Upstream Forcing of Tidewater Glacier Retreat

Ian Hewitt, University of Oxford

- Tidewater glaciers currently discharge around half of Greenland's ice loss to the ocean, and can change rapidly.
- Central question: **what controls ice discharge?** and, related to that, **what determines the location of the ice front?**

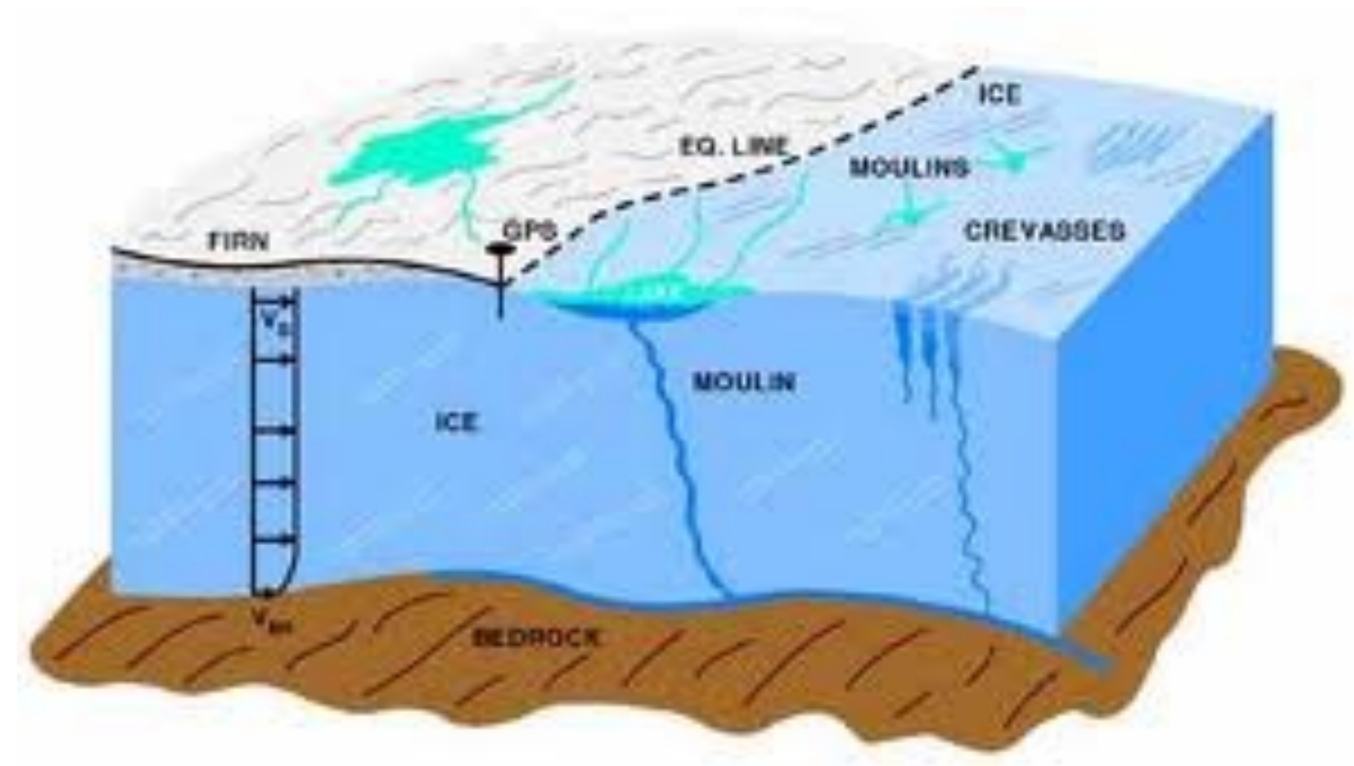
Summary

- Certain positions of the ice front act as '**pinning points**', at which the glacier achieves a roughly steady balance (accumulation≈discharge).

  Changes in forcing can cause such points to disappear or lose stability.
- The highly non-linear response is inherent to the dynamics of tidewater glaciers, whether forcing is **from the ocean or from upstream.**
- I'll describe a simplified model that helps elucidate this.

Motivation: impact of subglacial lubrication

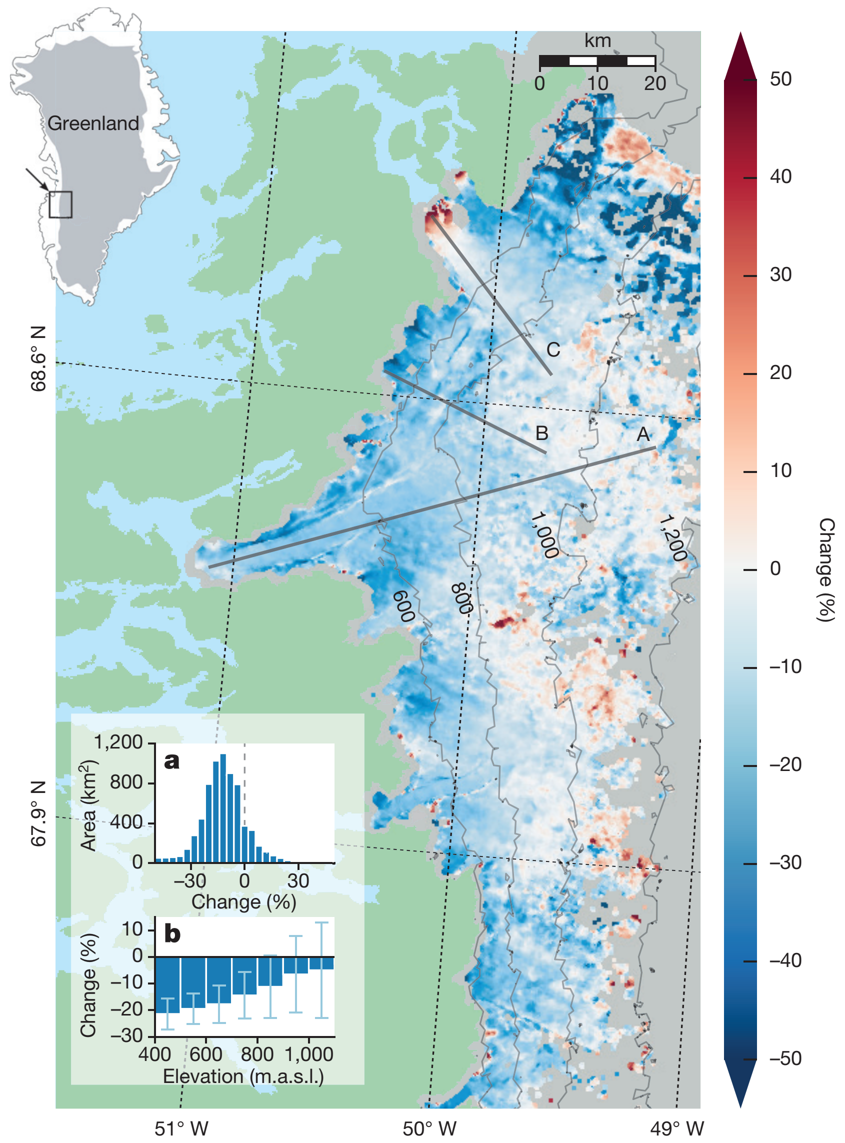
- Drainage of **surface meltwater** to the bed affects **ice speed** (due to influence on water pressure).
- Possibility that increased surface melt could cause increased ice speeds, and consequently (perhaps?) ice loss.



Zwally et al 2002

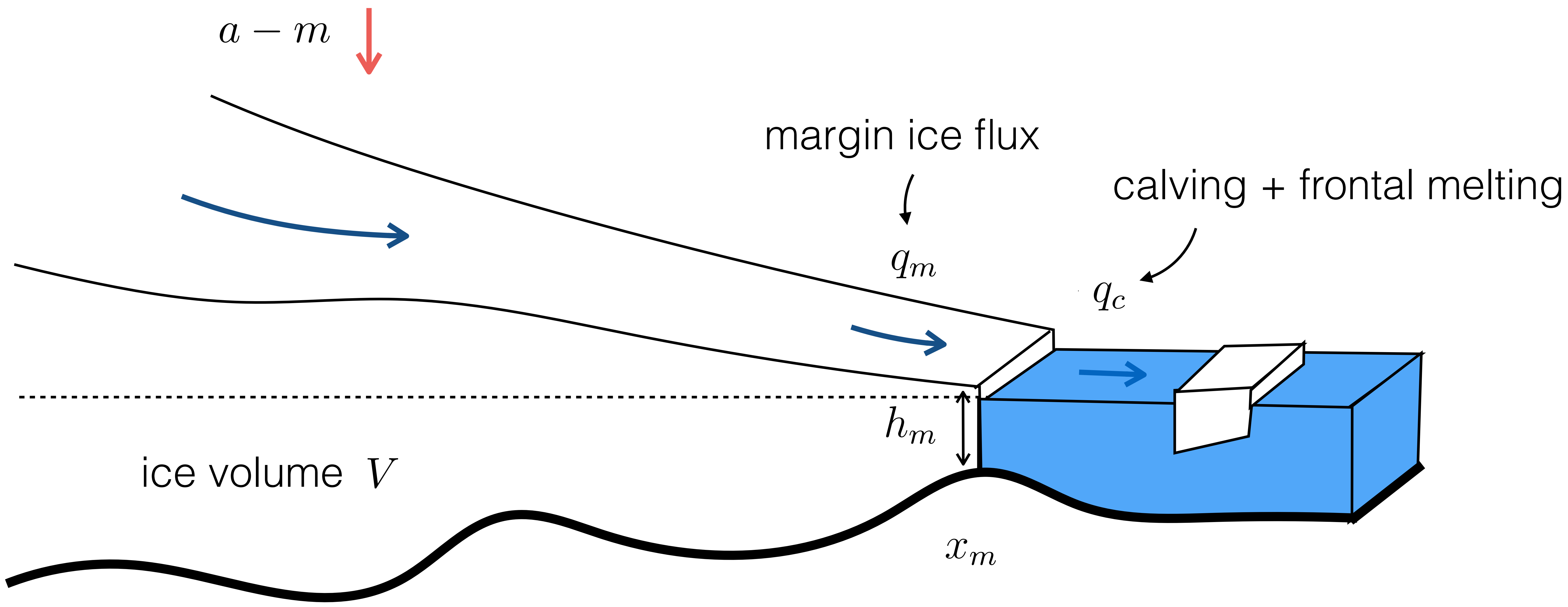
- Some recent studies suggest increased surface melt may have caused a slight **decrease** in average ice speeds (due to more efficient subglacial drainage).

→ **What impact do we expect such changes to have on a tidewater glacier?**



Tedstone et al 2015

Ice front evolution



Kinematic condition

$$h_m \frac{\mathrm{d}x_m}{\mathrm{d}t} = q_m - q_c$$

- Primary control on discharge is ice **depth** at the margin.
- It is typically observed that $q_m \approx q_c$

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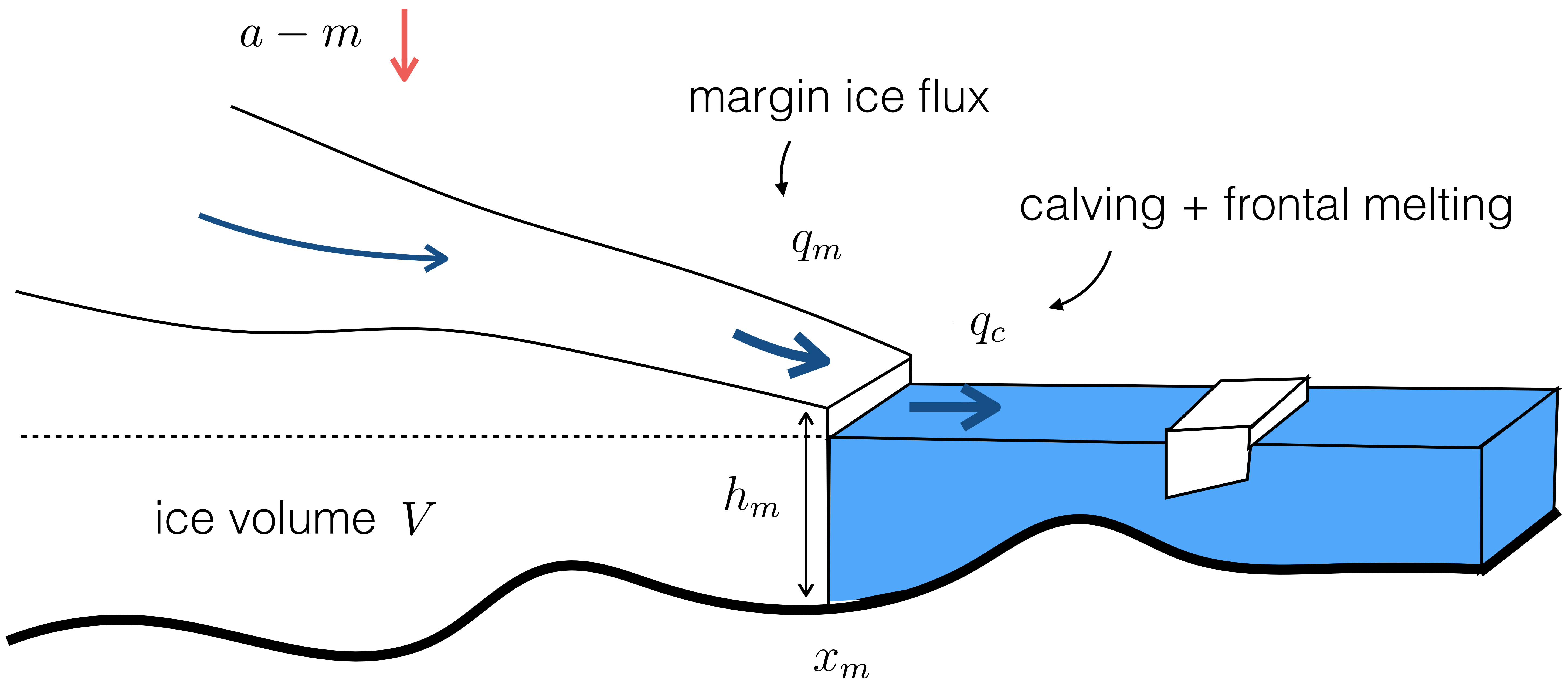

