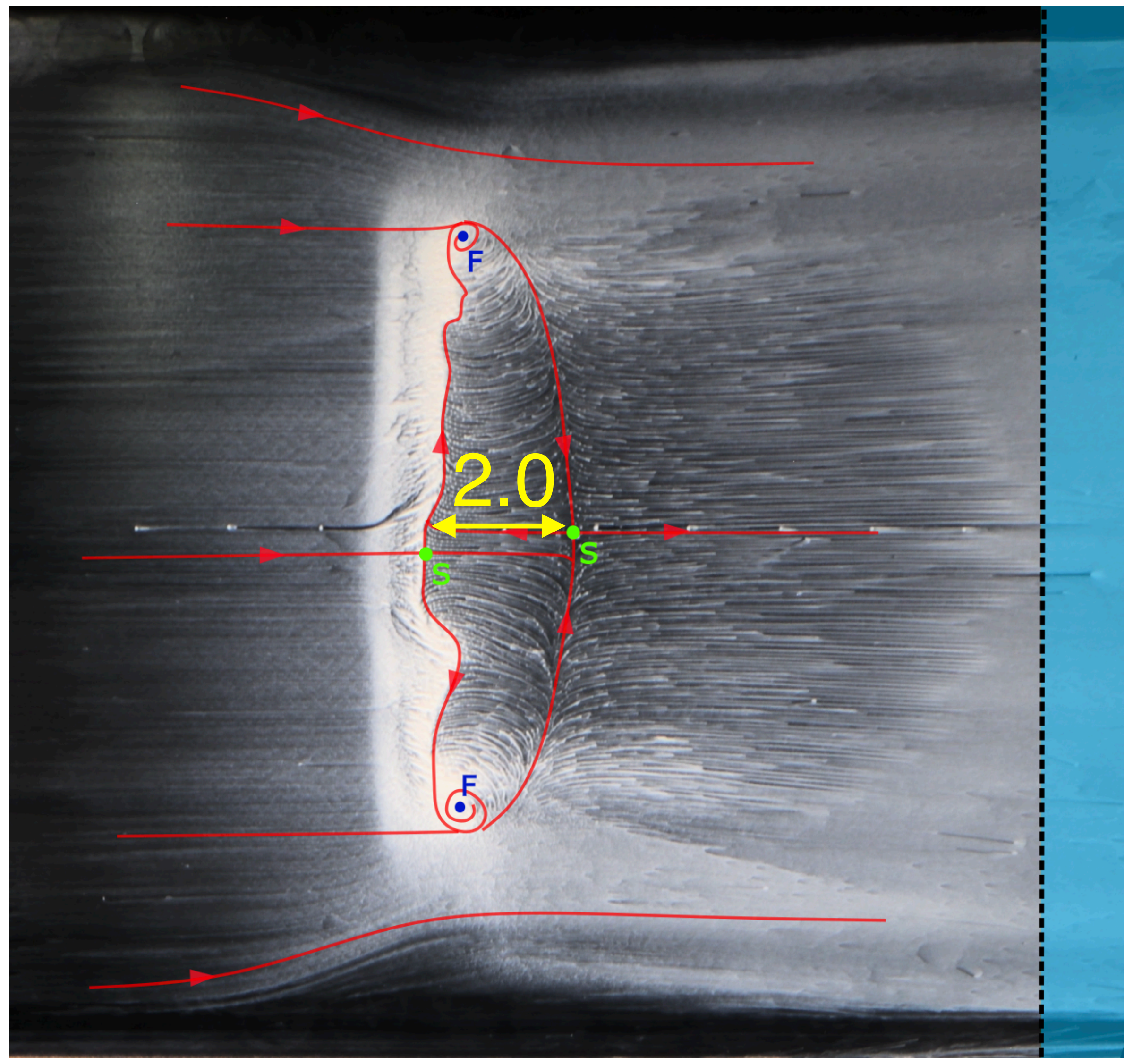
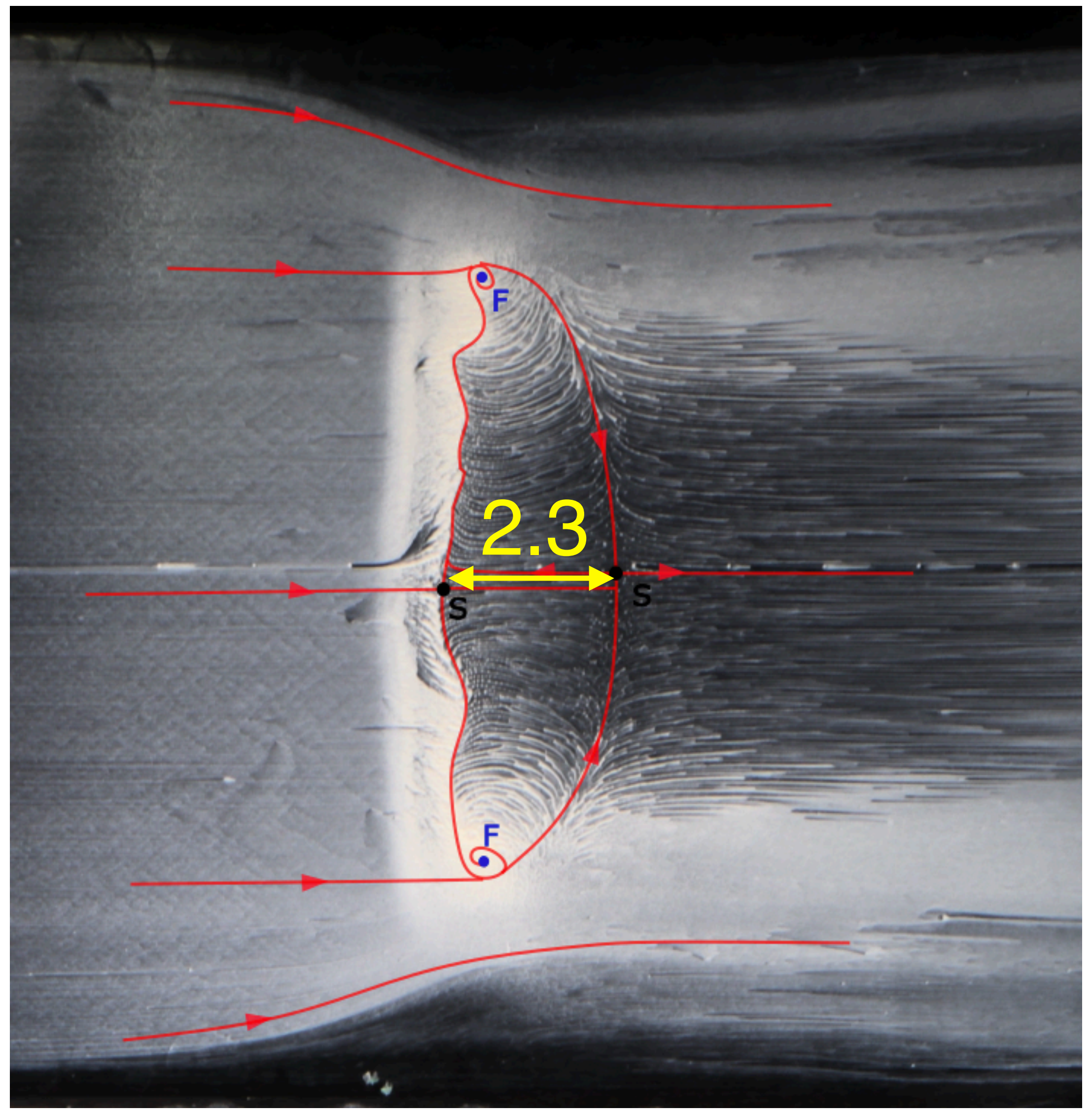
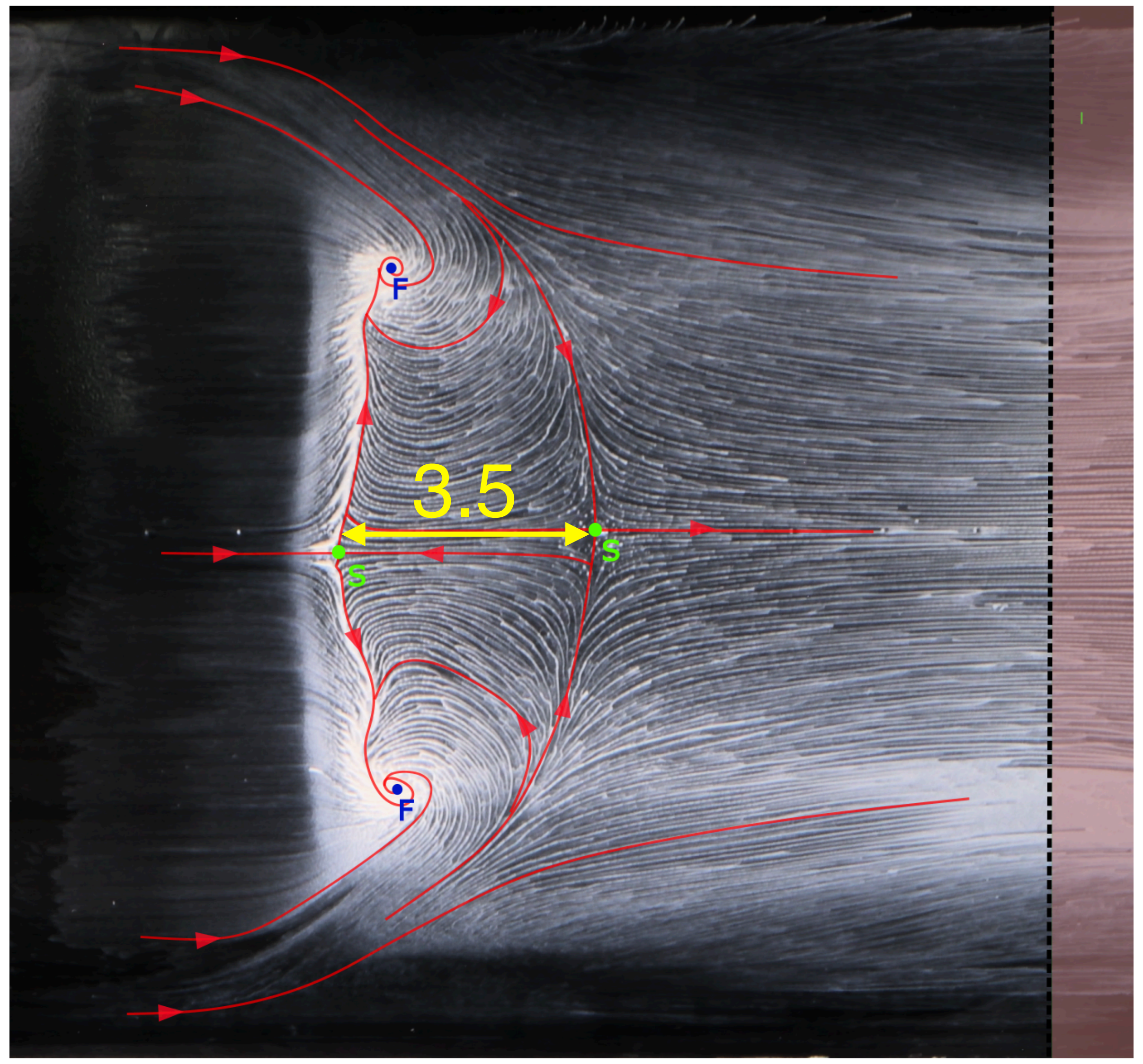
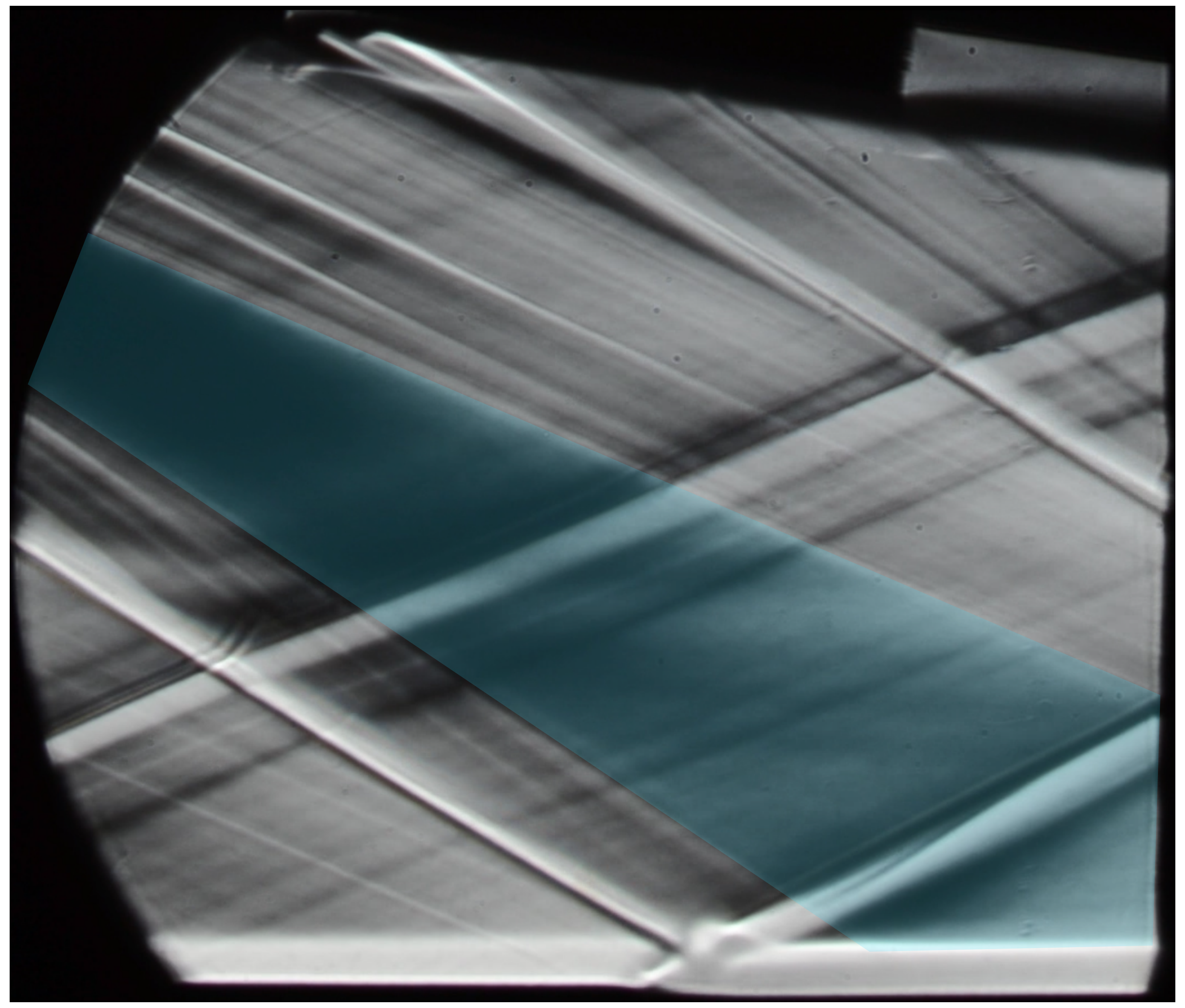


