Limiting Regimes of a 3D Buoyant Hydraulic Fracture Emerging from a Point Source

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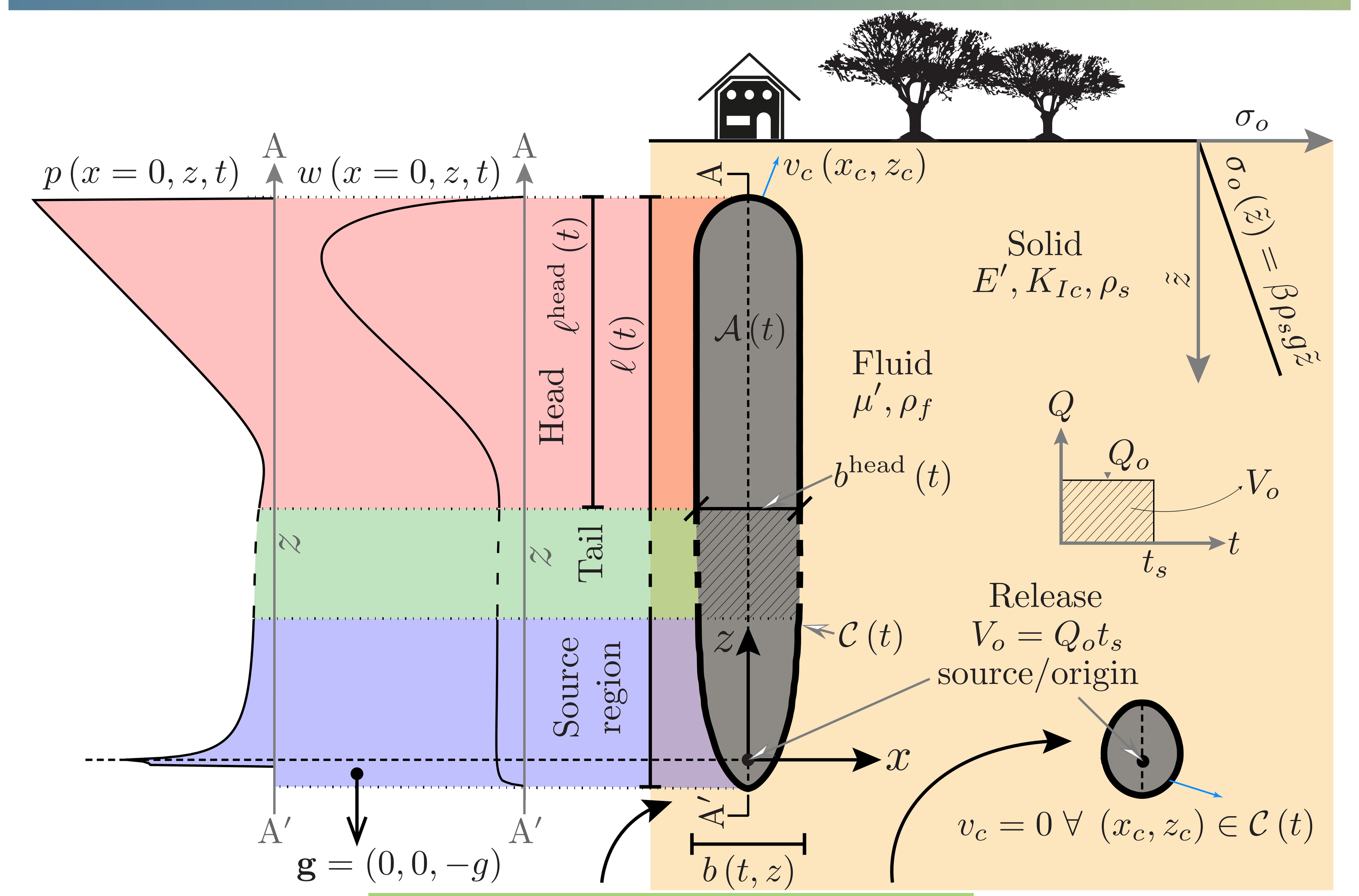
1. Problem formulation



