‘Sensitivity boosting’ in ice sheets: tipping points and time-scales

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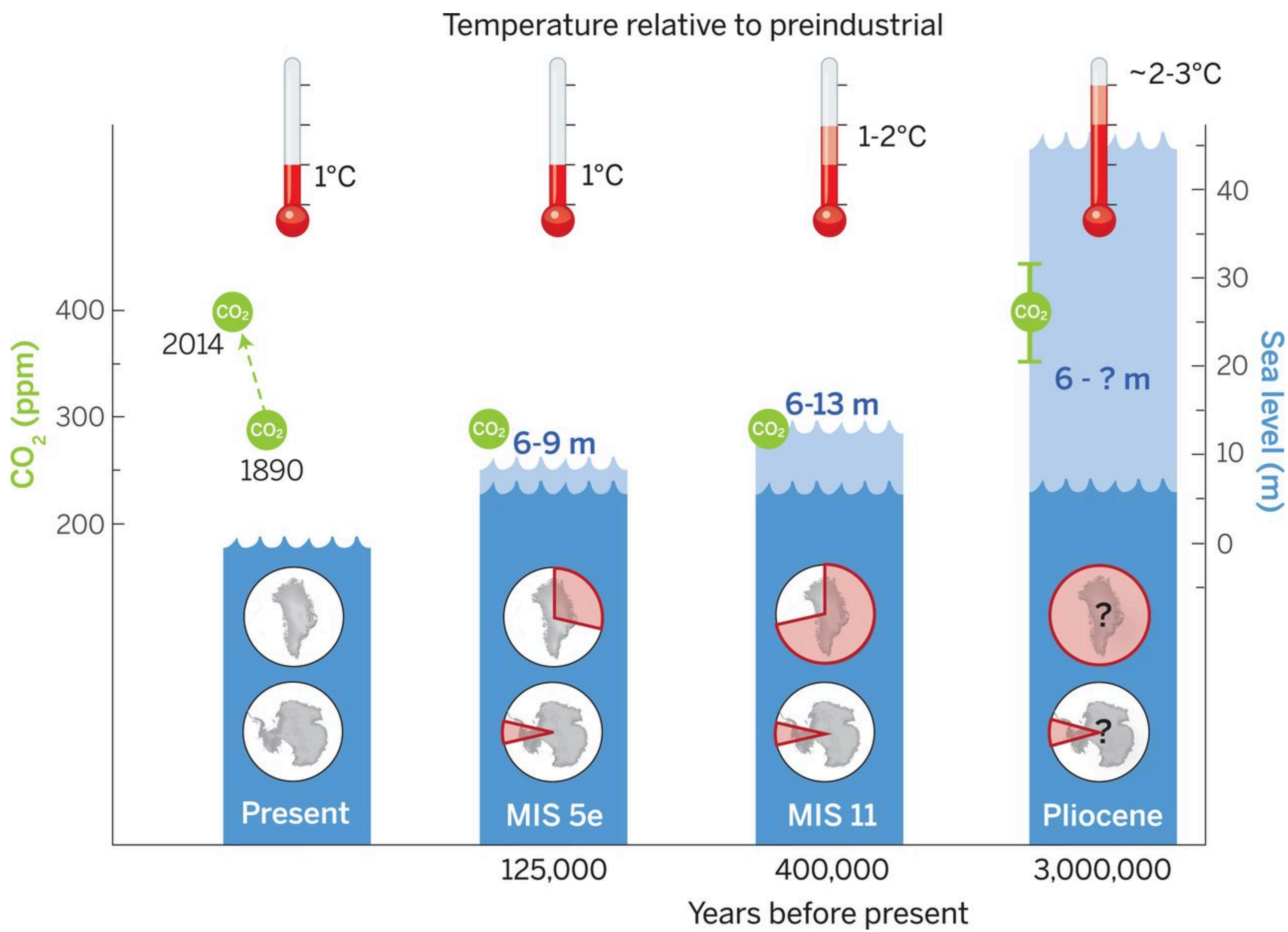
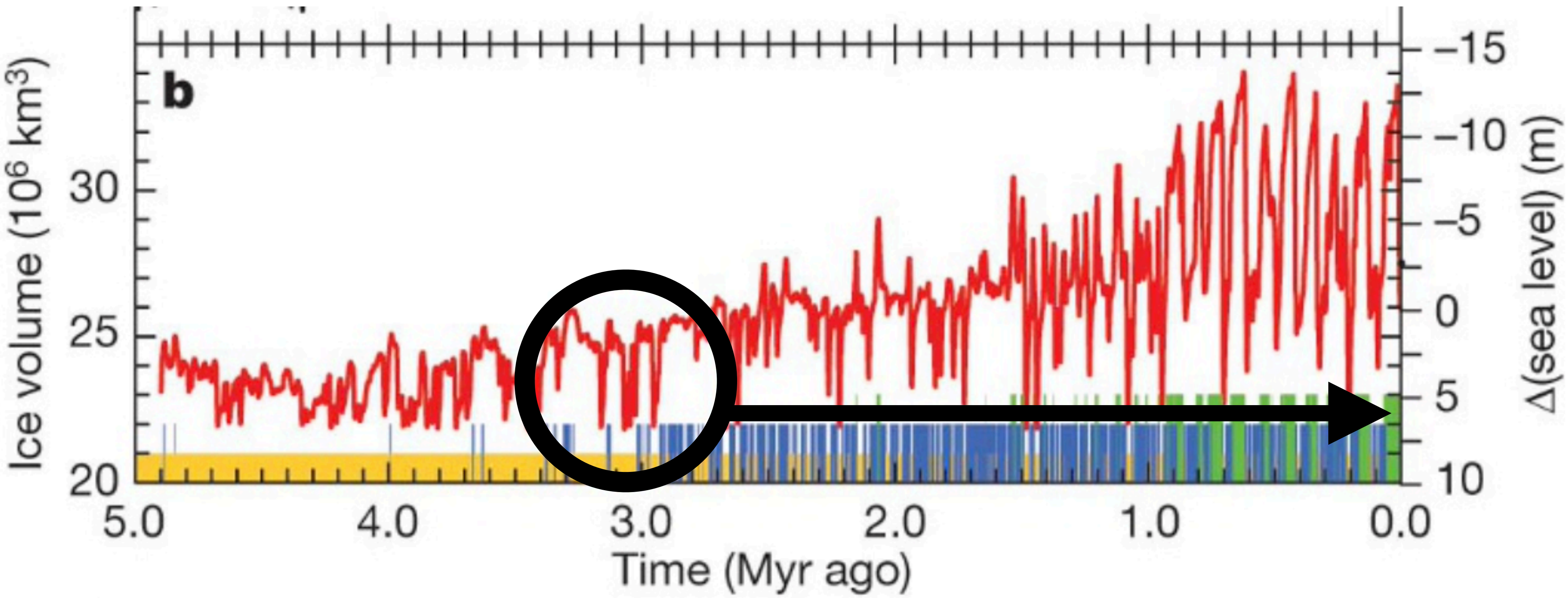
NATURAL ENVIRONMENT RESEARCH COUNCIL

Sea levels have been much higher than today with similar CO2 and temperatures

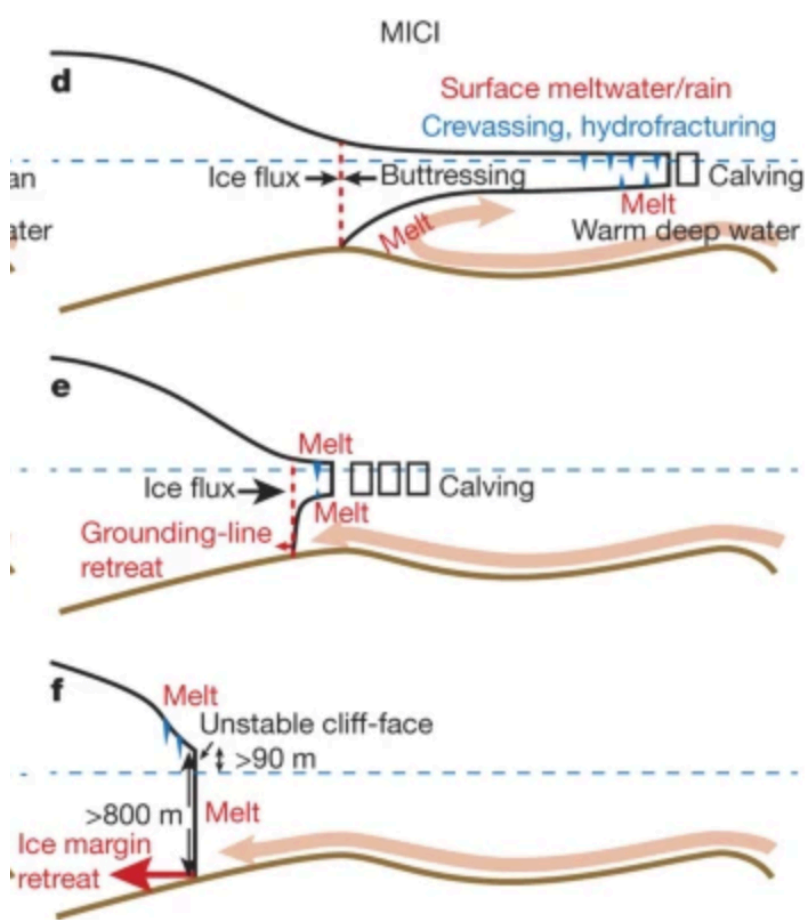


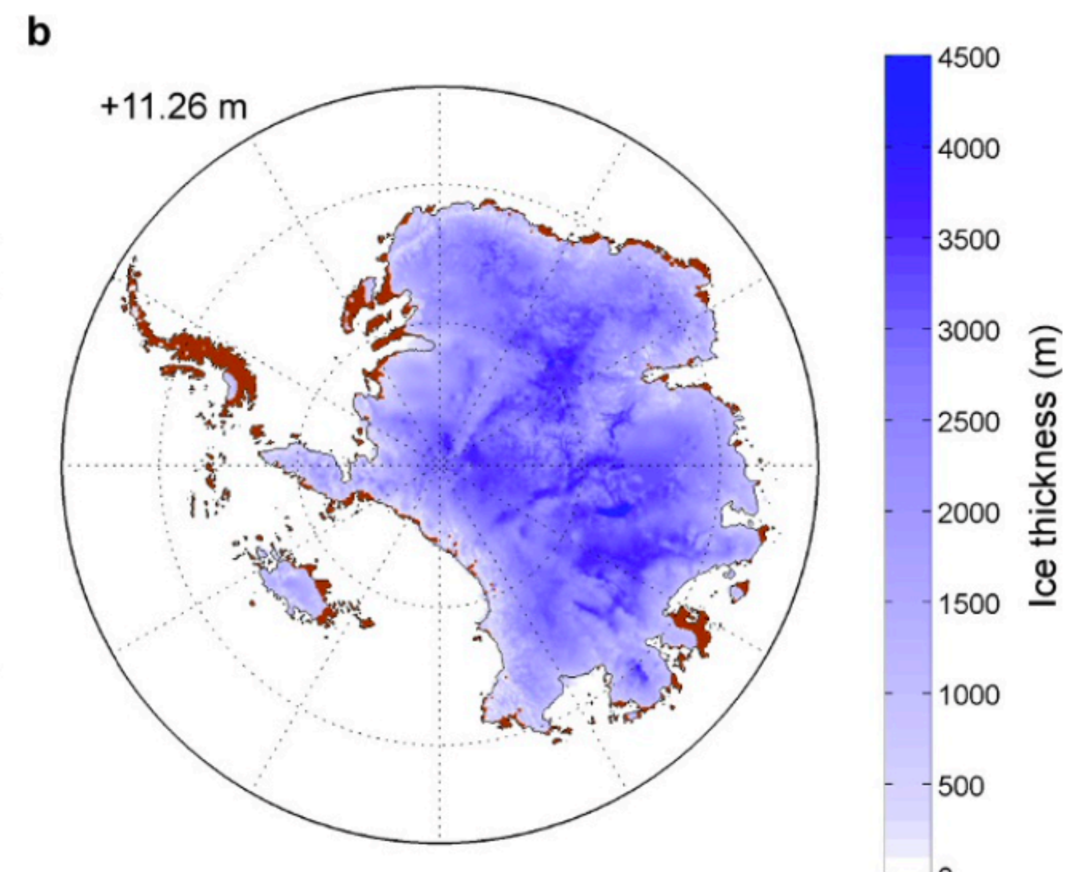
Models struggle to simulate this retreat