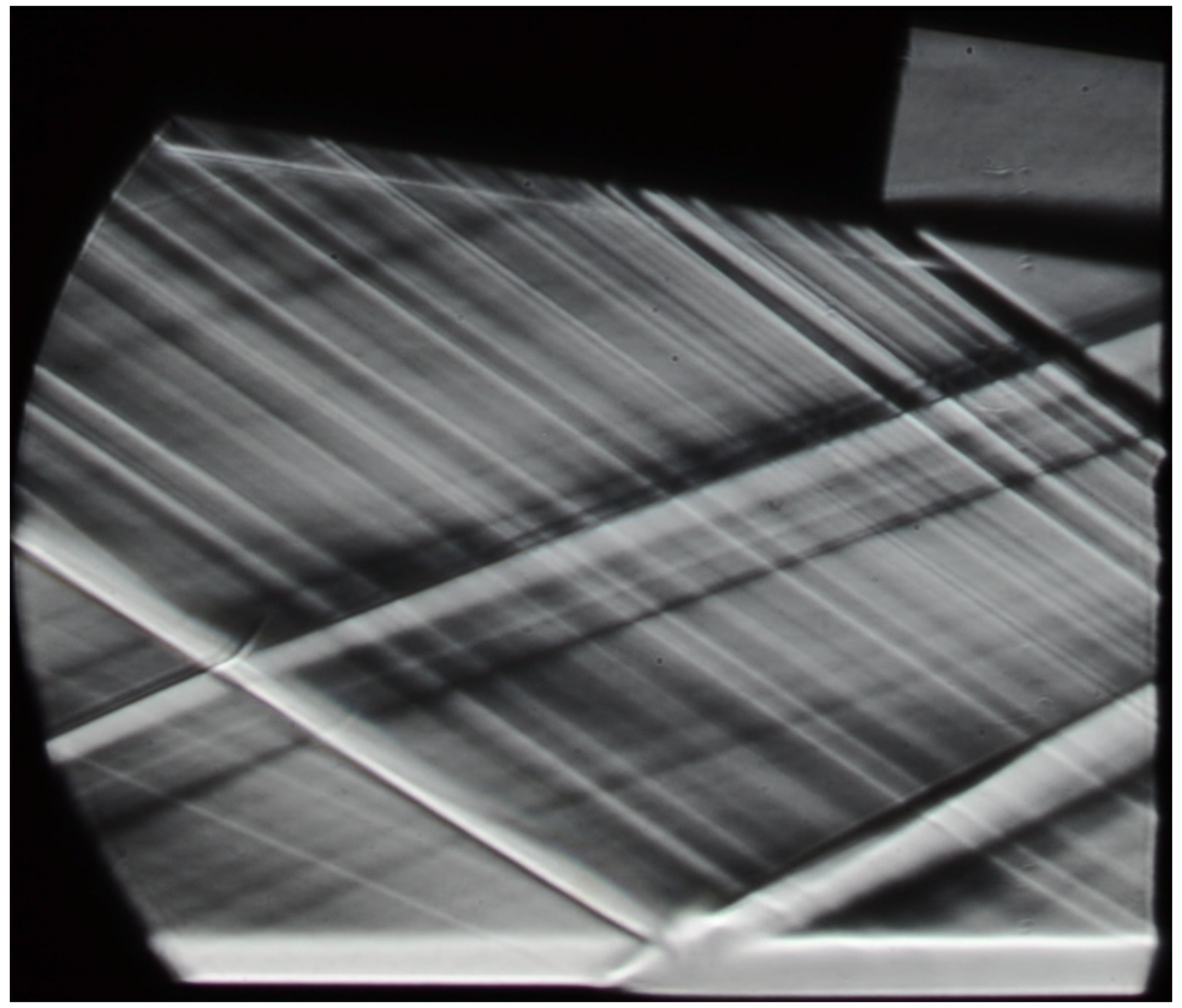




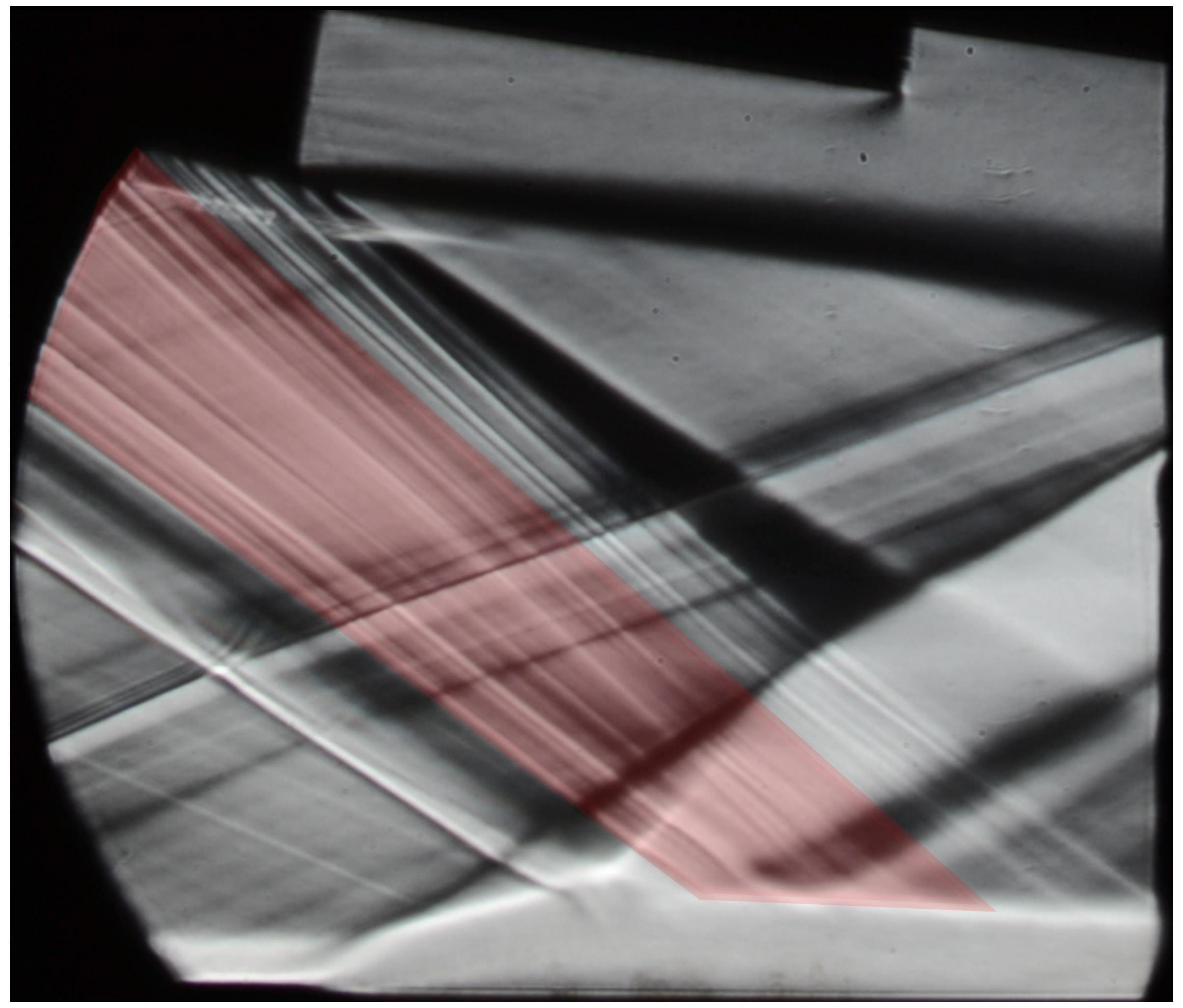
Effect of distance



$\overline{d}_f = 1.2$



Baseline



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