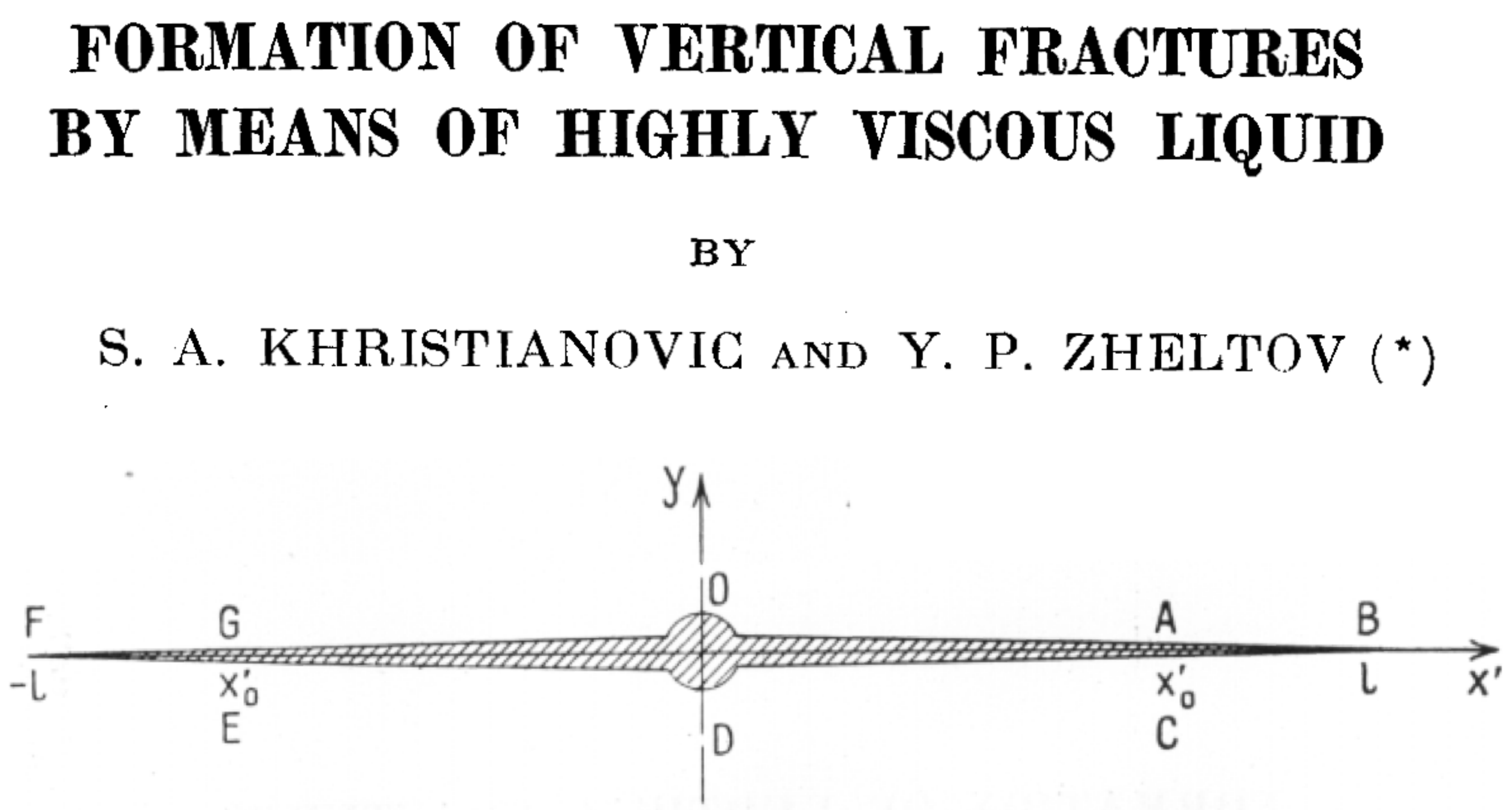
Mechanics of Fluid-Driven Fracture: an Update

Emmanuel Detournay and many collaborators
University of Minnesota

60th Rock Mechanics/Geomechanics Symposium
Tucson, Arizona

The Four Ages of HF Modeling

- The age of the pioneers (1955-80)
  - Simple HF Geometries (KGD, Radial, PKN, P3D)
  - Khristianovitch & Zheltov, Perkins & Kern, Nordgren, Geertsma, Cleary, Nolte…


FORMATION OF VERTICAL FRACTURES BY MEANS OF HIGHLY VISCOUS LIQUID

BY

S. A. KHRISTIANOVIC AND Y. P. ZHELTOV (*)

Fig. 1

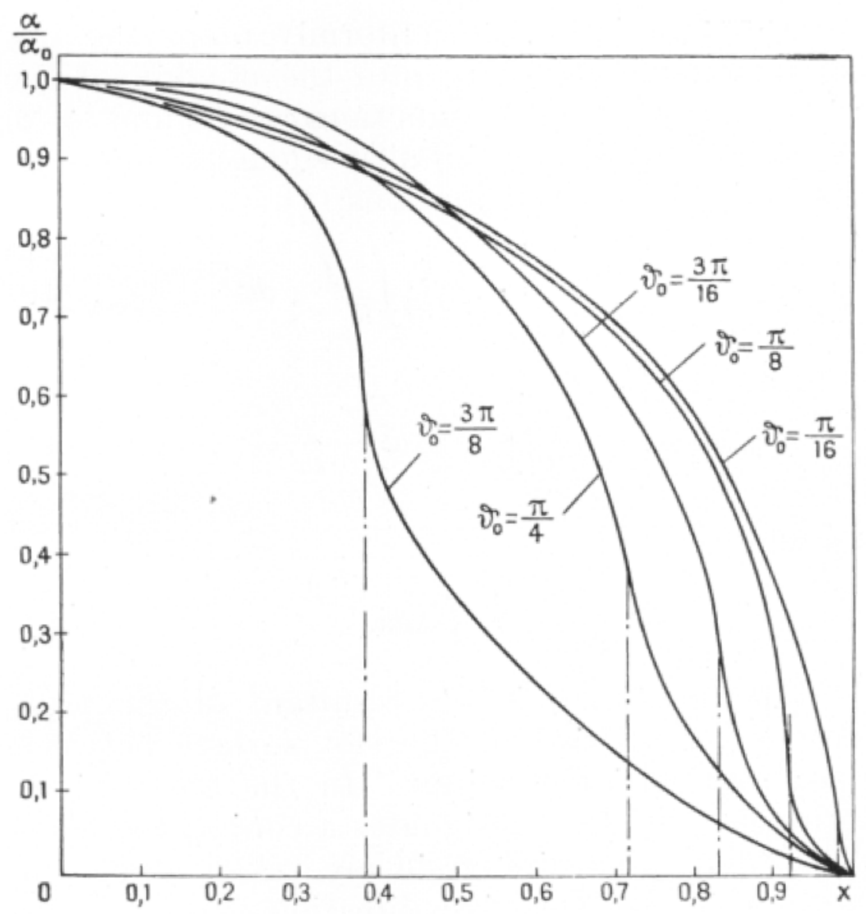


Fig. 3

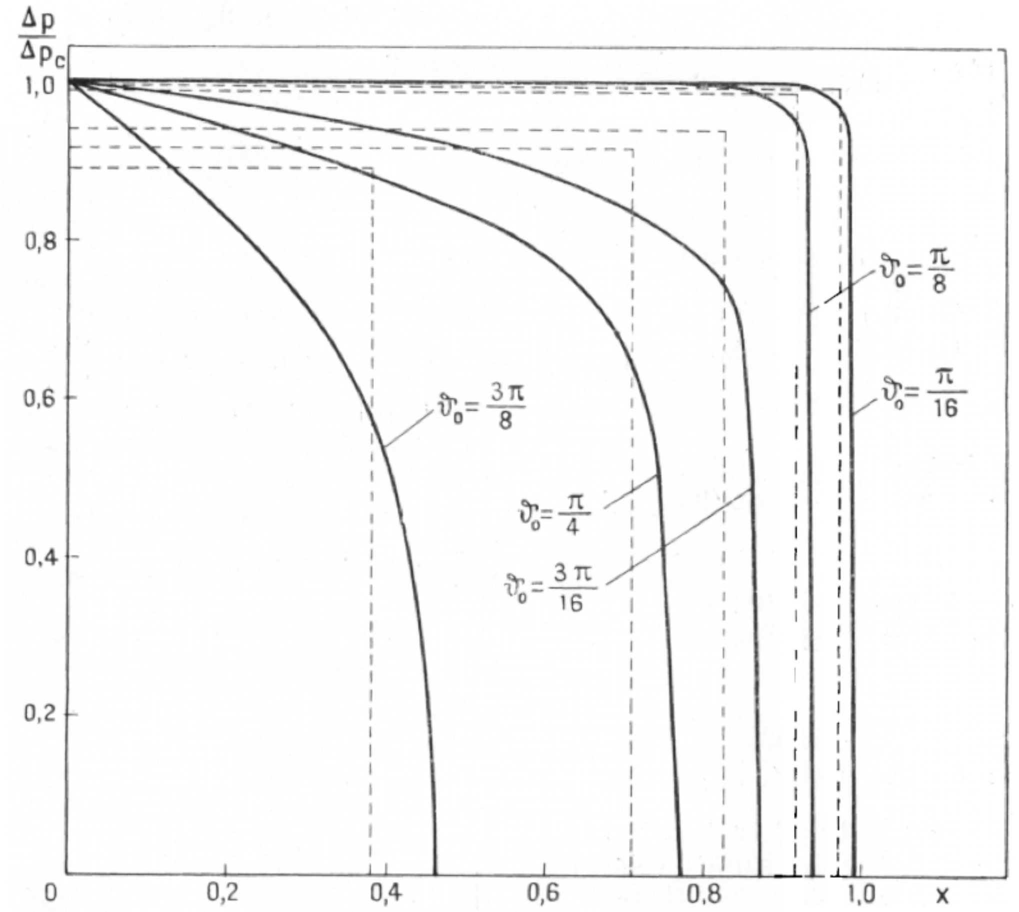


Fig. 5.

- The dark age (1975-   )
  - Numerical models, but little understanding of the real complexities
  - How to handle the evolving footprint of the fracture?