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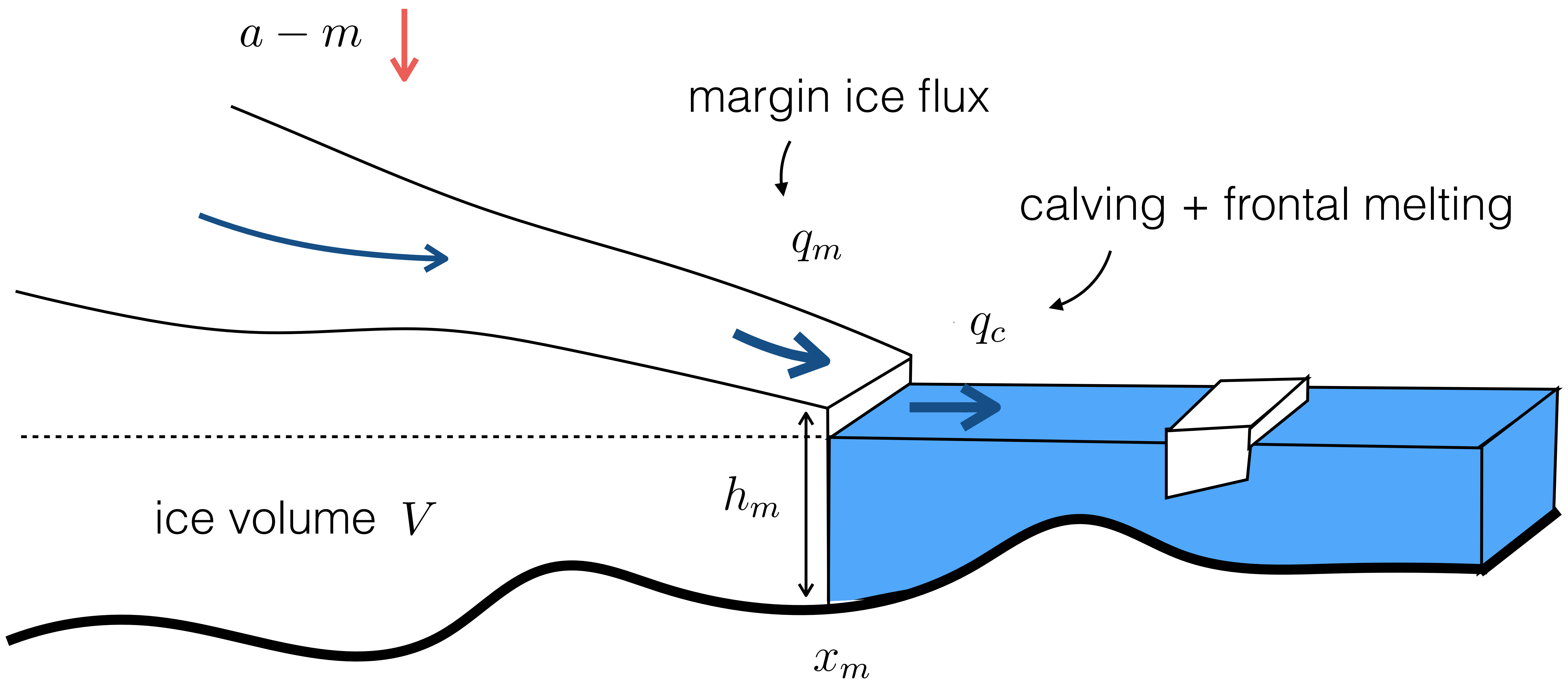

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Global mass balance

$$\frac{\mathrm{d}V}{\mathrm{d}t} = q_b - q_c$$

balance flux $q_b = \int_0^{x_m} (a - m)\,\mathrm{d}x$

Time-lapse movie

Extreme Ice Survey - Time-lapse camera
Columbia Glacier, Alaska

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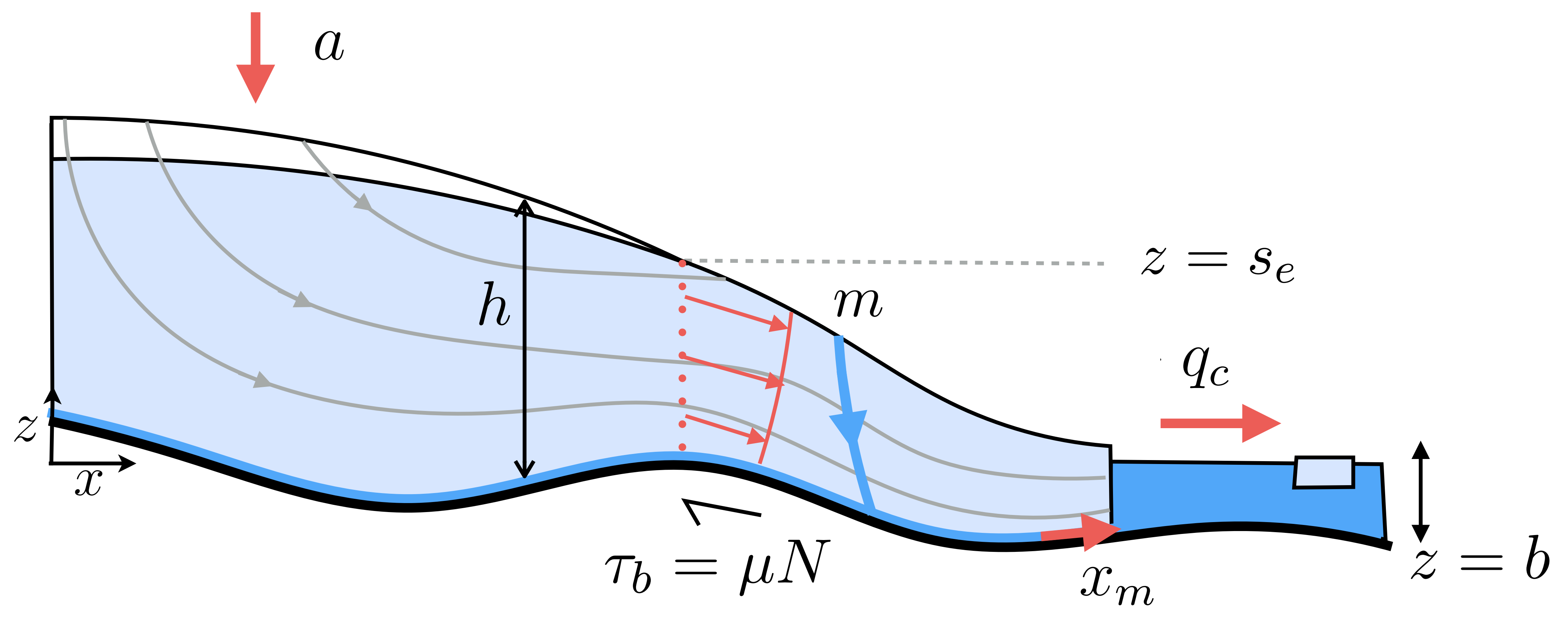
A simplified model of a tidewater glacier



Two-dimensional. Ice motion dominated by basal sliding.

A **plastic** (rate-independent) friction law.

Mass conservation $$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = a - m \qquad q = hu$$

Force balance $$\frac{\partial}{\partial x}\left(4\eta_i h \frac{\partial u}{\partial x}\right) - \rho_i g h \frac{\partial}{\partial x}(b+h) - \tau_b = 0$$

At ice front $x = x_m$ $$4\eta_i h \frac{\partial u}{\partial x} = \frac{1}{2}\left(\rho_i g h^2 - \rho_o g b^2\right) \quad \text{(stress balance)}$$

$$h = f\left(-\frac{\rho_o}{\rho_i} b\right) \quad \text{(calving criteria)}$$

flotation factor

flotation depth

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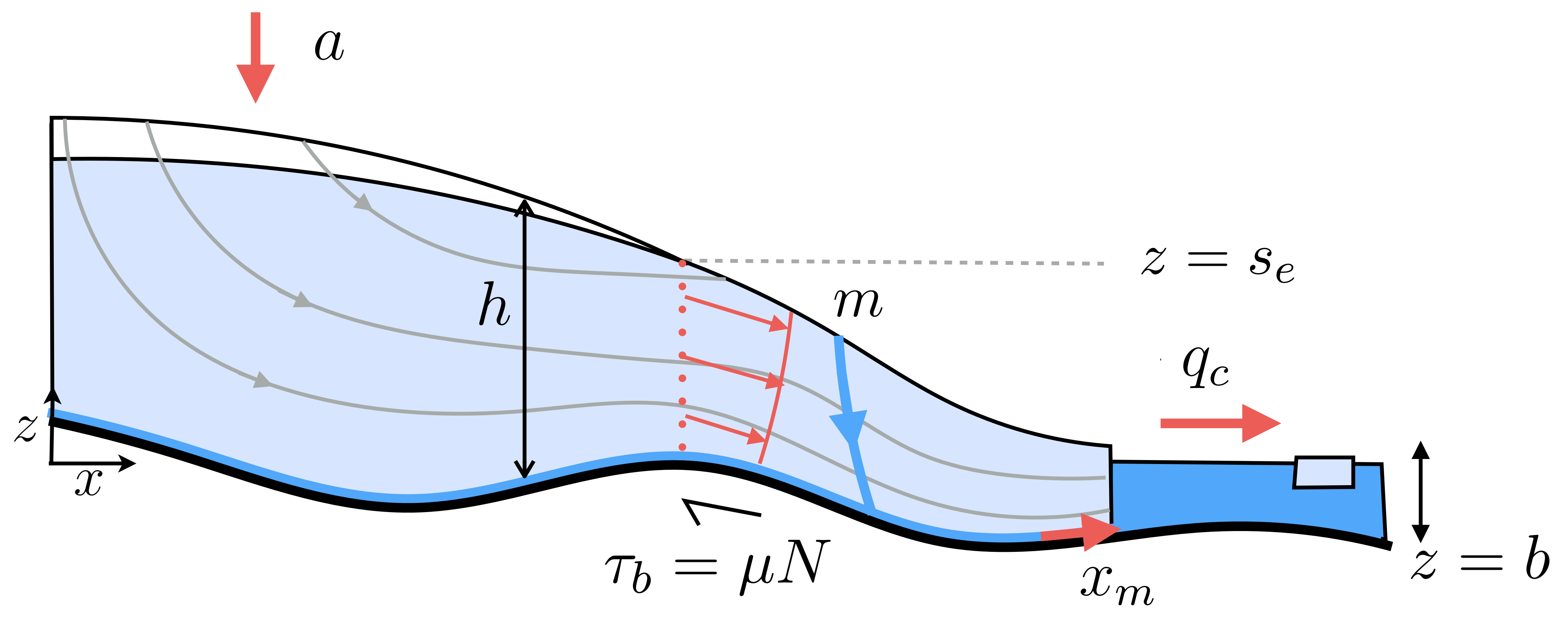

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flotation factor (f) — flotation depth ($-\frac{\rho_o}{\rho_i} b$)

Model reduction

- Away from the front, force balance $-\rho_i g h \frac{\partial}{\partial x}(b + h) \approx \tau_b$

→ ice thickness and **volume** determined purely by **margin position** and **basal friction**

cf. Nye 1951, Weertman 1961, Ultee & Bassis 2016

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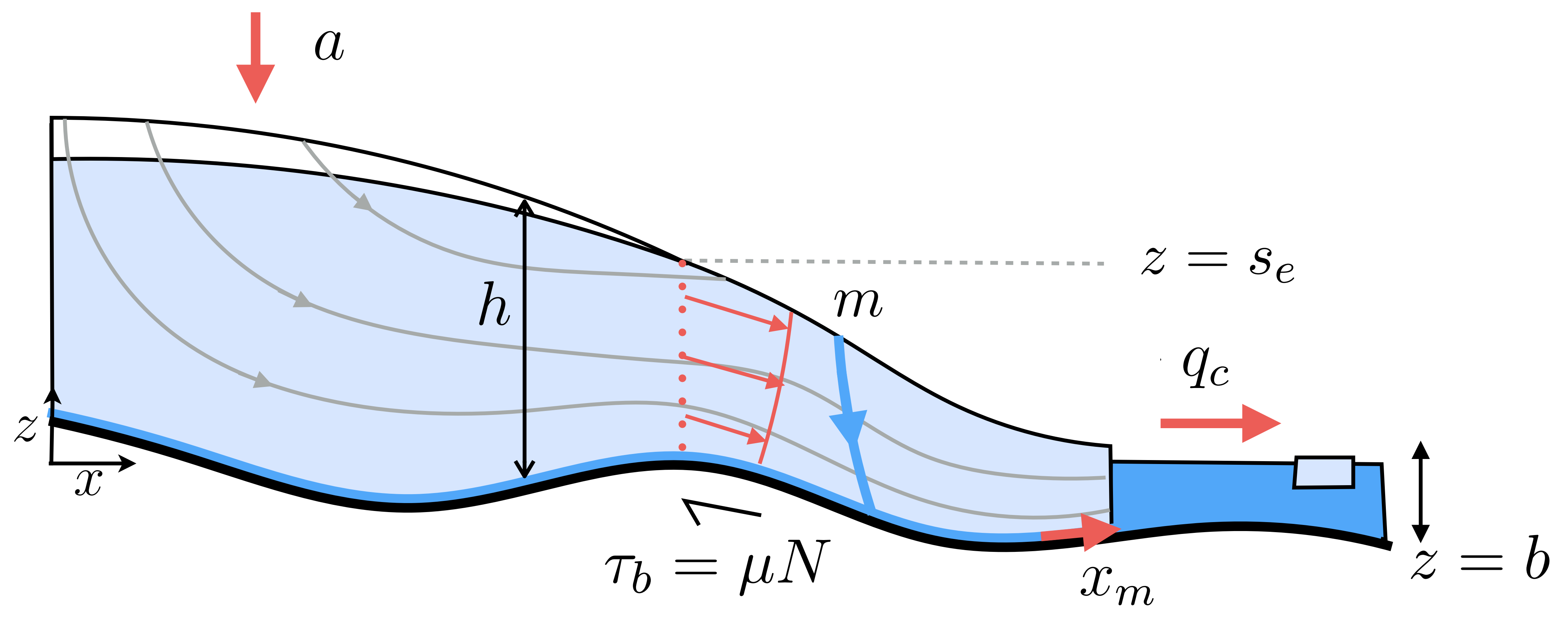

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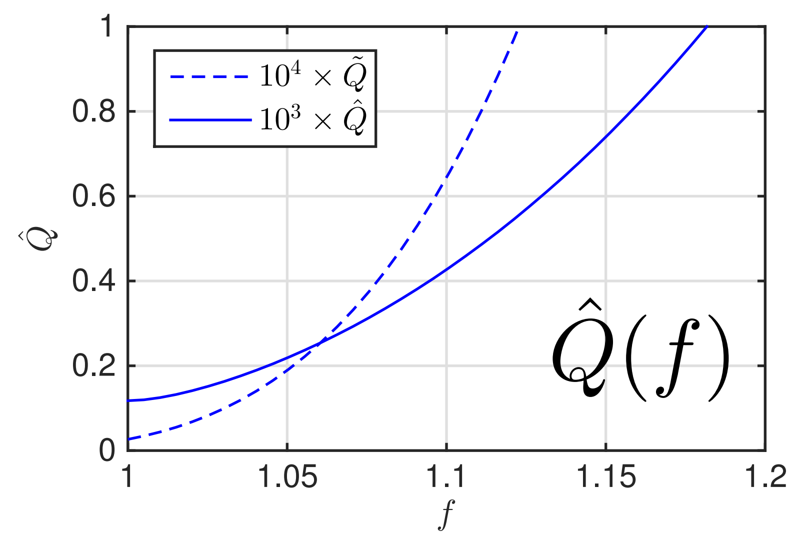
- Near the front, a boundary-layer analysis relates **calving flux** to local **water depth**

cf. Schoof 2007, Tsai et al 2015

→ $$q_c = \frac{A(2\rho_i g)^n}{\mu} \hat{Q}(f) \left(-\frac{\rho_i}{\rho_o} b\right)^{n+2}$$