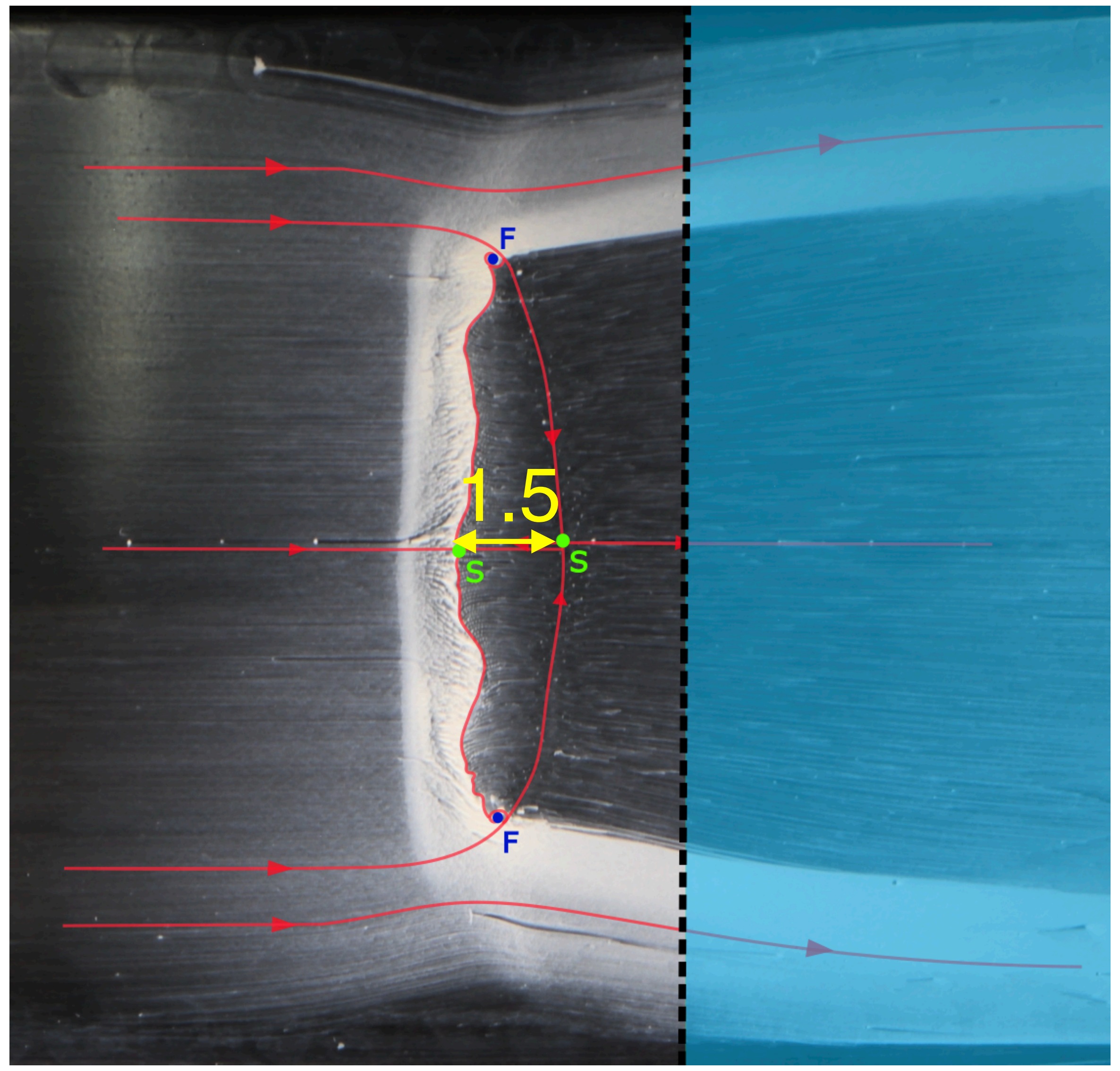
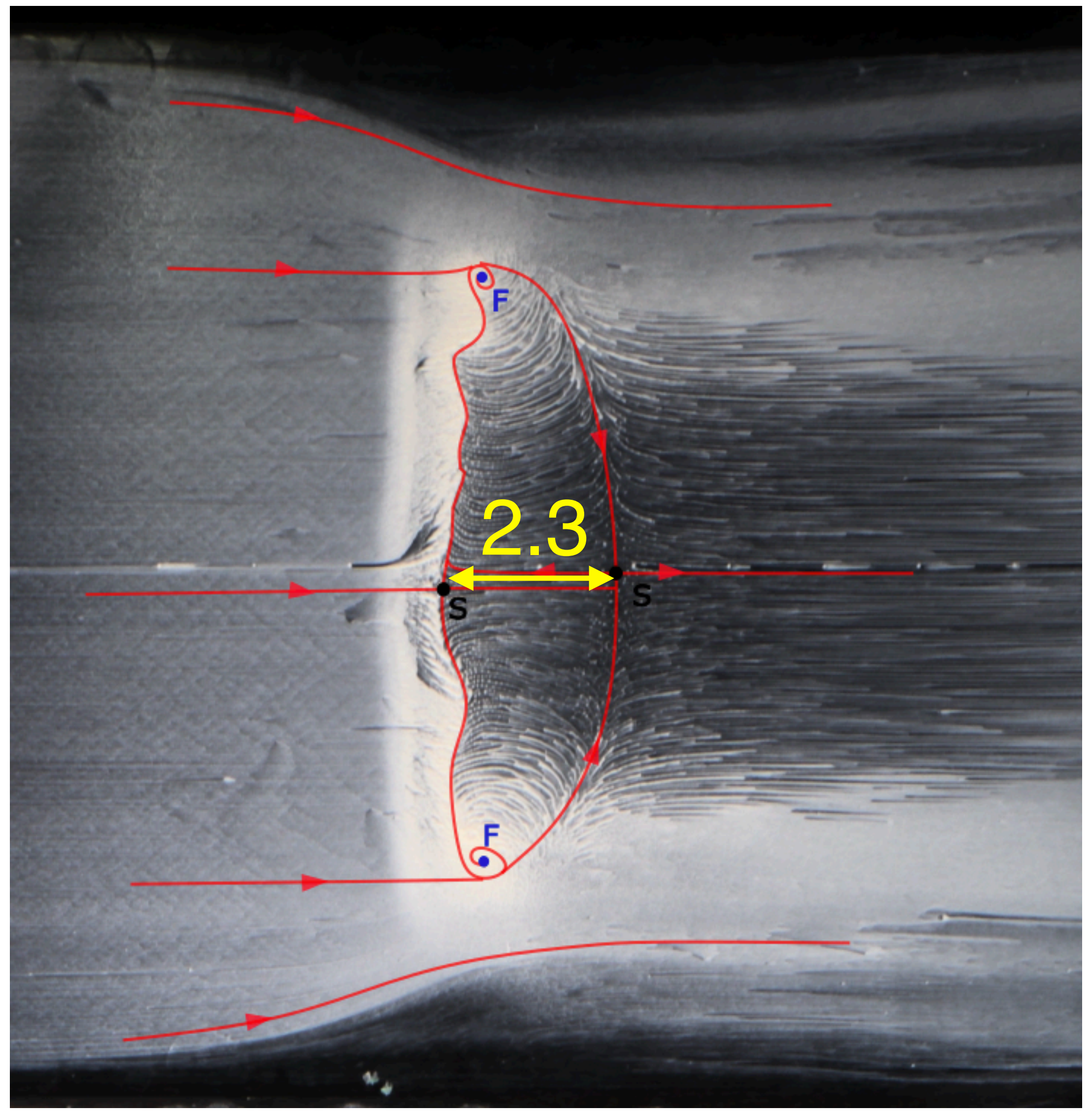
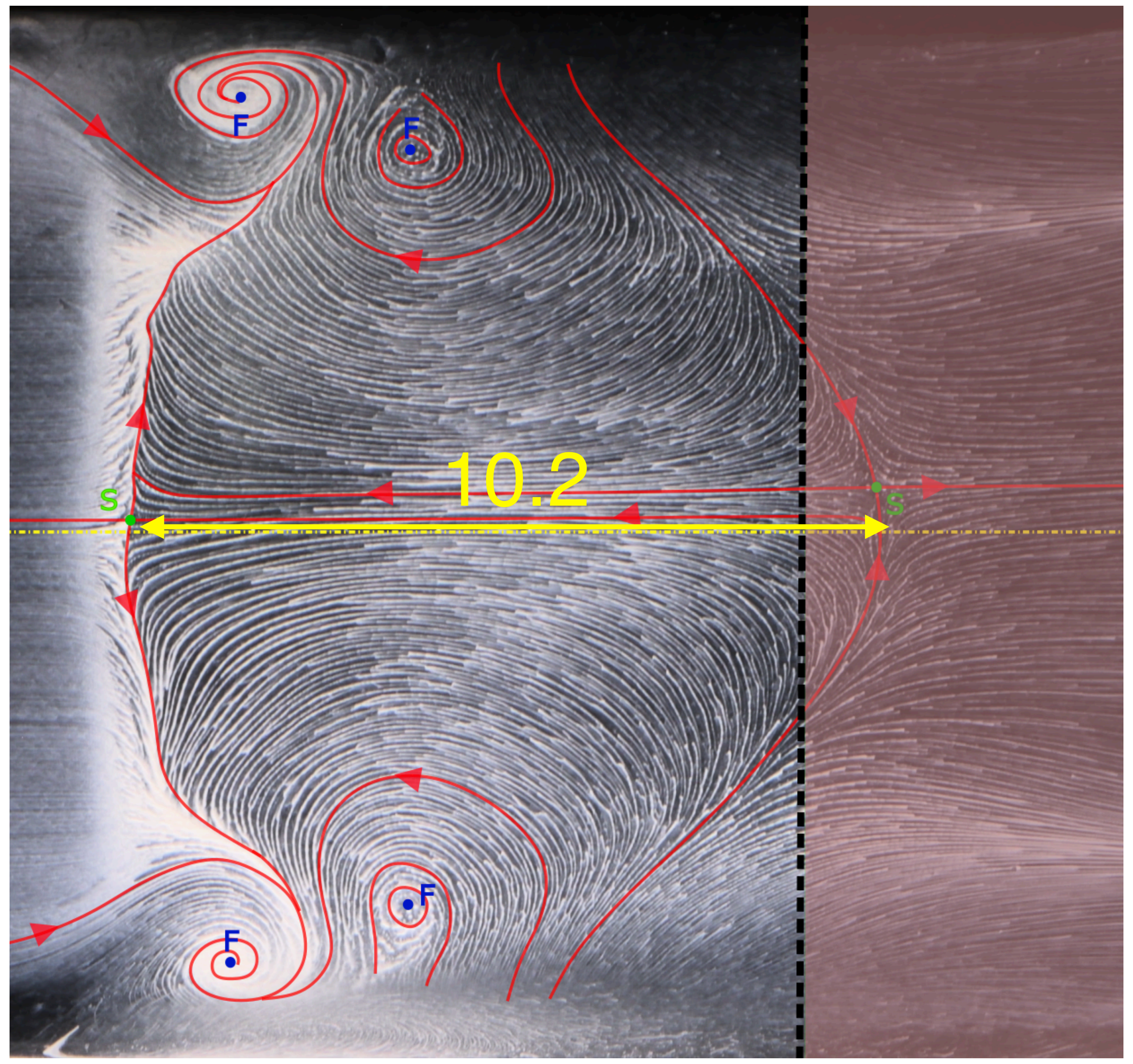
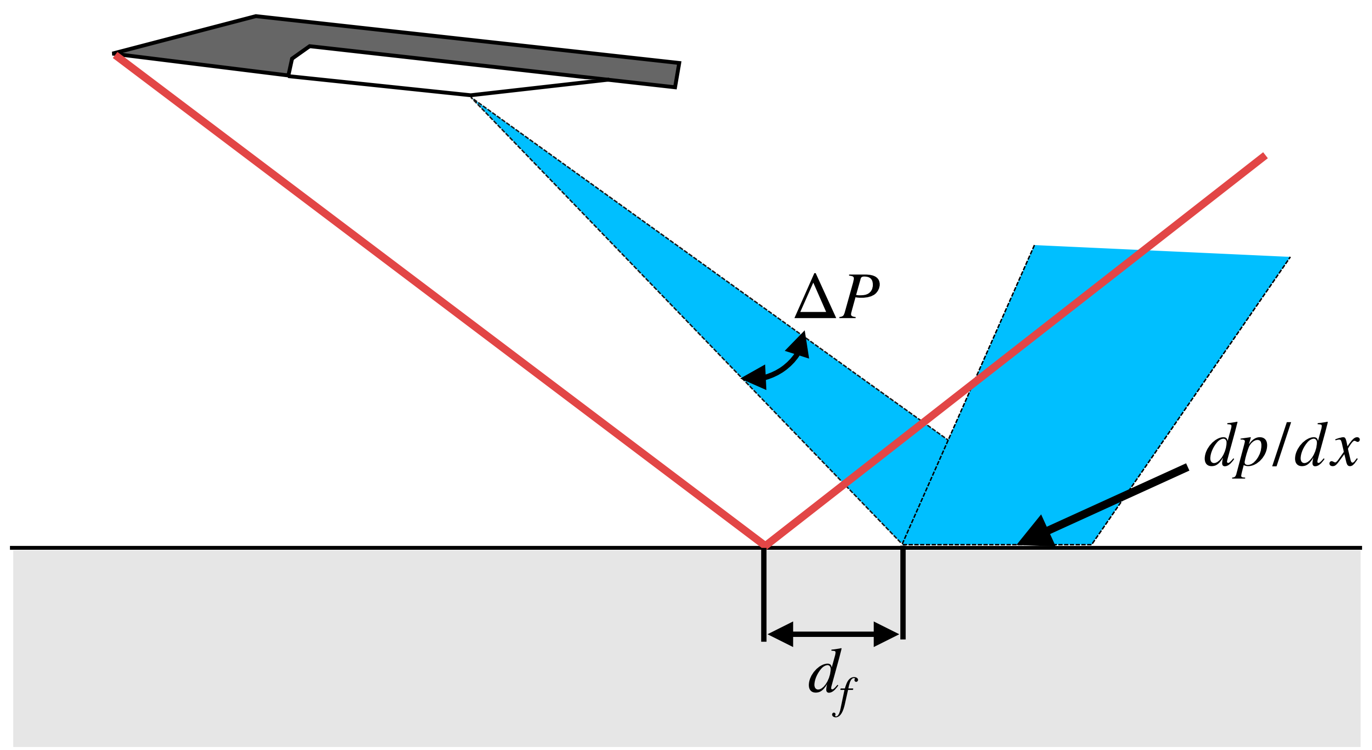