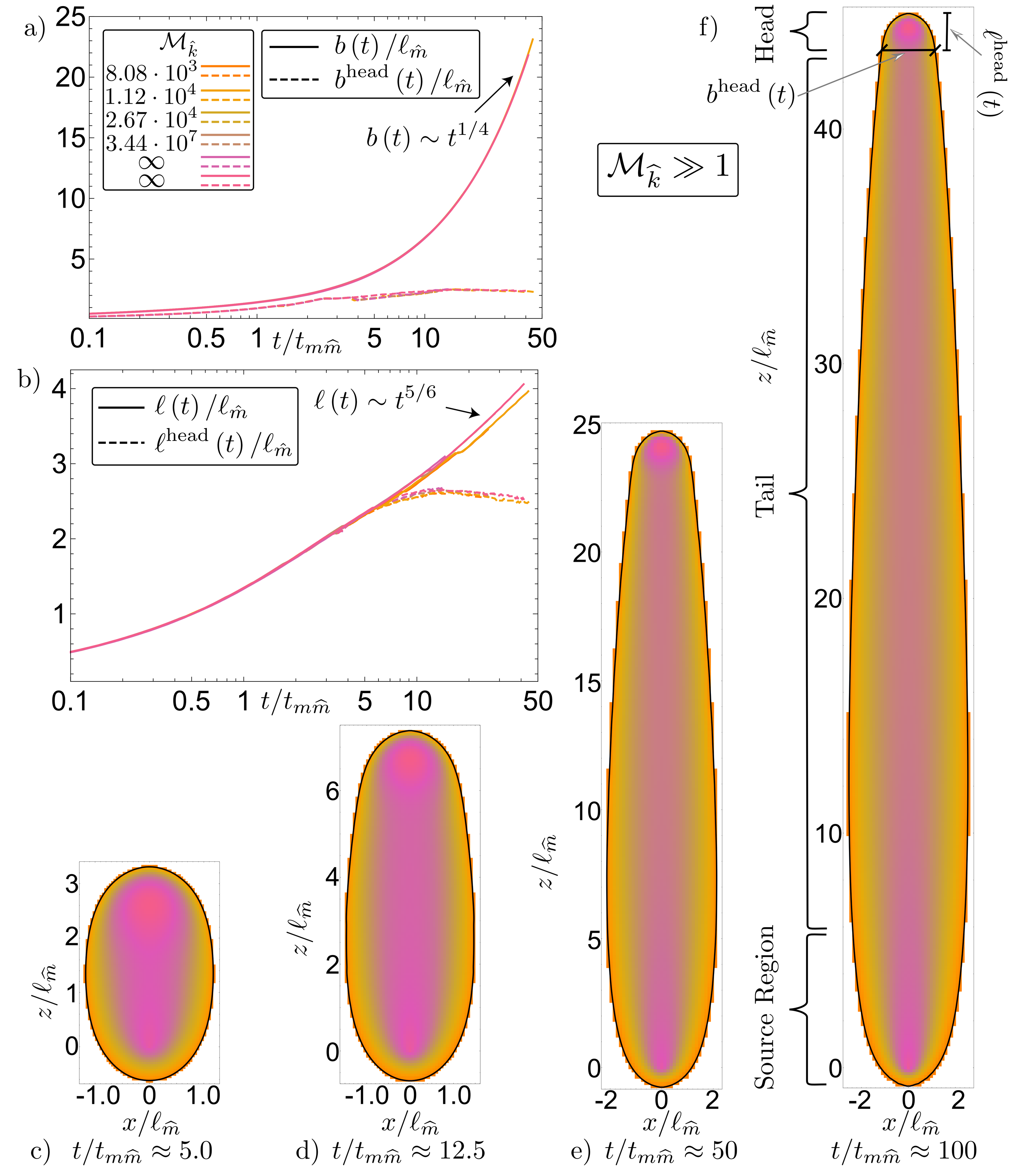
Does a self-sustained buoyancy-driven fracture emerge, or will the fracture arrest and remain at depth?