Pollard and DeConto, 2009

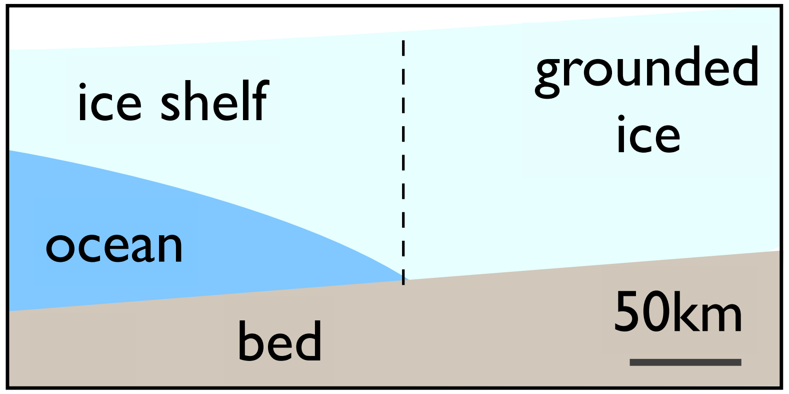


DeConto and Pollard, 2016





Grounding zone melt boosts ice sheet sensitivity



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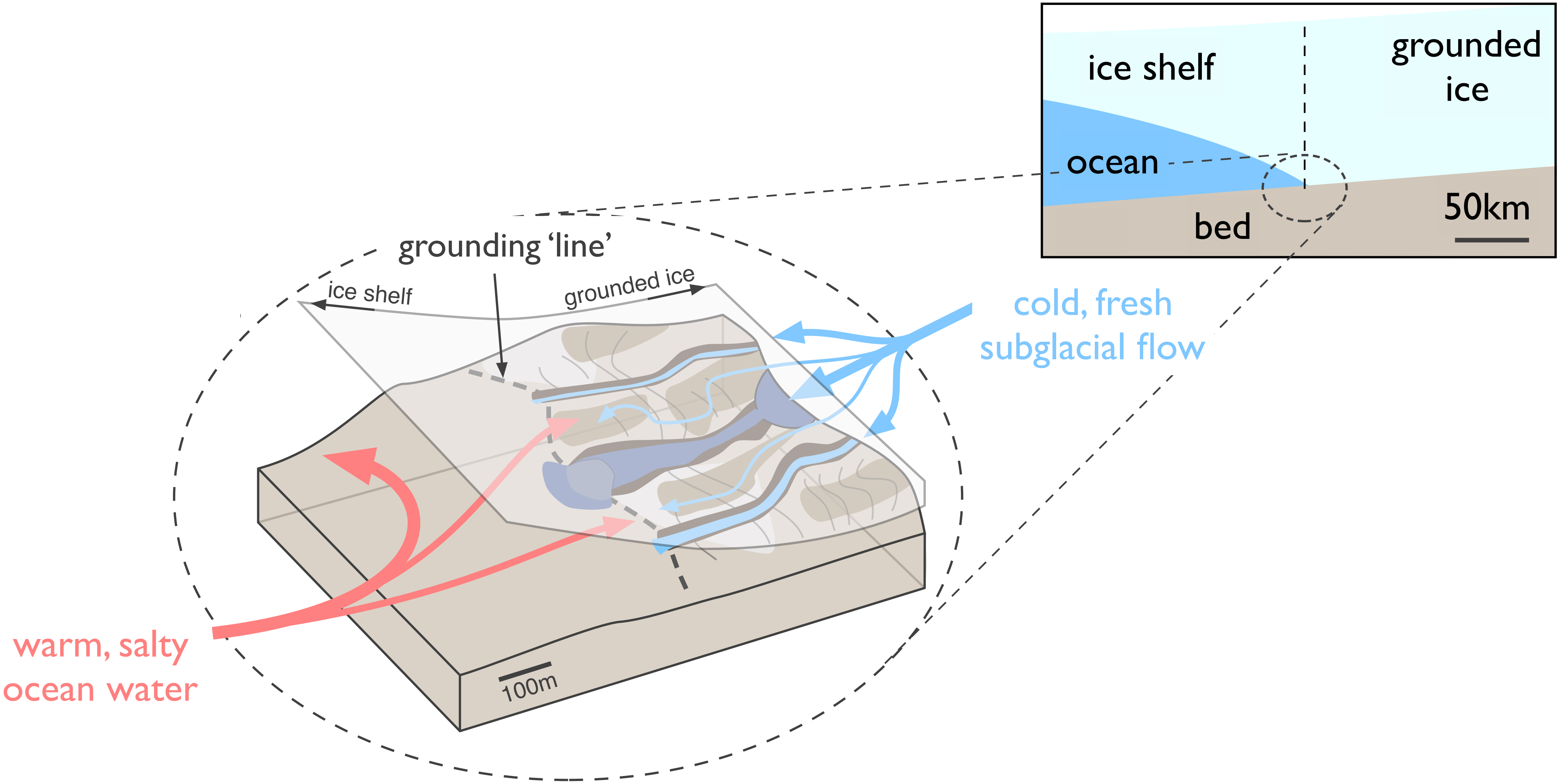

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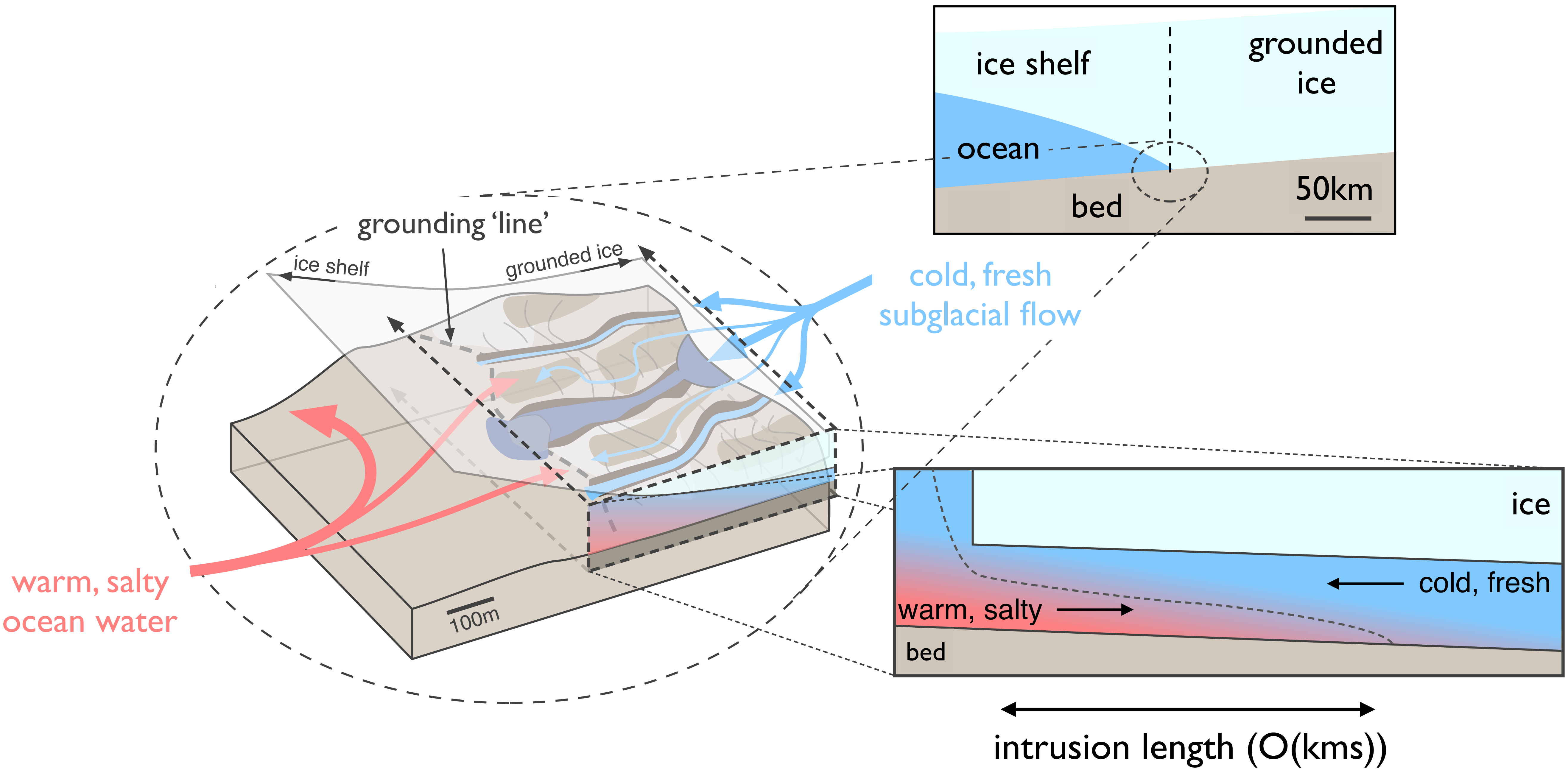
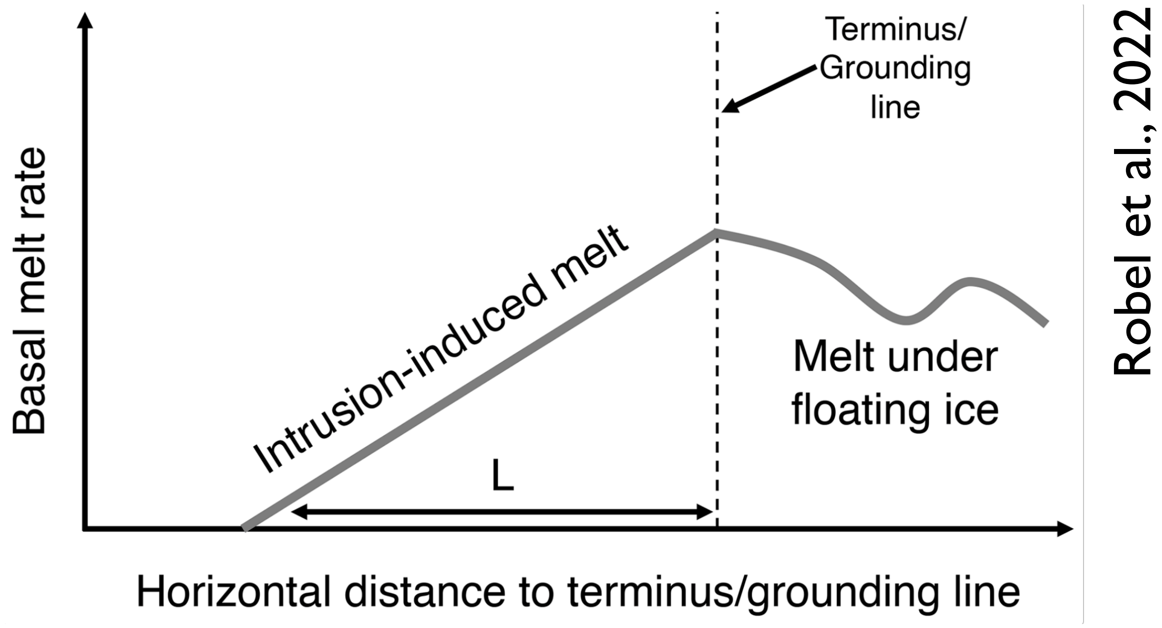
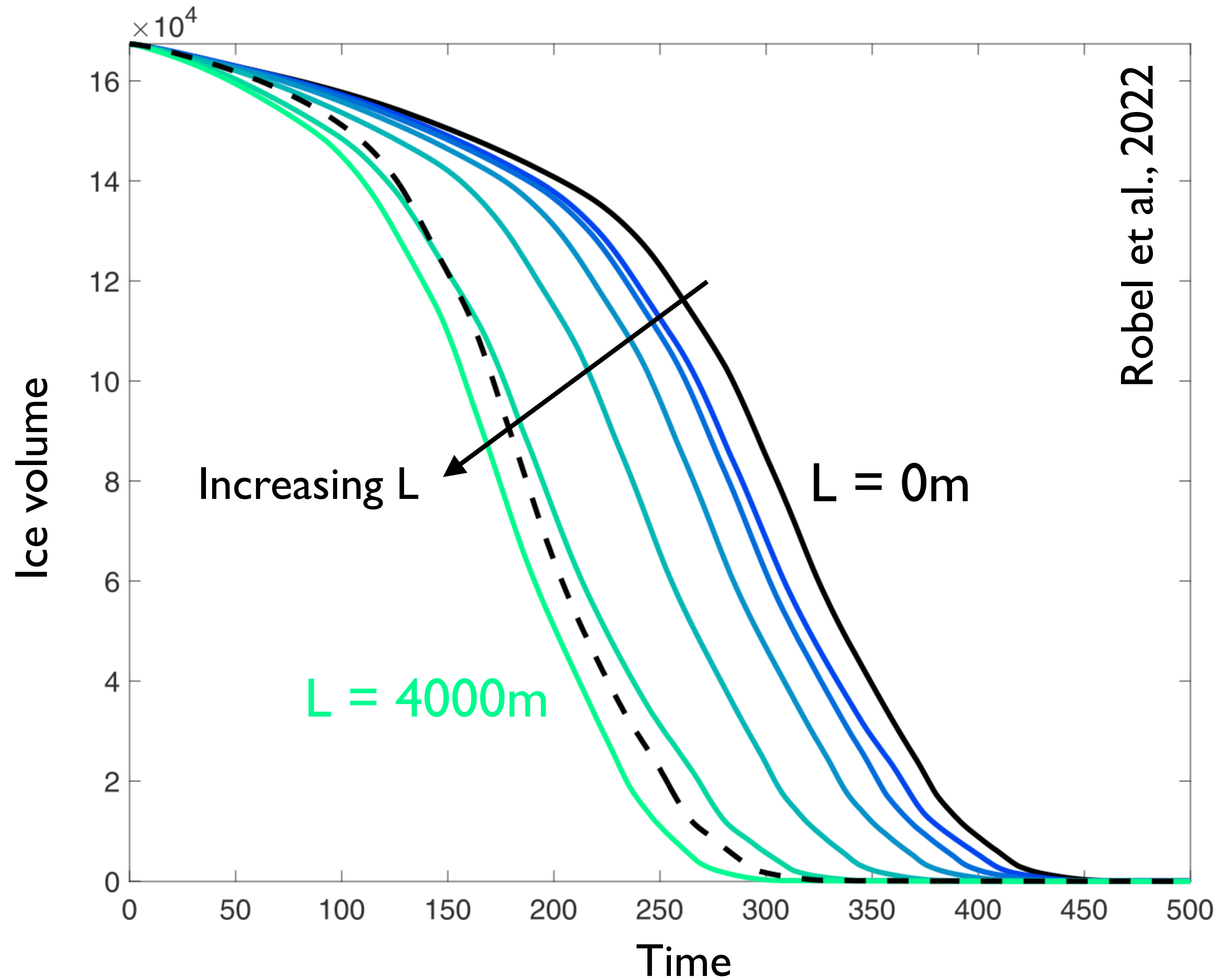