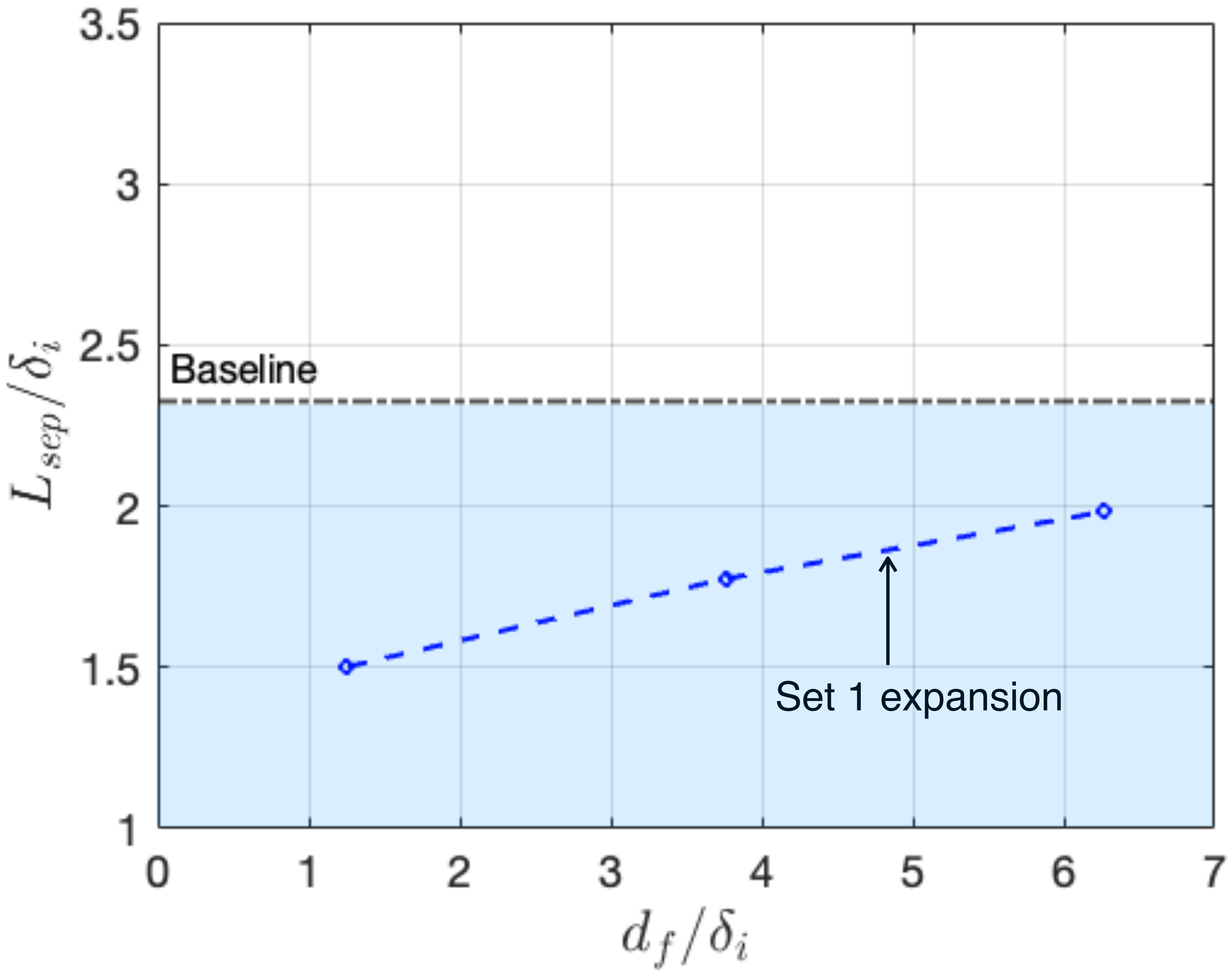




Key observations on length scales - Expansions

L_{sep} decreases as d_f decreases

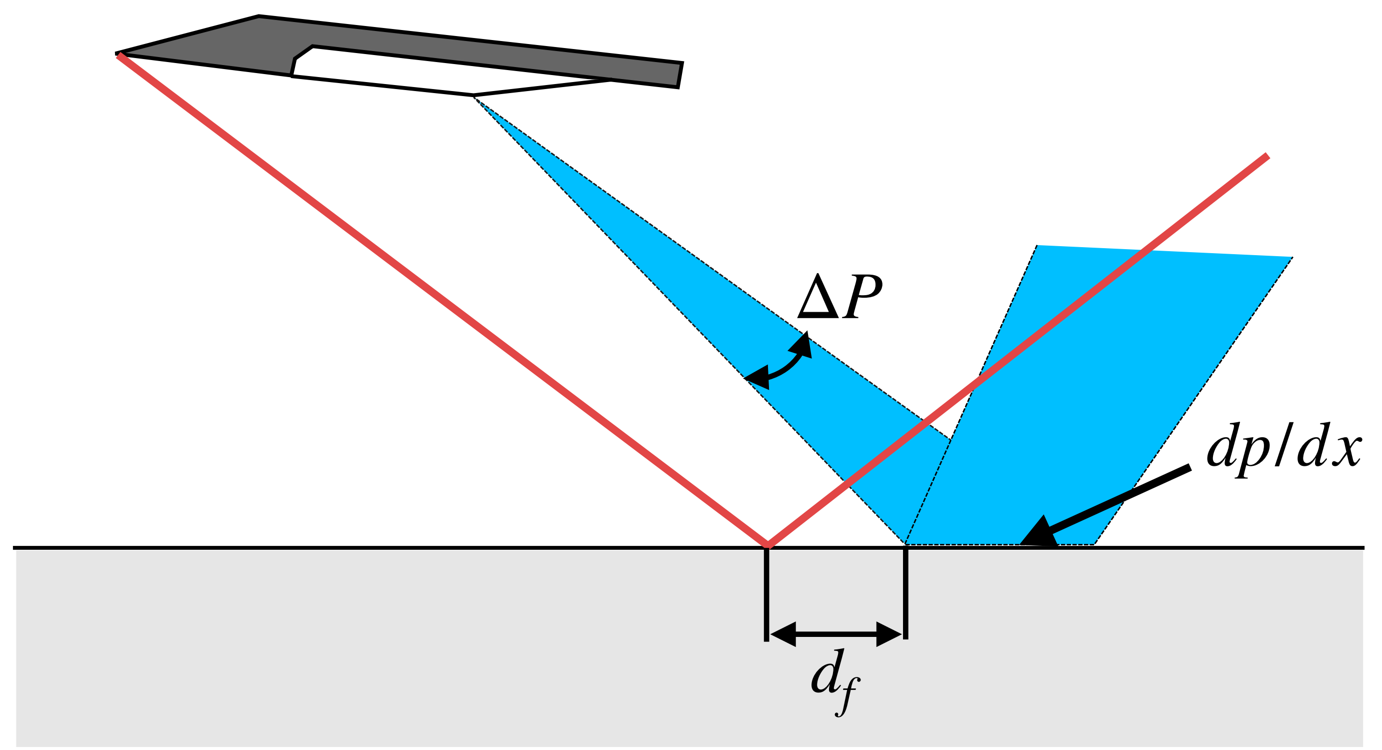


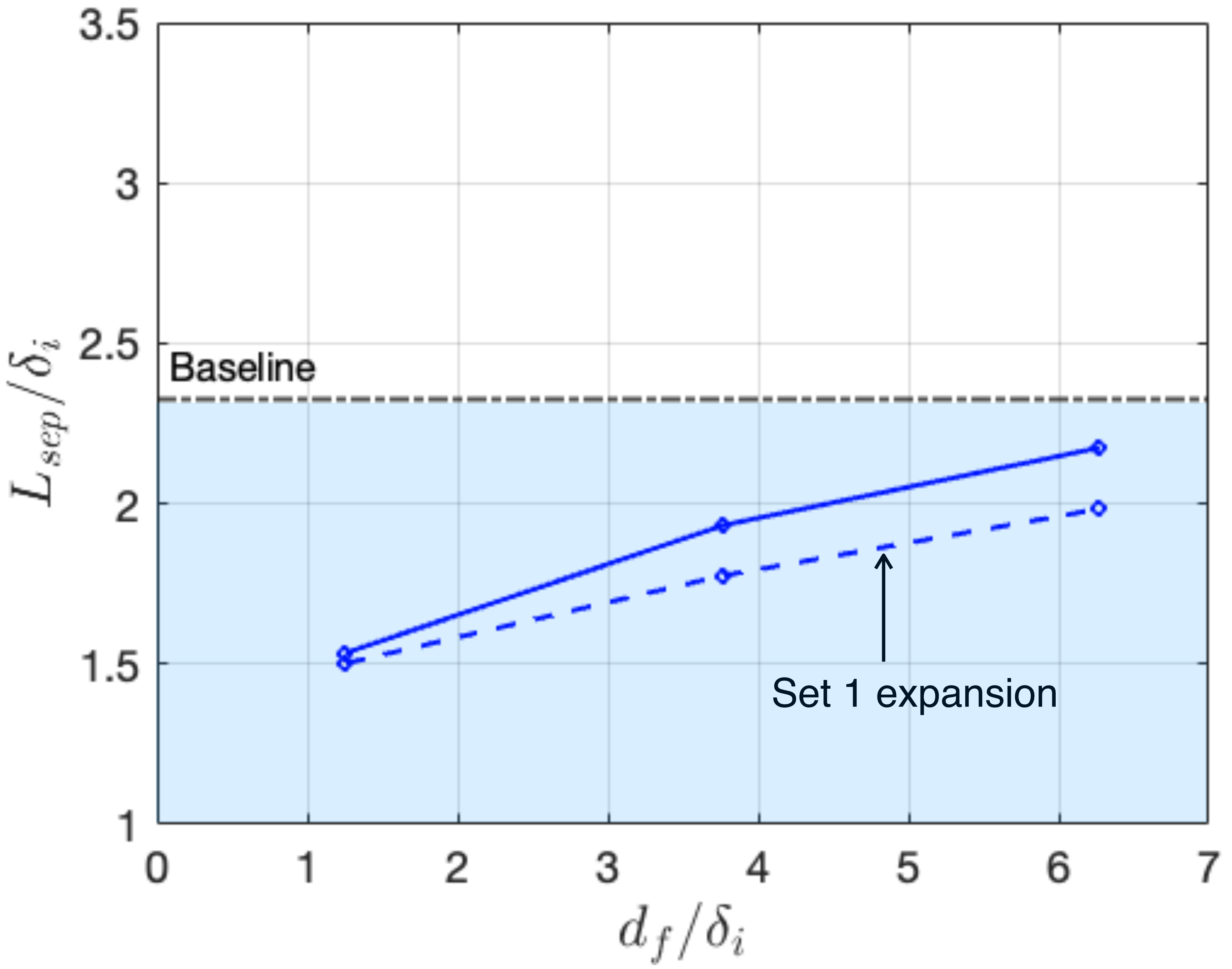


Key observations on length scales - Expansions

L_{sep} decreases as d_f decreases

Set 1 and Set 2 similar despite different ΔP and dp/dx





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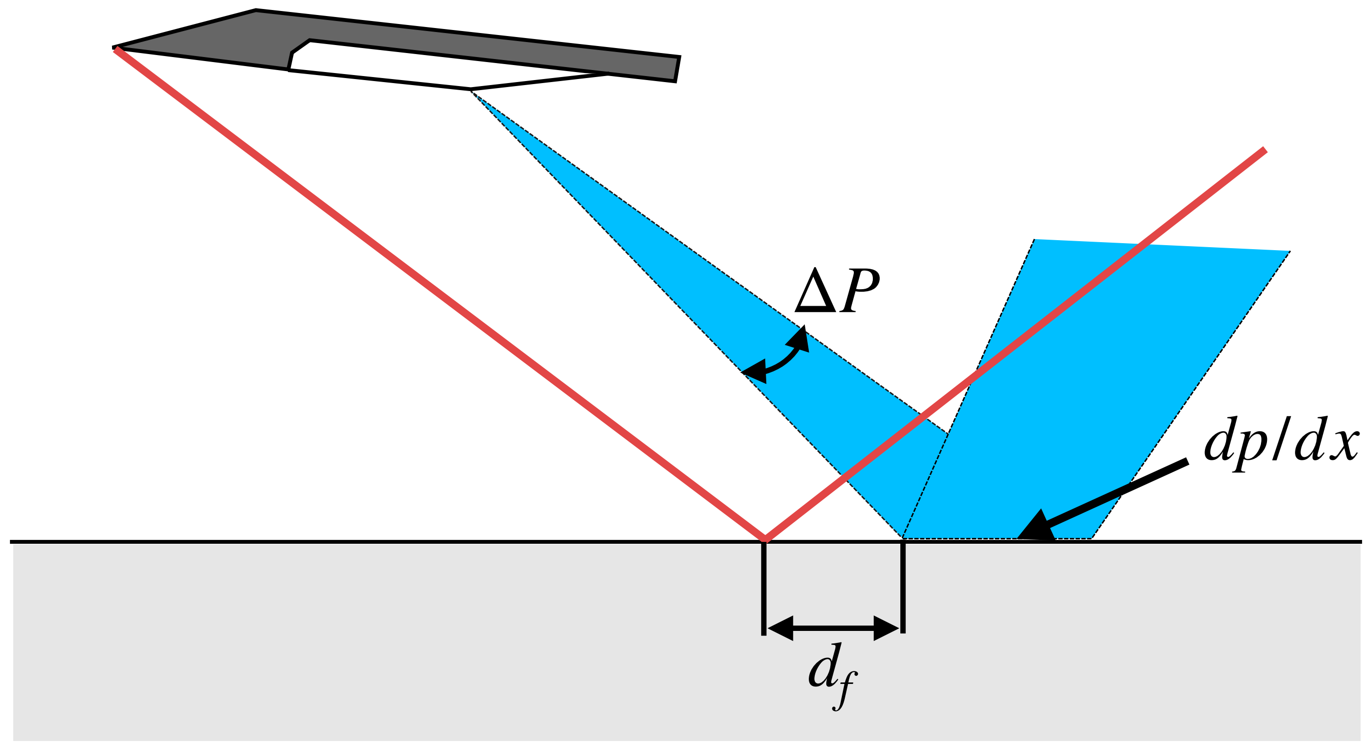

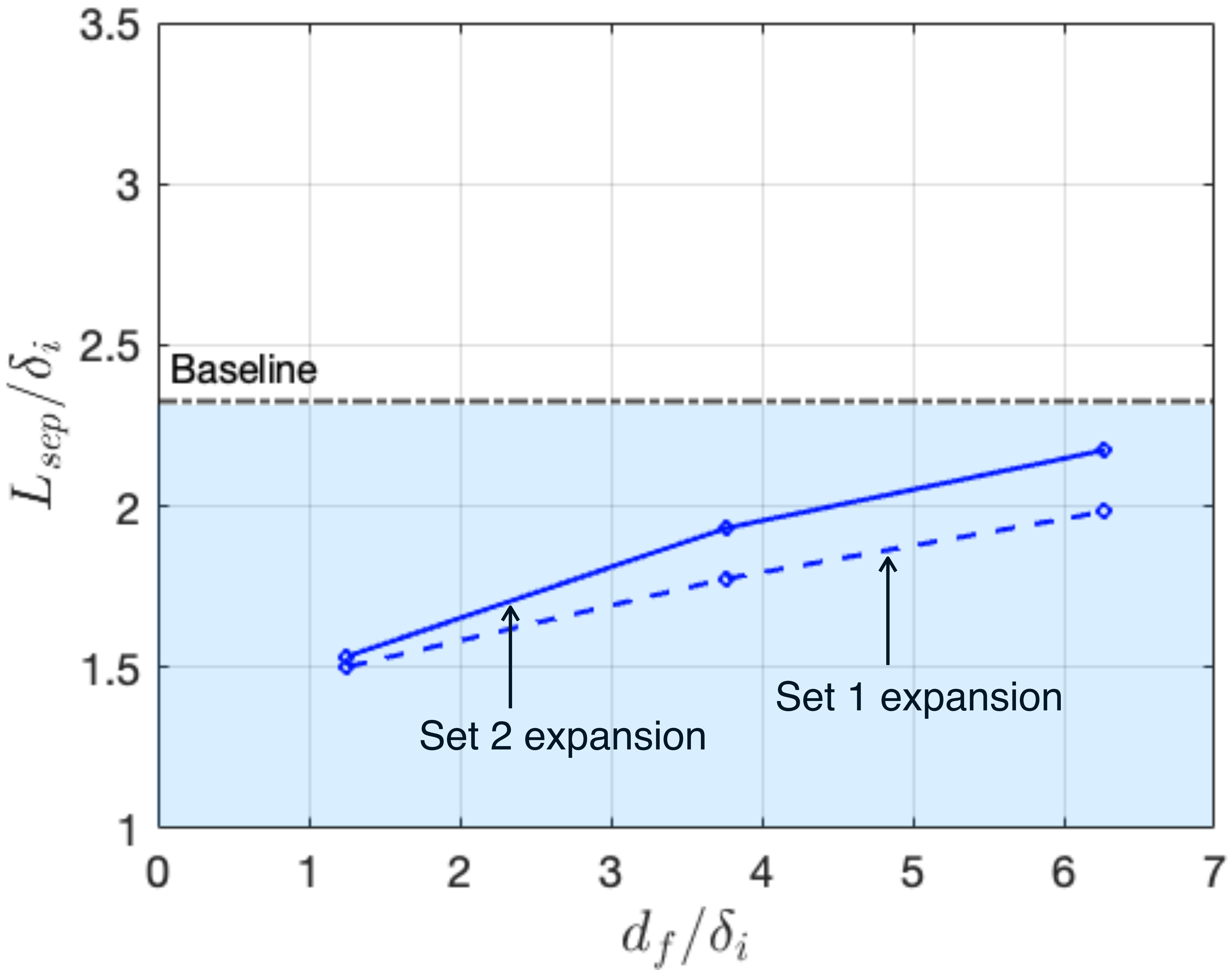

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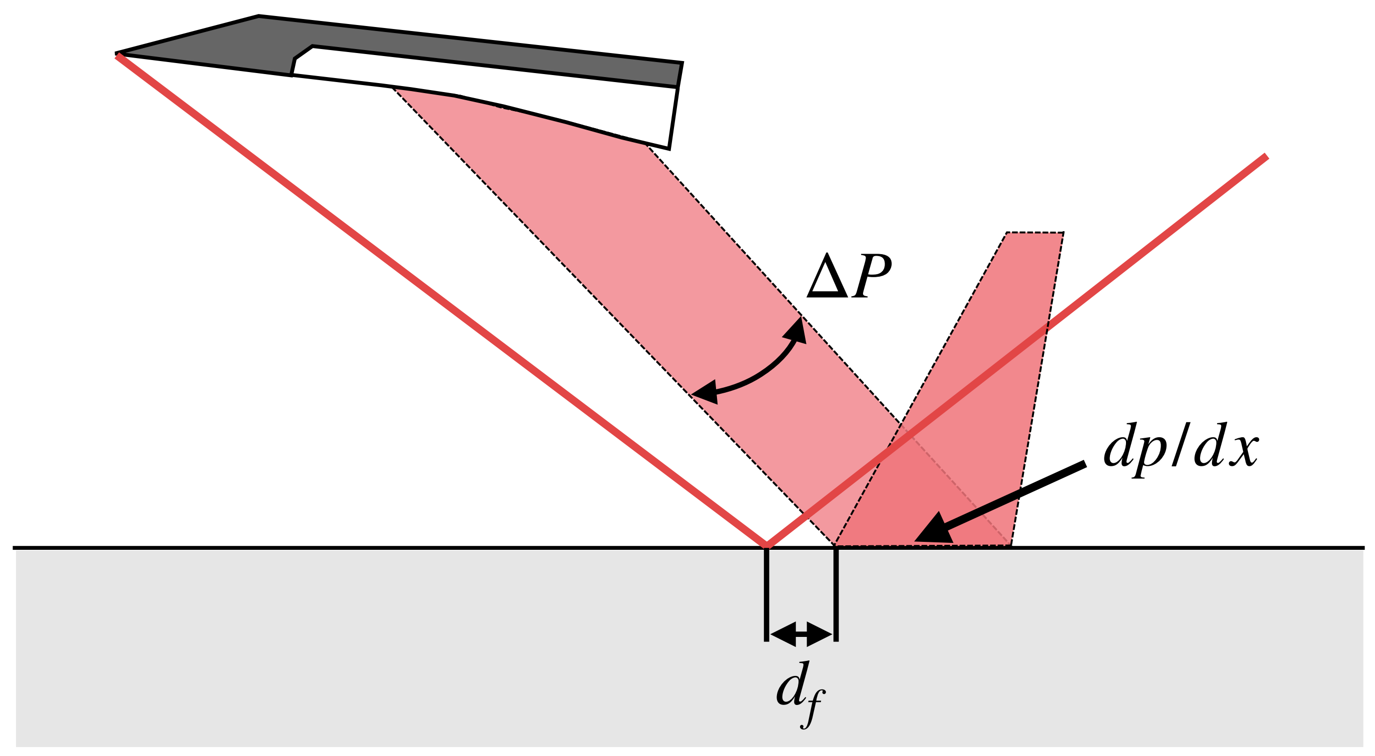