The problem of a planar mode I fracture assuming LEFM, no leak-off, and zero fluid-lag, is solved using PyFrac (Zia and Lecampion, 2020), an ILSA-based open-source solver. A scaling analysis reveals three main dimensionless coefficients

$$\mathcal{M}_{\hat{k}} = \mu' \frac{Q_o E'^3 \Delta\gamma^{2/3}}{K_{Ic}^{14/3}}, \quad \mathcal{B}_{\bar{k}} = \frac{\Delta\gamma E'^{3/5} V_o^{3/5}}{K_{Ic}^{8/5}}, \quad \mathcal{B}_{\bar{m}} = \frac{\Delta\gamma V_o^{1/3} t_s^{4/9}}{E'^{5/9} \mu'^{4/9}}$$

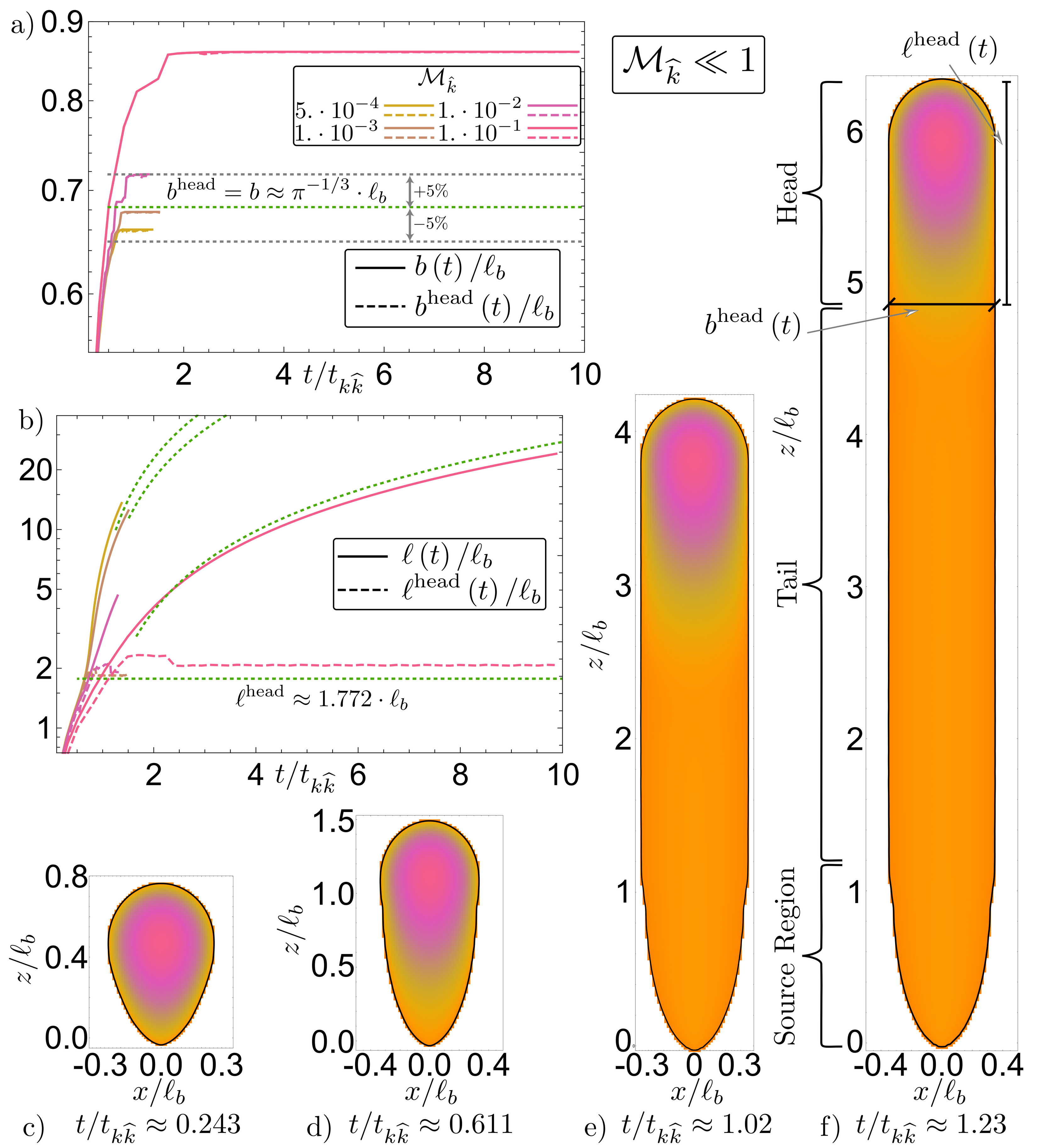
with $\Delta\gamma = (\beta\rho_s - \rho_f)\, g$. $\mathcal{M}_{\hat{k}}$ is a dimensionless viscosity parametrizing the continuous release and $\mathcal{B}_{\bar{k}}$ and $\mathcal{B}_{\bar{m}}$ dimensionless buoyancies parametrizing the finite volume release.