Robel et al., 2022, Wilson et al. 2020

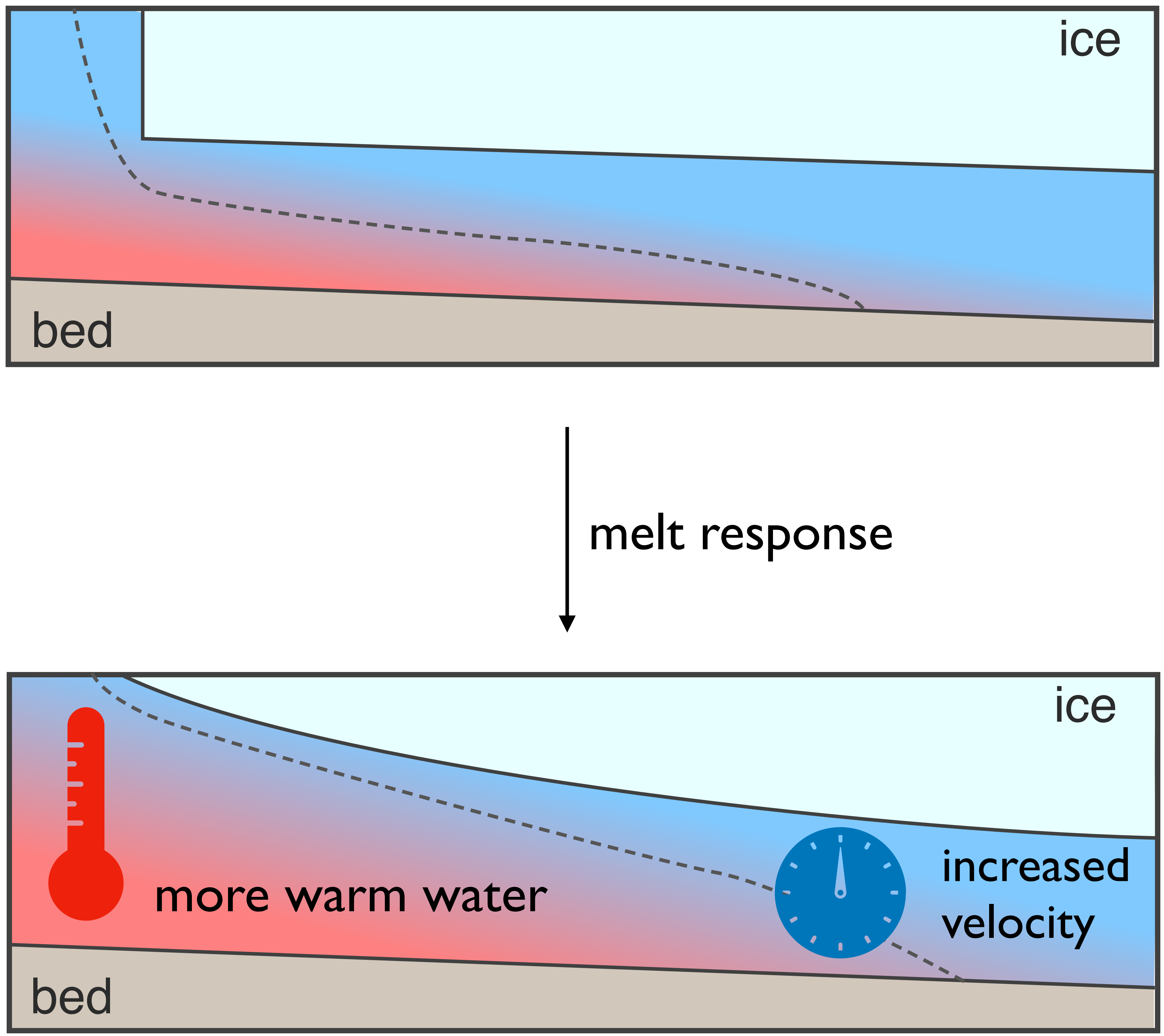
Grounding zone melt boosts ice sheet sensitivity

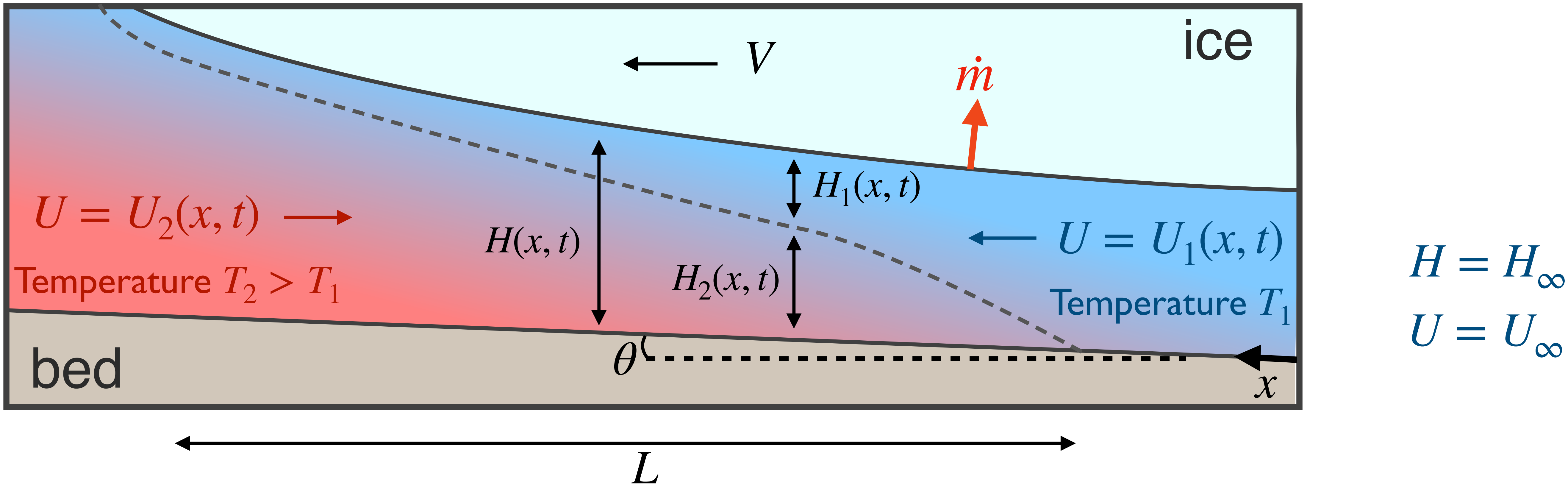




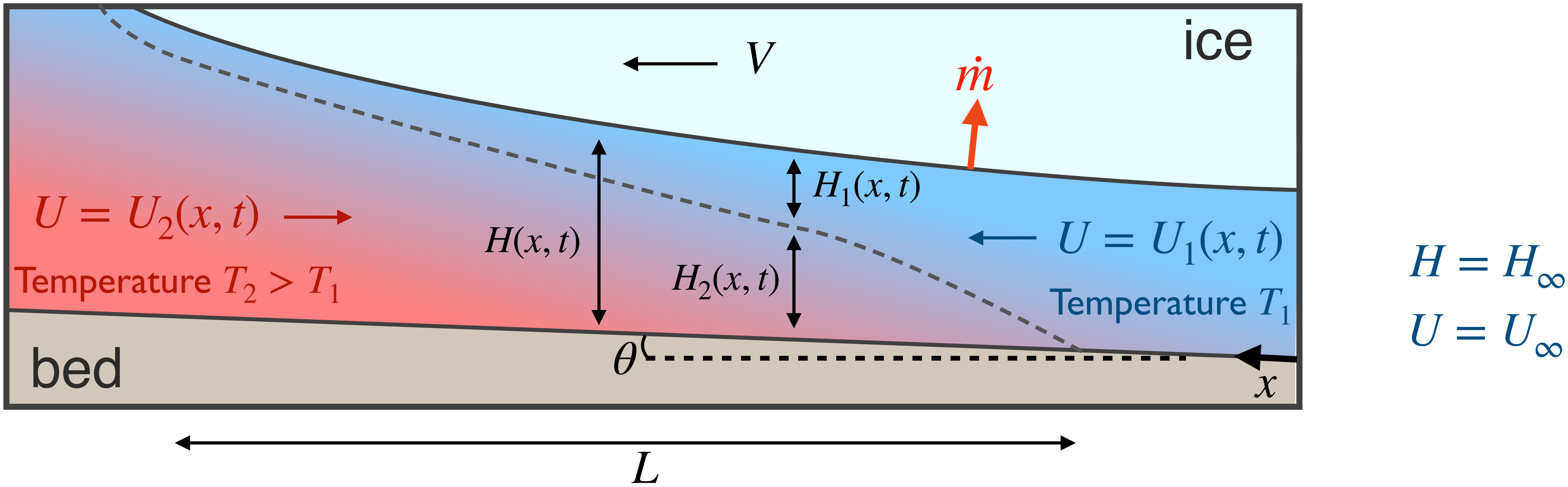
Significant seawater intrusion has dramatic consequences for ice dynamics