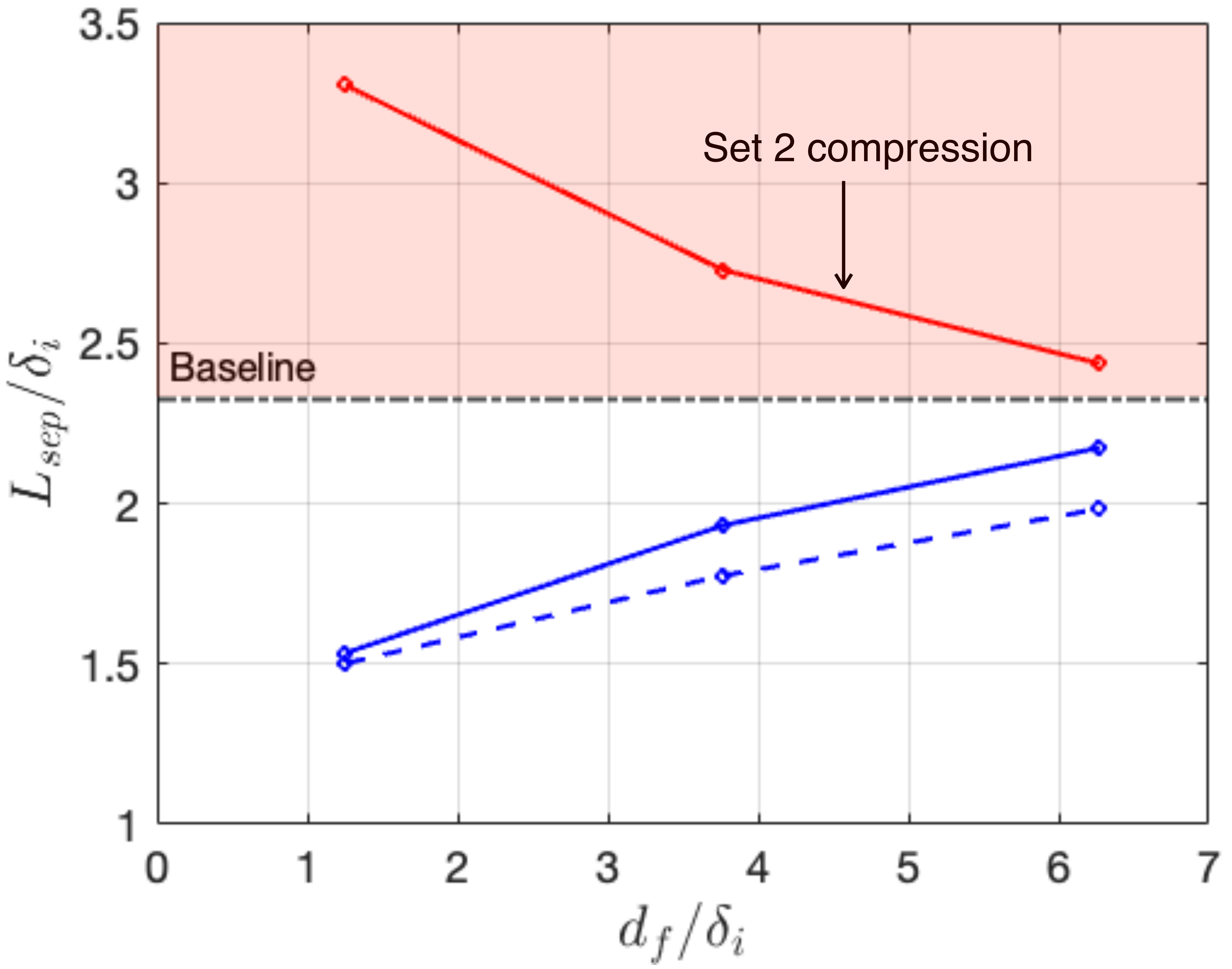

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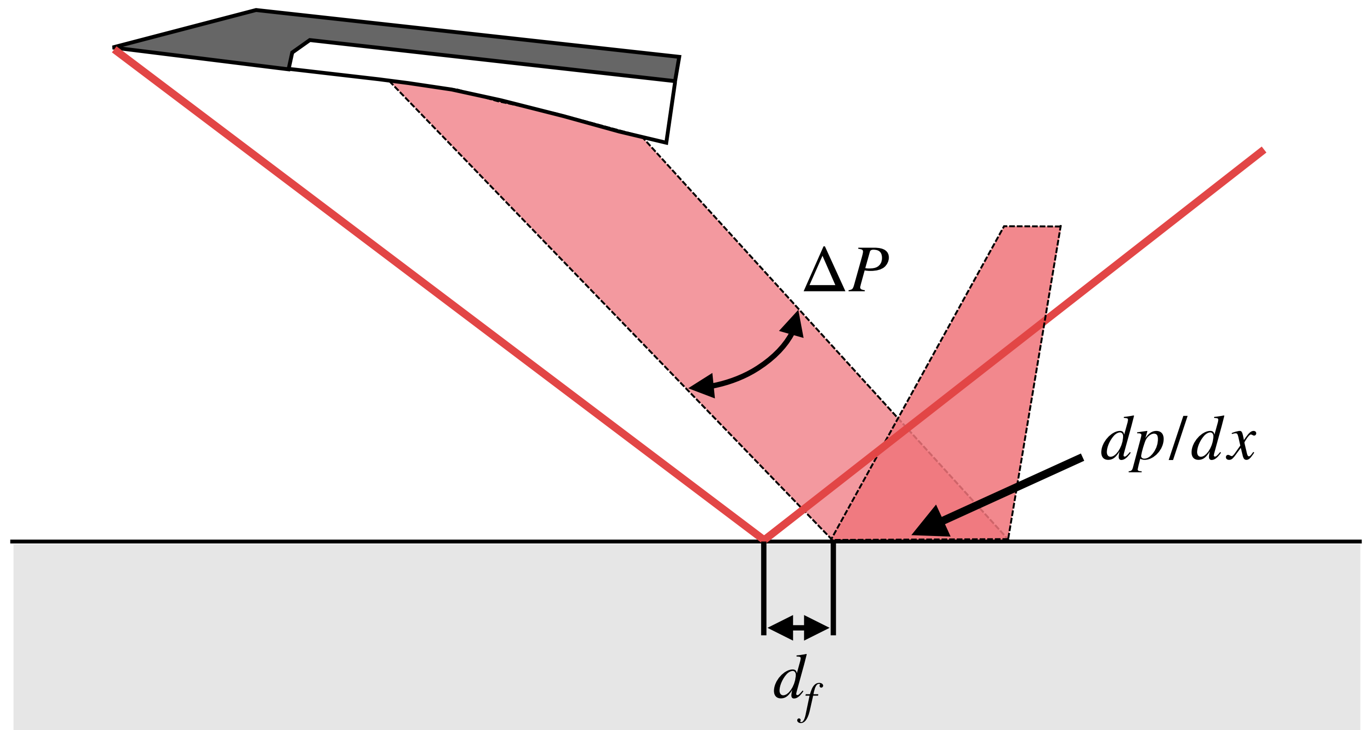