2. Continuous release, negligible toughness



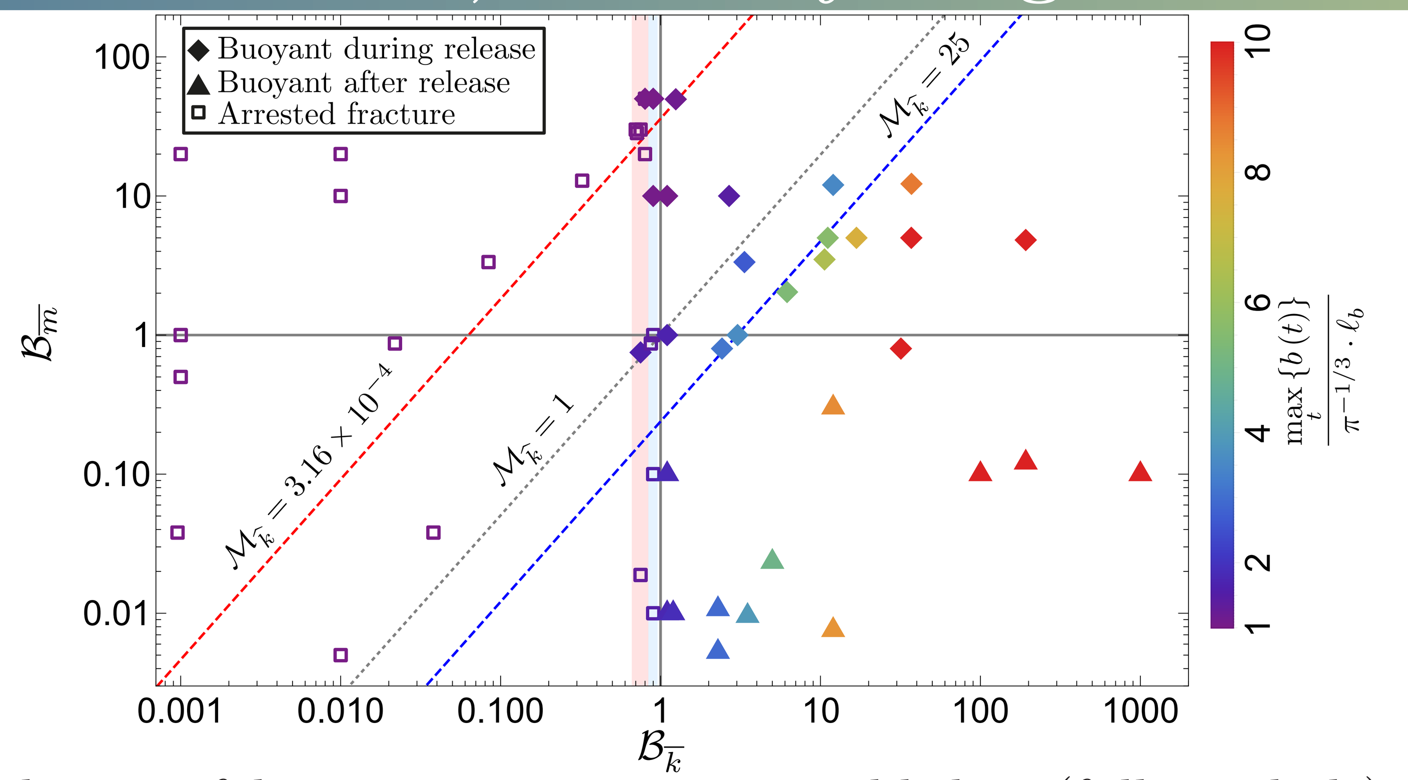
Evolution of a hydraulic fracture with a viscosity-dominated buoyant stage. A teardrop-shape with a increasing maximum breadth according to the pseudo-3D, zero-toughness prediction of Lister (1990) emerges. We indicate the corresponding power laws in time for the maximum breadth b and the fracture height ℓ in Figs. a) and b). A distinction in head ($\sim$ cst.), tail, and source region is possible. a) Maximum and head breadth. b) Head and total length. c-f) Footprints with opening distribution at different times. $t_{m\hat{m}}$ is the transition time from radial to buoyant, $\ell_{\hat{m}}$ the viscous buoyancy length-scale.