Melt feedbacks on seawater intrusions





ice
V
$\dot{m}$
$H_1(x,t)$
$U = U_2(x,t)$
$H(x,t)$
$U = U_1(x,t)$
Temperature $T_2 > T_1$
$H_2(x,t)$
Temperature T_1
$H = H_\infty$
$U = U_\infty$
bed
θ
x
L

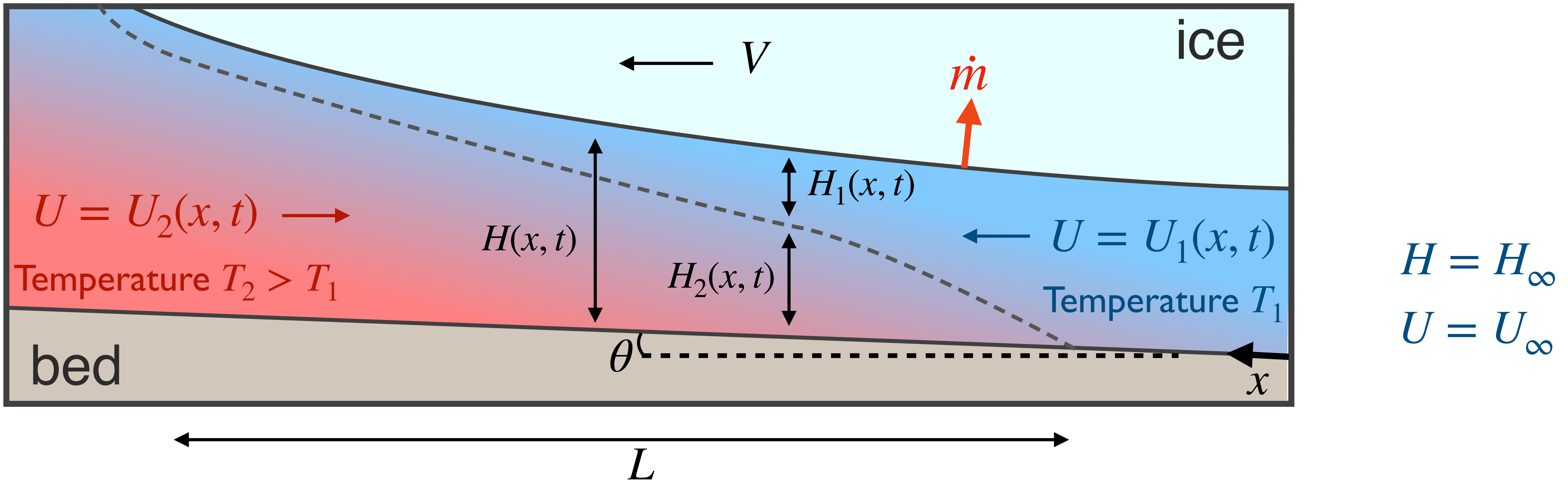


Momentum Conservation:

inertia | barotropic pressure gradient | interfacial drag | wall drag | gravitational driving

$$\begin{cases} \dfrac{\partial U_1}{\partial t} + U_1 \dfrac{\partial U_1}{\partial x} + \dfrac{1}{\rho}\dfrac{\partial P}{\partial x} + \dfrac{C_i |U_1 - U_2| (U_1 - U_2)}{H_1} + \dfrac{C_d U_1^2}{H_1} = 0 \\ \dfrac{\partial U_2}{\partial t} + U_2 \dfrac{\partial U_2}{\partial x} + \dfrac{1}{\rho}\dfrac{\partial P}{\partial x} - \dfrac{C_i |U_1 - U_2| (U_1 - U_2)}{H_2} + \dfrac{C_d U_2^2}{H_2} + g' \left(\dfrac{\partial H_2}{\partial x} + \tan\theta \right) = 0 \end{cases}$$

$$(\mathrm{Fr}^2 - 1)\frac{\partial H_1}{\partial x} = \mathrm{Fr}^2 \left(C_d + C_i \frac{H}{H - H_1} \right) - \left(\tan\theta + \frac{\partial H}{\partial x} \right)$$



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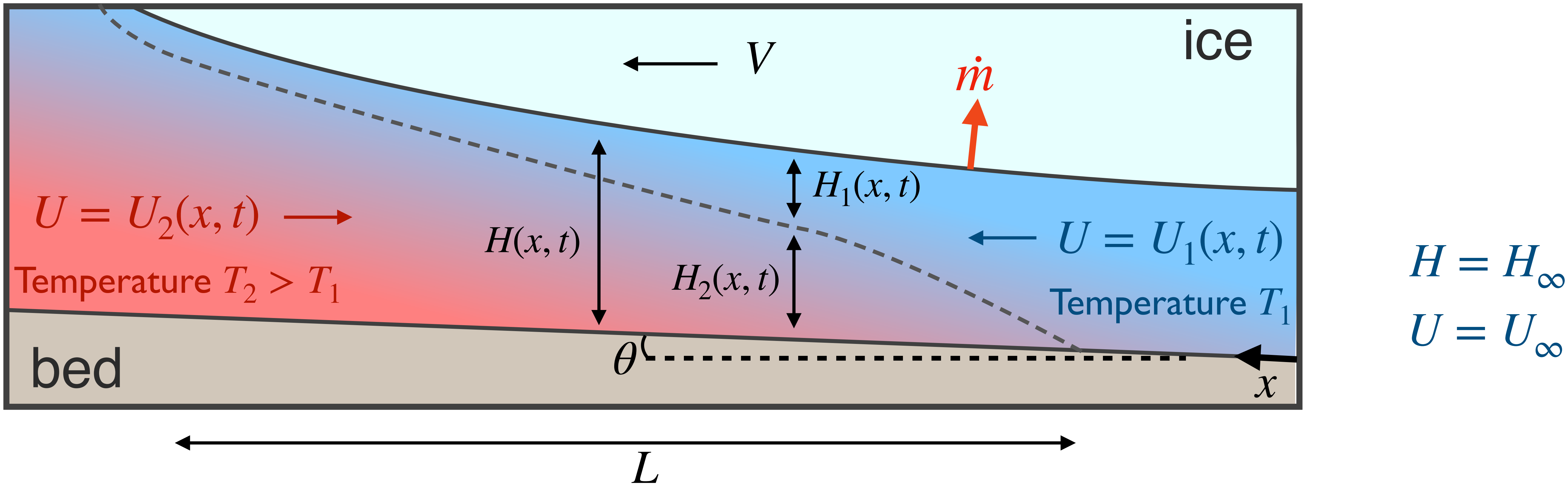

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Melting:

$$\dot{m} = \frac{\mathrm{St}C}{L}u^*\Delta T$$

thermal driving

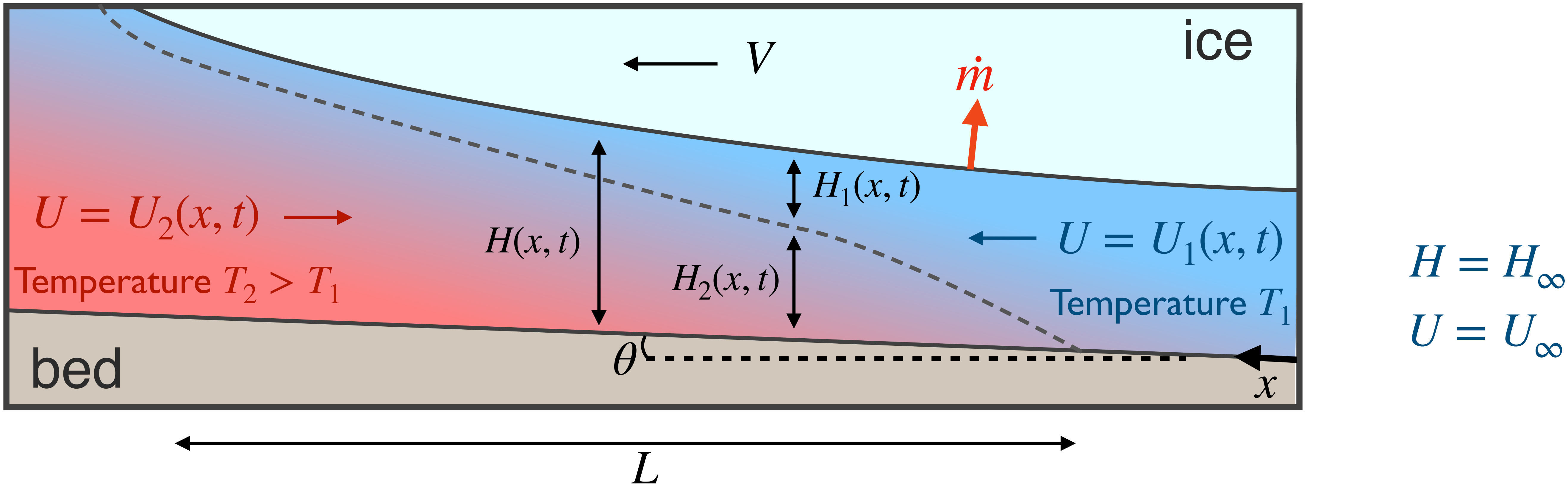
boundary layer velocity $u^* = U_1$

$$\Delta T = T - T_f$$

$$T = \frac{H_1}{H}T_1 + \left(1 - \frac{H_1}{H}\right)T_2$$

T_f: local freezing point

$$\dot{m} = \frac{\mathrm{St}C}{L}U_1\left[\frac{H_1}{H}T_1 + \left(1 - \frac{H_1}{H}\right)\right]$$



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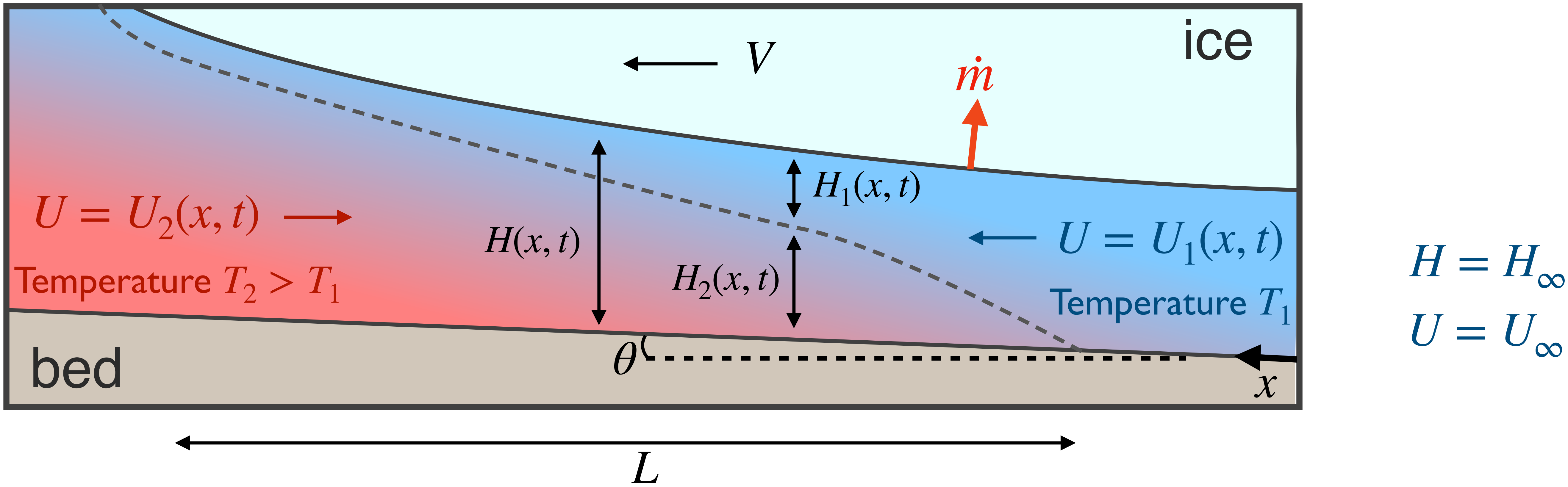