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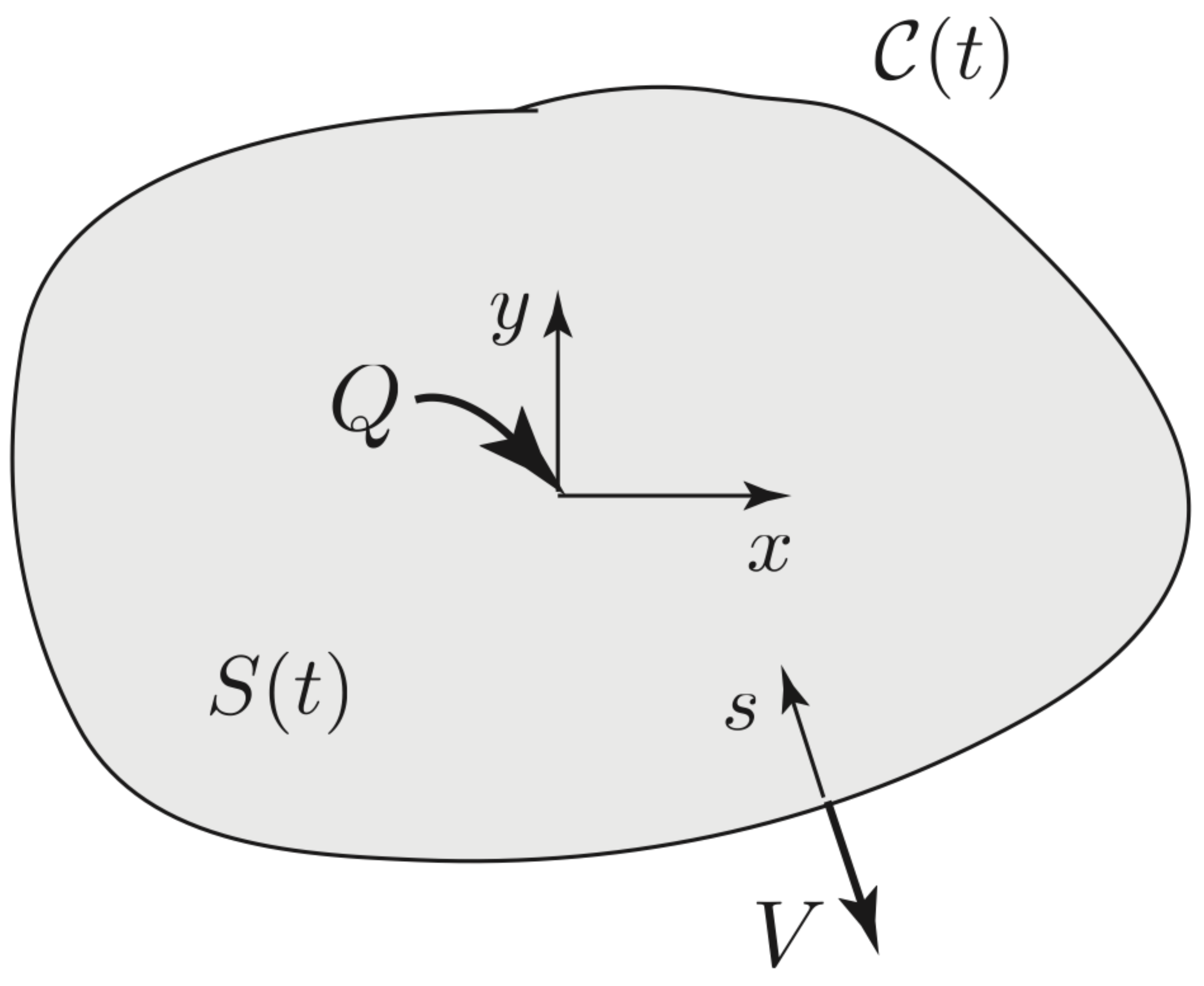
  - How to handle the evolving footprint of the fracture?
- The age of enlightenment (1985-05)
  - Seminal contributions from Spence and Sharp, Lister, ...
  - Multiscale problem, asymptotic analysis (tip), reference solutions
- The modern era (2000-)
  - Planar fractures with complex footprints, interaction with joints and other fractures



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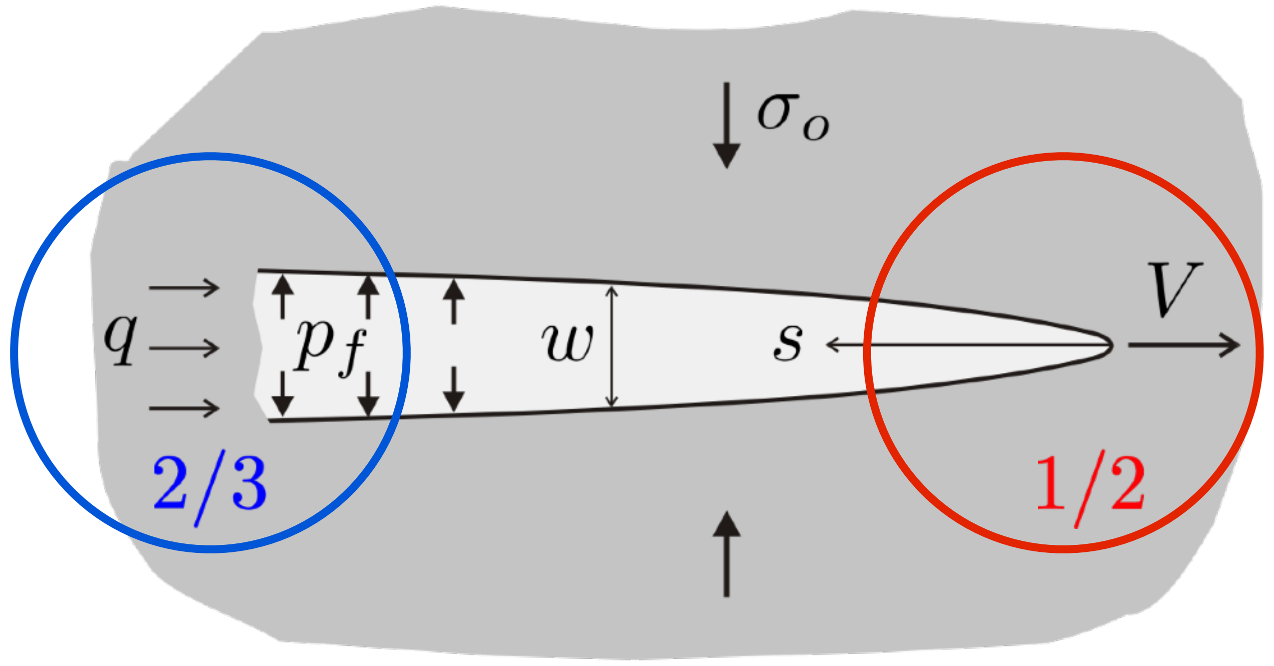

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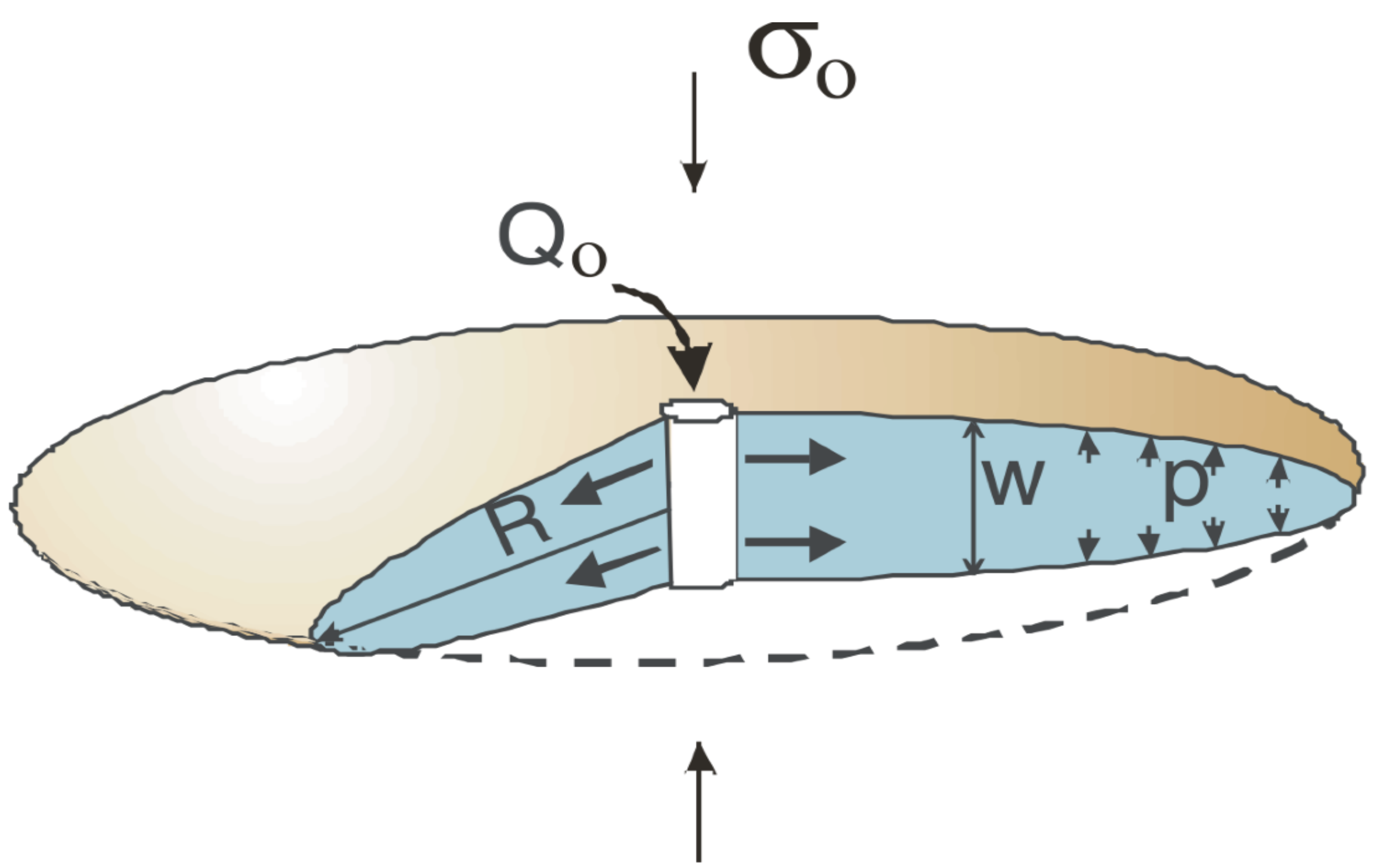
Penny-Shaped HF in Impermeable Elastic Rock

- Similarity solutions:
  - M-vertex ($K' = 0$) also small time solution
  - K-vertex ($\mu' = 0$) also large time solution
- Energy Dissipation:
  - Competition between viscosity (M) and toughness (K)
  - Time scale of the MK transition