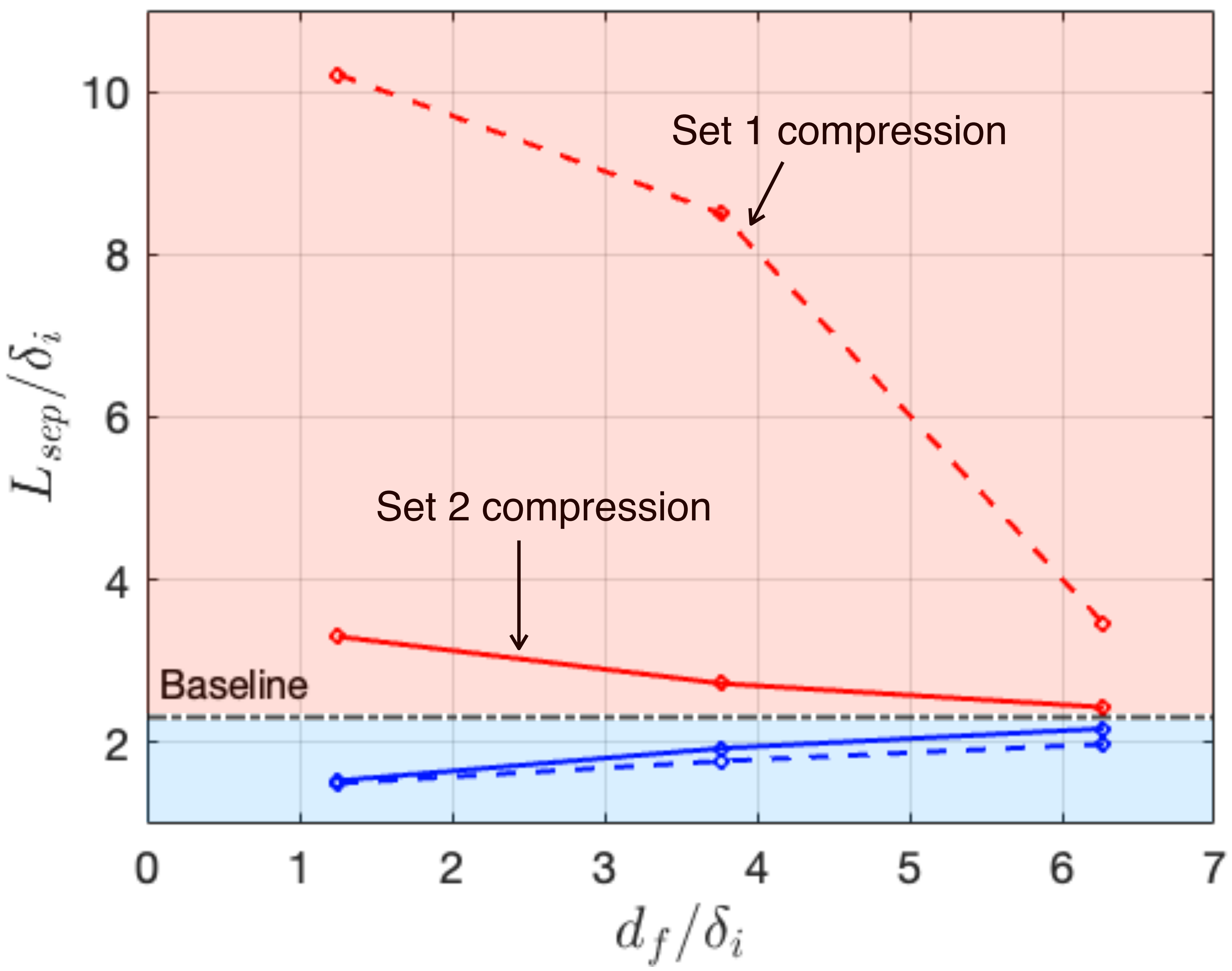

Key observations on length scales - Compressions

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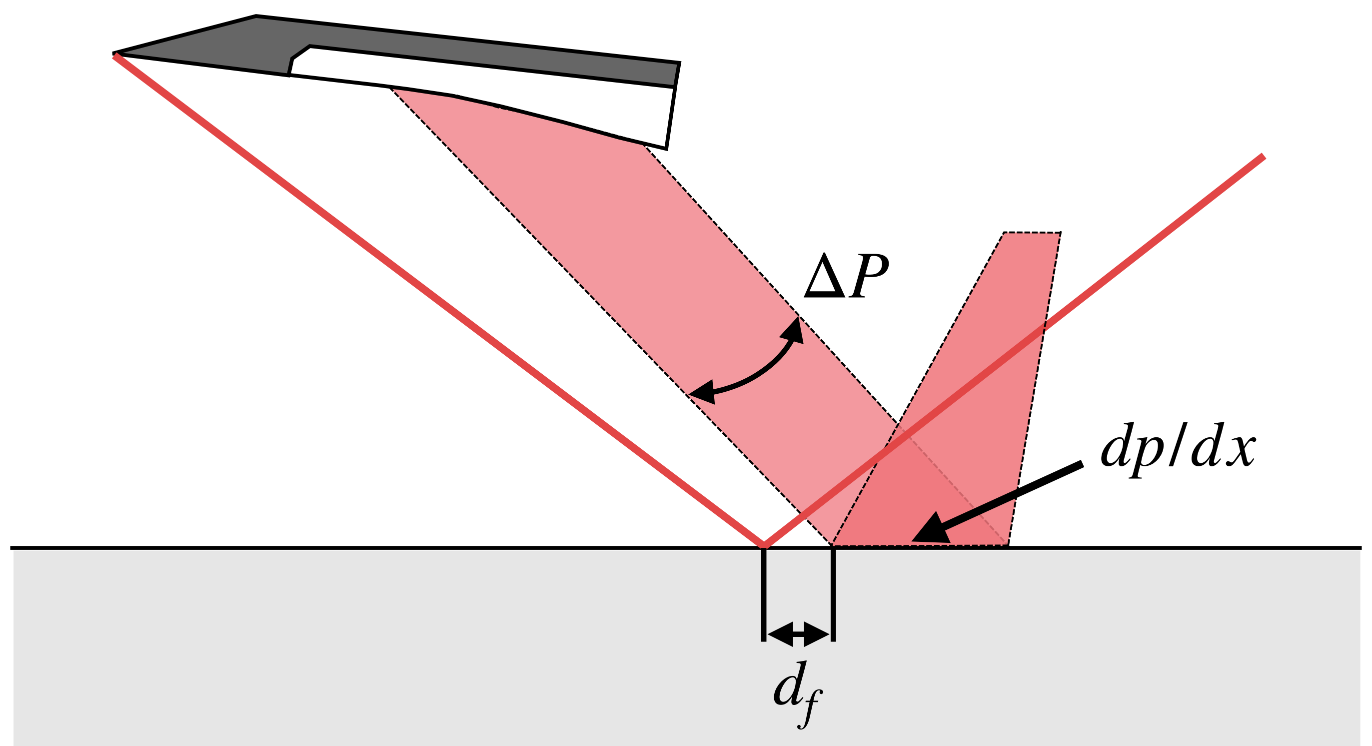
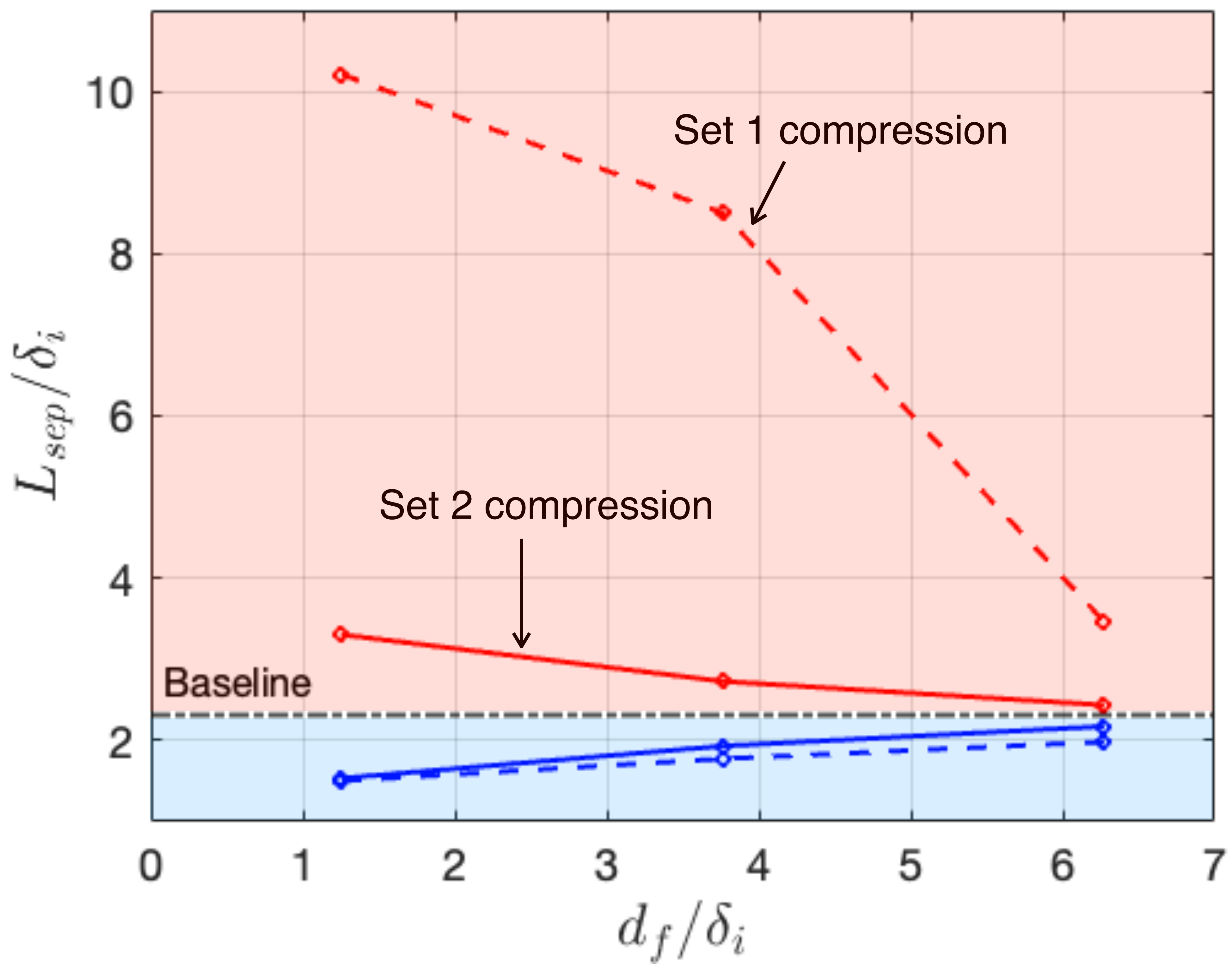
340% increase in Set 1 vs 40 % in Set 2





Key observations on length scales - Compressions

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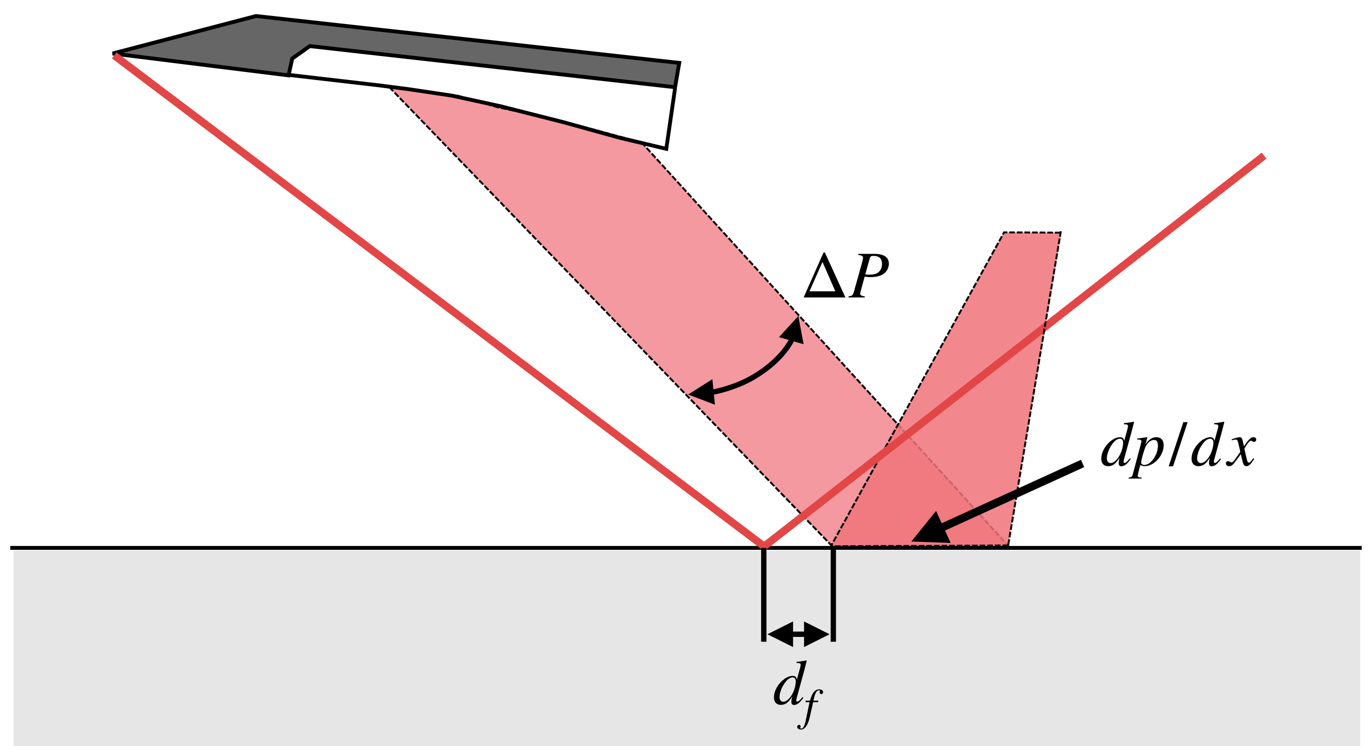
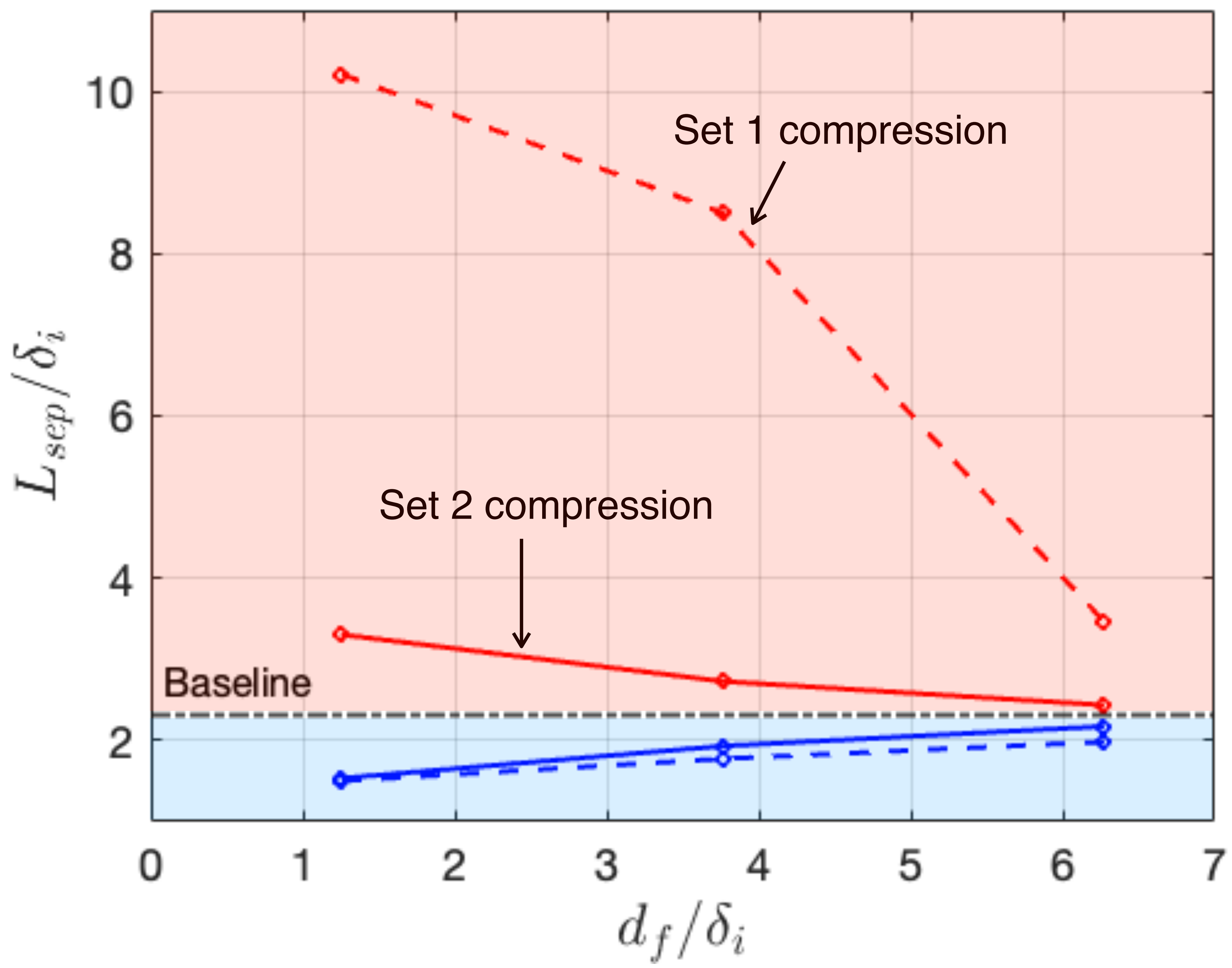
340% increase in Set 1 vs 40 % in Set 2