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Melting:

$$\dot{m} = \frac{\mathrm{St}C}{L}U_1\left[\frac{H_1}{H}T_1 + \left(1 - \frac{H_1}{H}\right)\right]$$

Kinematic Condition:

$$\frac{\partial H}{\partial t} + V\frac{\partial H}{\partial x} = \dot{m}$$

Momentum conservation:

$$\left(\frac{\mathrm{F}^2}{h_1^3}-1\right)\frac{\partial h_1}{\partial x}=\frac{\mathrm{F}^2}{h_1^3}\left(1+C\frac{h}{h-h_1}\right)-\left(S+\frac{\partial h}{\partial x}\right)$$

Melting + kinematic:

$$\frac{\partial h}{\partial t}+\frac{1}{M}\frac{\partial h}{\partial x}=\frac{1}{h_1}\left(1-\frac{h_1}{h}\right)$$

$$S=\frac{\tan\theta}{C_d}$$

dimensionless bed slope

$$F=\frac{U_\infty}{\sqrt{g' H_\infty}}$$

upstream Froude number

$$C=\frac{C_i}{C_d}$$

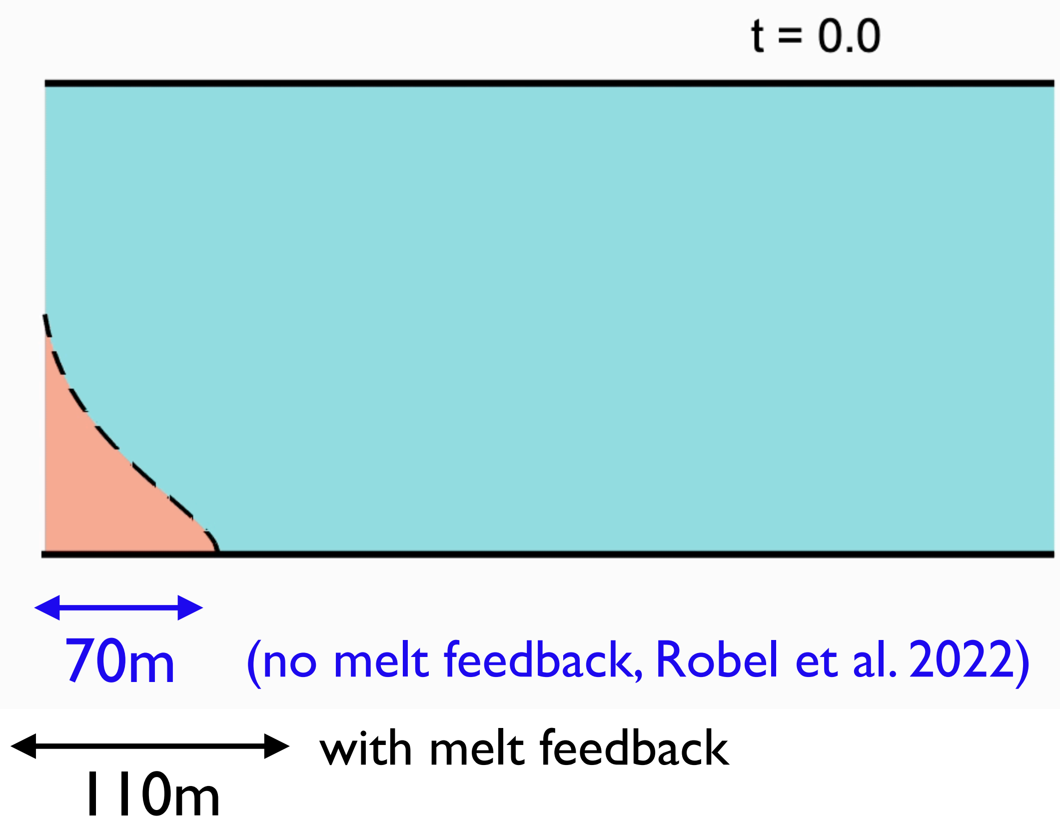
dimensionless drag

$$M=\frac{u_\infty}{V}\frac{\mathrm{St}}{c_d}\frac{T_2-T_1}{L/c}$$

dimensionless melt

+ boundary condition: $h_1^{3/2}=\mathrm{F}^{2/3}$ at $x=0$

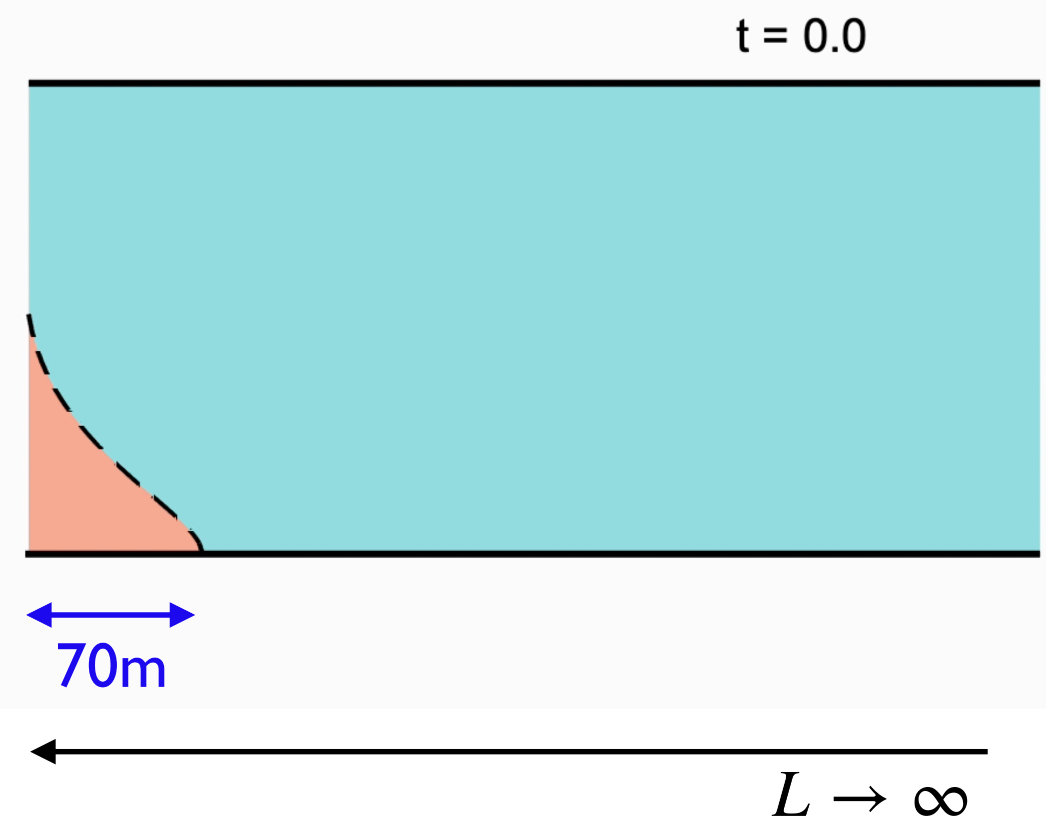
$T_2 = 1.9^\circ C \quad (M = 0.38)$



'bounded intrusion'

$M < M_c$

$T_2 = 2^\circ C \quad (M = 0.4)$



'unbounded intrusion'

$M > M_c$

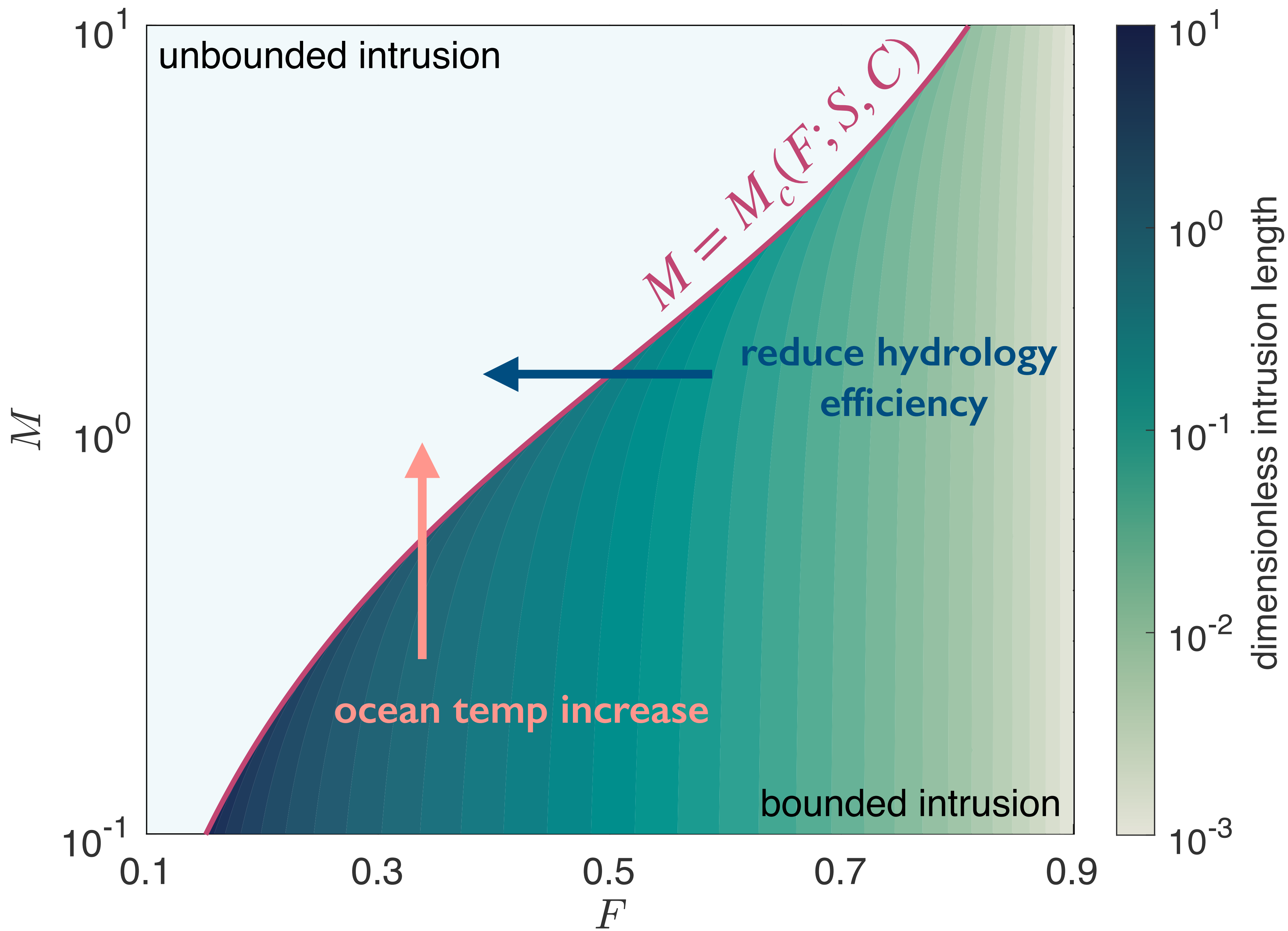
A **small change** in **ocean temperature** leads to a **large response** in **grounding zone melting,** with significant **implications for ice dynamics**