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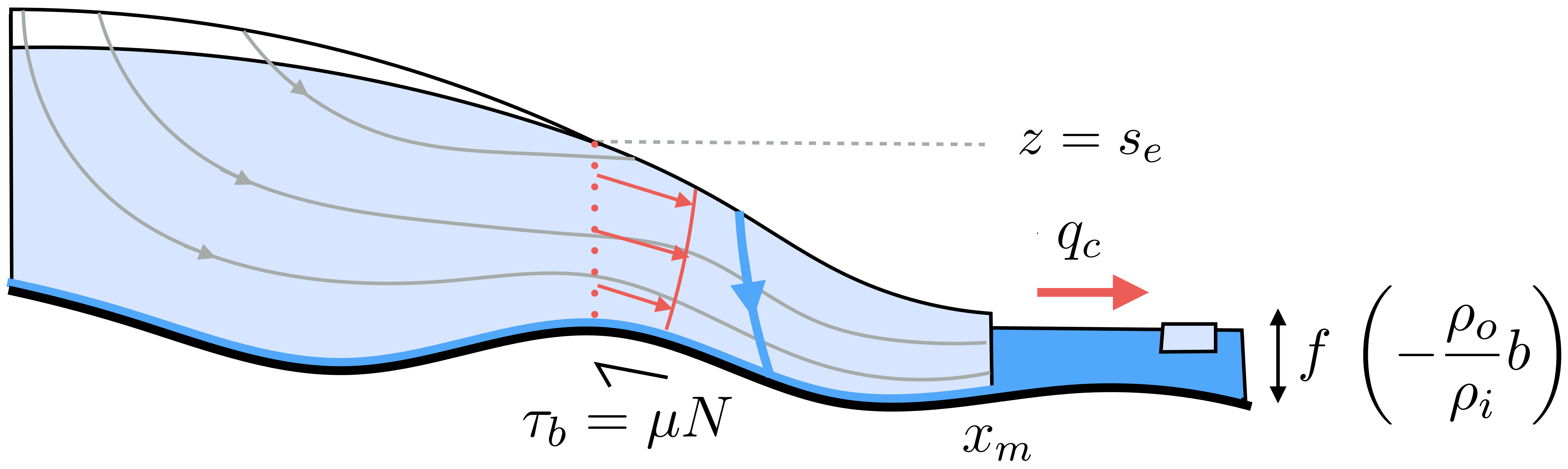
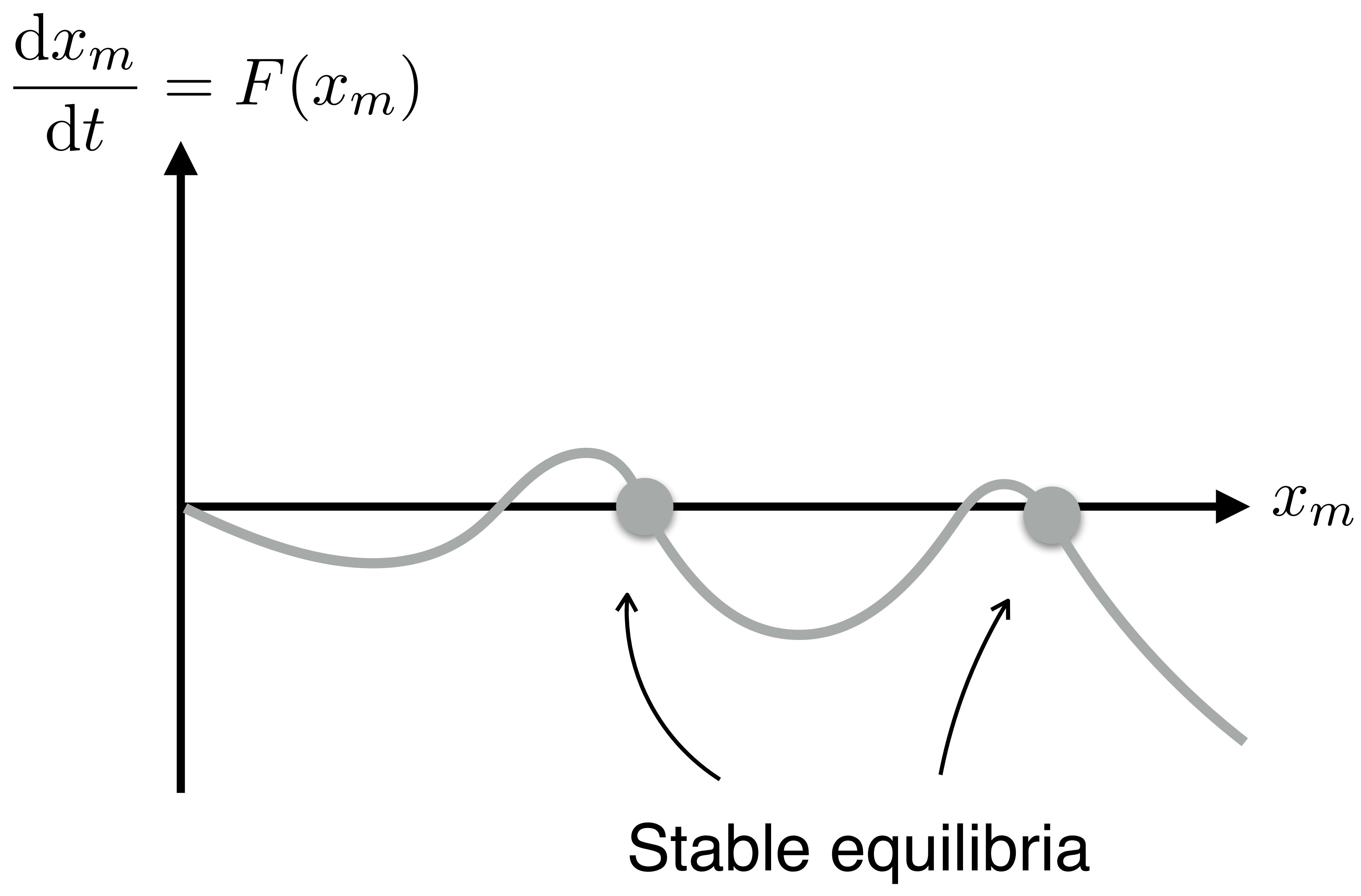


Global mass balance

$$\frac{\mathrm{d}V}{\mathrm{d}t} = q_b - q_c \quad \rightarrow \quad \boxed{\frac{\mathrm{d}x_m}{\mathrm{d}t} = F(\, x_m \,;\, N, s_e, f)}$$



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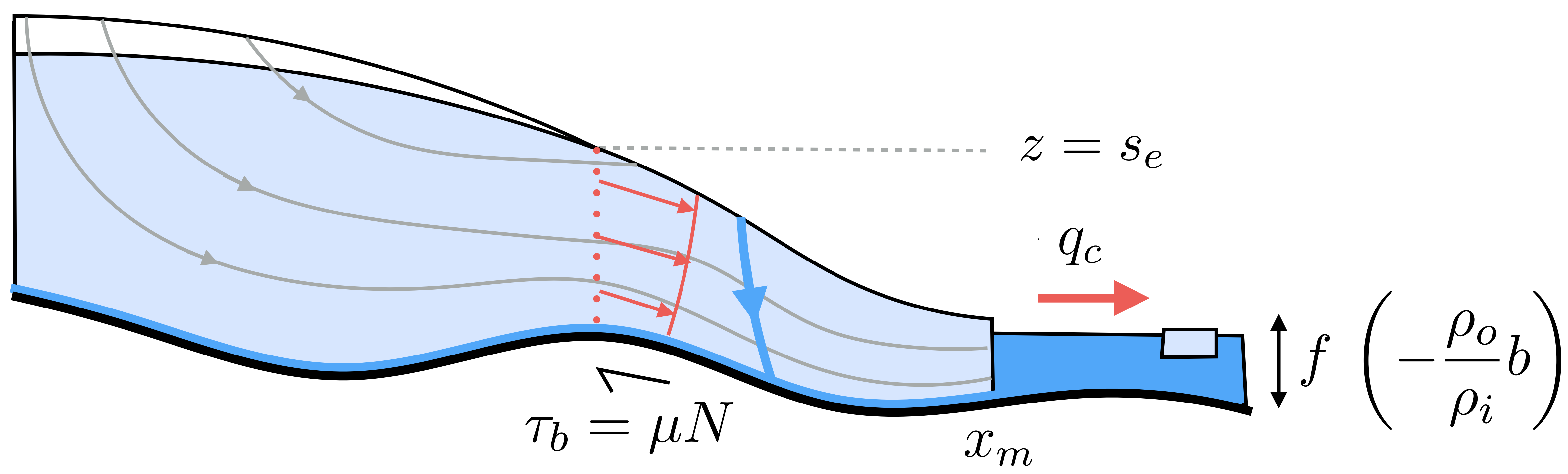

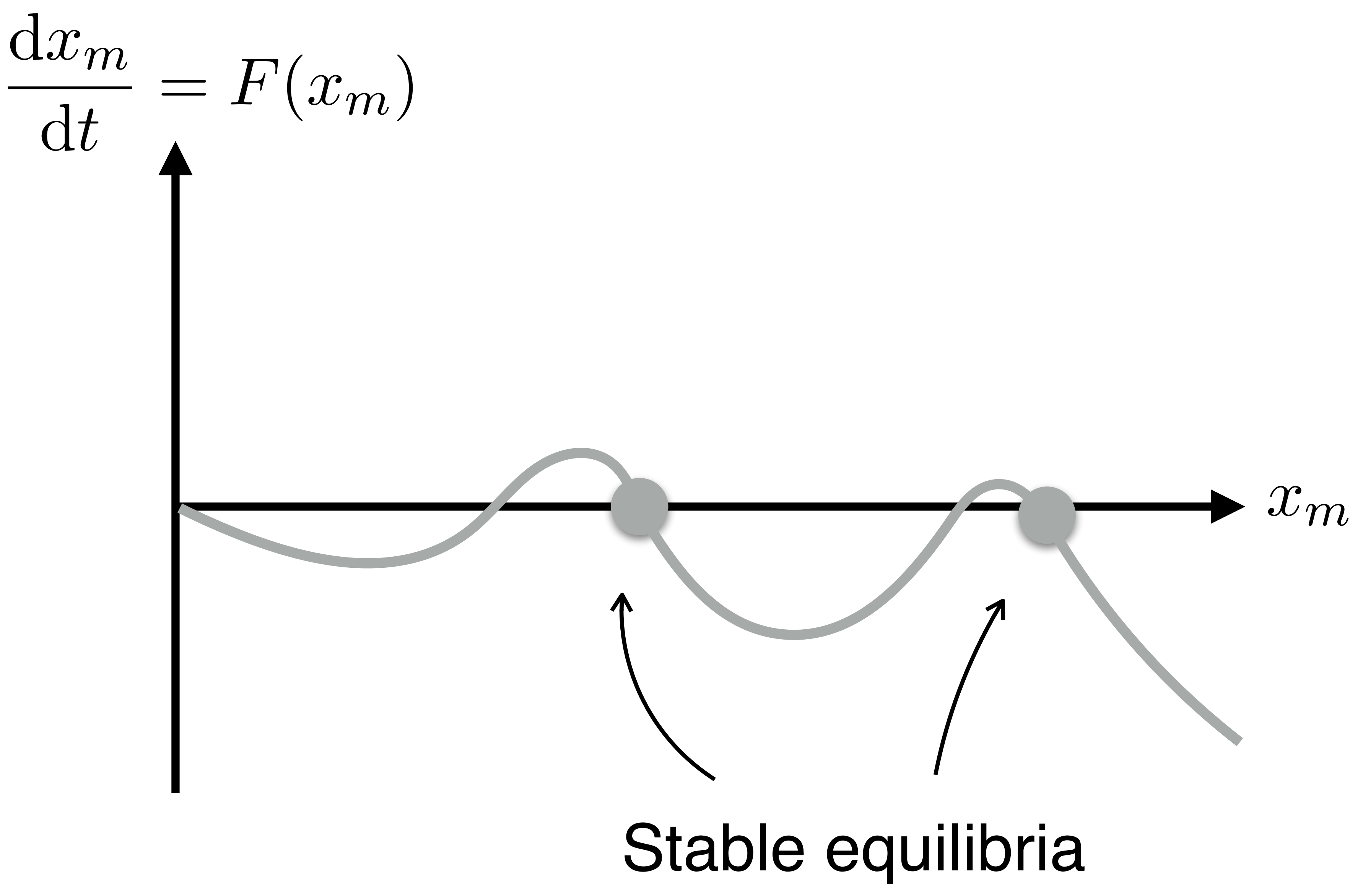

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Forcing parameters:

N	Bed strength
s_e	Equilibrium line altitude (ELA)
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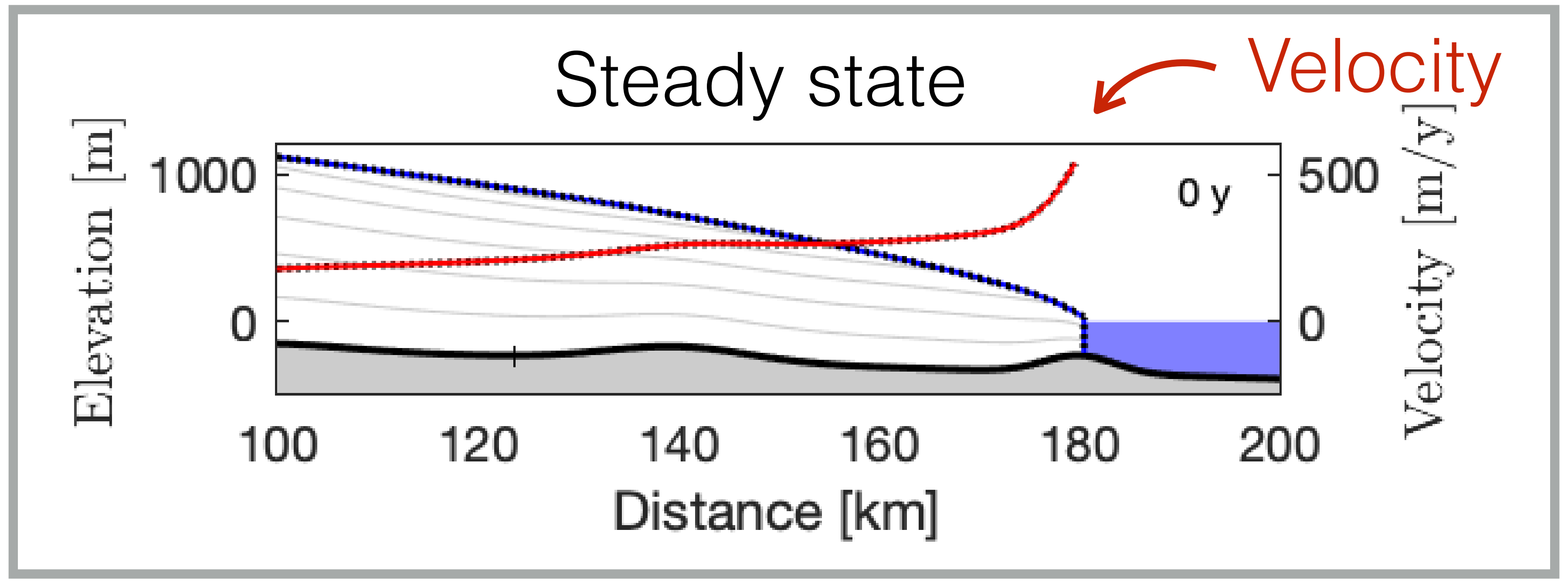
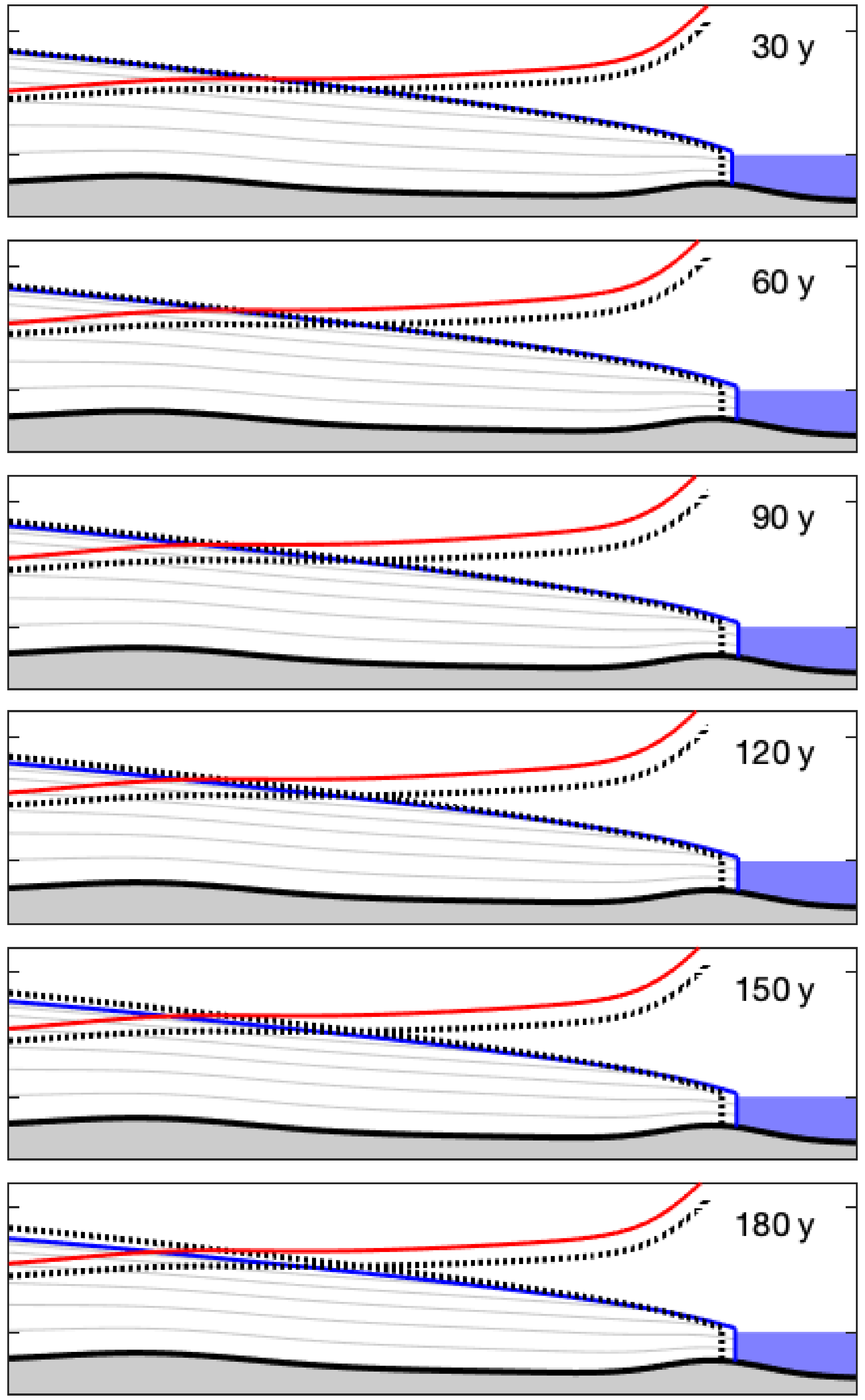
Motivation: impact of subglacial lubrication



Decreasing basal friction

Time



Speed up

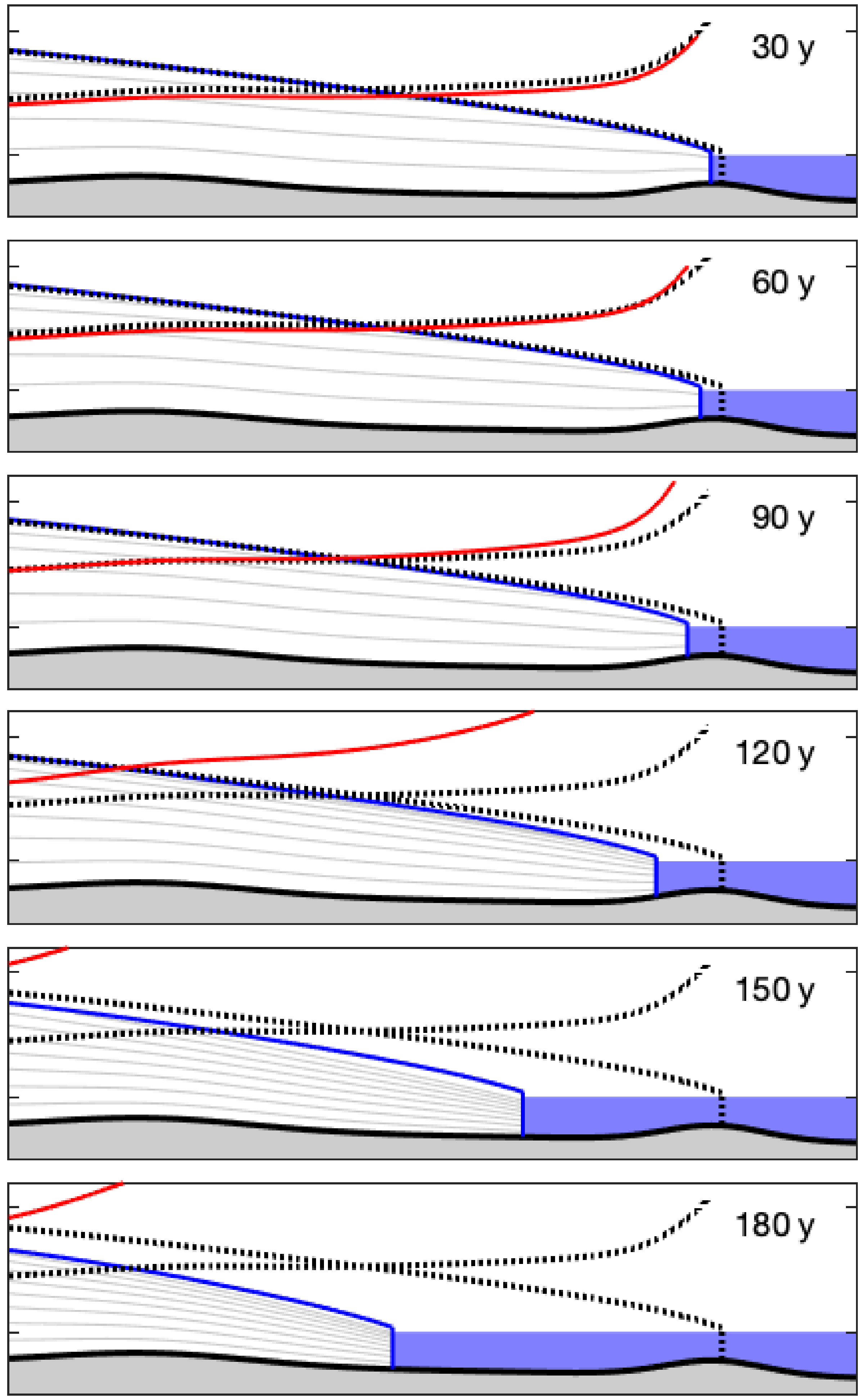
↓

Advance

↓

Increased mass loss

Increasing basal friction



Slow down

↓

Retreat

↓

Speed up

↓

Greater mass loss

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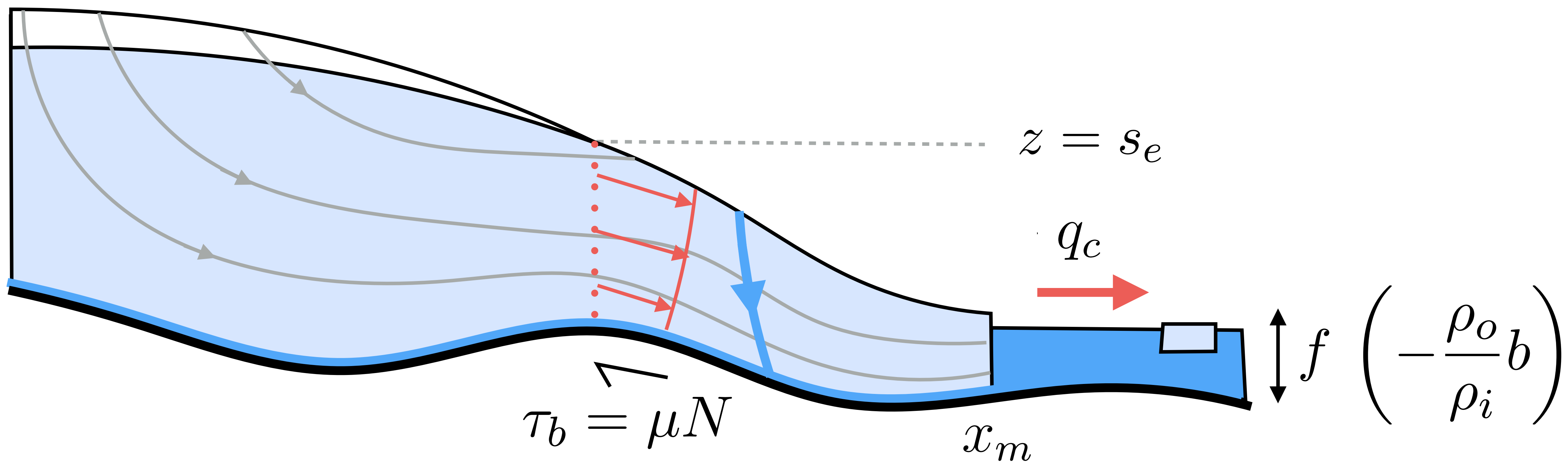

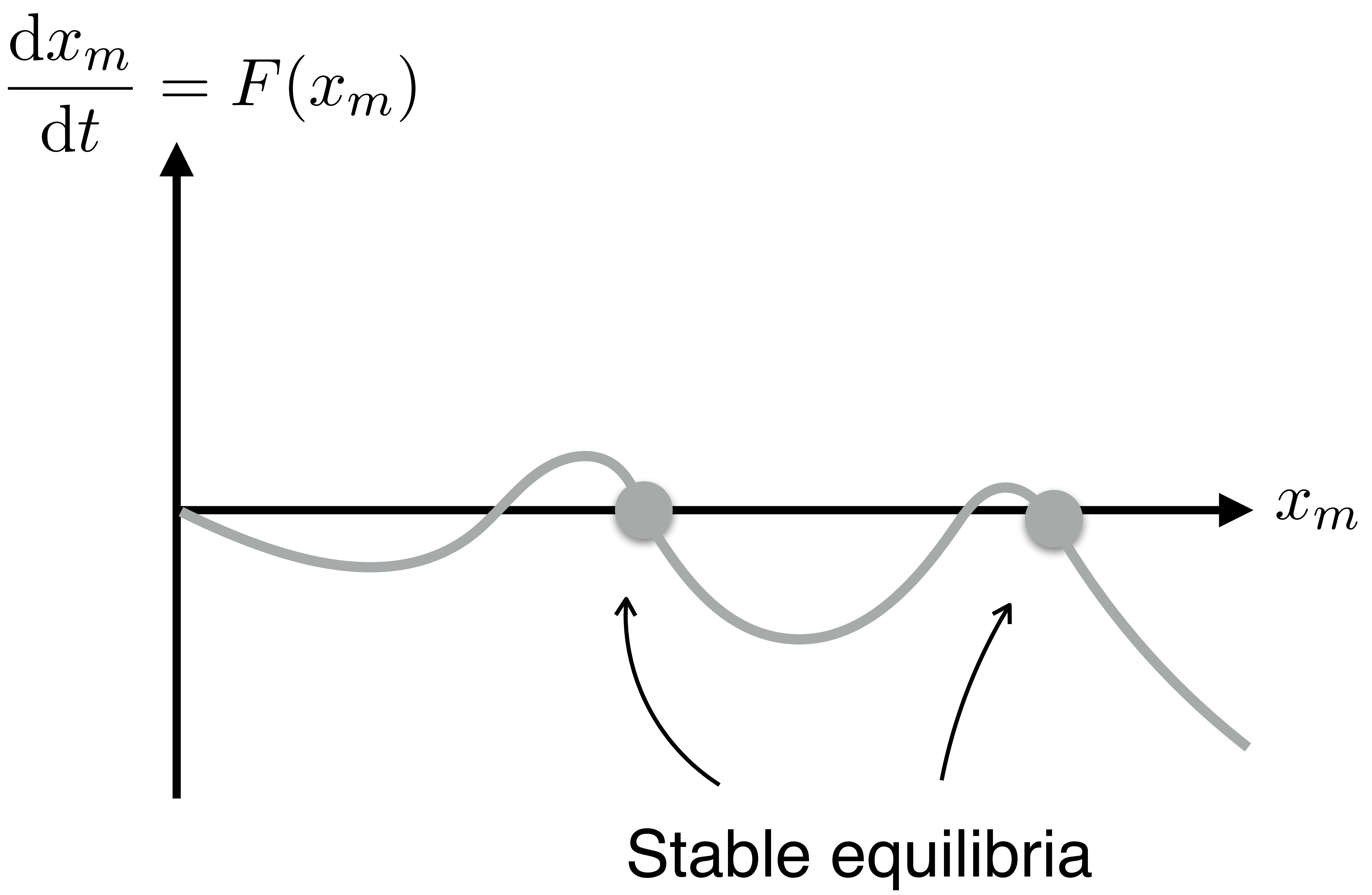

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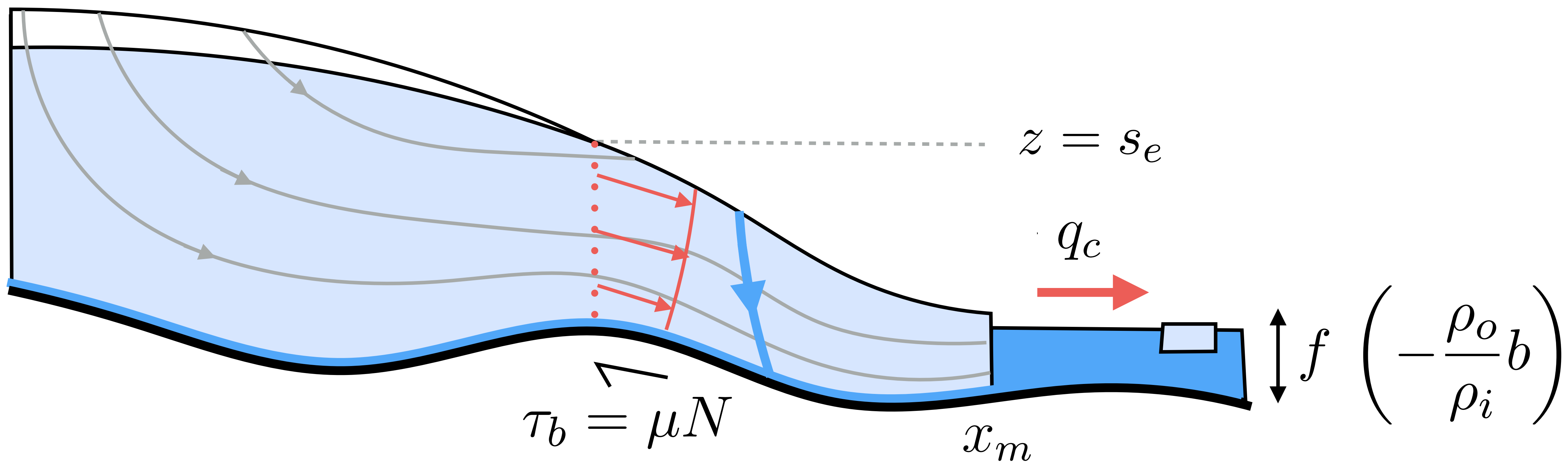