time, *t*

M-Vertex

Viscosity

$$R \sim t^{4/9}$$
$$w \sim t^{1/9}$$
$$p \sim t^{-1/3}$$

$$t_{mk} = \left(\frac{Q_o^3 \mu'^5 E'^{13}}{K'^{18}} \right)^{1/2}$$

Radial Fracture

K-Vertex

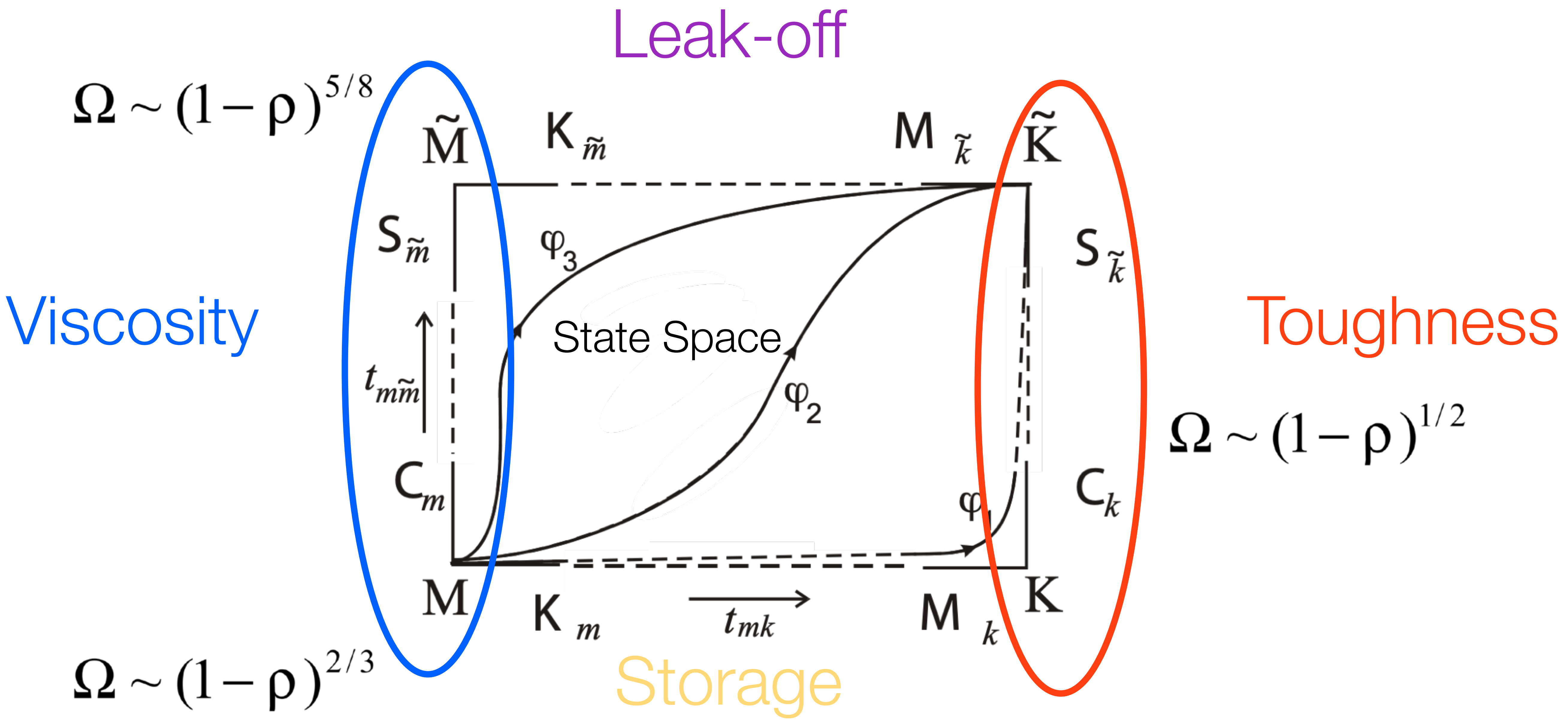
Toughness

$$R \sim t^{2/5}$$
$$w \sim t^{1/5}$$
$$p \sim t^{-1/5}$$

Savitsky & D, 2002

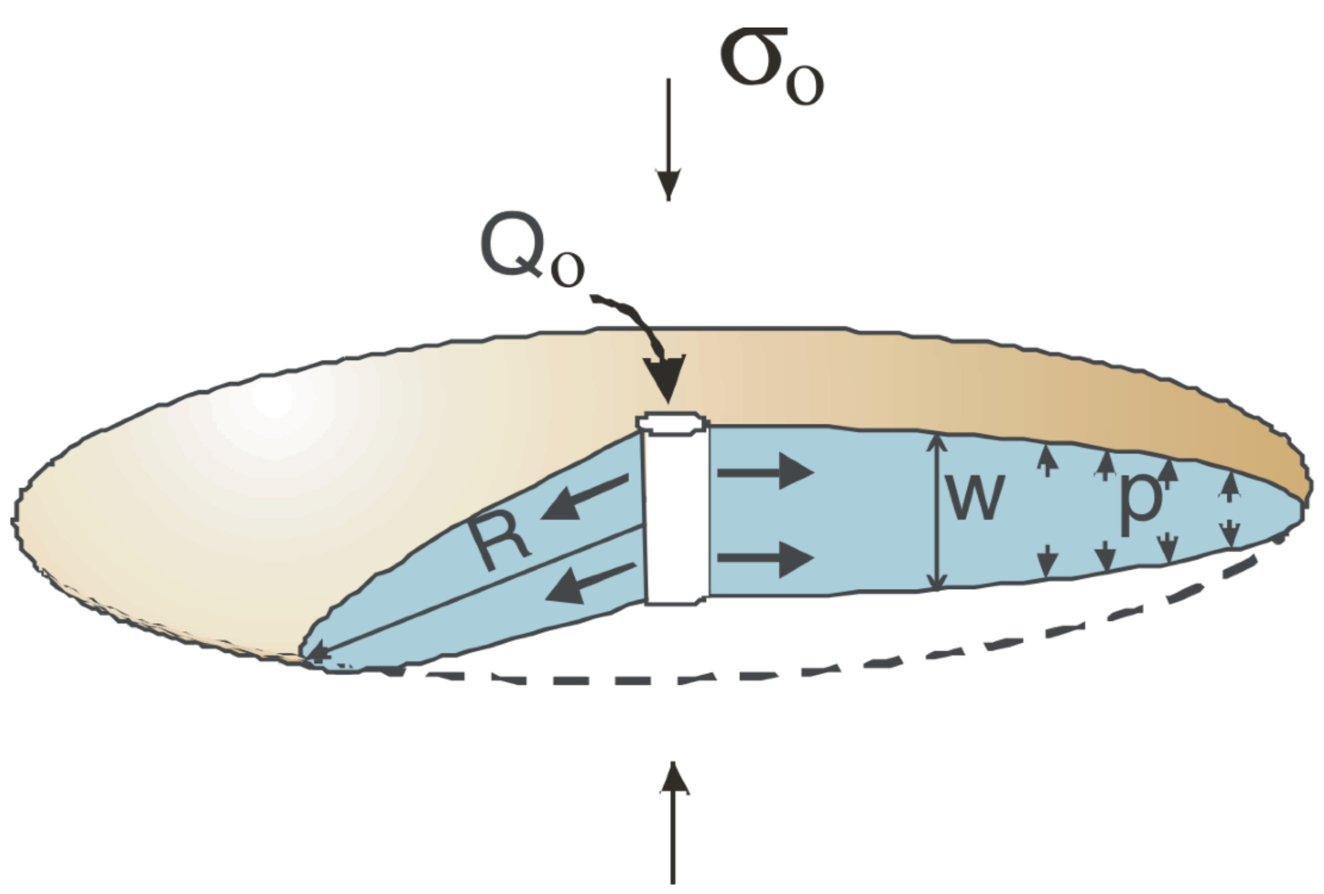
Penny-Shaped HF in Permeable Elastic Rock

- How is the energy dissipated?
- Where is the fluid stored?
- Two time scales



Trajectory parameter: $\varphi = \dfrac{t_{mk}}{t_{m\tilde{m}}}$

$$t_{mk} = \left(\frac{\mu'^5 E'^{13} Q_o^3}{K'^{18}}\right)^{1/2}, \quad t_{m\tilde{m}} = \left(\frac{\mu'^4 Q_o^6}{E'^4 C'^{18}}\right)^{1/7}$$



Energy Dissipation	=	Fluid Viscosity	+	Material Toughness

Timescale 1

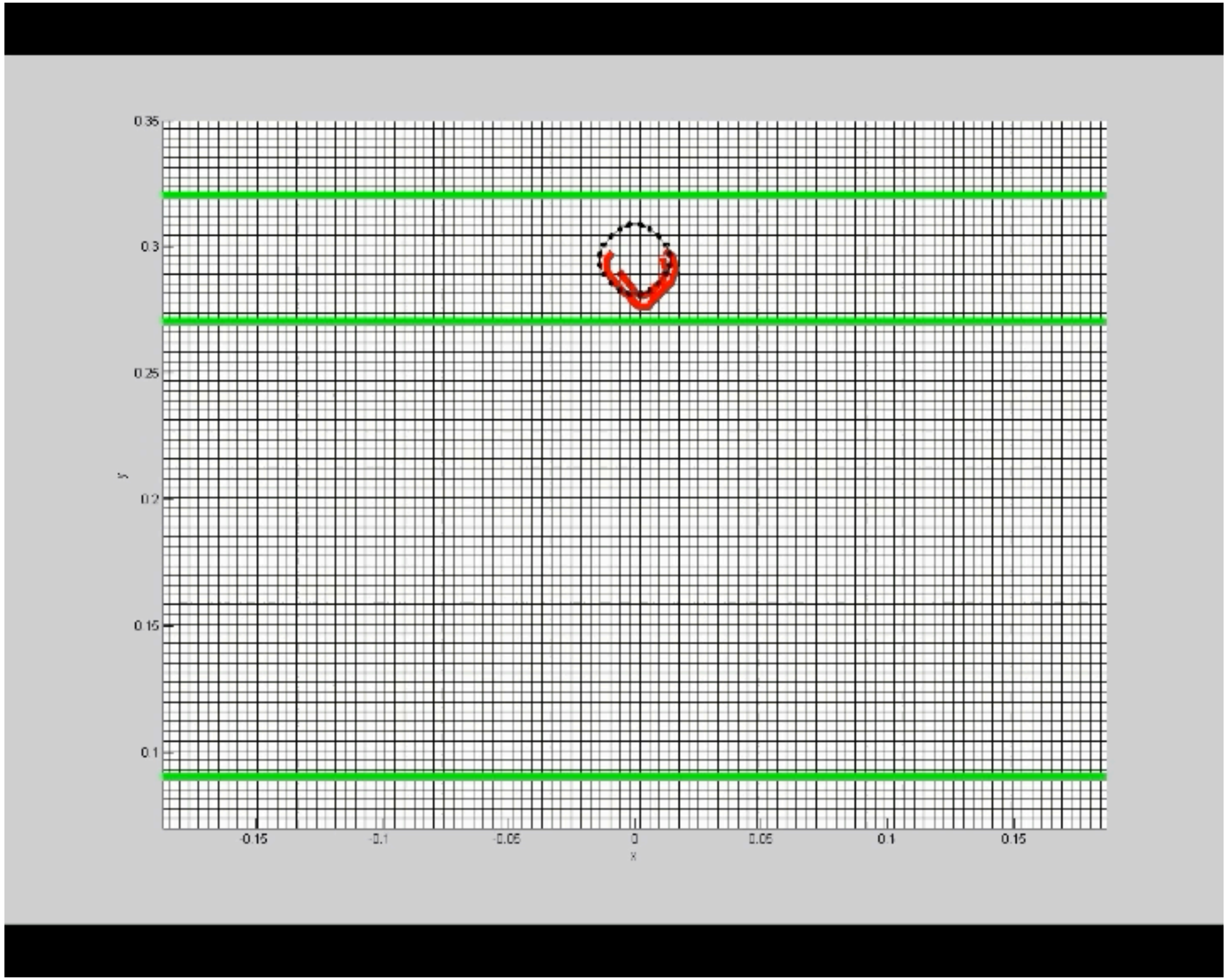
Injected Volume	=	Crack Volume	+	Leaked-off Volume