Discrepancy due to large difference in gradients



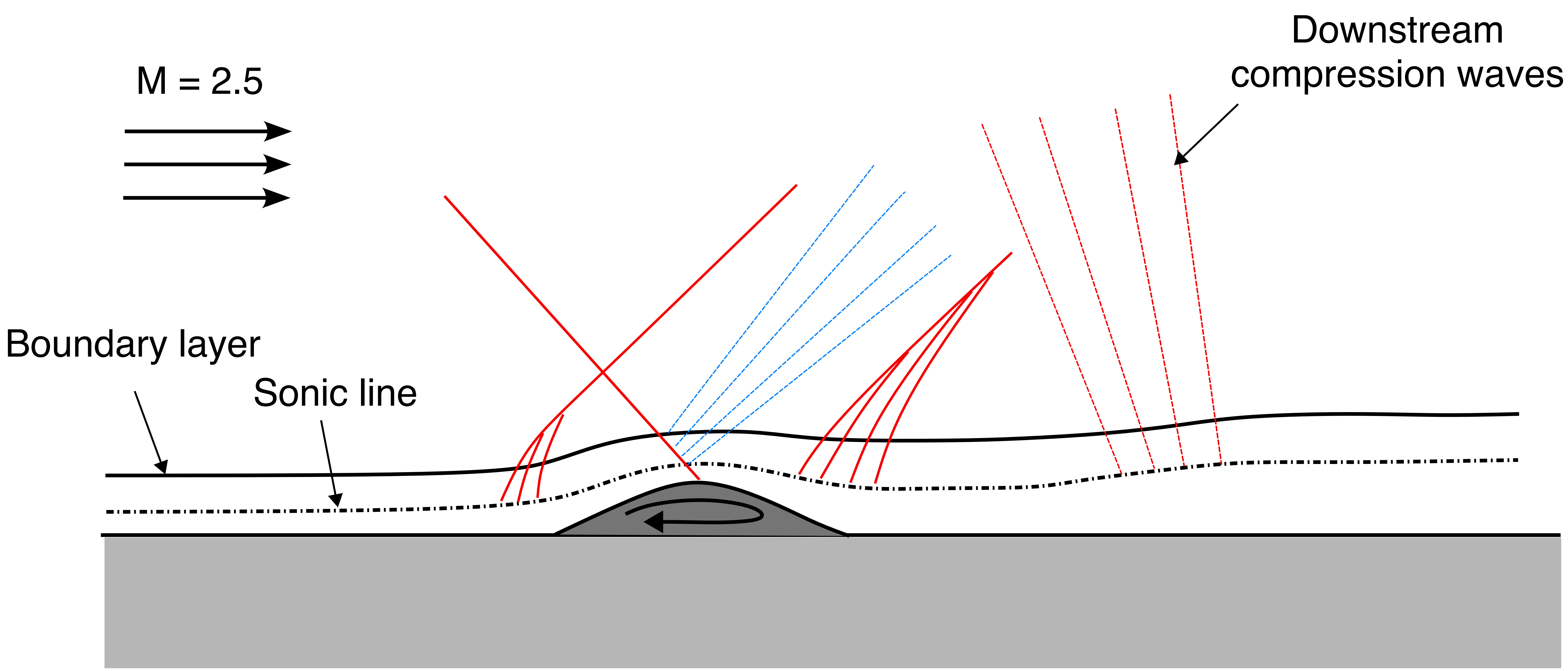


Set 2 $\overline{\Delta P} = +0.64$ $\overline{dp/dx} = +0.07$

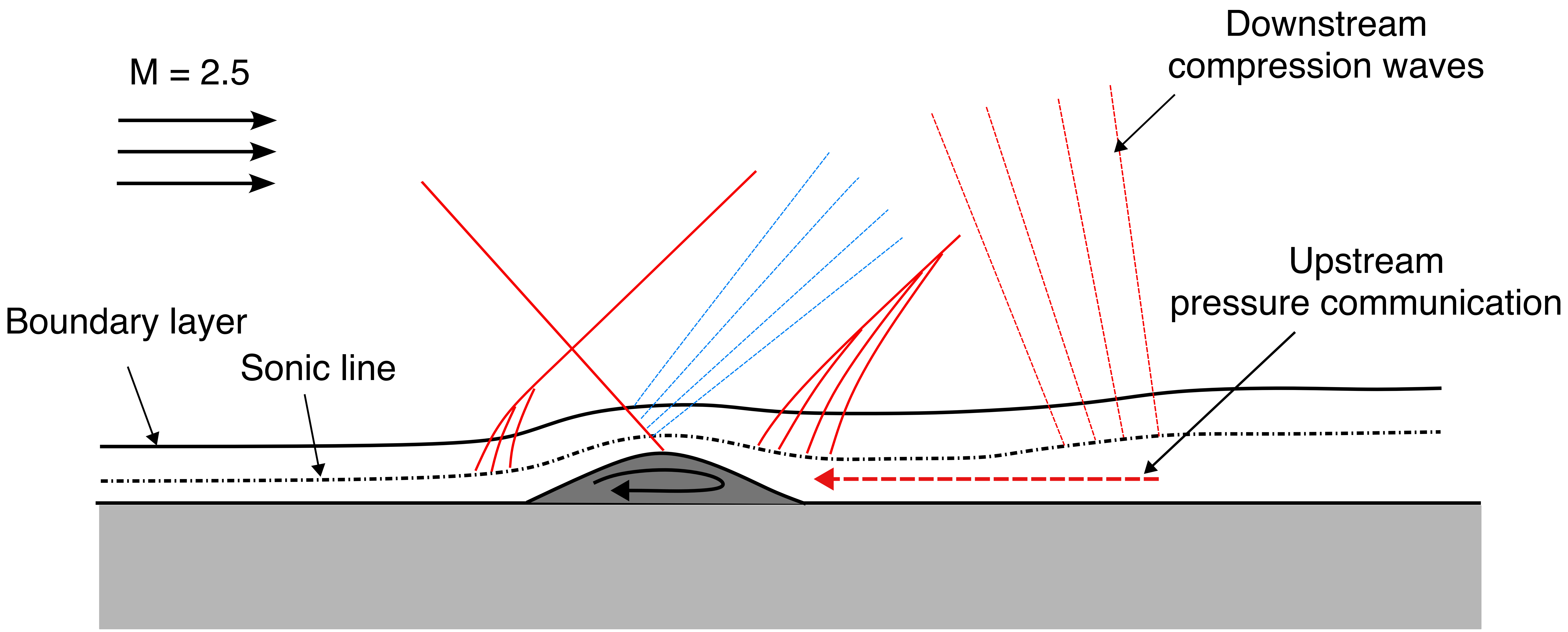
Set 1 $\overline{\Delta P} = +0.91$ $\overline{dp/dx} = +0.32$

What is the mechanism?

Mechanism 1

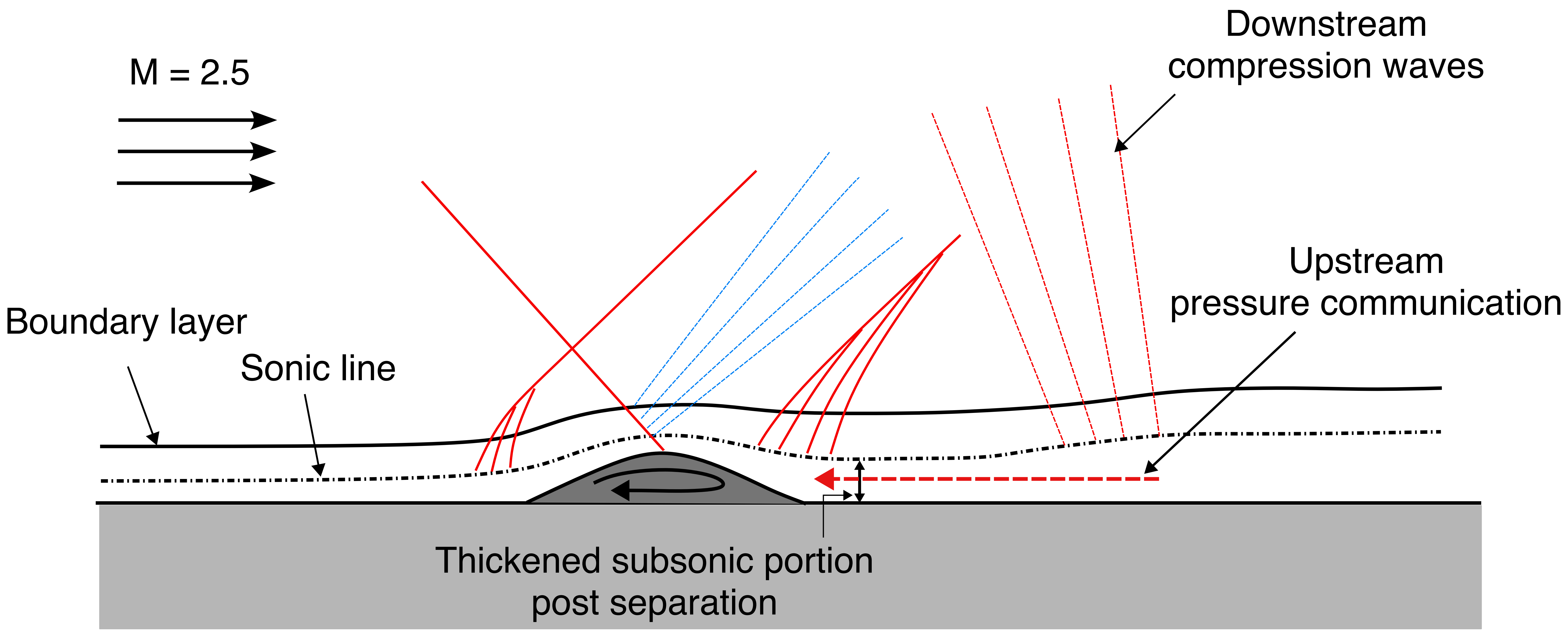

M = 2.5
Downstream compression waves
Boundary layer
Sonic line

Mechanism 1



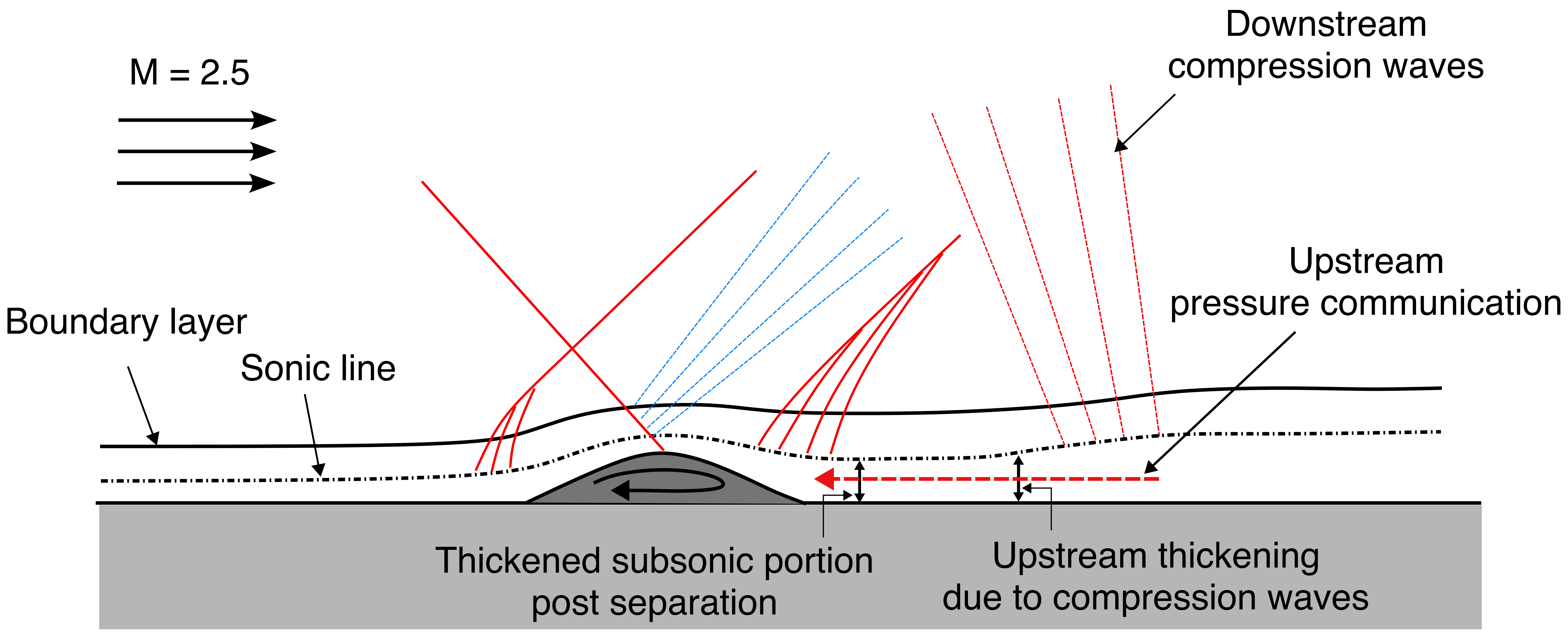
M = 2.5
Downstream compression waves
Upstream pressure communication
Boundary layer
Sonic line

Mechanism 1

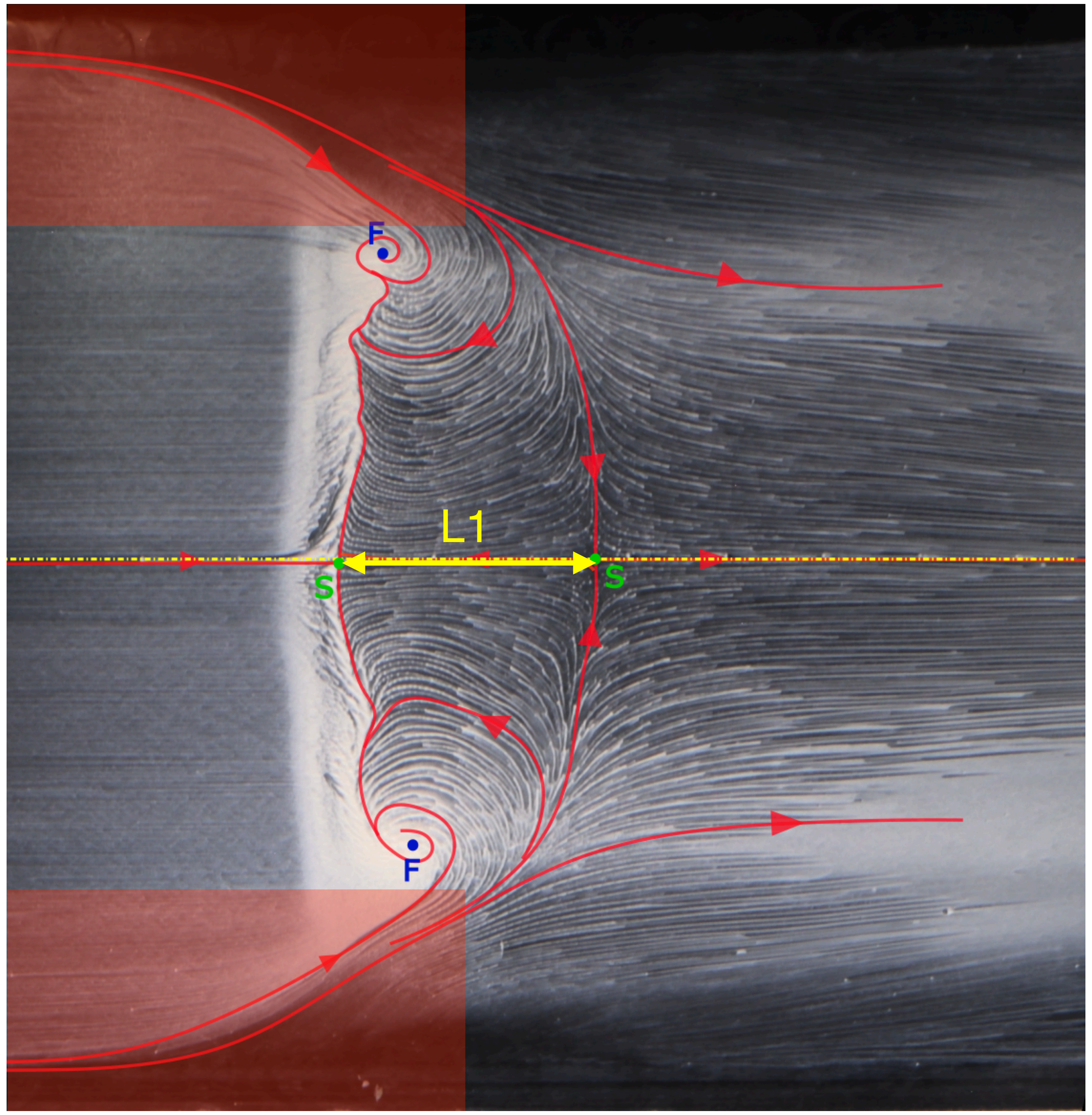


M = 2.5
Downstream compression waves
Upstream pressure communication
Boundary layer
Sonic line
Thickened subsonic portion post separation