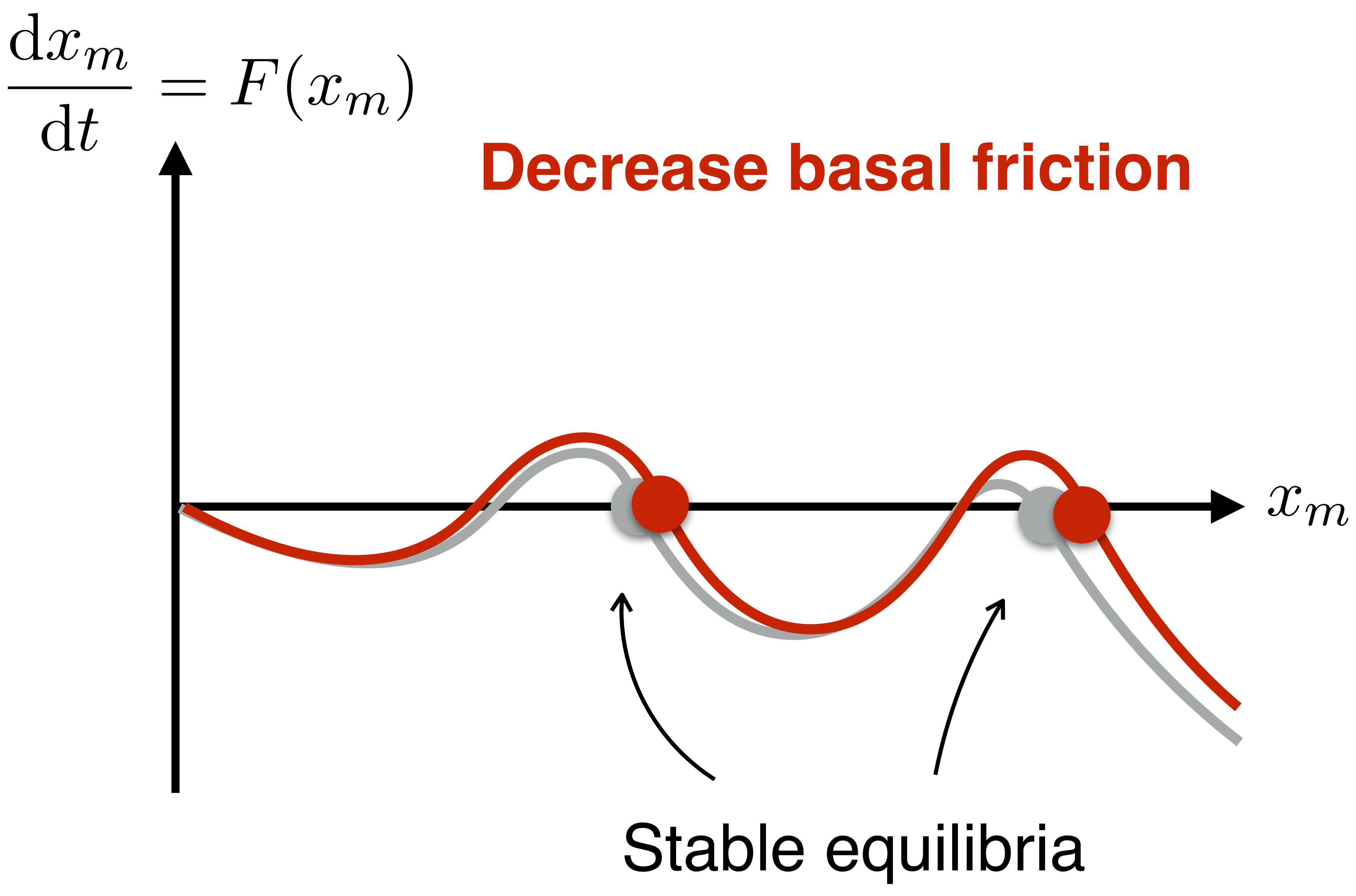

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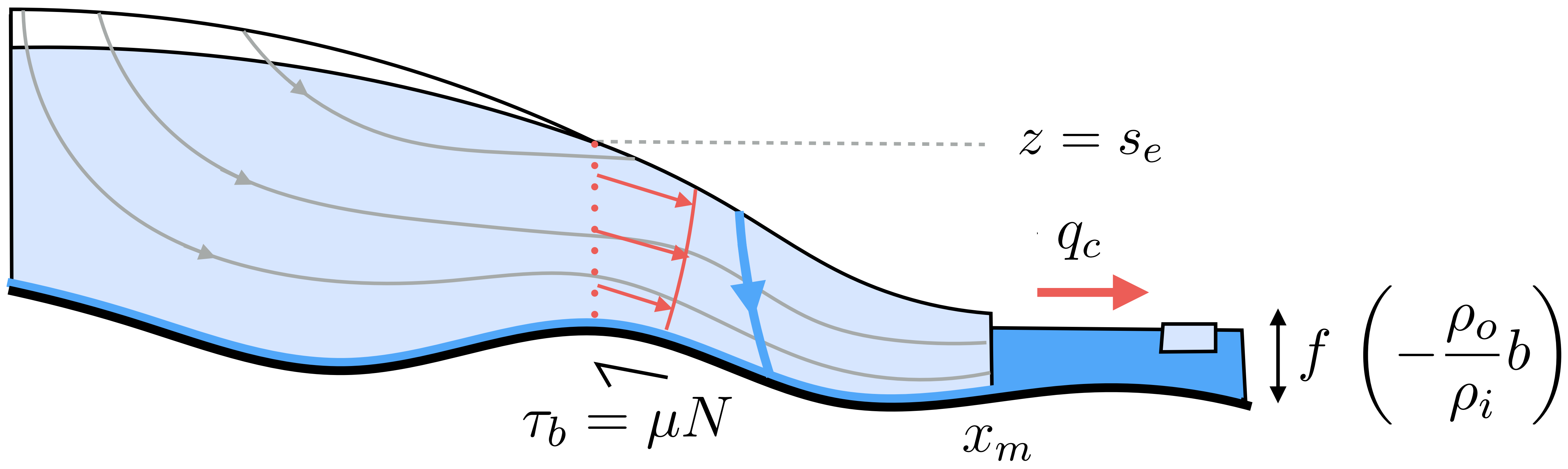

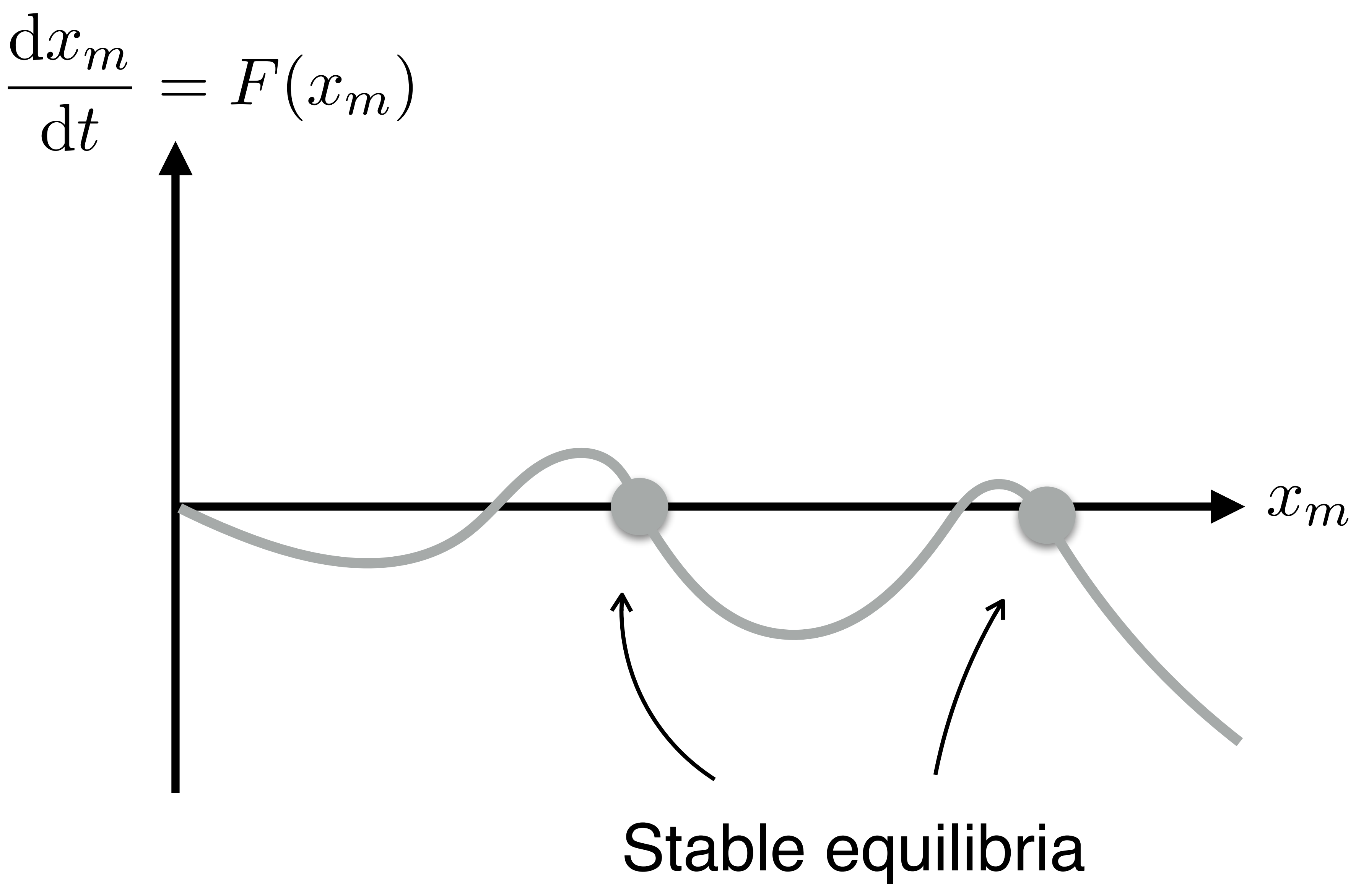

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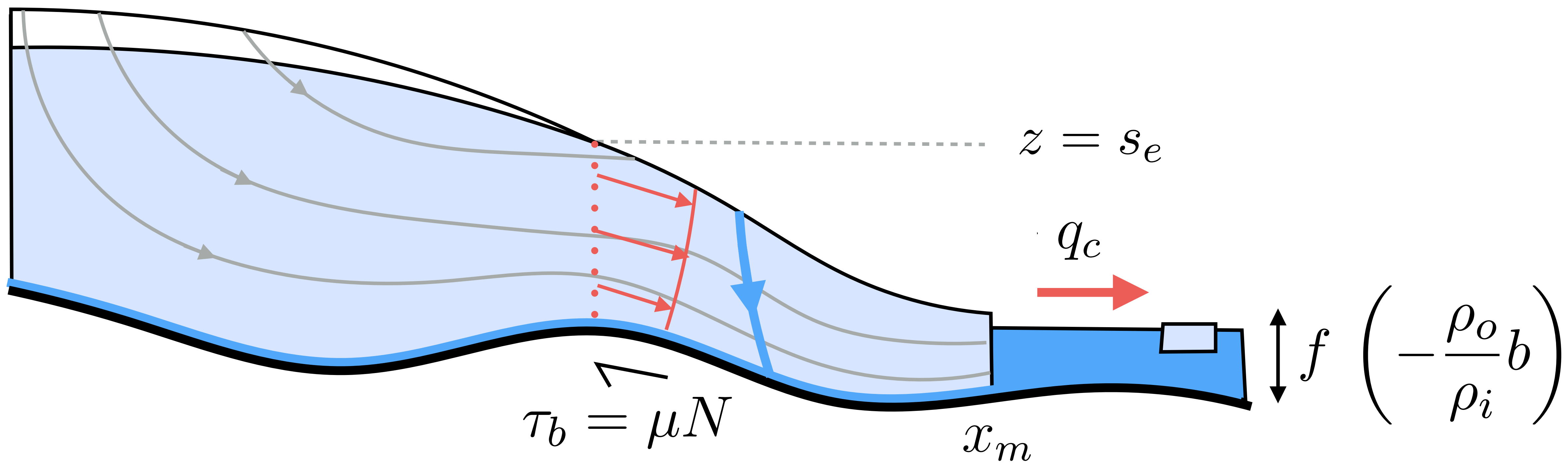

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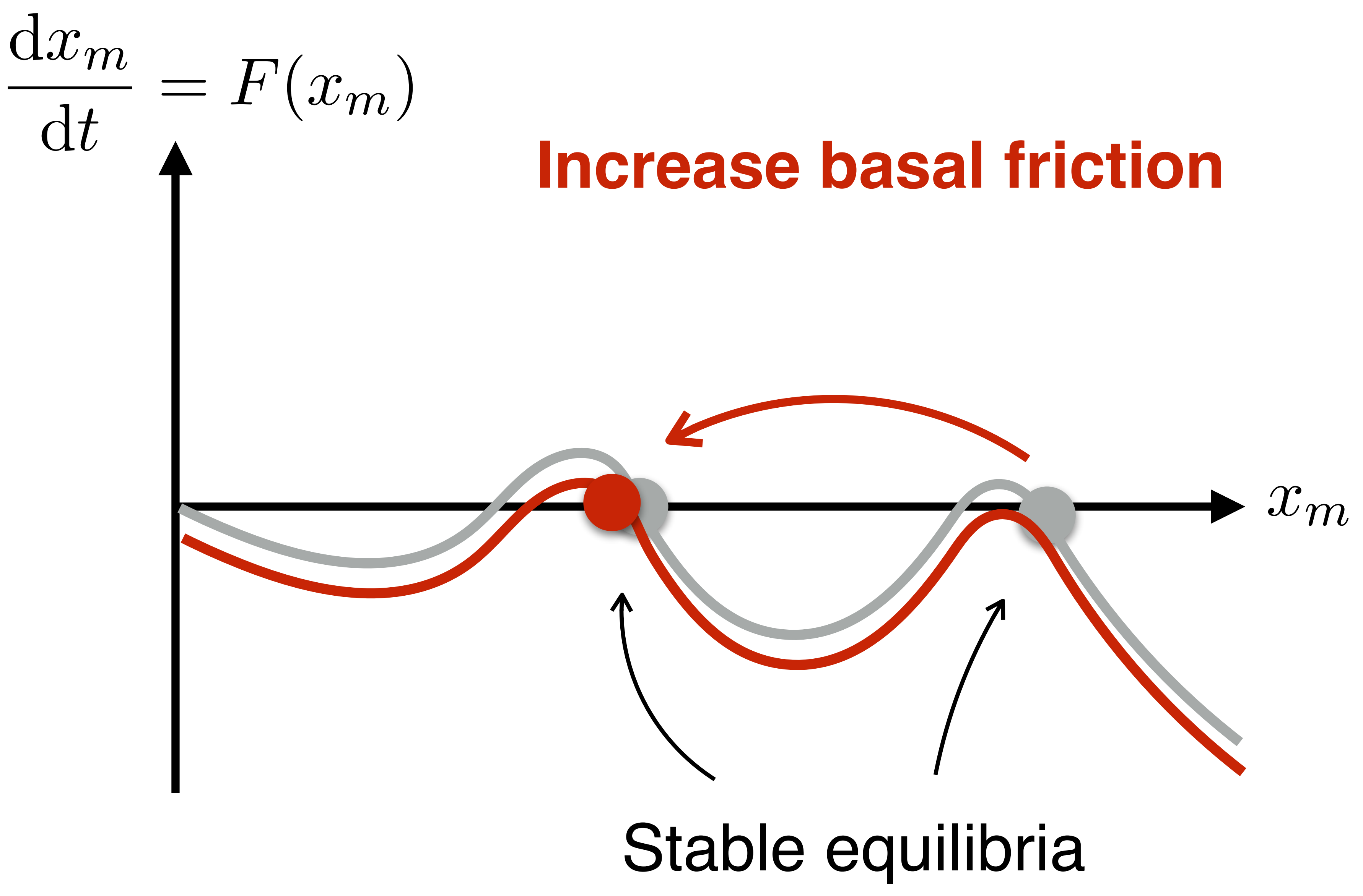