$$M = \frac{u_\infty}{V}\frac{\mathrm{St}}{c_d}\frac{T_2 - T_1}{L/c}$$

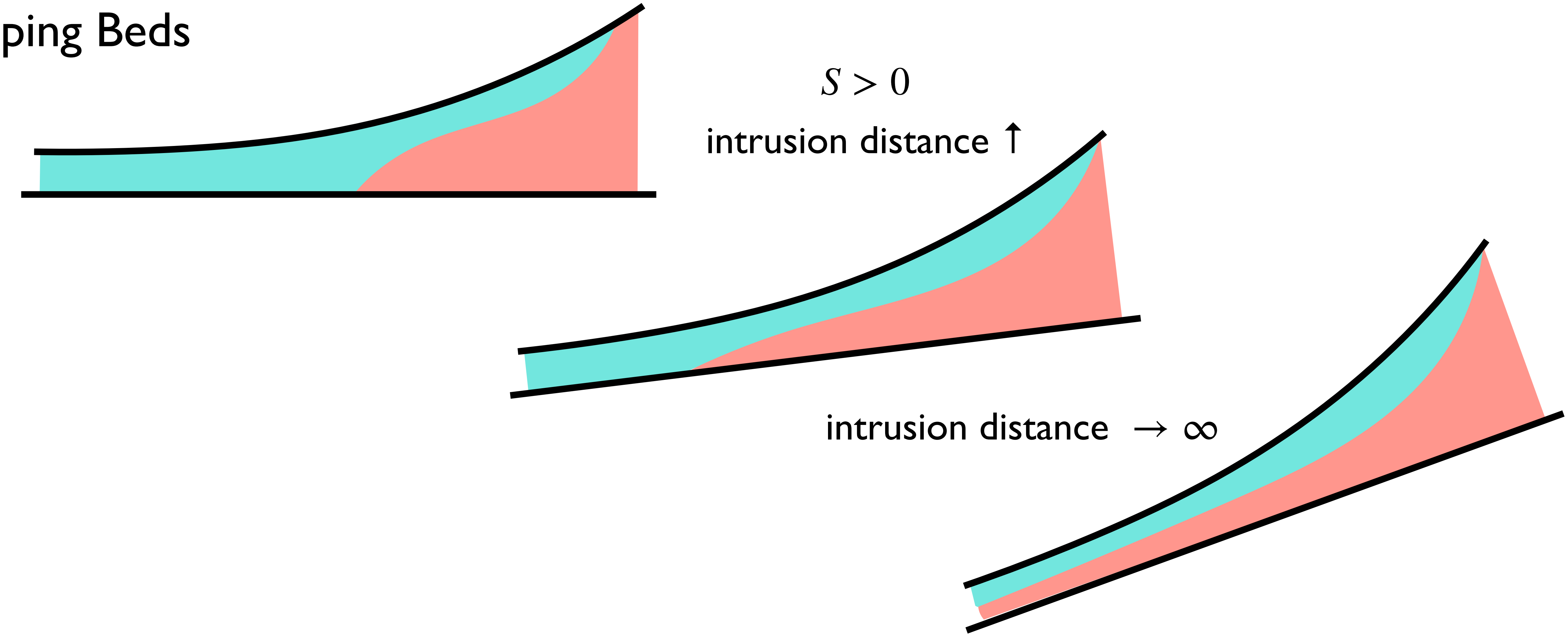
V: ice velocity

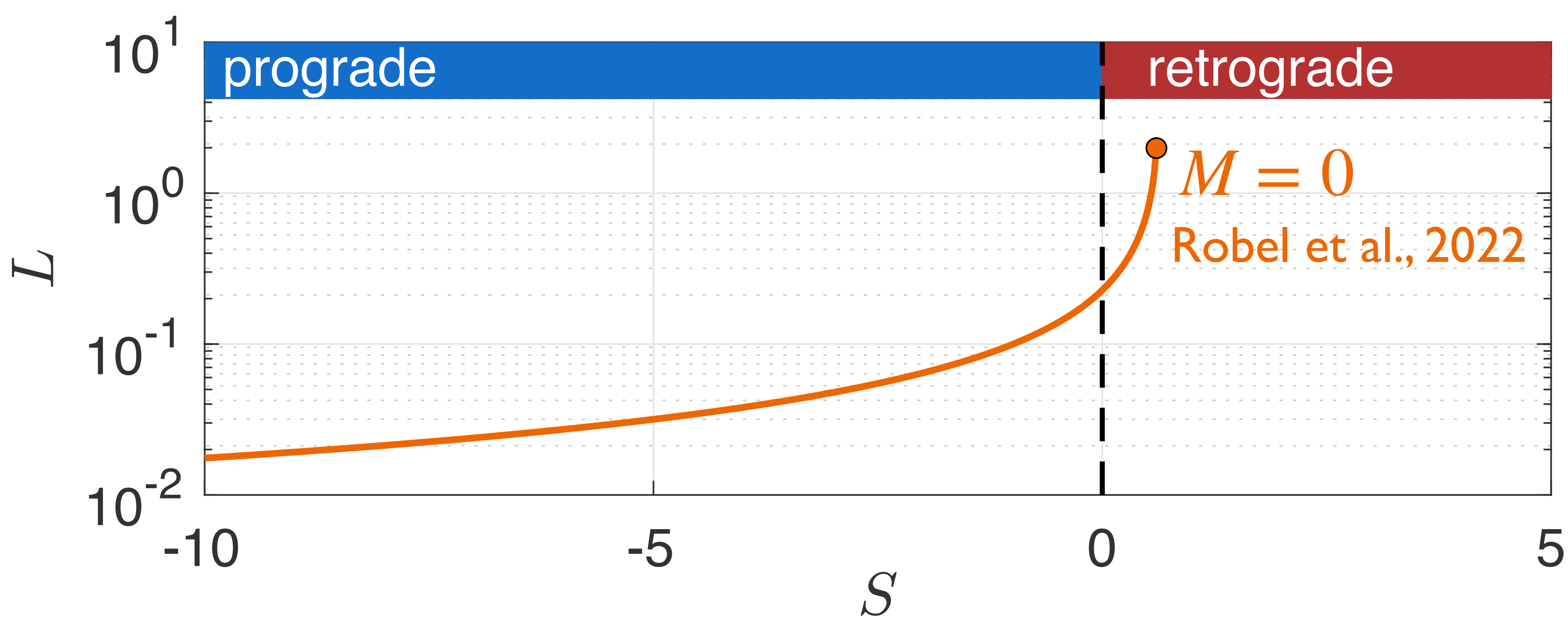
u_∞: upstream meltwater velocity

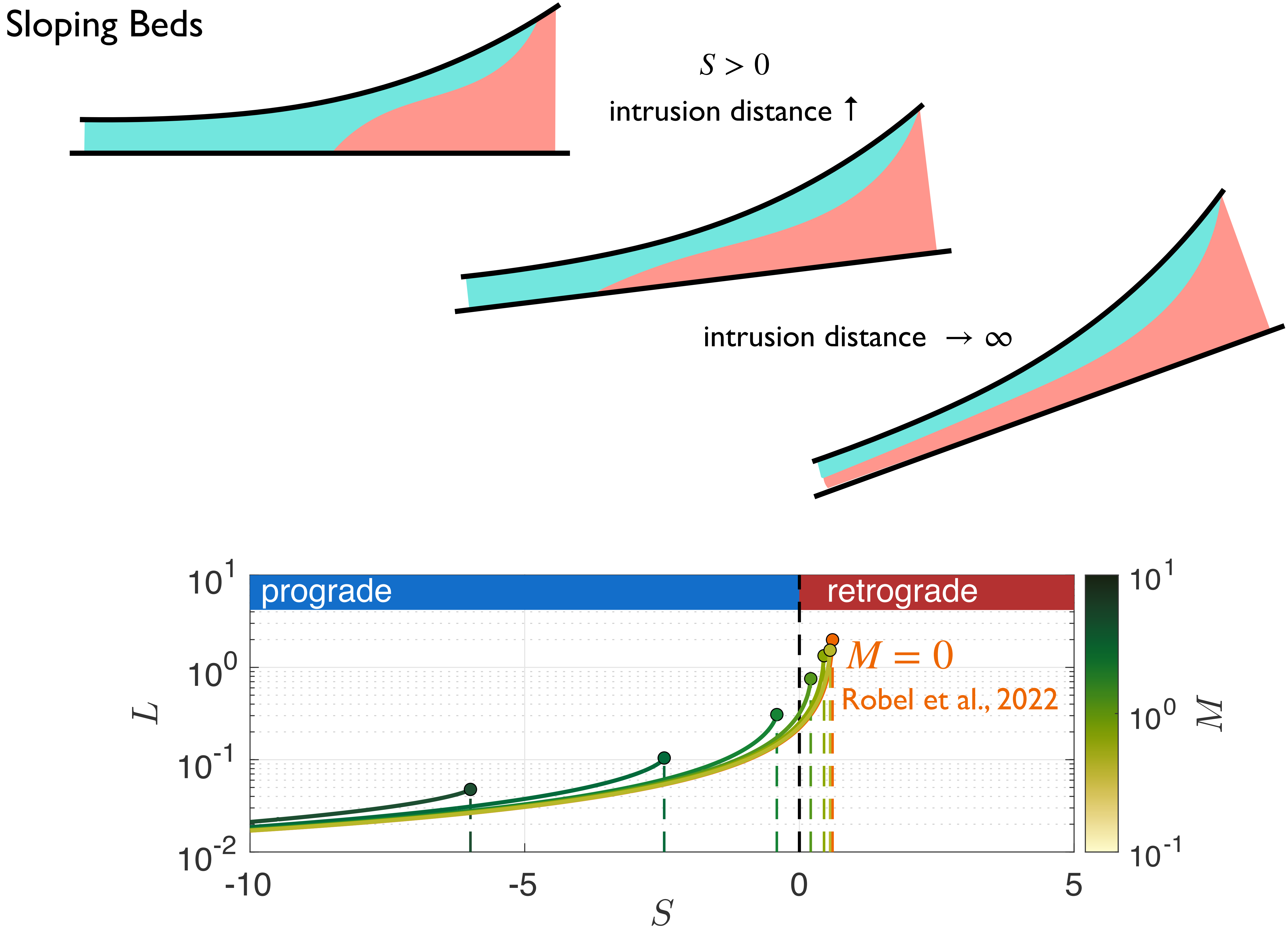
$T_2 - T_1$: ocean forcing



Sloping Beds

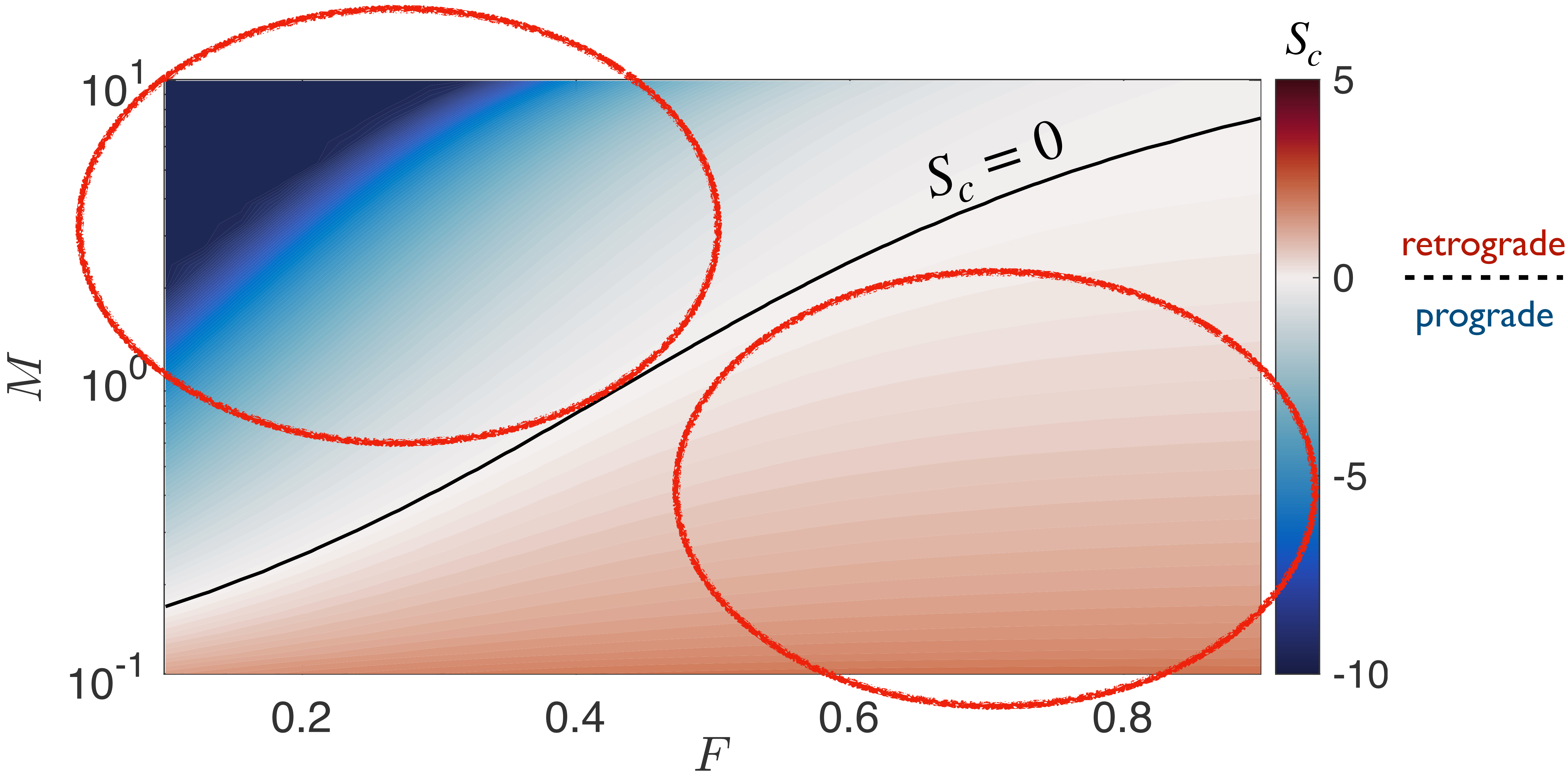






Sloping Beds
$S > 0$
intrusion distance ↑
intrusion distance → ∞
prograde
retrograde
$M = 0$
Robel et al., 2022
L
S
M

prograde bedslopes can also have **unbounded intrusion - less stable than we think?**