Timescale 2

Experiment-Simulation

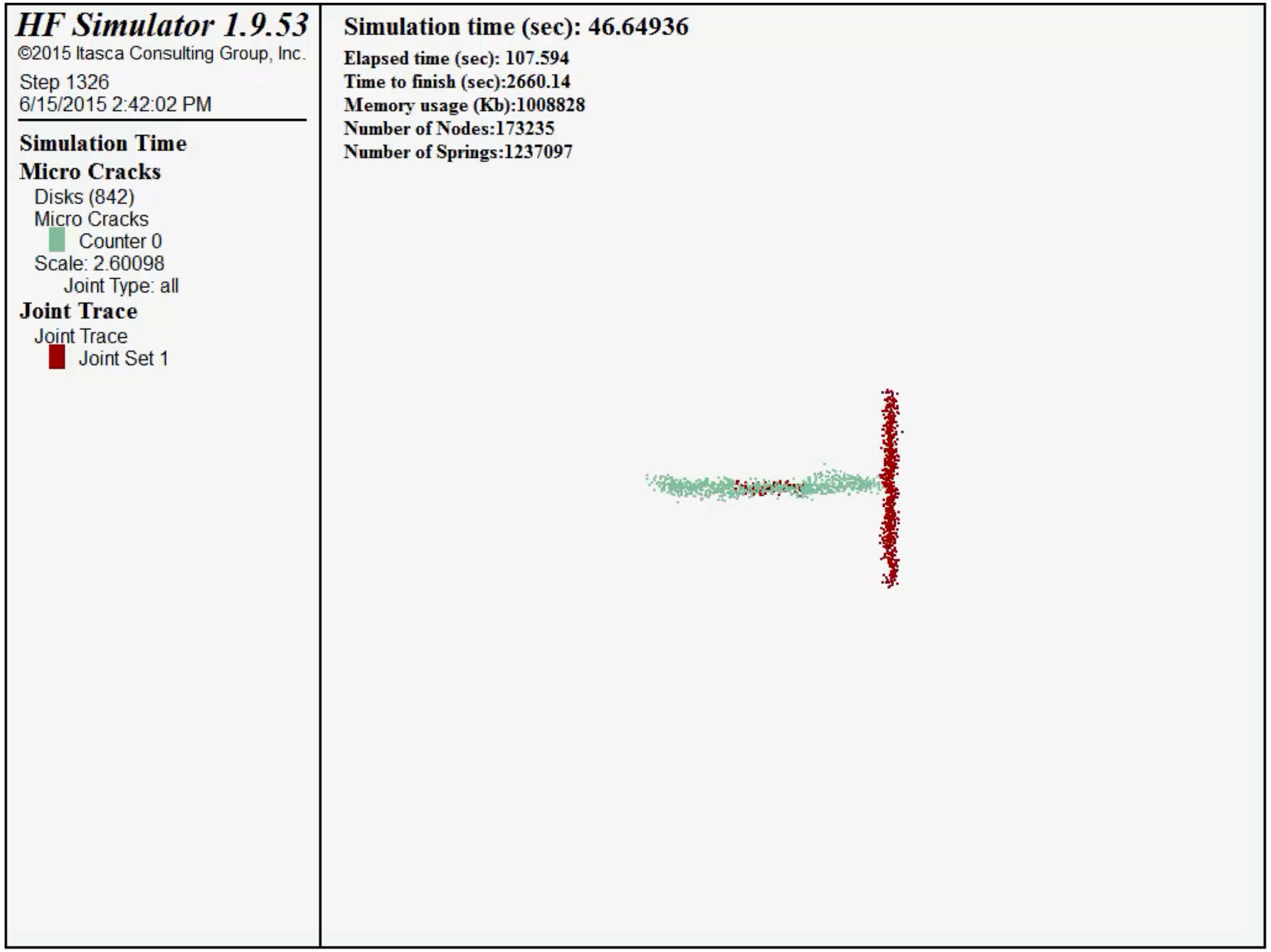
(Jeffrey & Bunger, 2009)
(Peirce, 2013)

Viscosity Regime



Lattice Model

- Interaction of HF with a preexisting joint



(Damjanac, Detournay-Piette, Cundall, 2015)

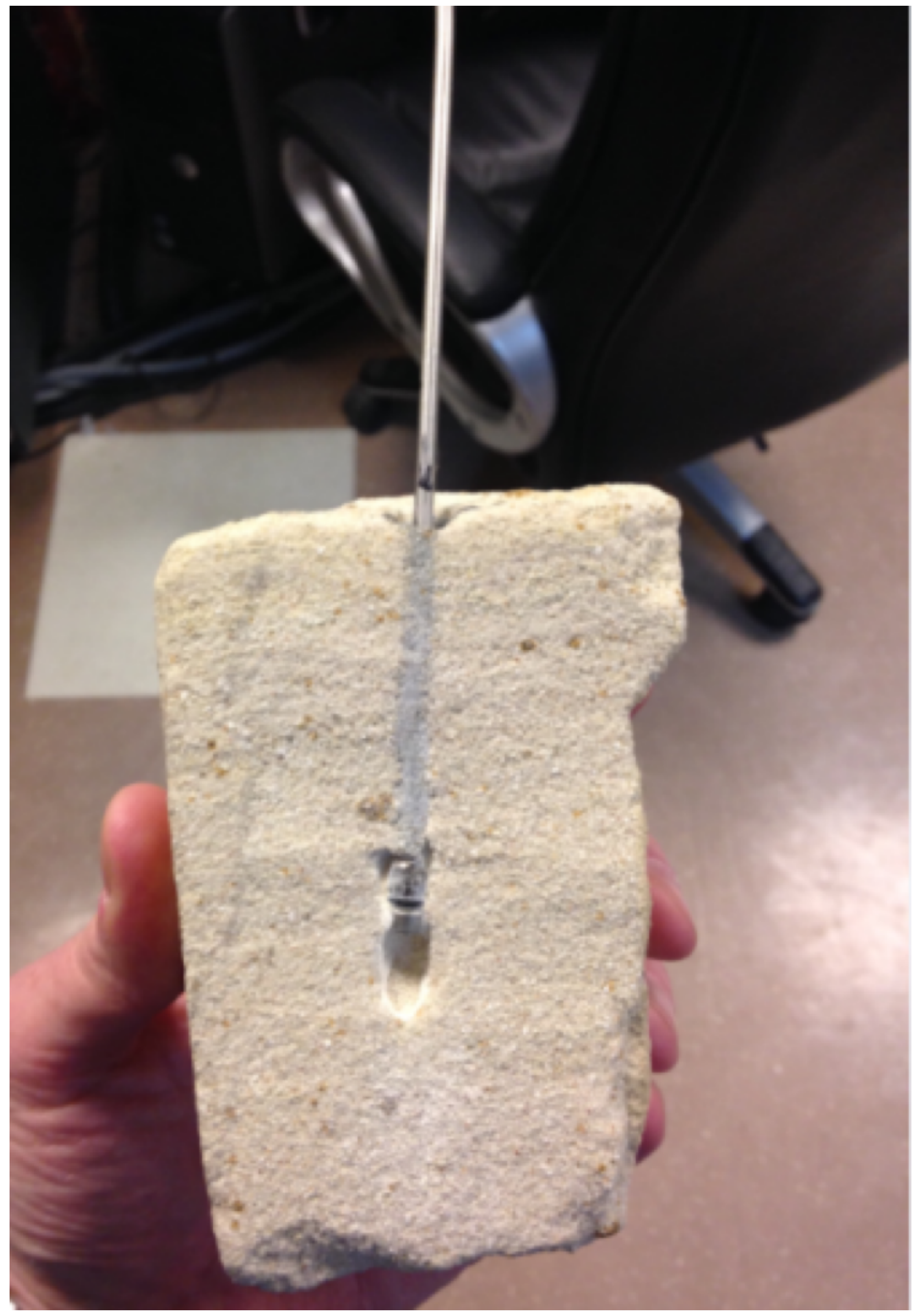
Propagating Hydraulic Fracture in Poroelastic Rock

- Nature of the solution?
- Applicability of 1D (“Carter”) leak-off

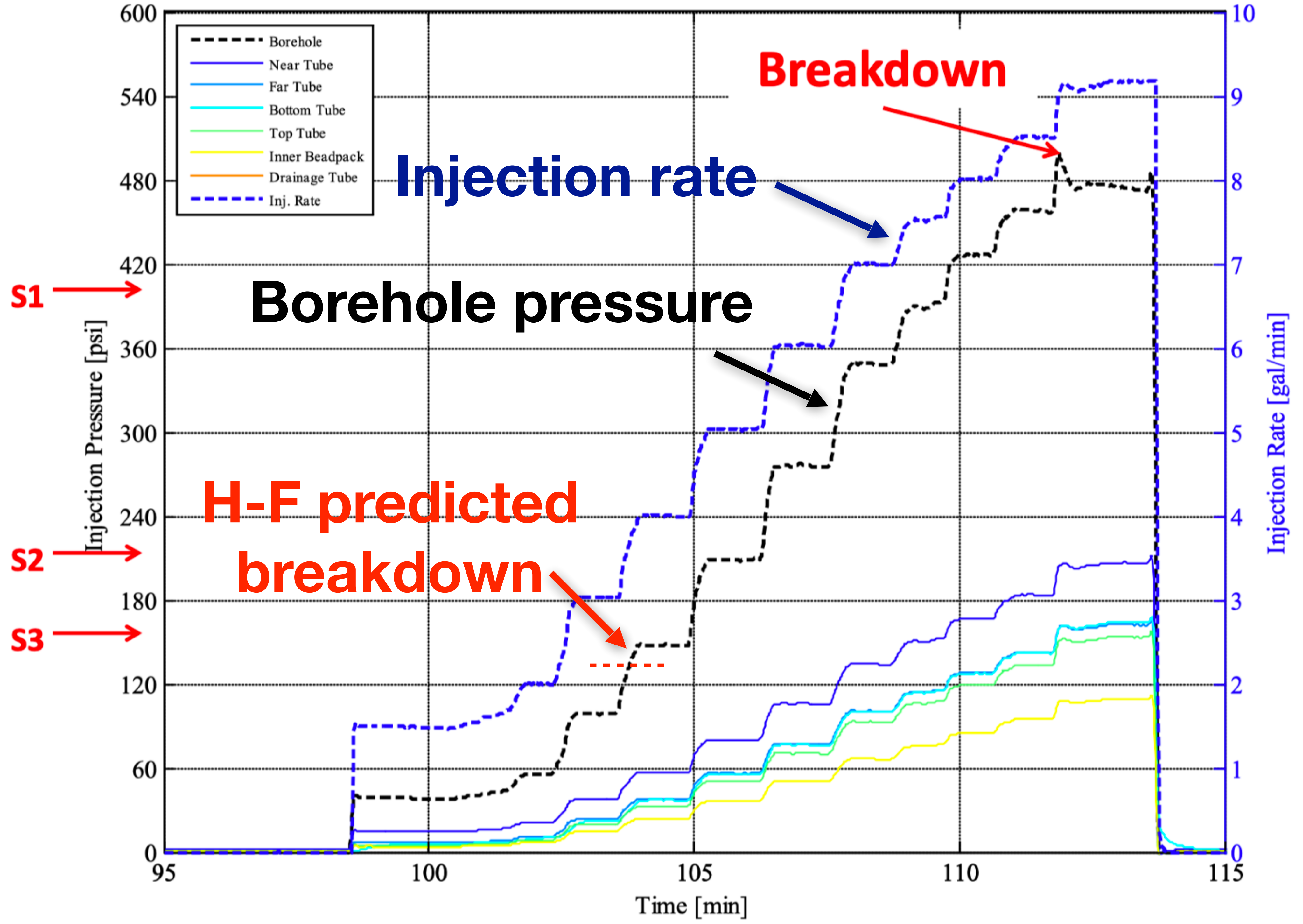
Yue Gao
Yera Hakobyan
Fengshou Zhang
Cexuan Liu

Laboratory Experiment: Water Injection in Weak Rock

- Weak and highly permeable sandstone: $E \sim 1$ GPa, $\sigma_c \sim 1$ MPa, $k \sim 1$ Darcy
- Rock is subjected to a triaxial stress state with a constant boundary pore pressure
- Breakdown pressure much larger than expected from Haimson-Fairhurst criterion