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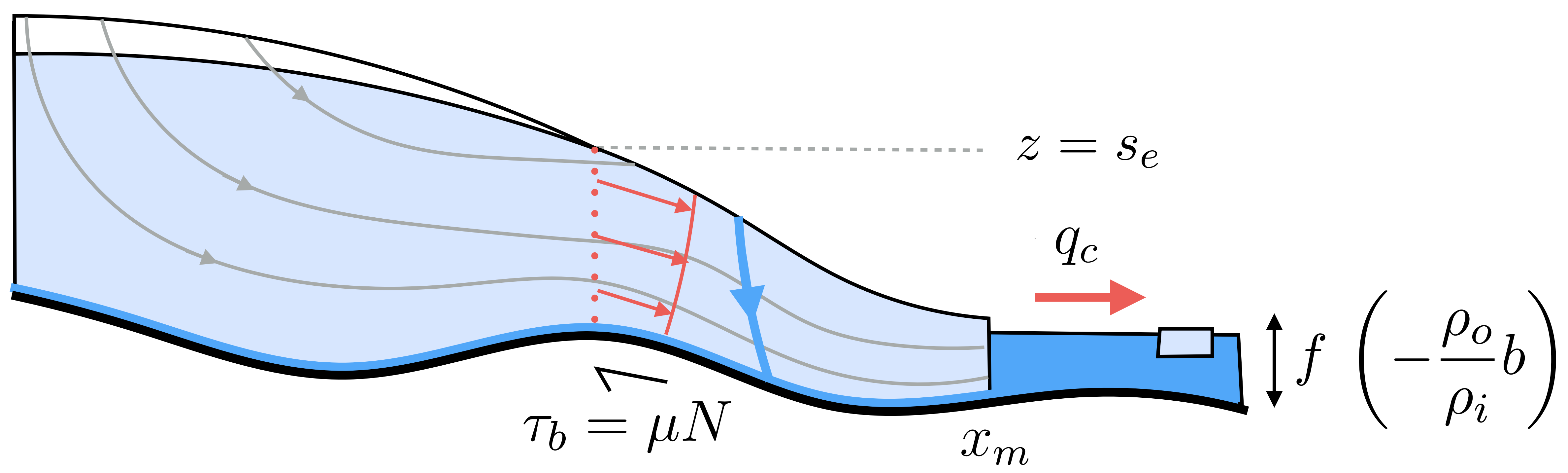

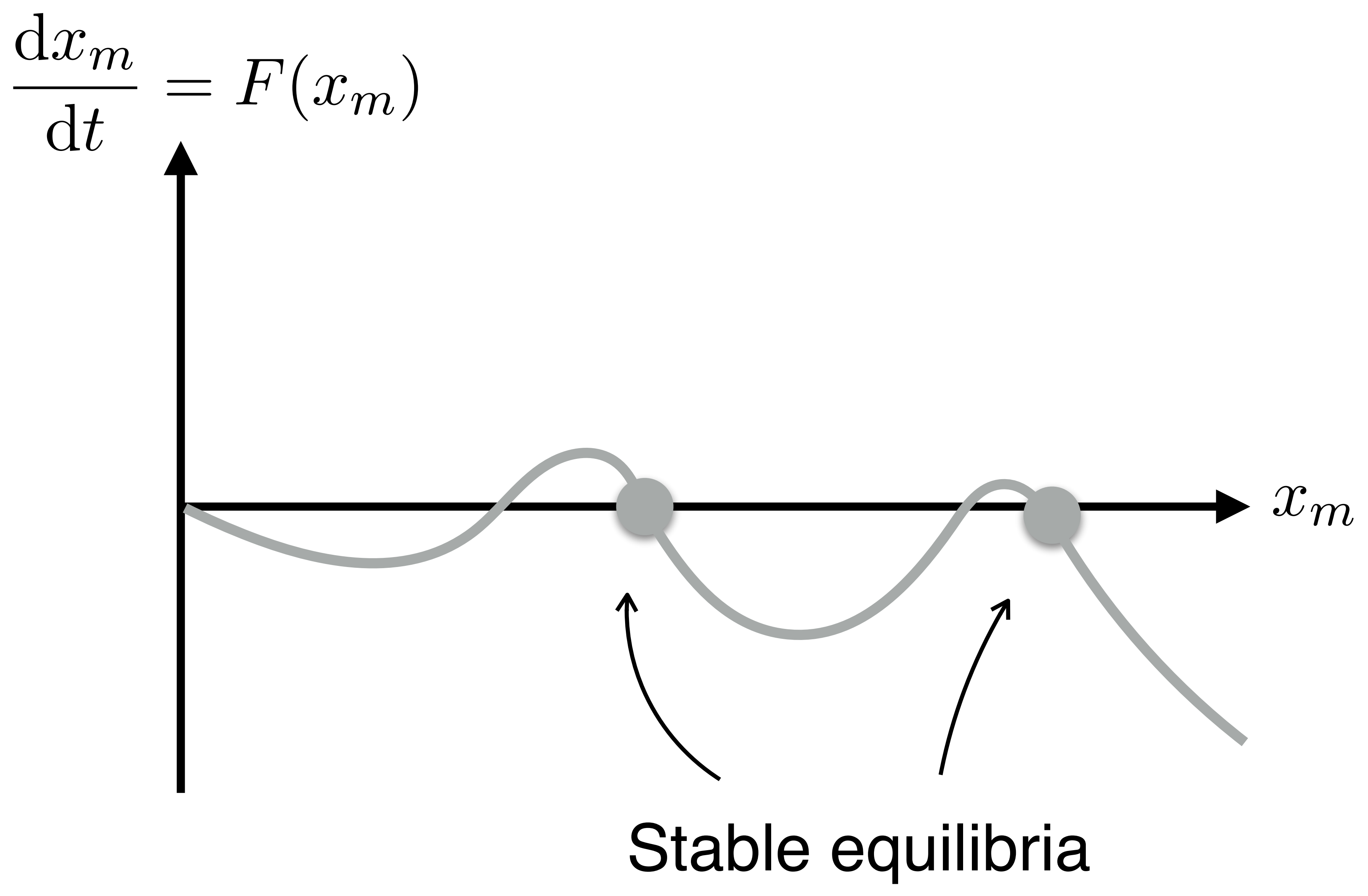

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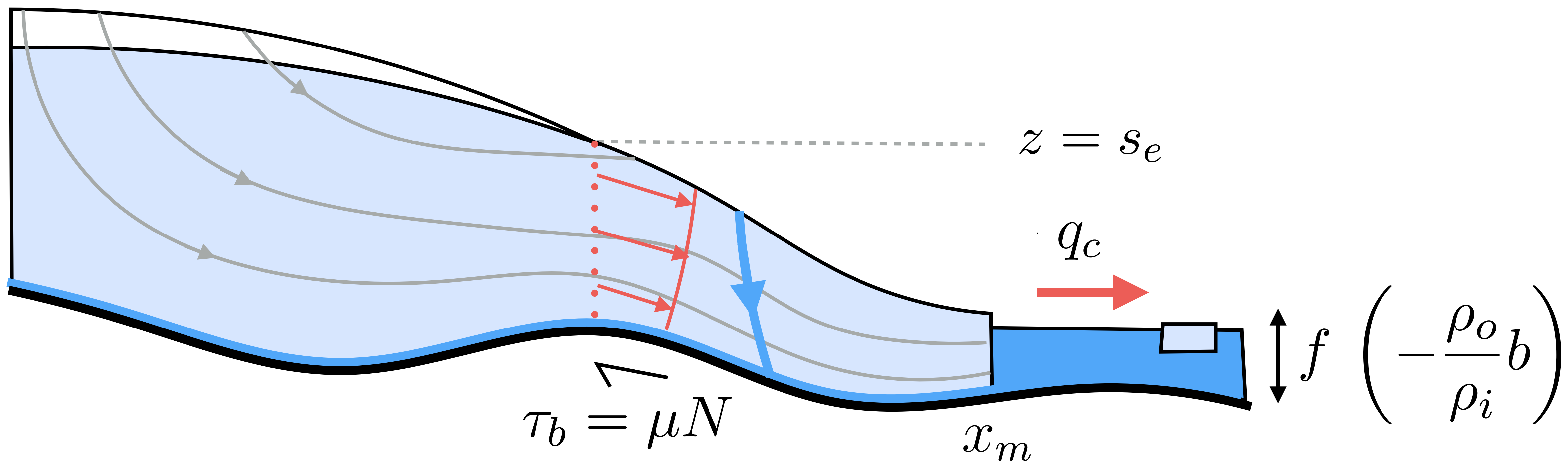

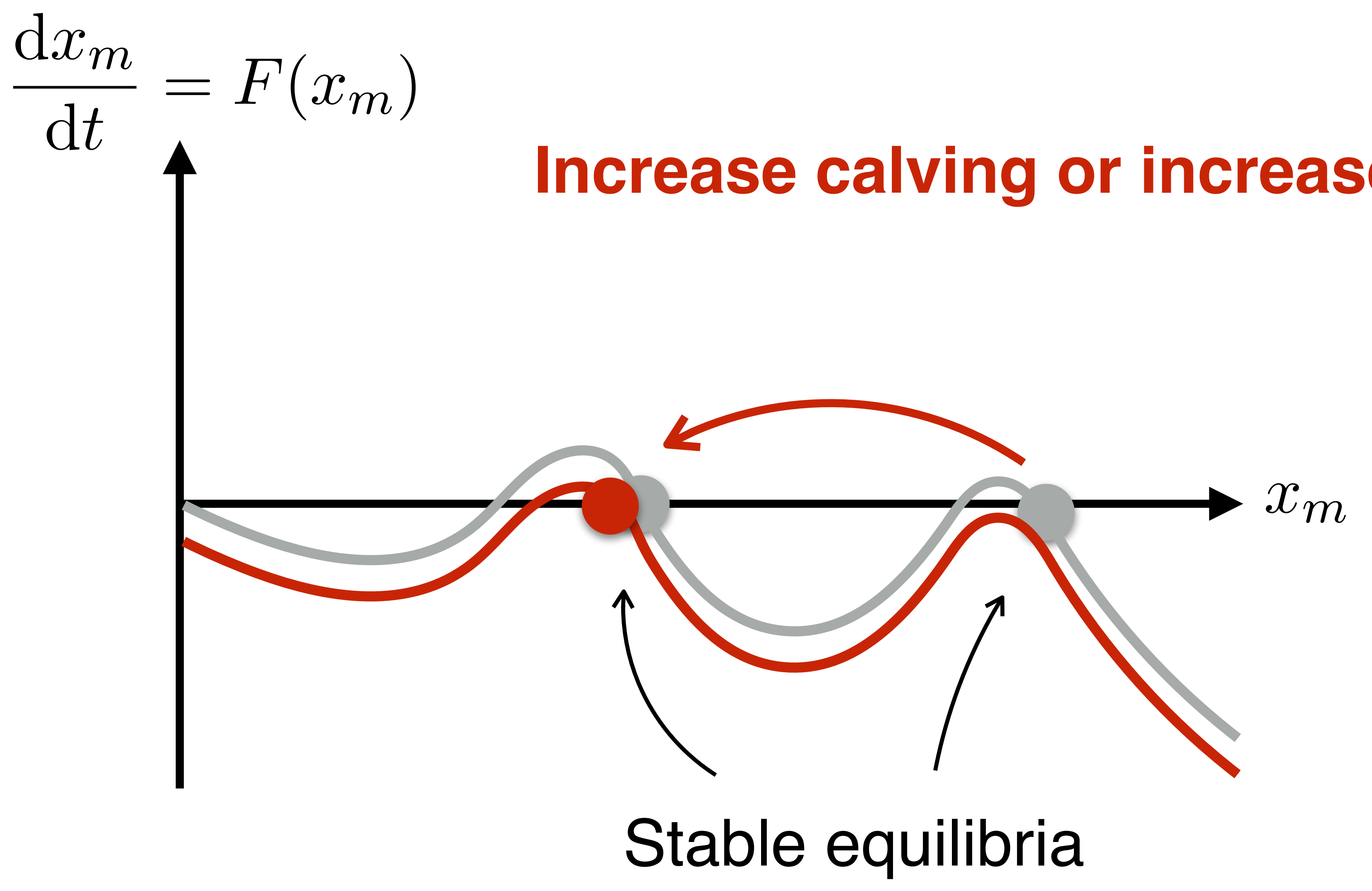

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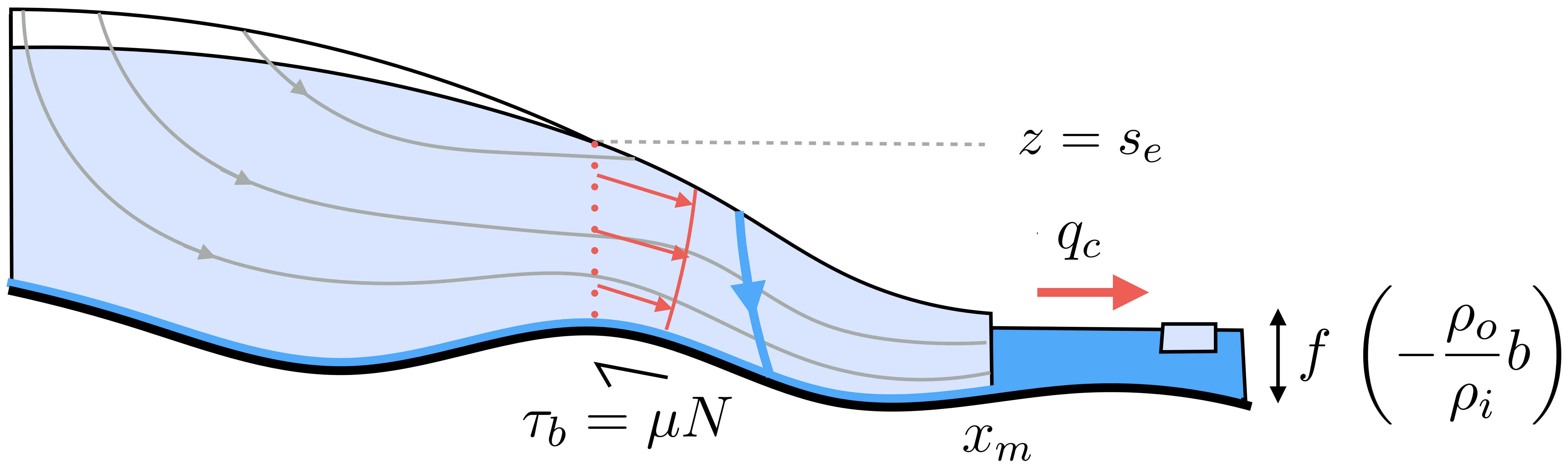