3. Continuous release, large toughness



Evolution of a hydraulic fracture with a toughness-dominated buoyant stage. We validate the linear net pressure in the head, leading to a constant breadth of the fracture. Germanovich et al. (2014) derived a semi-analytical solution for this configuration, which we validate within numerical precision (green dotted lines). Their unique pre-factor on the stable breadth represents a zero-viscosity limit. Solutions with a larger stable breadth exist. The fracture form features a cst. head, an elongating tail, and a source region. a) Maximum and head breadth. b) Head and total length. c-f) Footprints with opening distribution at different times. $t_{k\hat{k}}$ is the transition time from radial to buoyant, ℓ_b the buoyancy length-scale (Lister and Kerr, 1991).

4. Pulse release, arbitrary toughness



$\mathcal{B}_{\bar{k}}$ indicates if buoyant propagation establishes (full symbols). At late time, the head breadth approaches the zero-viscosity limit. The color code shows the fraction between maximum and limiting breadth. Various general shapes for the final buoyant crack exist, the shape is largely dominated by a combination of $\mathcal{B}_{\bar{k}}$ (x-axis) and $\mathcal{B}_{\bar{m}}$ (y-axis).

5. Conclusions

- During the release, a family of solutions in function of $\mathcal{M}_{\hat{k}}$ with two limiting regimes emerges. The toughness limit is akin to a finger-like / blade-shaped fracture || the viscous limit has a teardrop shape with an increasing maximum breadth.
- For a finite volume release, a self-sustained, buoyancy-driven crack emerges if $\mathcal{B}_{\bar{k}} \geq 1$. Its shape additionally depends on $\mathcal{B}_{\bar{m}}$.
- Most geotechnical and natural applications have negligible toughness or are in between the limits and have $\mathcal{B}_{\bar{k}} > 1$.

For more information and references, see the online version of the poster or check our labs' webpage for publications (see QR-codes).

Take home message

Calculating a **single coefficient** $\mathcal{B}_{\bar{k}}$ from solid, fluid, and release properties is sufficient to know if a **buoyancy-driven, self-sustained** fracture emerges.