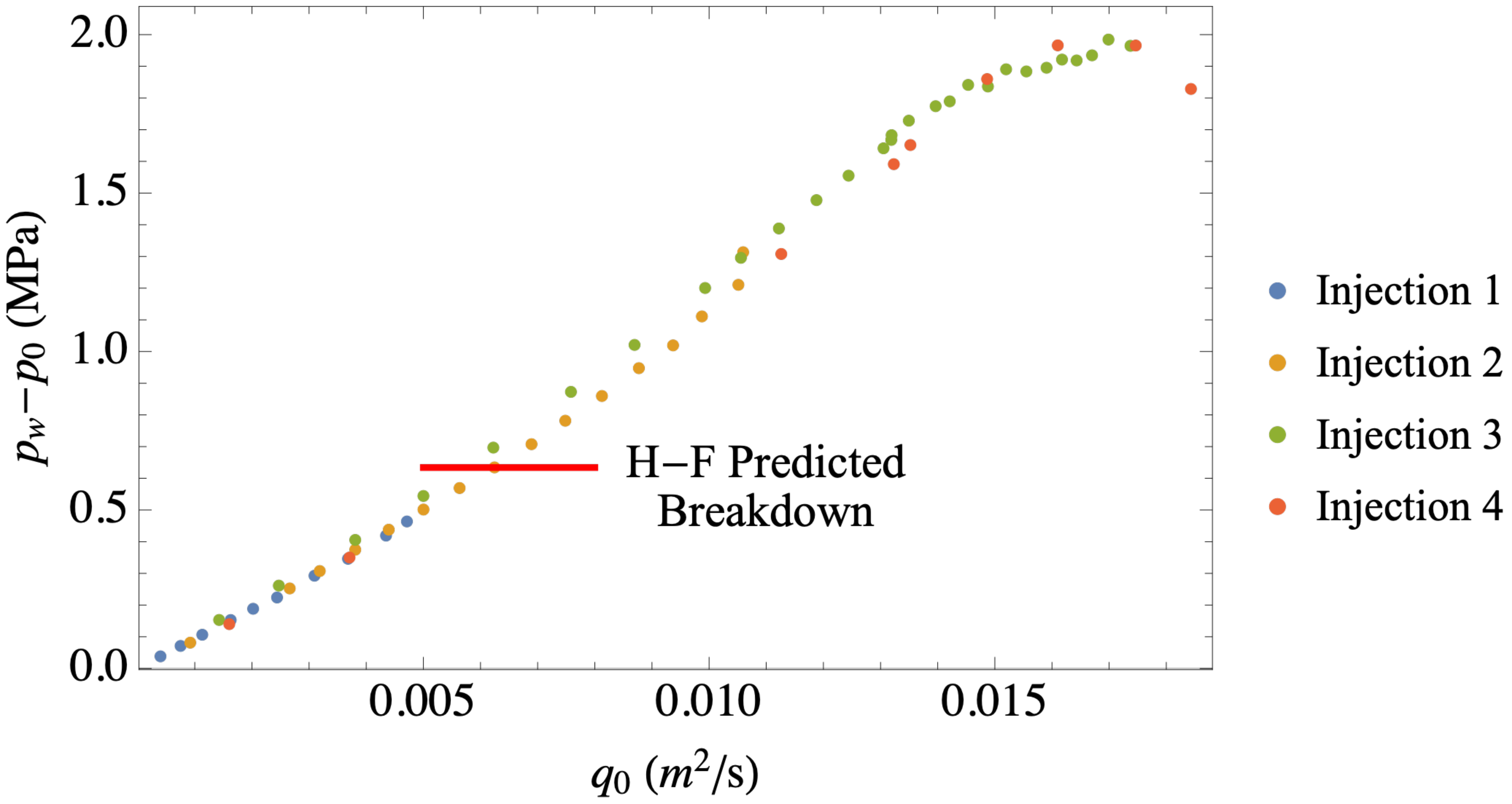
BP - TerraTek Experiments

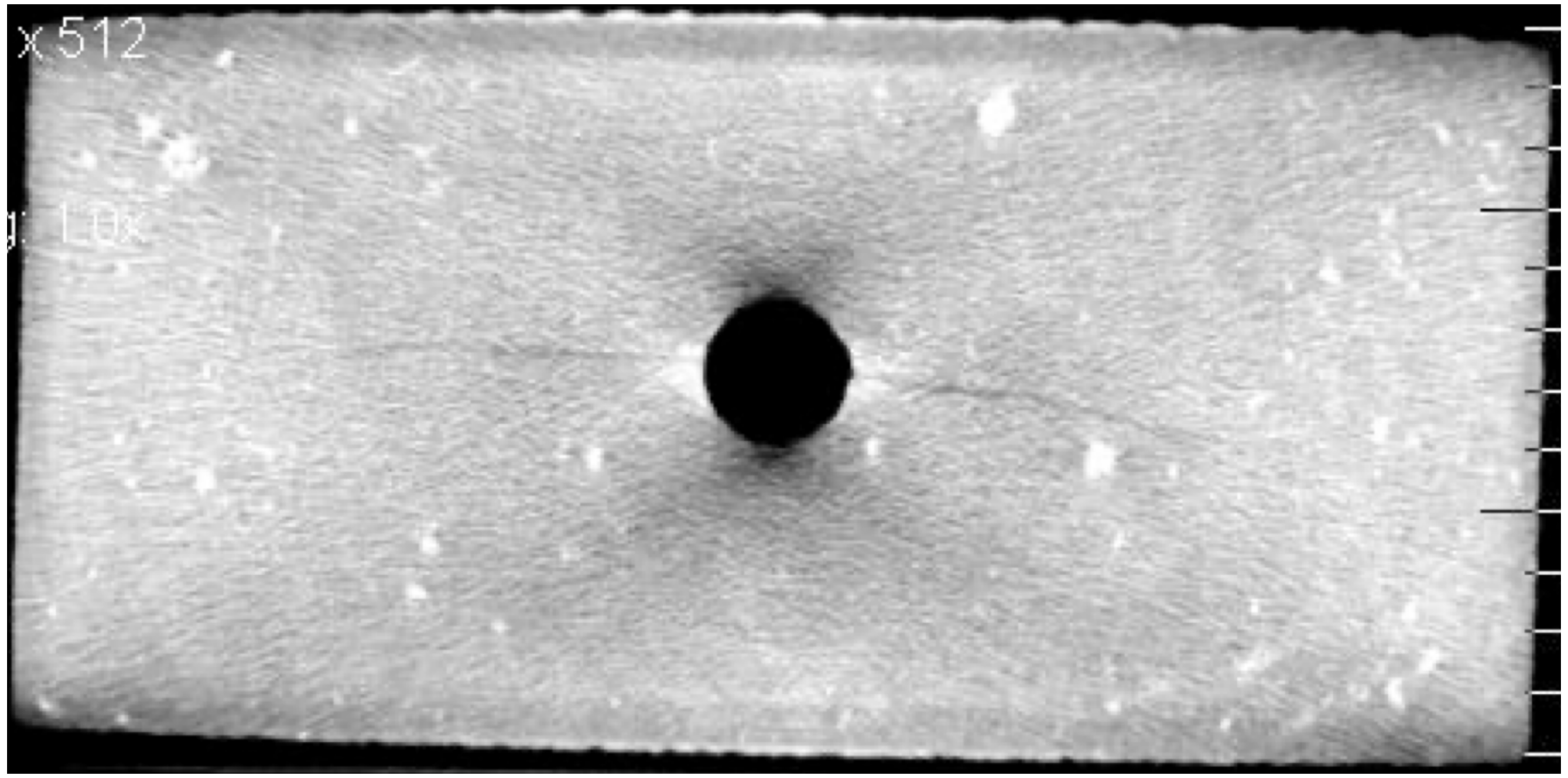


(Heller and Eve, 2015)

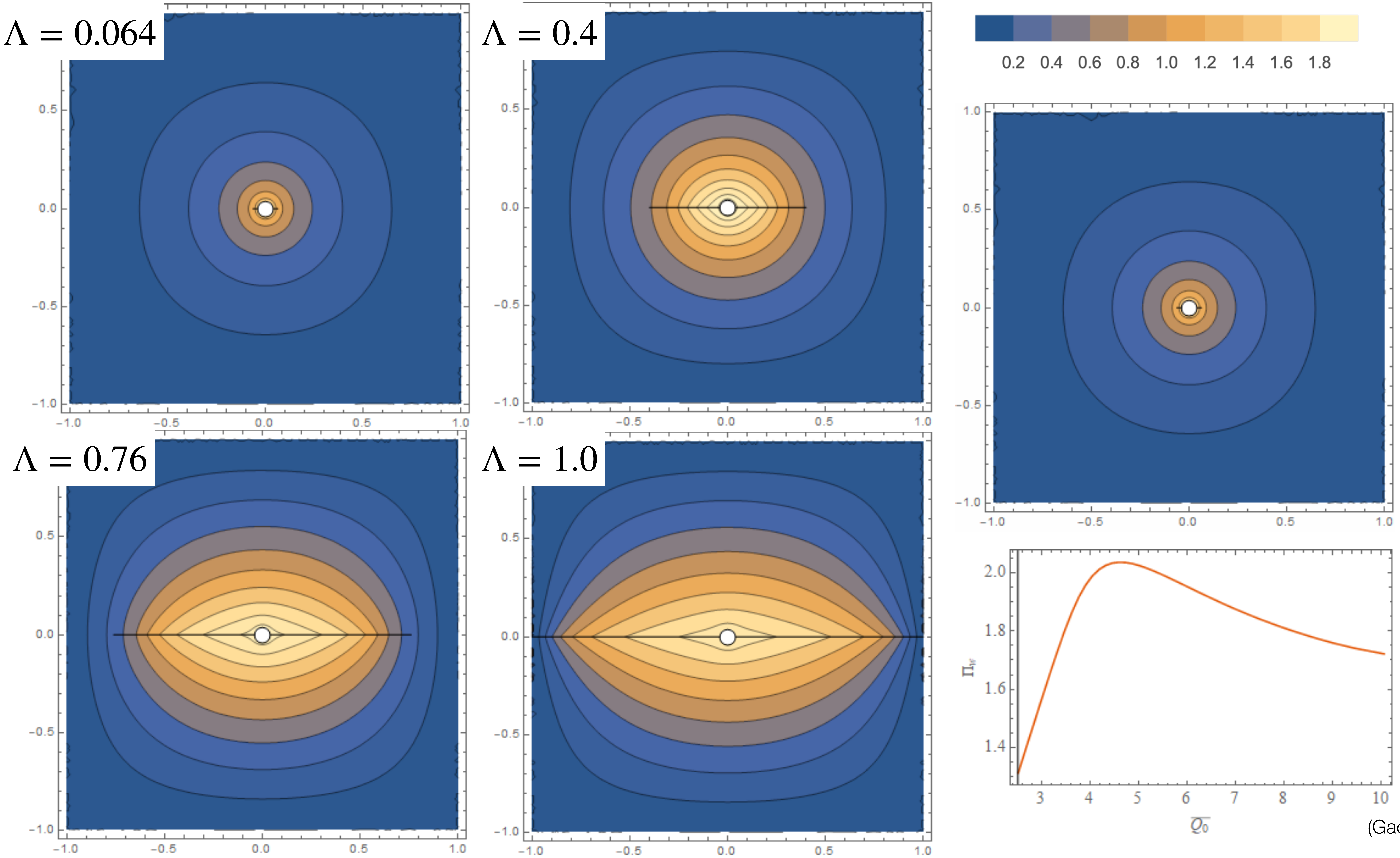
Results of Laboratory Tests (BP/TerraTek)

- Steady state flow
- Borehole pressure adjusts “instantaneously” to injection rate
- Hairline crack