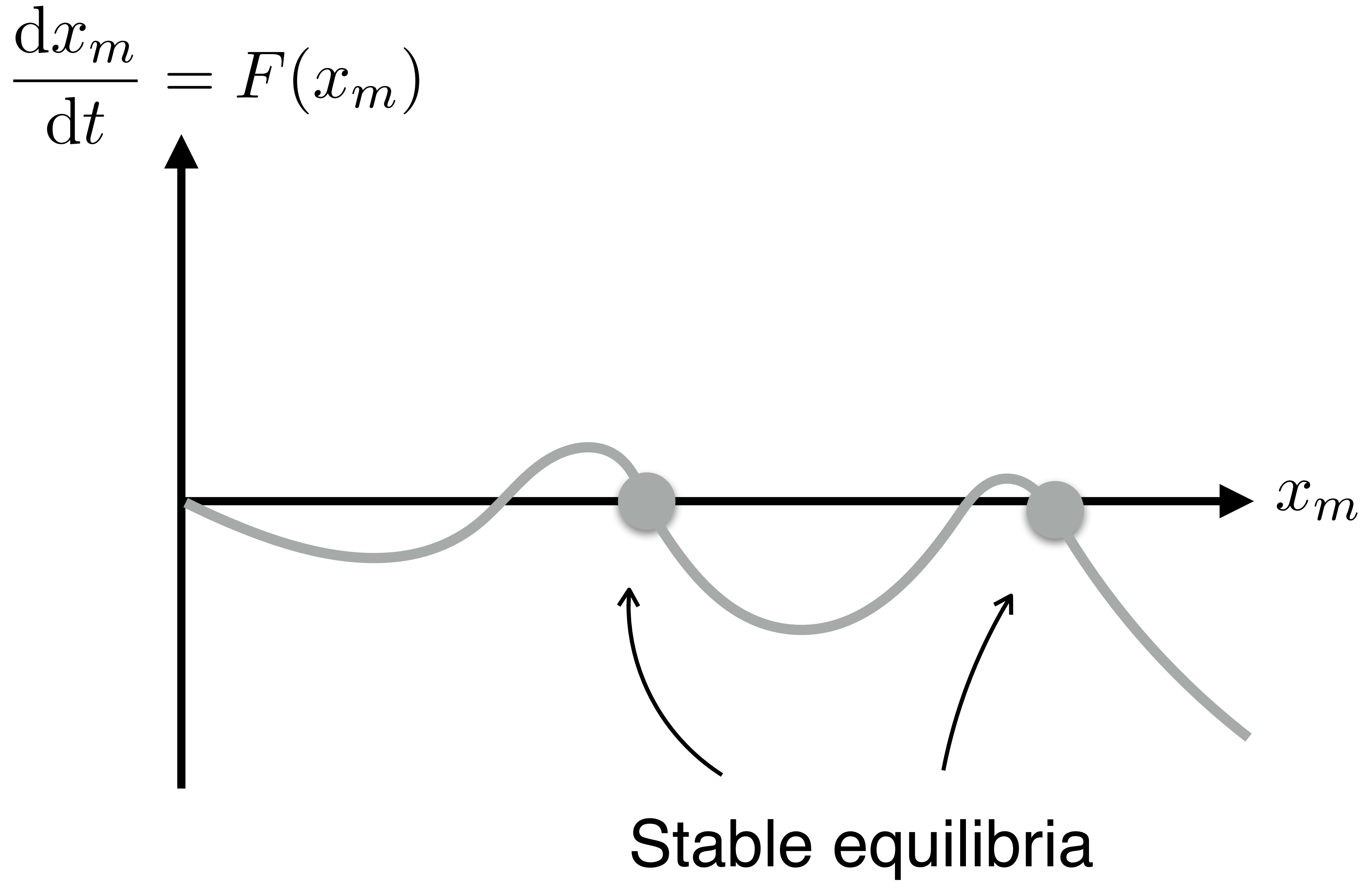

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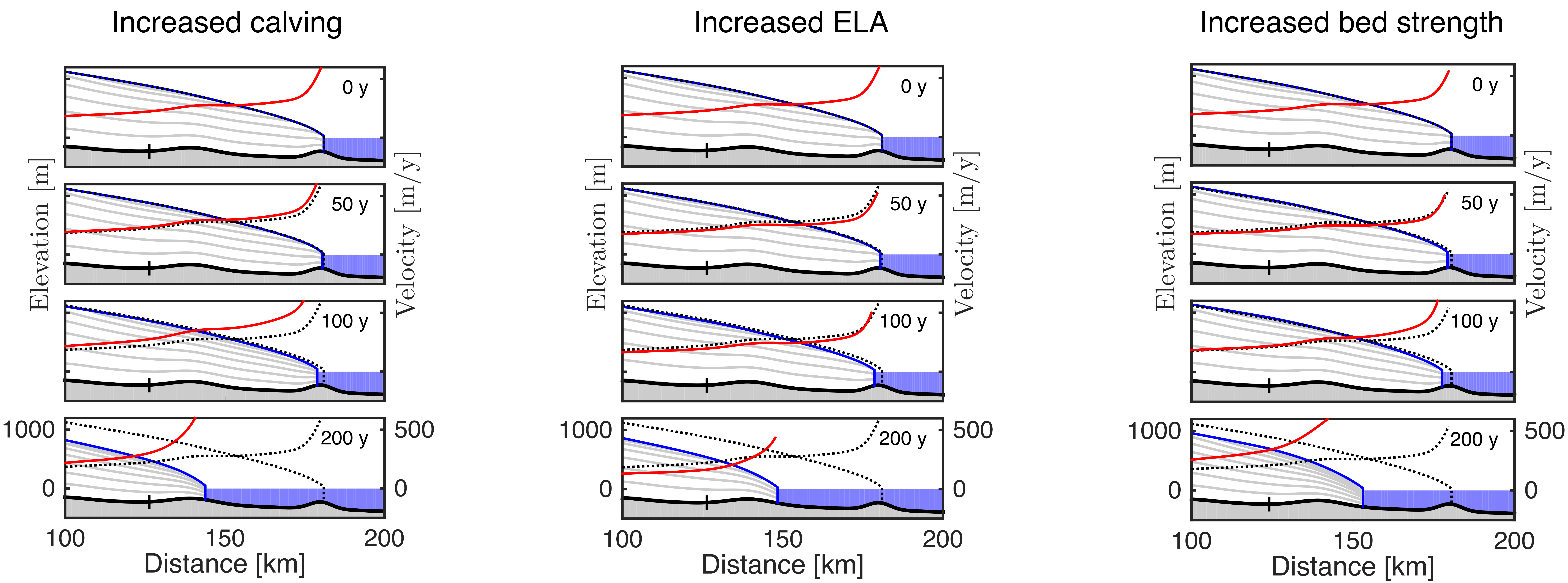
Response to different forcing

An essentially **indistinguishable** response can occur to very distinct forcing mechanisms.



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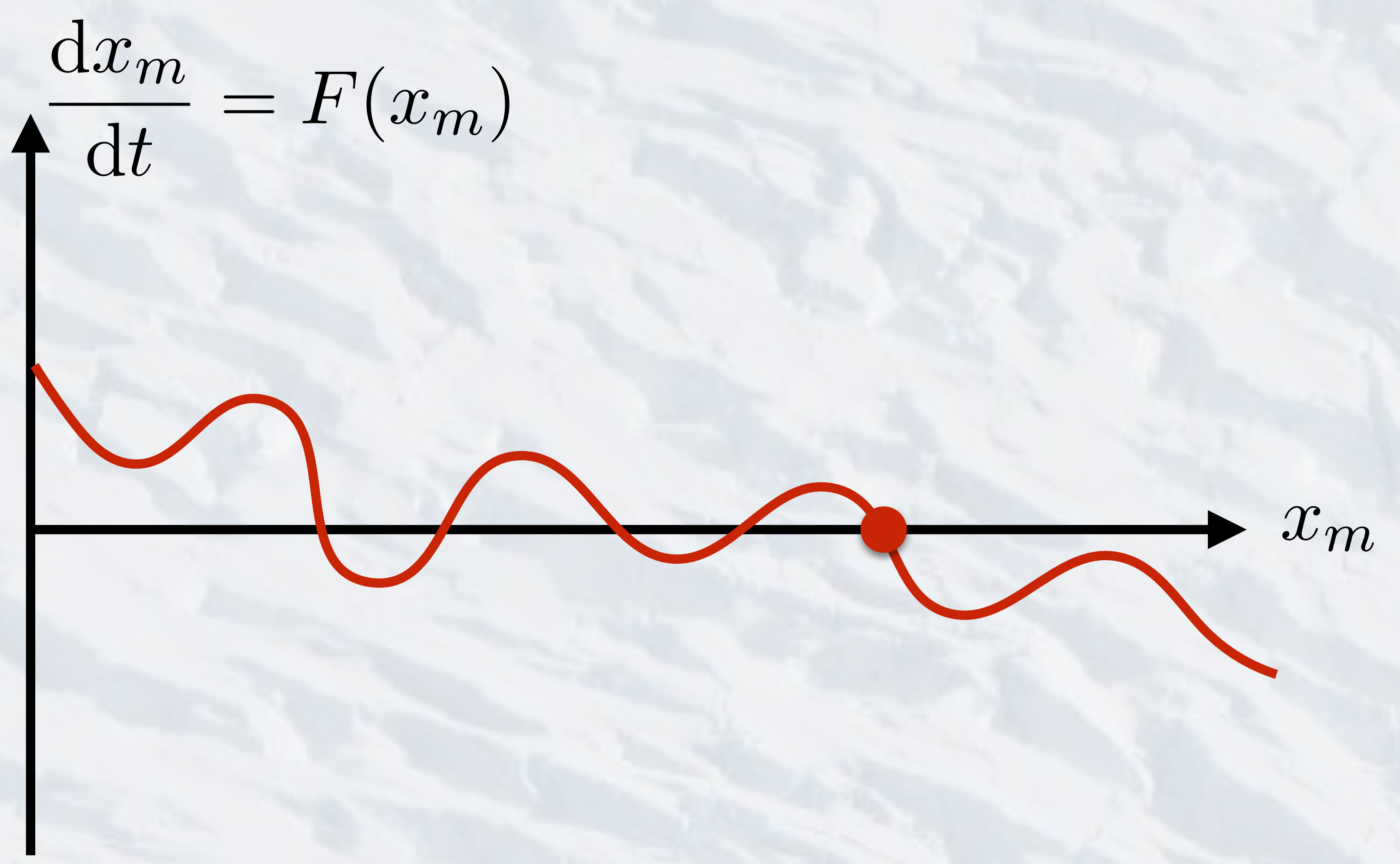
- Tidewater glaciers can be described as **a forced dynamical system.**
- **Episodic acceleration and deceleration** of a tidewater glacier is **generic**, in response to changes in **both oceanic and upstream** forcing.



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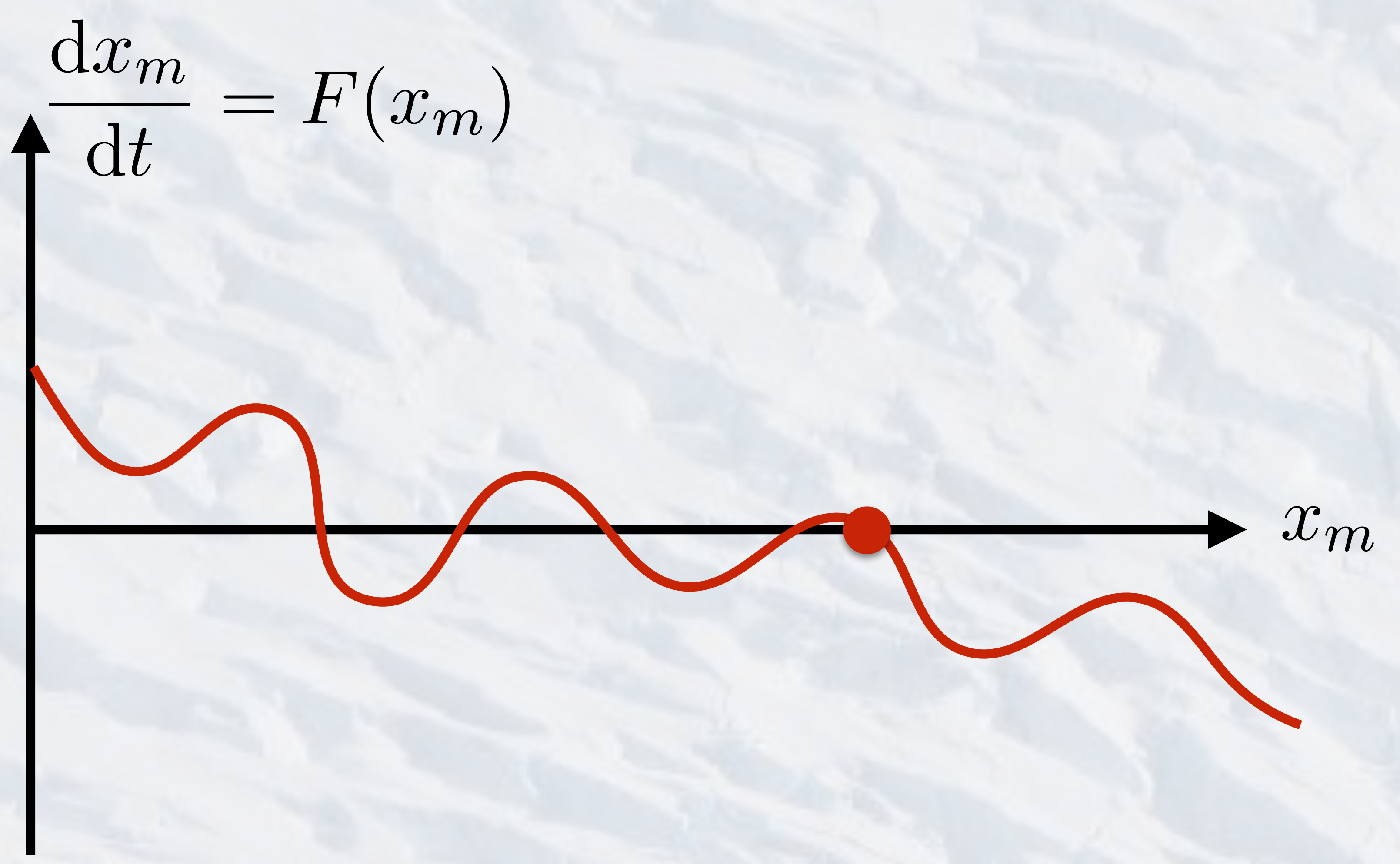