melt feedback makes **unbounded intrusion easier** on **retrograde** bedslopes - **candidate mechanism** to explain warm period retreat?

F is poorly constrained, plot as a function of M, S

$$S = \frac{\tan\theta}{C_d}$$

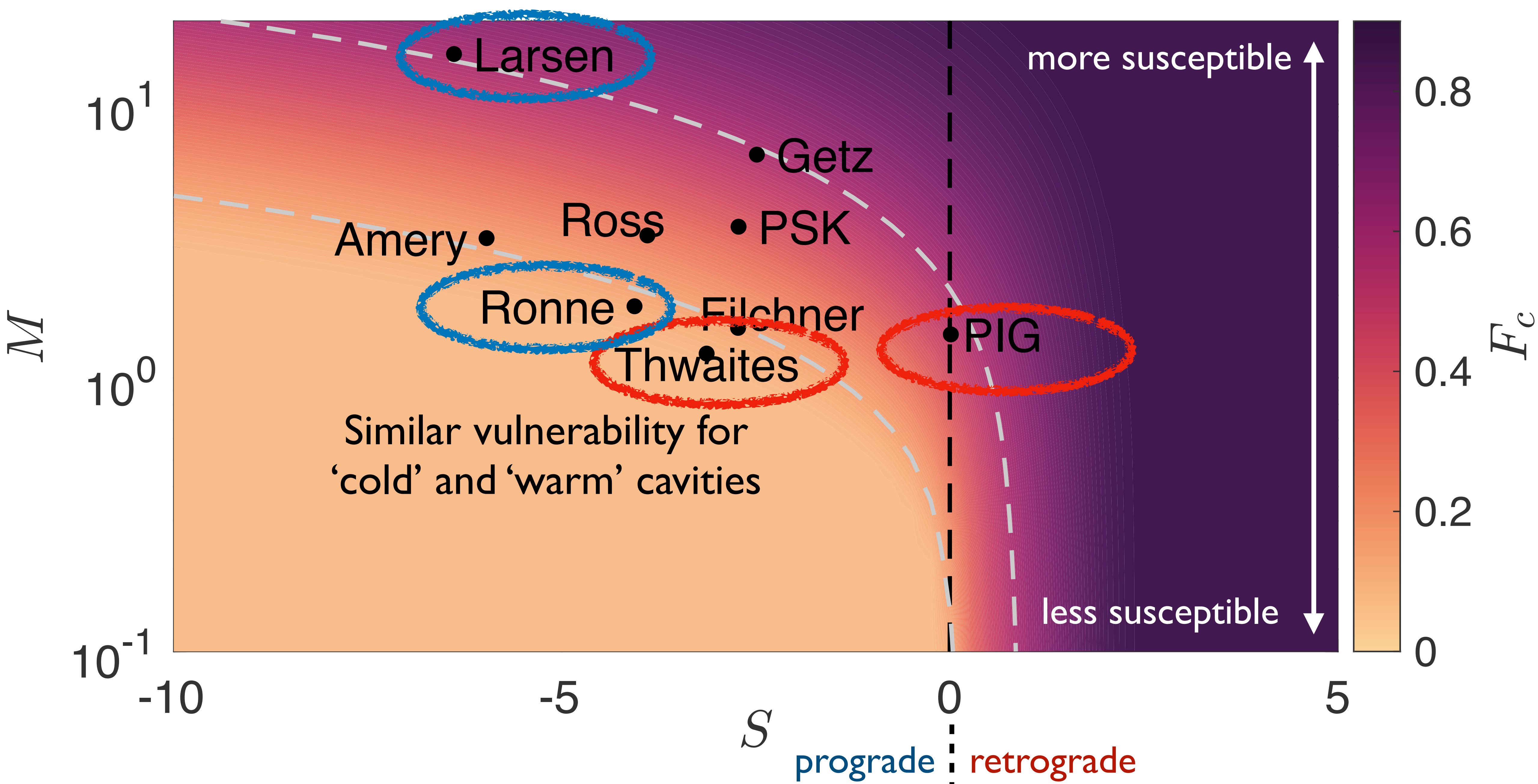
dimensionless bed slope

$$F = \frac{U_\infty}{\sqrt{g' H_\infty}}$$

upstream Froude number

$$M = \frac{u_\infty}{V}\frac{\mathrm{St}}{c_d}\frac{T_2 - T_1}{L/c}$$

dimensionless melt



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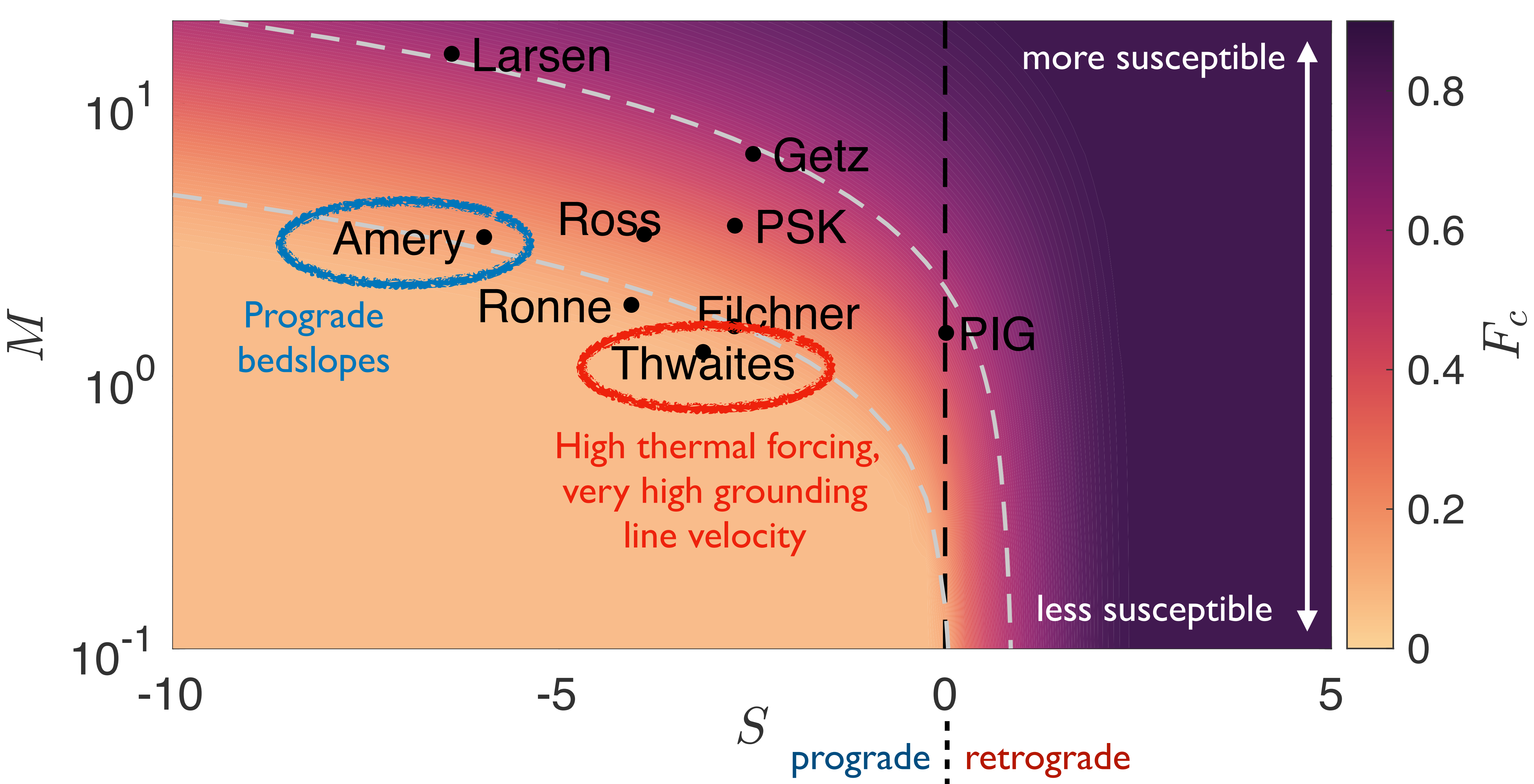