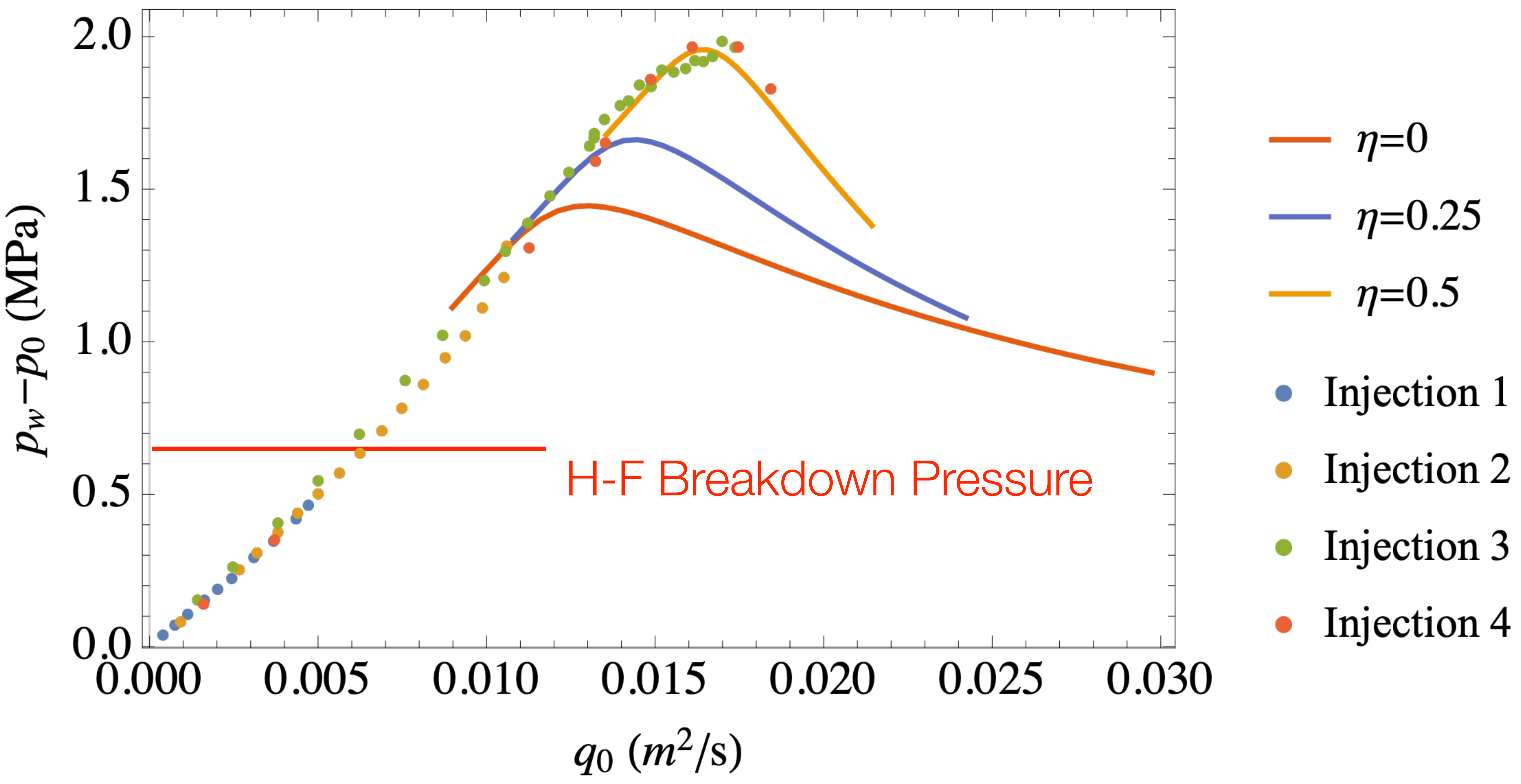
Predicted Evolution of Pore Pressure with Crack Length



(Gao & D, 2020)

Comparison with Experiments

- Weak sandstone, KCl Brine
- Computed peak pressure about much larger than H-F breakdown pressure
- Difference between theoretical model (2D) and experiment (3D)

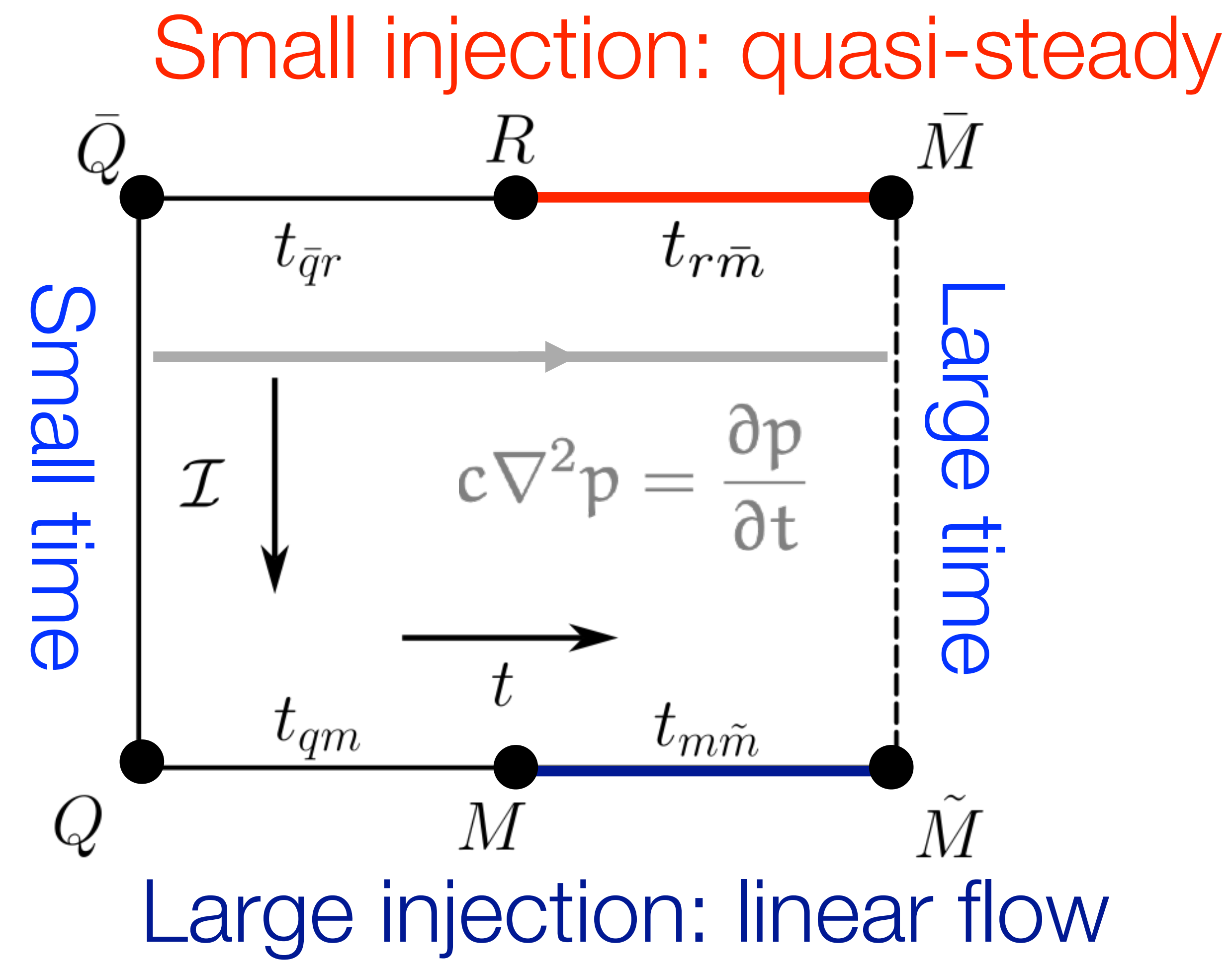


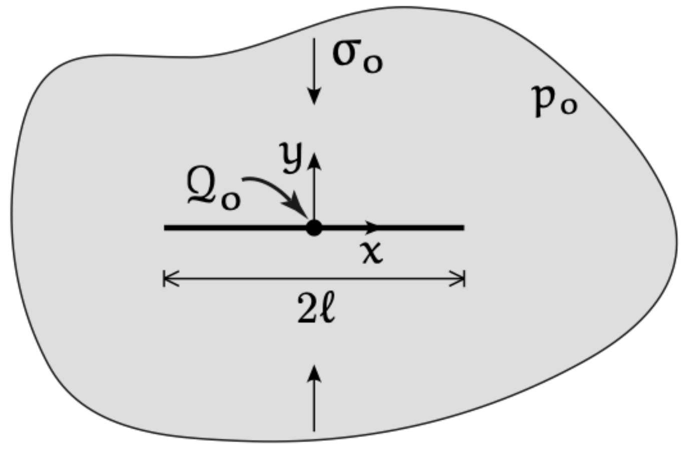
(Gao & D, 2020)