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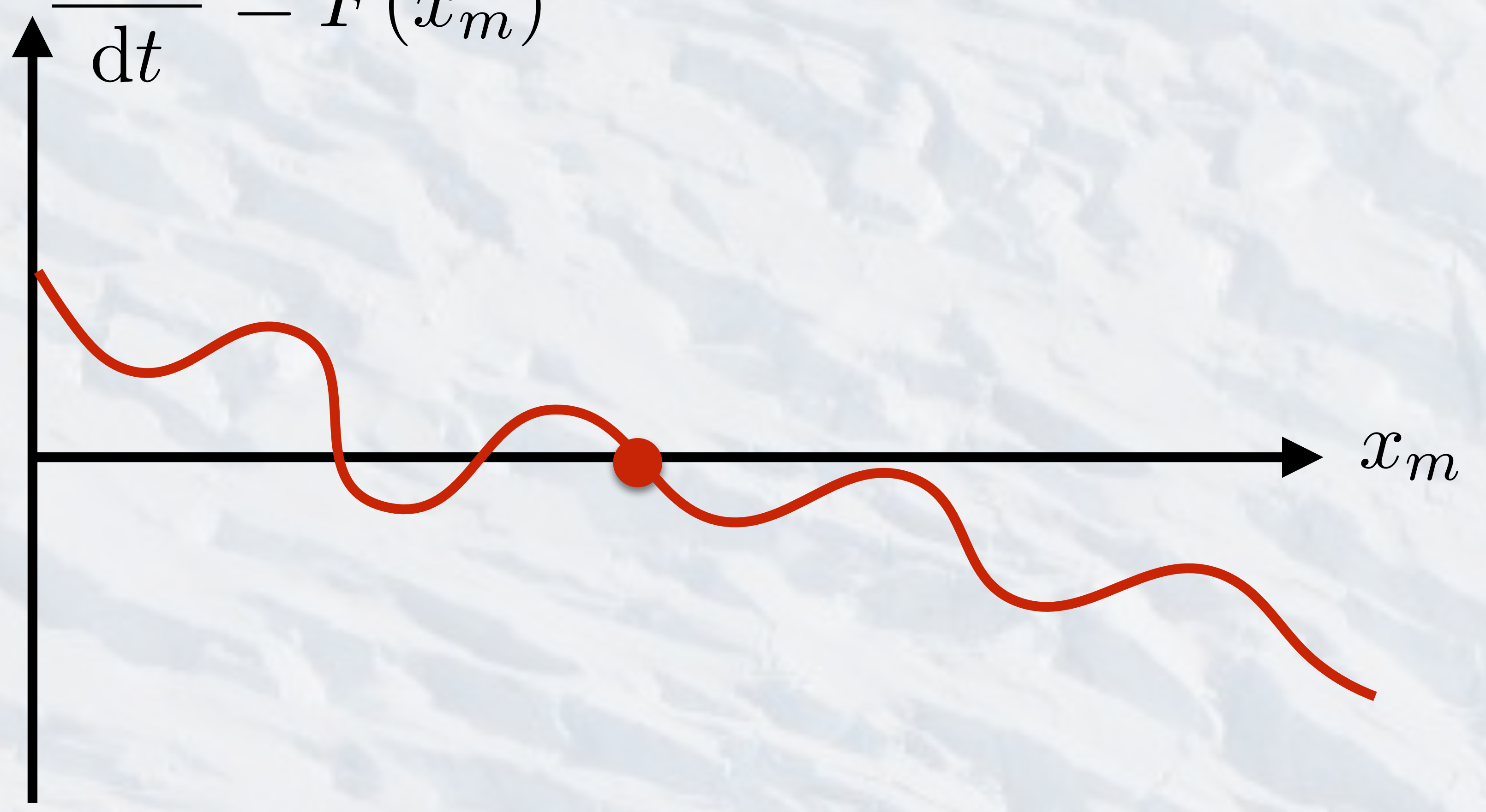

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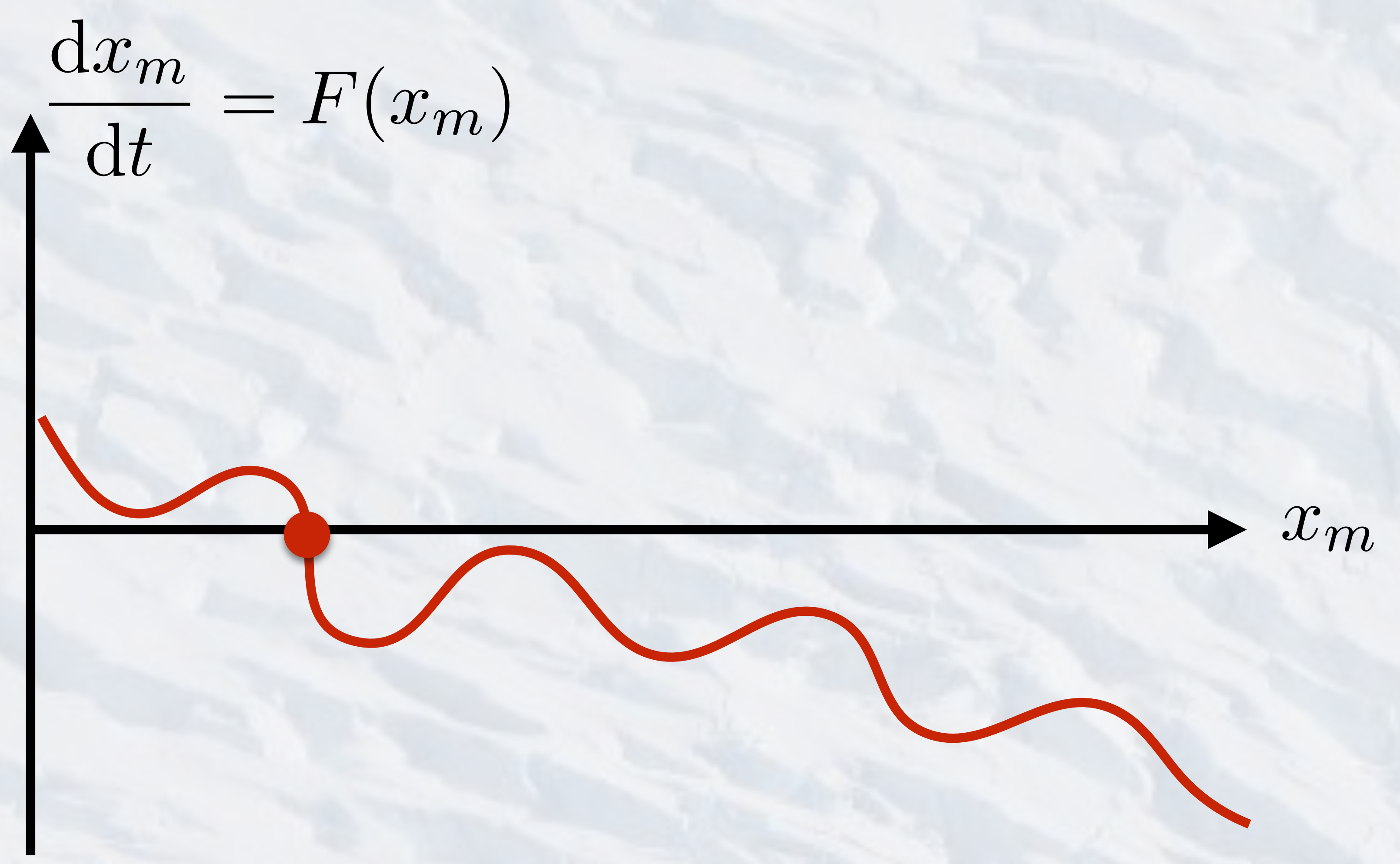

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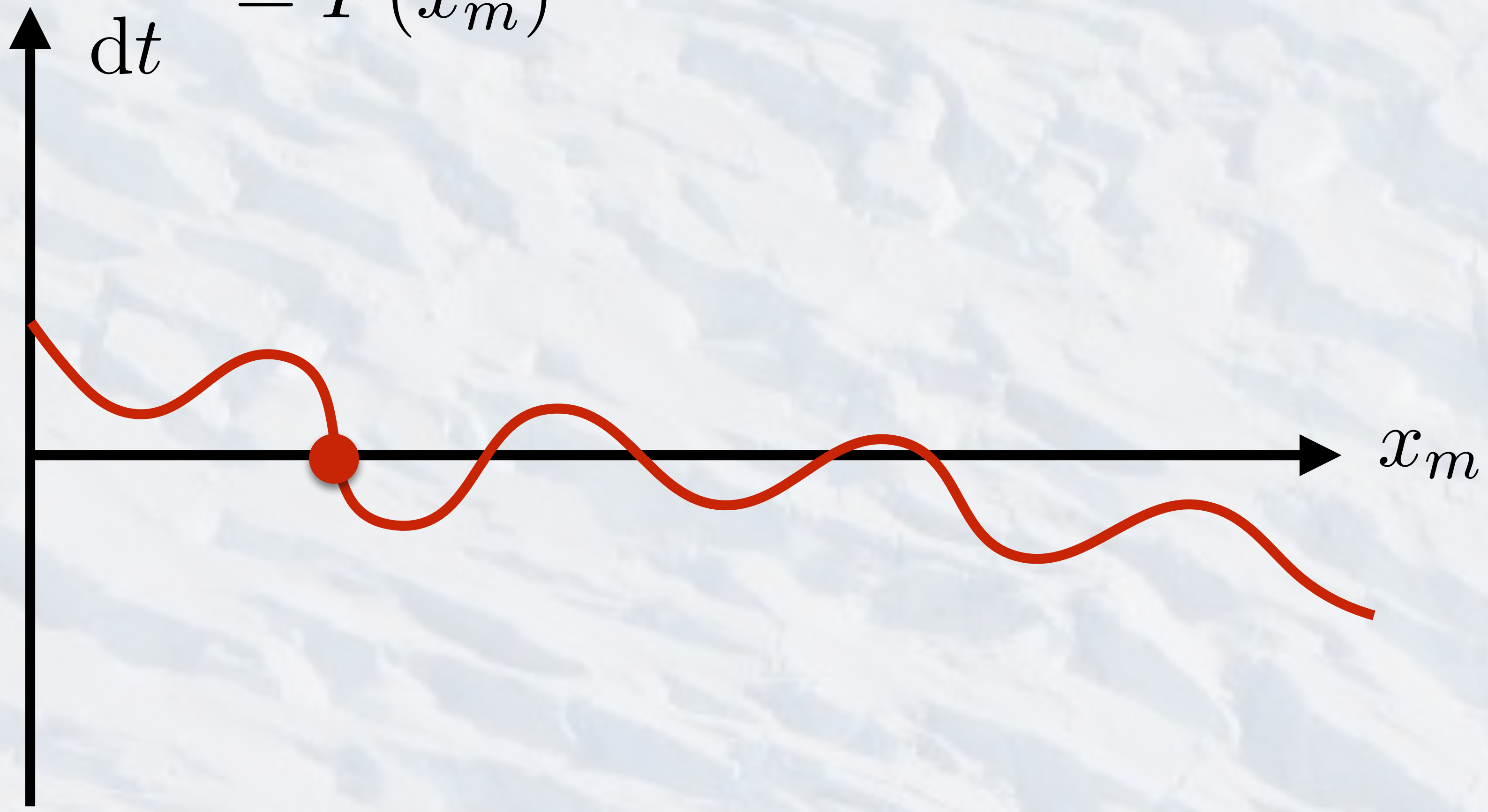

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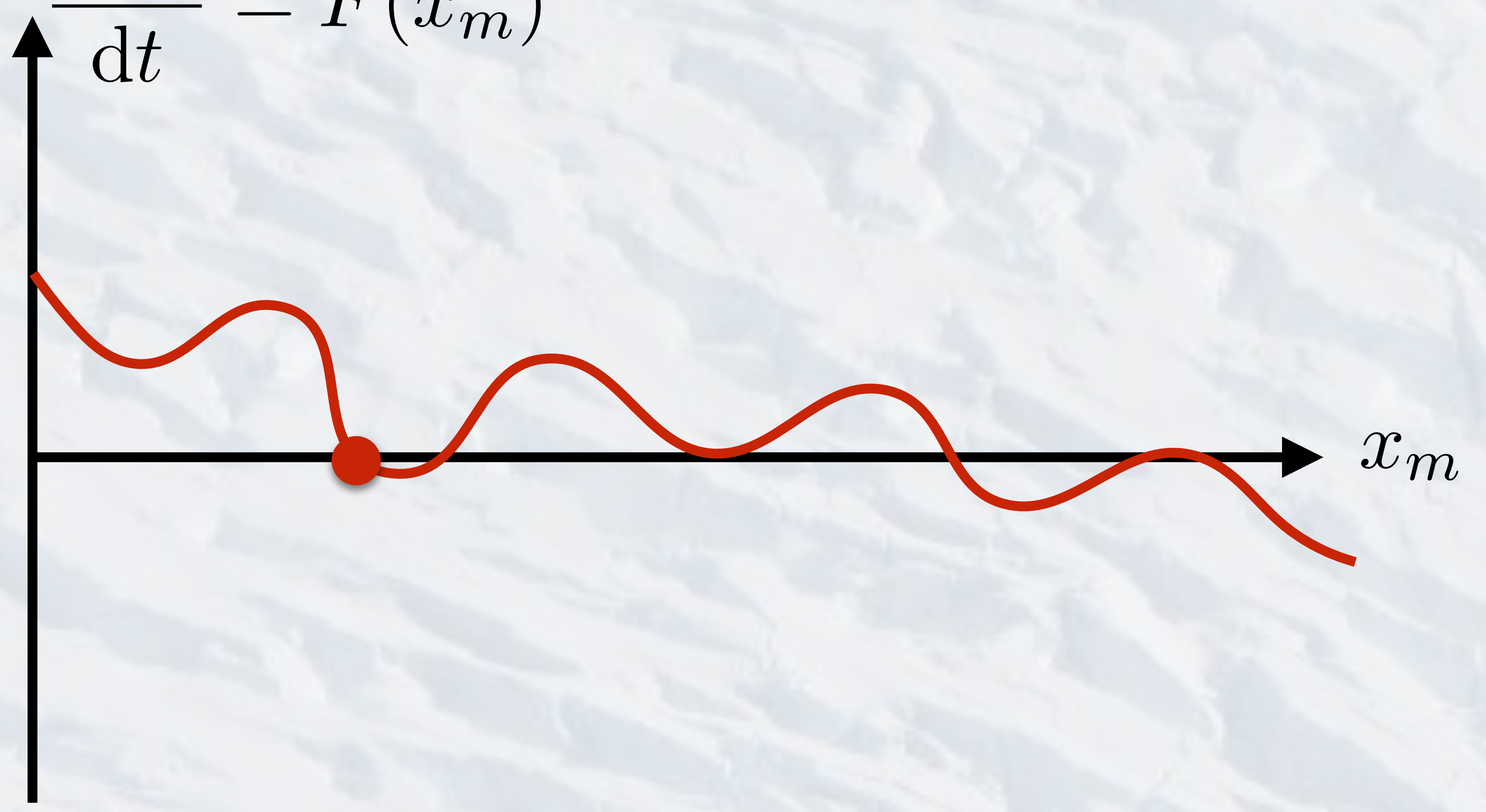

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