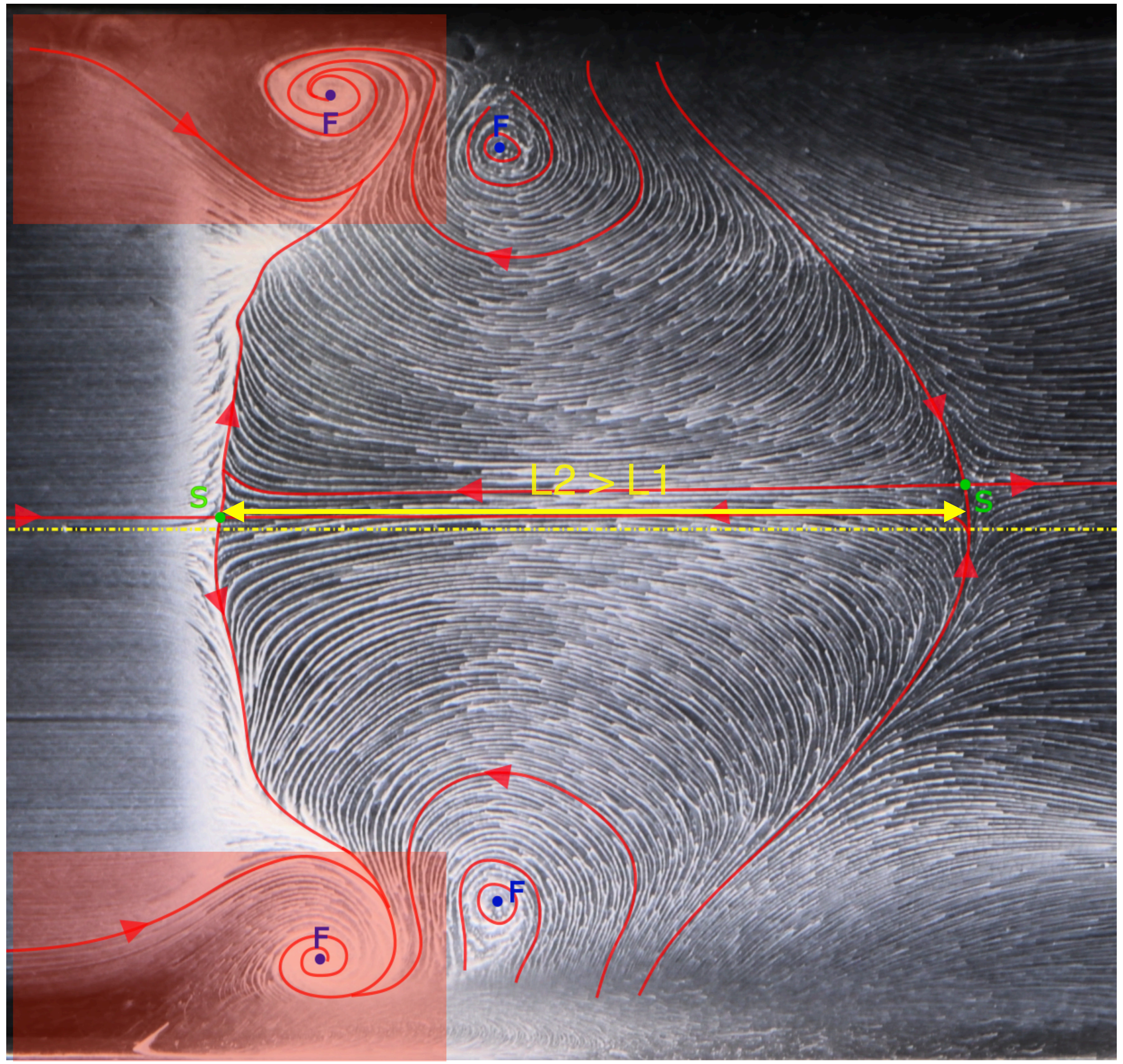
Mechanism 1


M = 2.5
Downstream
compression waves
Upstream
pressure communication
Boundary layer
Sonic line
Thickened subsonic portion
post separation
Upstream thickening
due to compression waves

Corner flow



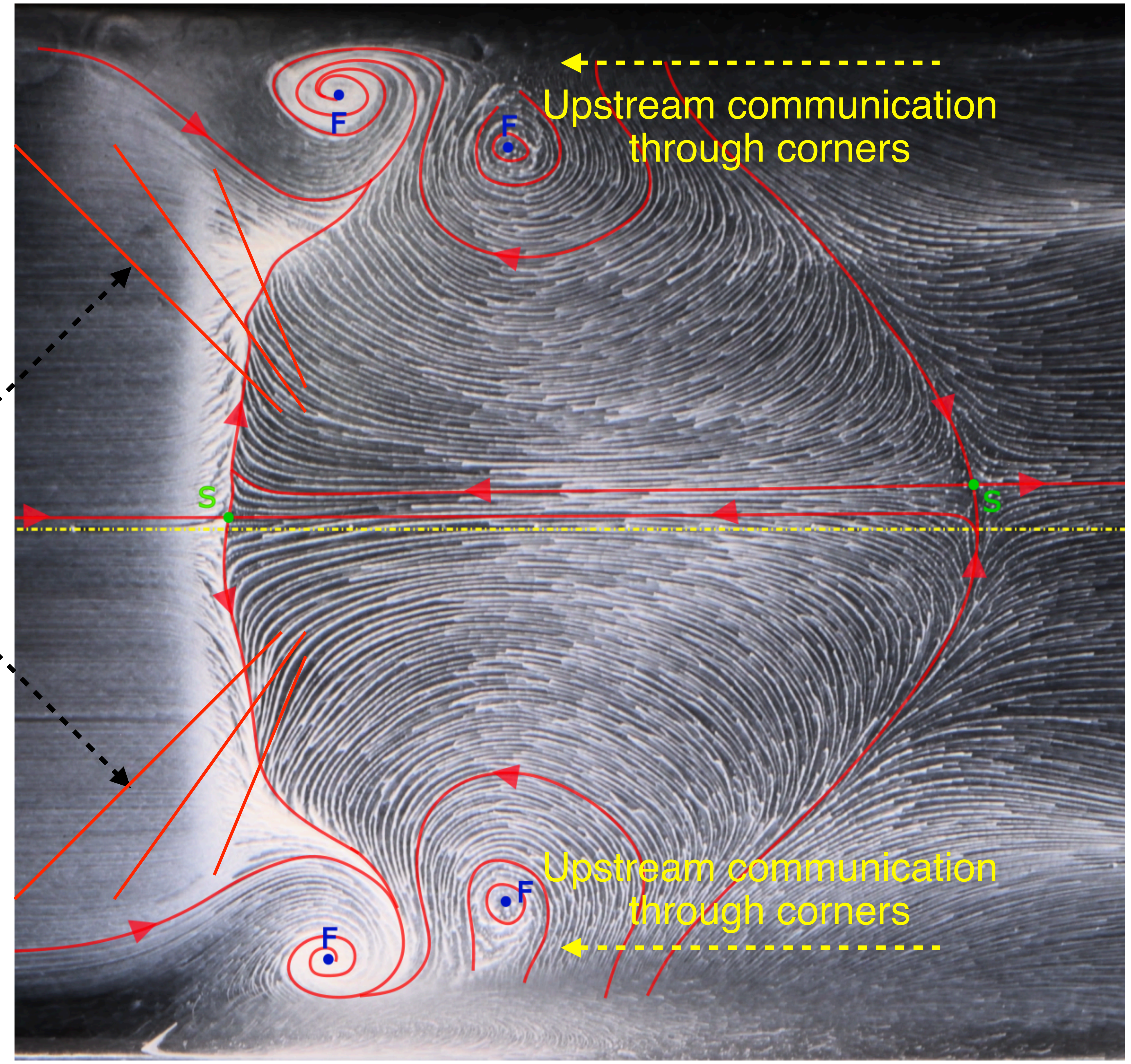
Set 2 compression



Set 1 compression

Mechanism 2

Corner waves



Conclusions

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Influence reduces with distance to the interaction

Two possible mechanisms were proposed

References

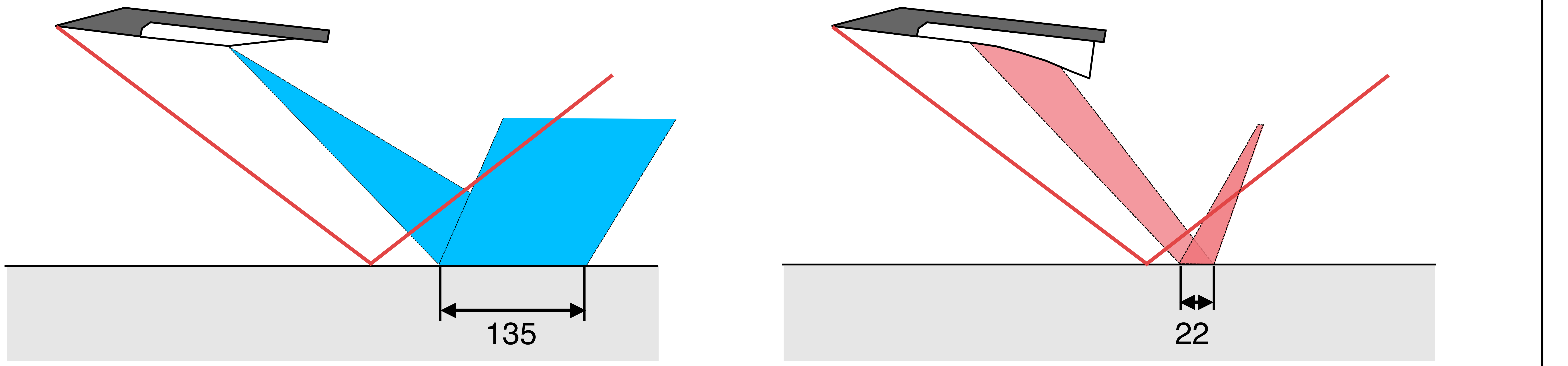
1. Grossman, I. J., and Bruce, P. J., “Confinement effects on regular-irregular transition in shock-wave-boundary-layer interactions,” Journal of Fluid Mechanics, Vol. 853, 2018, pp. 171-204. *https://doi.org/10.1017/jfm.2018.537.*

2. Missing, T., and Babinsky, H., Corner effects on oblique shock wave boundary layer interactions in rectangular channels, AIAA SciTech 2023 Forum, 2023-0650. *https://doi.org/10.2514/6.2023-0650.*

Additional slides: Setup details and data

Details of test setups

Set 1



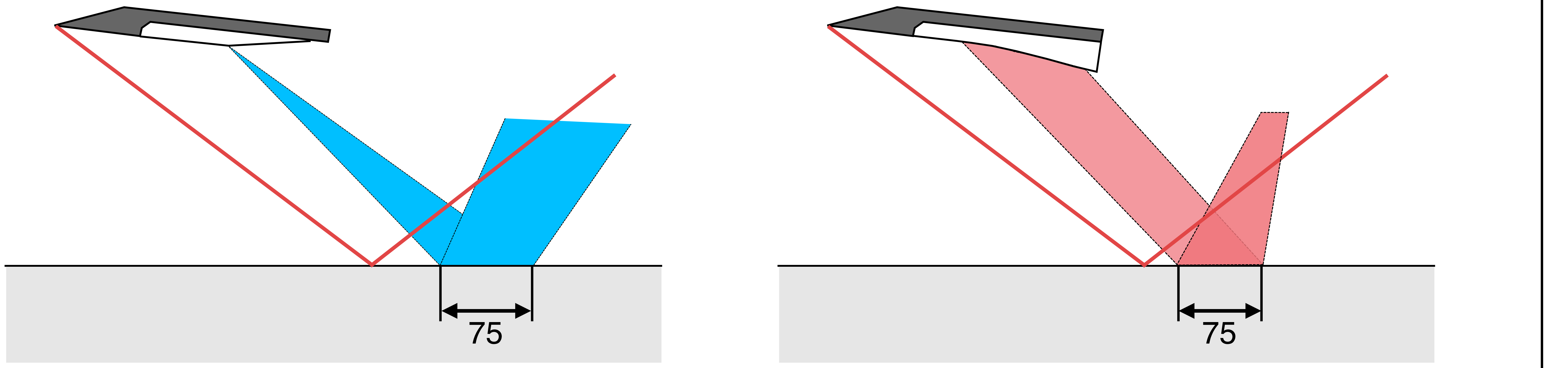
$\overline{\Delta P} = -1 \quad \overline{dp/dx} = -0.06$

$\overline{\Delta P} = +0.91 \quad \overline{dp/dx} = +0.32$

Three $\overline{d_f}$'s

- 1.2
- 3.8
- 6.3

Set 2



$\overline{\Delta P} = \pm 0.64 \quad \overline{dp/dx} = \pm 0.07$

Three $\overline{d_f}$'s

- 1.2
- 3.8
- 6.3

Centreline separation lengths

Set 1

Case	Expansion			Baseline	Compression		
d_f/δ_i	1.25	3.76	6.27	-	6.27	3.76	1.25
L_{sep}/δ_i	1.49	1.78	1.98	2.33	3.46	8.51	10.21

Set 2

Case	Expansion			Baseline	Compression		
d_f/δ_i	1.25	3.76	6.27	-	6.27	3.76	1.25
L_{sep}/δ_i	1.53	1.93	2.17	2.33	2.43	2.74	3.30