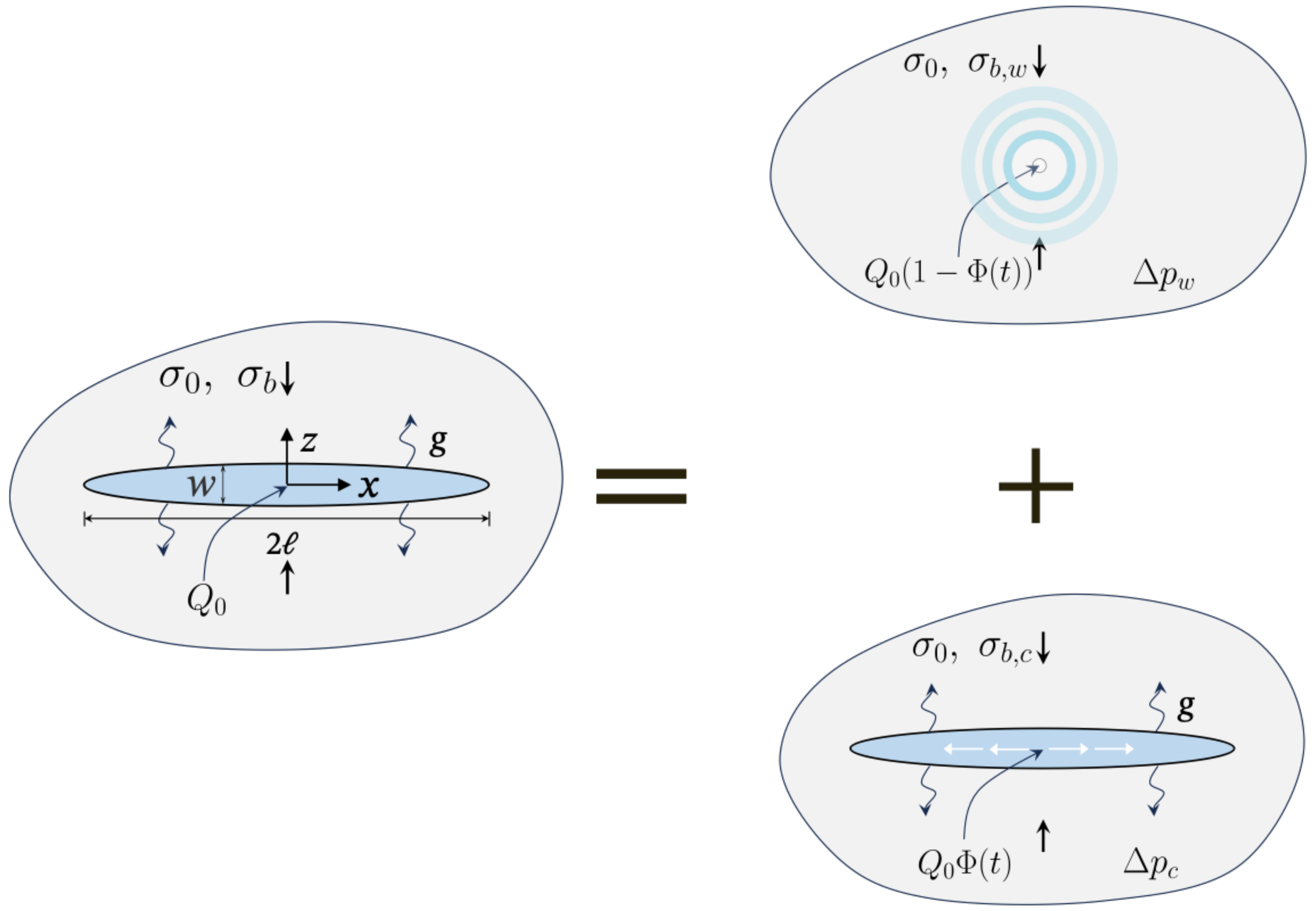
Application to Infinite Domain

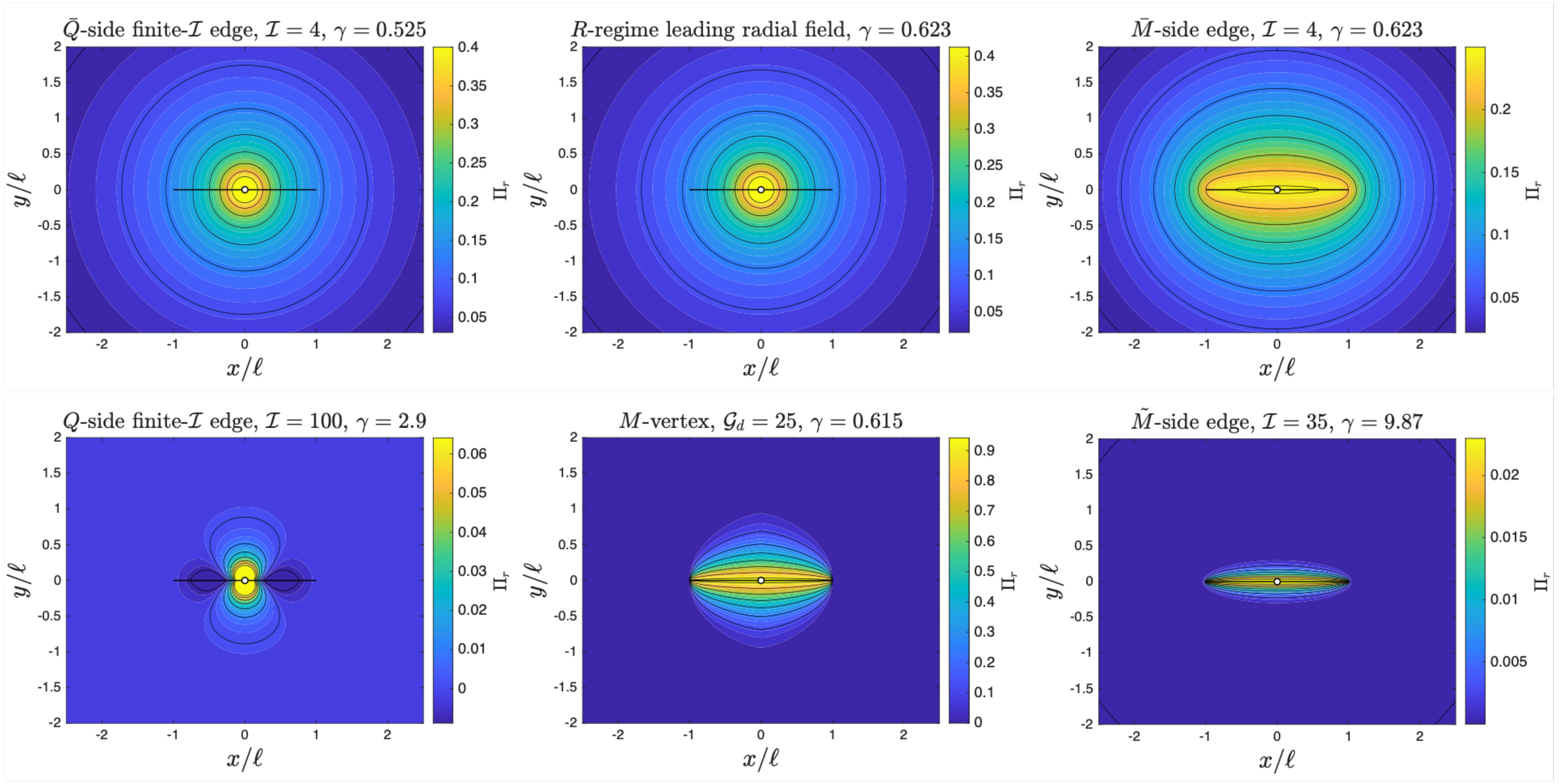
- KGD-type geometry (plane strain), but include borehole
- Negligible toughness, diffusion equation, poroelasticity
- Partitioning of injected fluid between borehole and fracture

$$\boxed{\mathcal{I} = \frac{Q_o}{\kappa(\sigma_o - p_o)}}$$







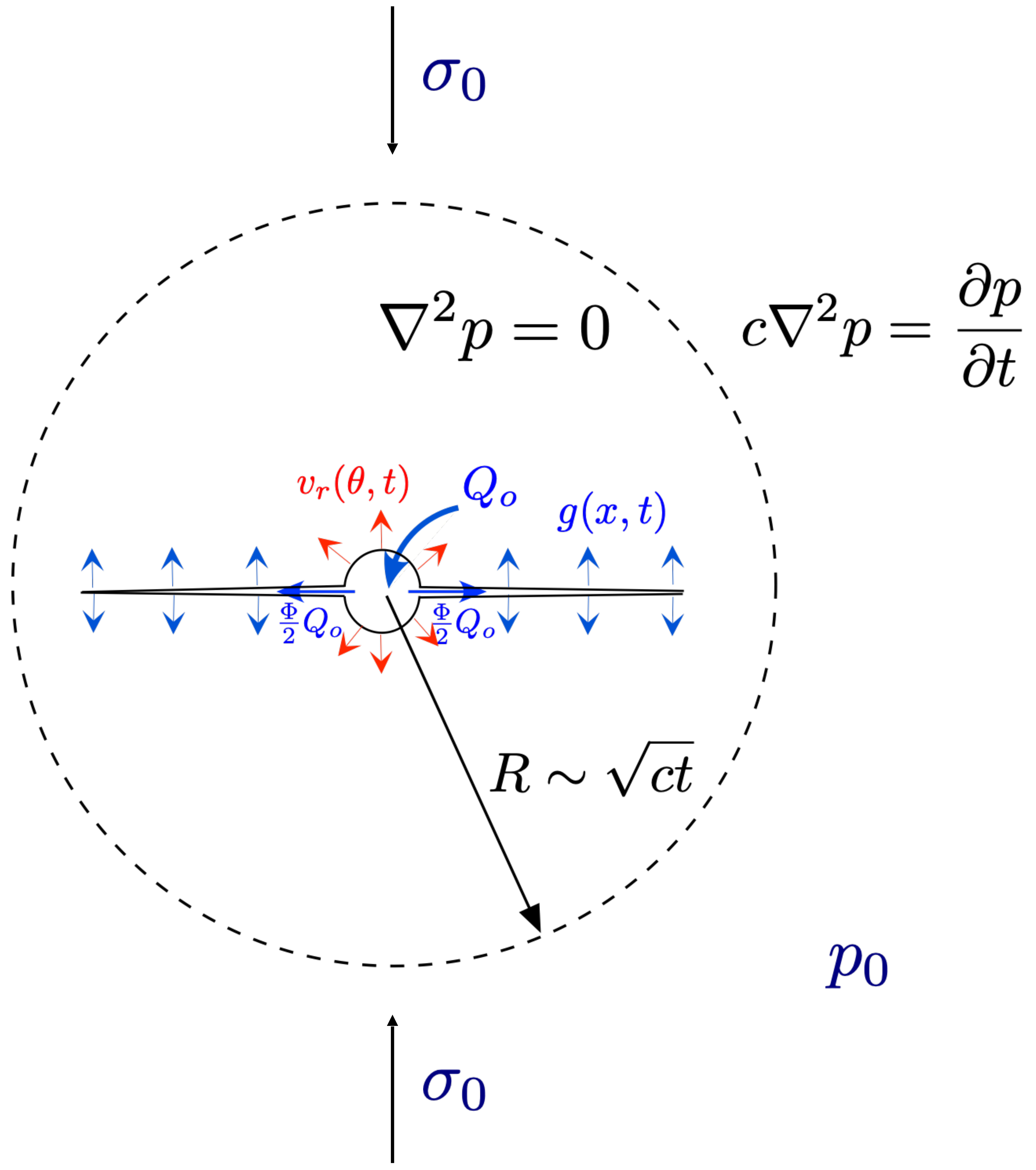


(Liu & al., 2026)

Small Injection Regimes ($\mathcal{I} \lesssim 4$): Pseudo-Steady Flow

- KGD-type geometry (plane strain), but include borehole
- Negligible toughness
- Negligible storage
- Fracture propagate inside in $\nabla^2 p = 0$ region
- Fluid partitioning: $0 \leq \Phi(t) \leq 1$
    - $\Phi \simeq 0$: radial flow from borehole
    - $\Phi \simeq 1$: leak-off from fracture
- Dimensionless injection rate

$$\boxed{\mathcal{I} = \frac{Q_o}{\kappa(\sigma_o - p_o)}}$$



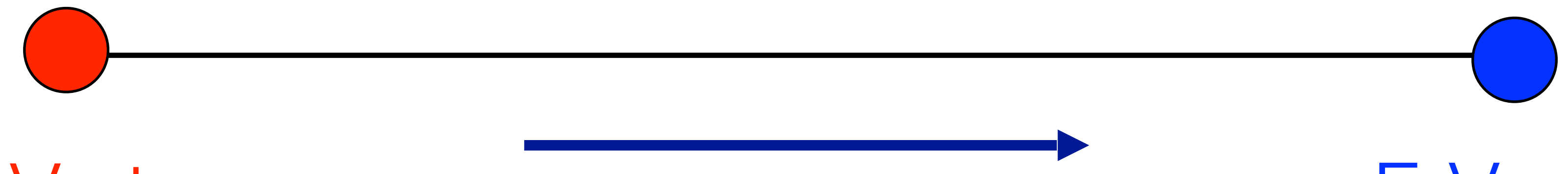
Two Asymptotic Flow Regimes ("Bare-Bone" Model)

- Crack hydraulically invisible
- Radial flow
- No leak-off
- Stable crack growth

Rock Flow

time t/t_K

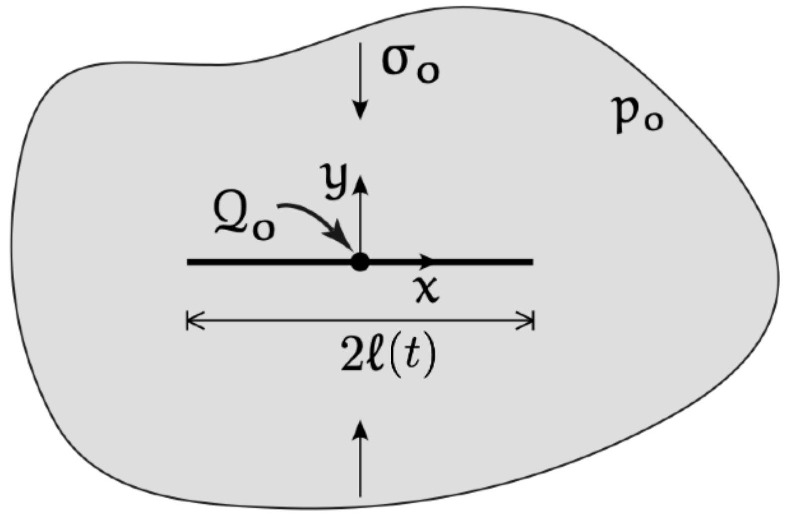
Fracture Flow



R-Vertex

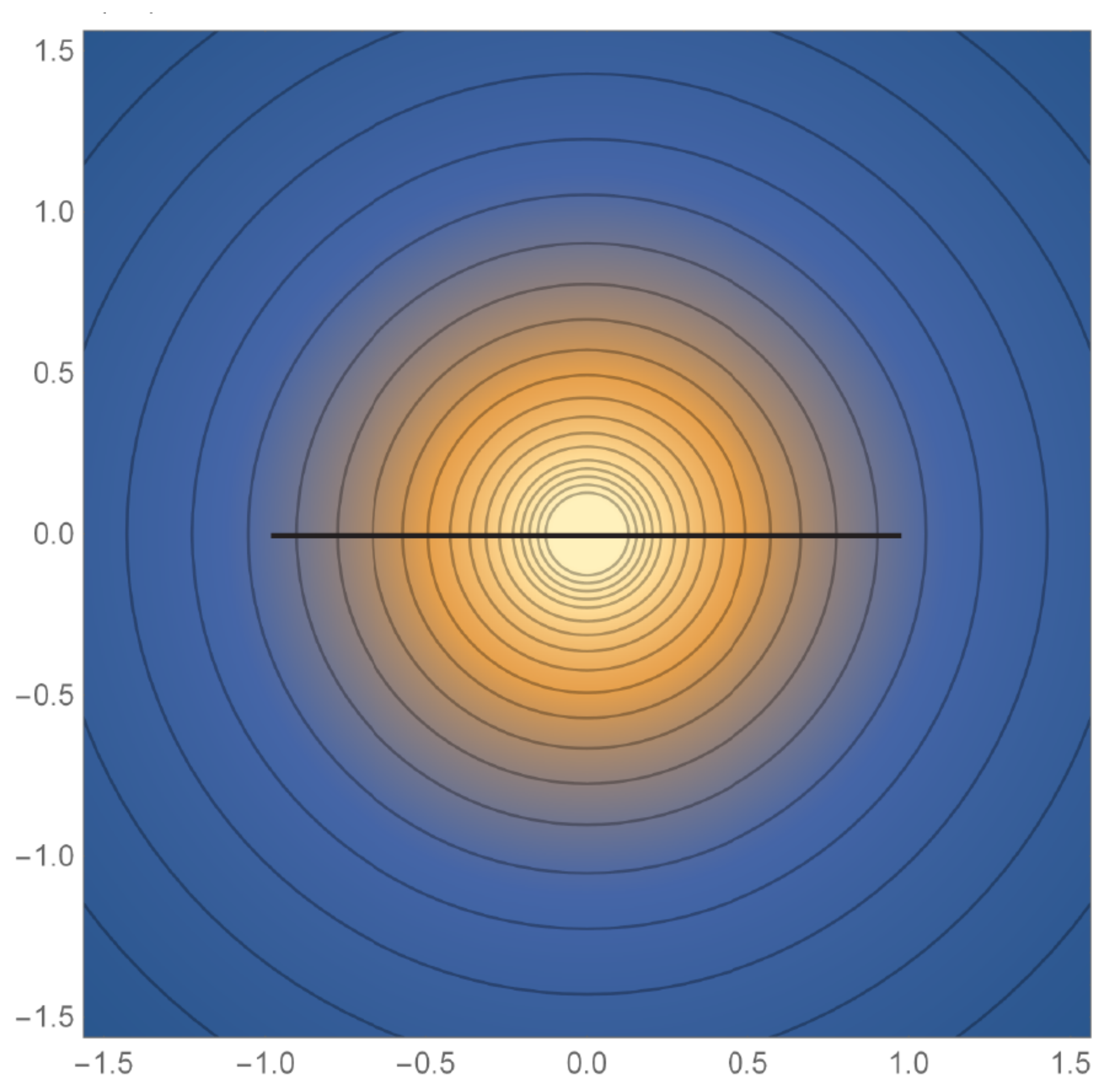
F-Vertex

$\Phi = 0$

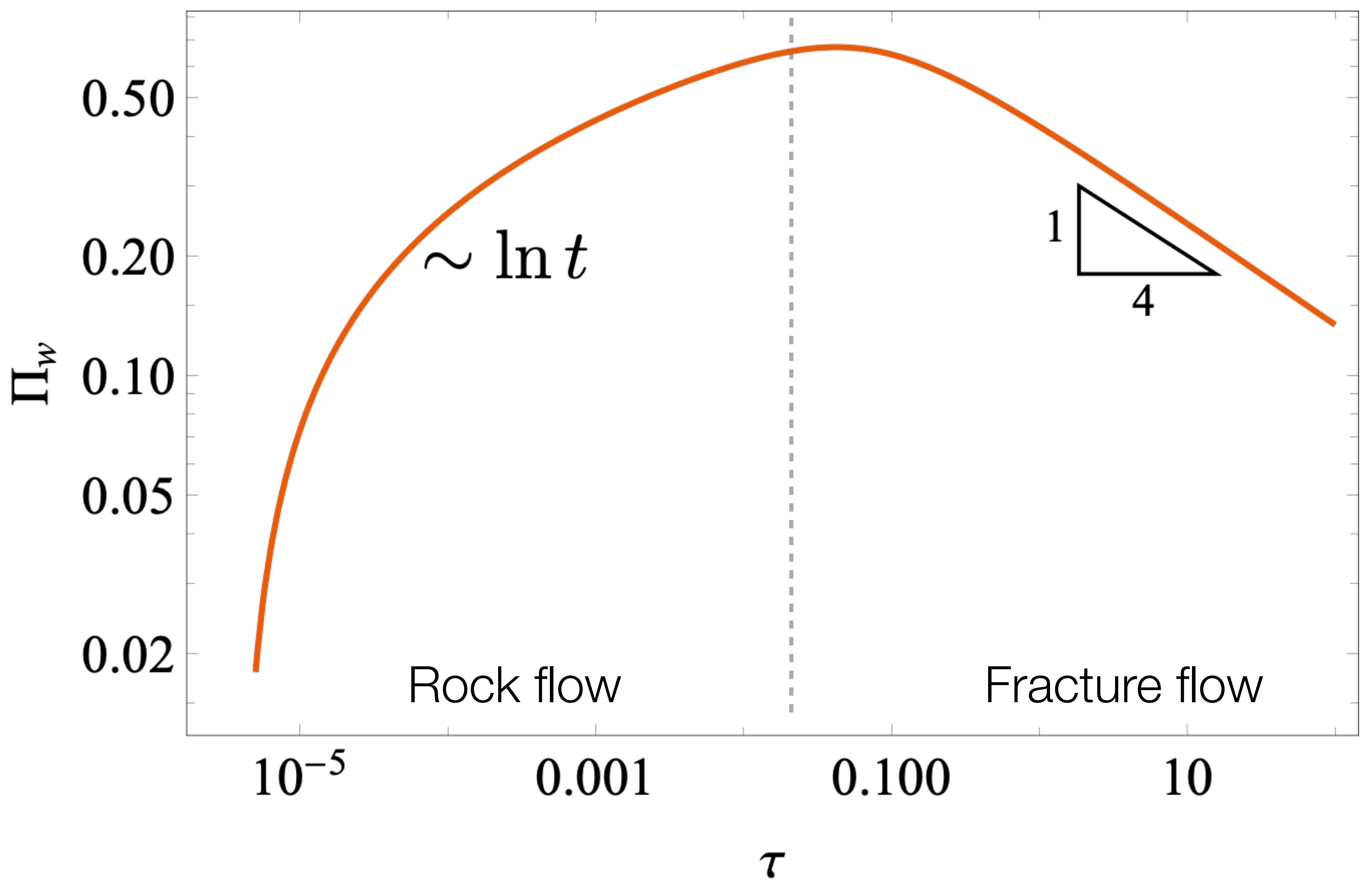


$\Phi = 1$

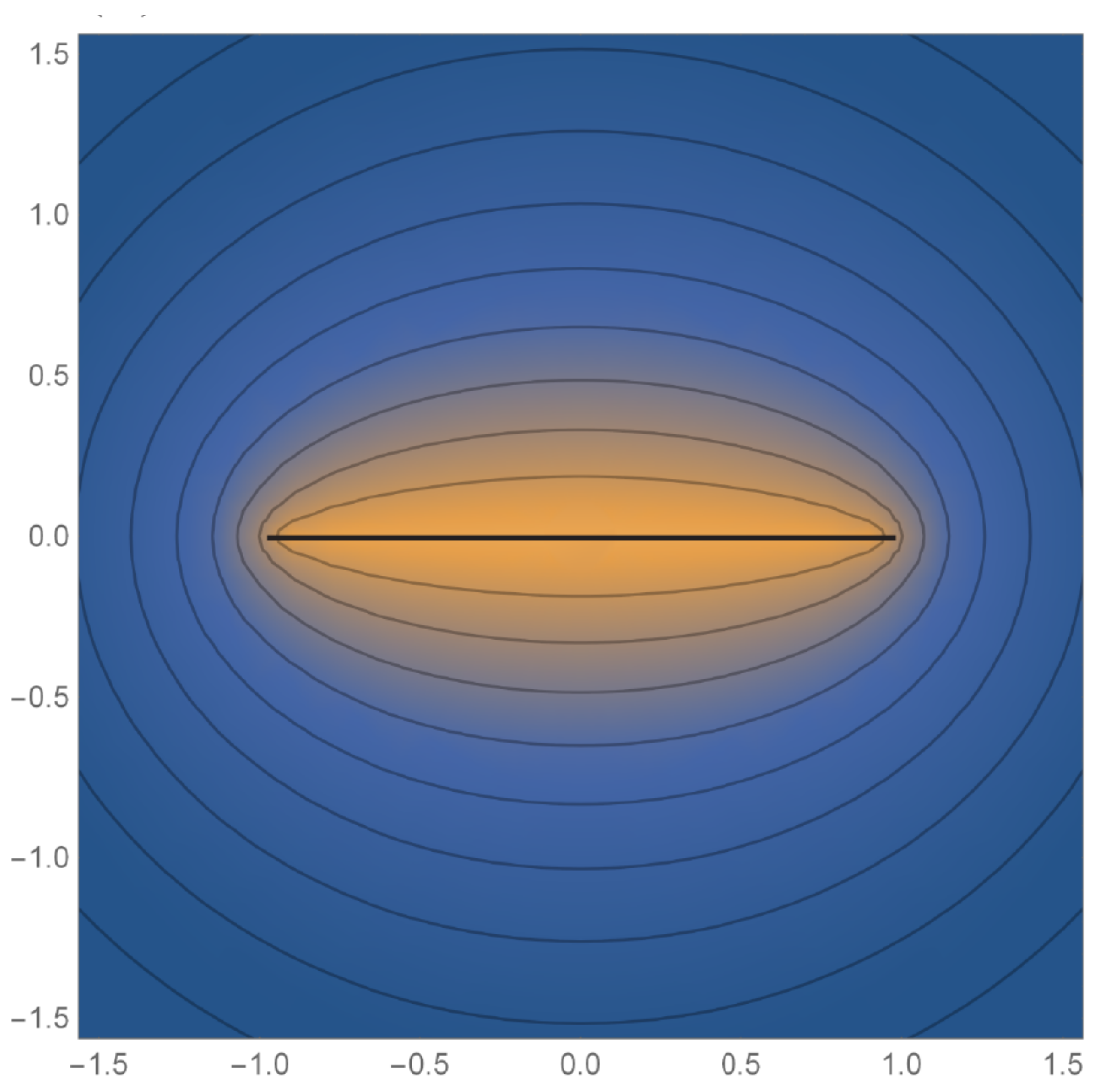
- Injection point invisible
- Linear flow $= Q_o$
- Total leak-off
- "Unstable" crack



Pore pressure field



Injection pressure *vs* time



Pore pressure field

Conclusions

- Much has been learned in the last 25 years
  - Rigorous approach triggered by the seminal paper of Spence & Sharp (1985)
  - Development of tip asymptotics and their application to numerical simulators
  - Robust numerical algorithm
- Complementary role of numerical and analytical solutions
- Much is left to be done
  - Topology of the solution space
  - Near-surface fracture
  - Fracture swarm
  - …