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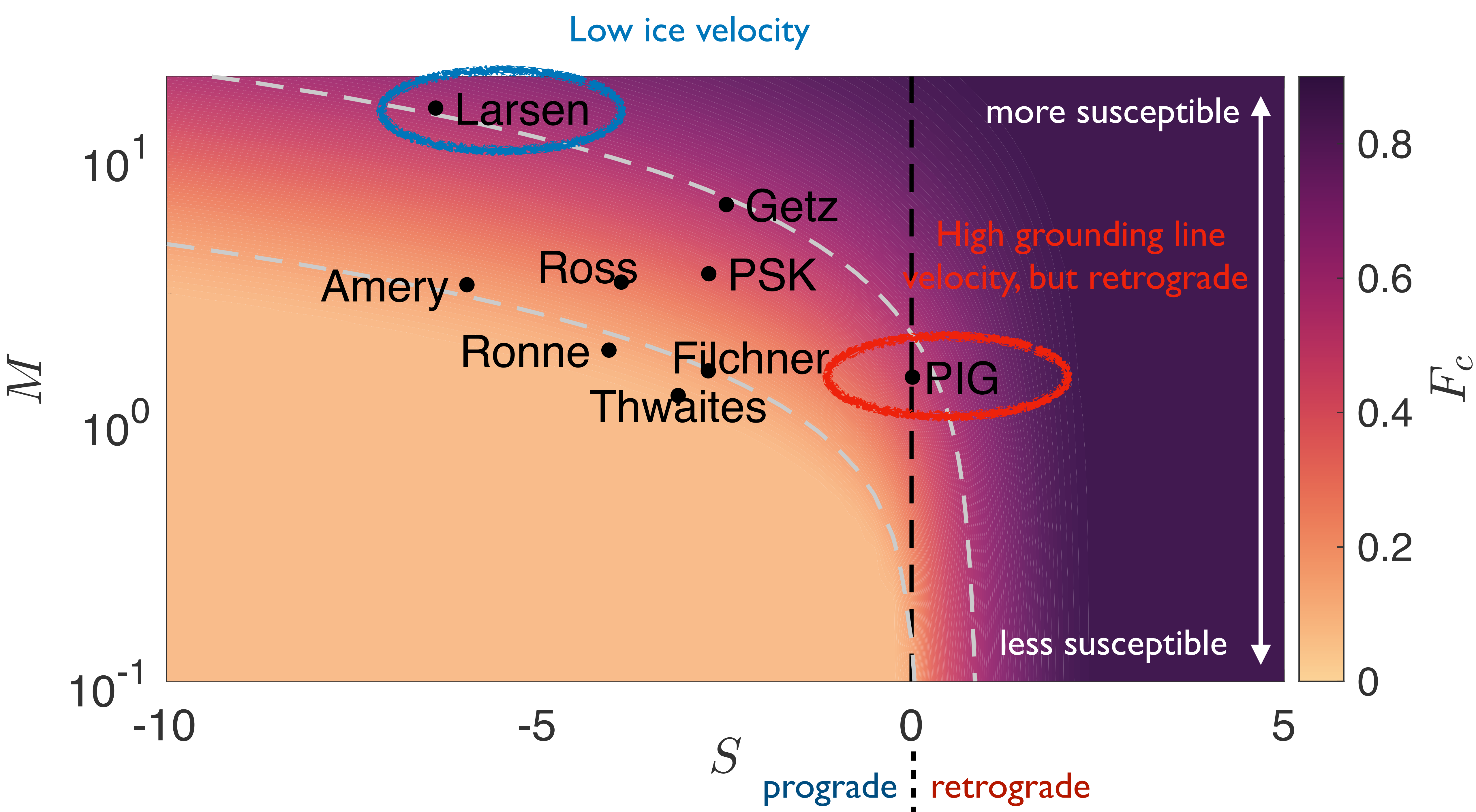
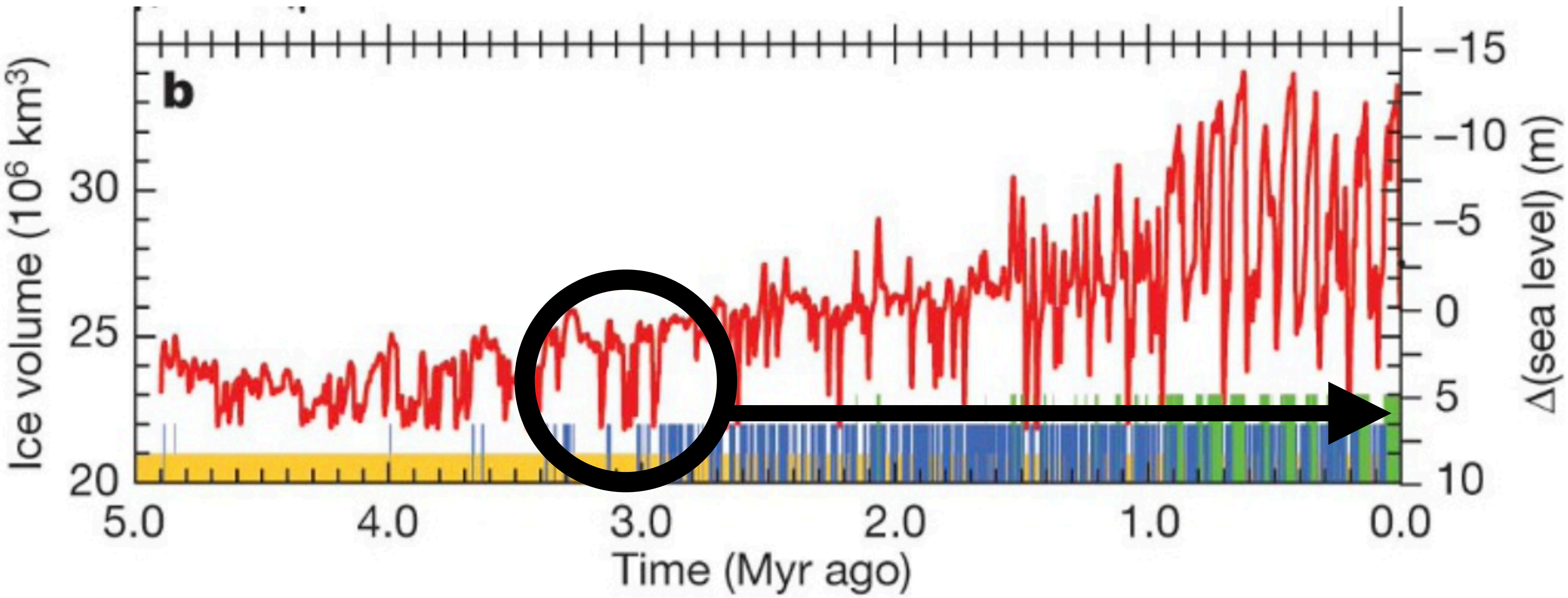
dimensionless melt

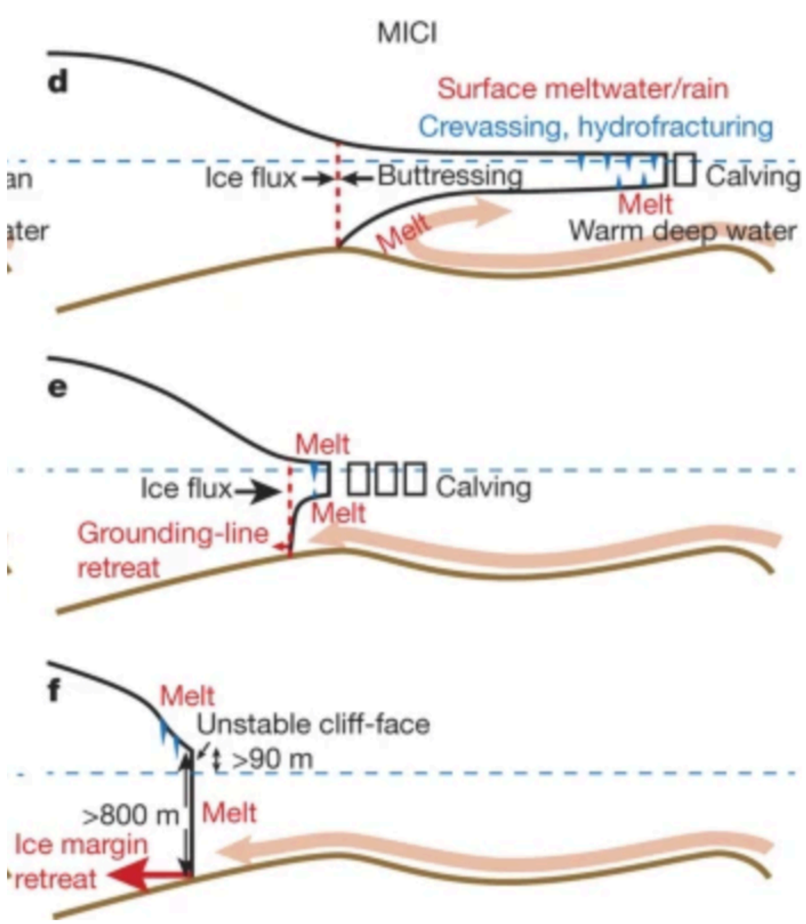


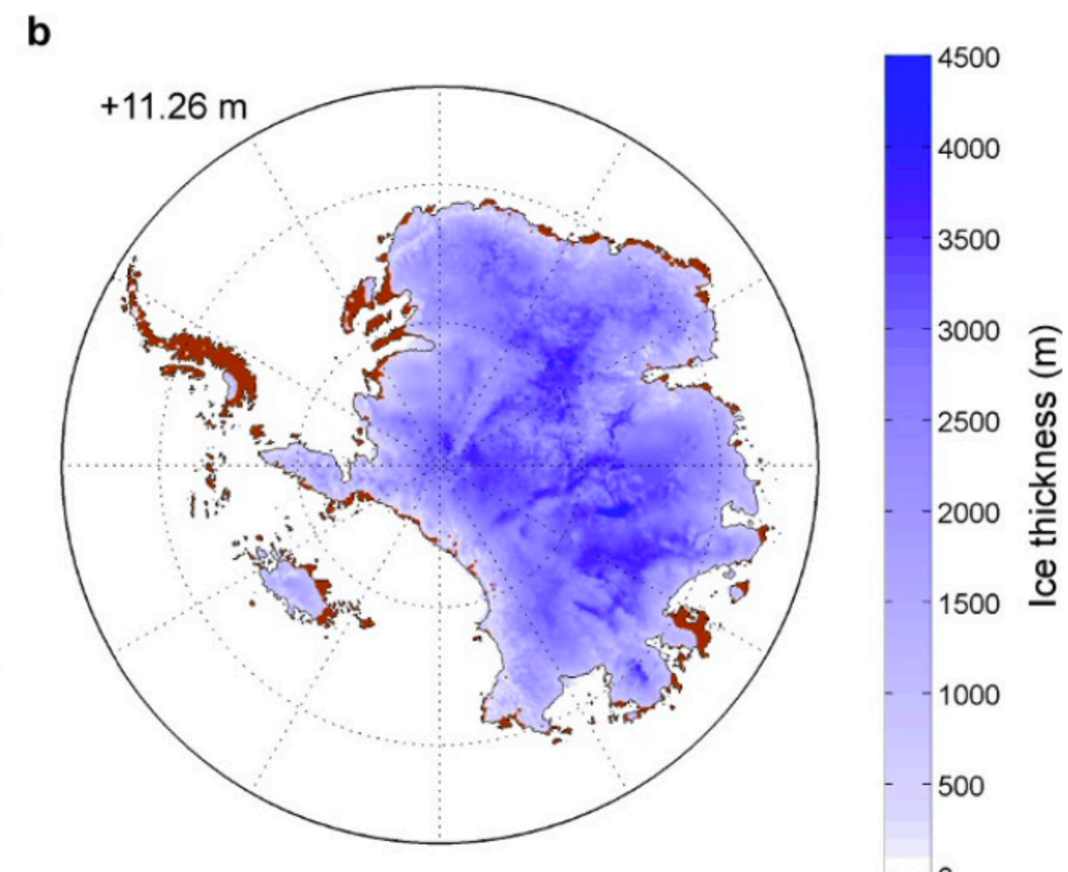
Models struggle to simulate this retreat

Pollard and DeConto, 2009

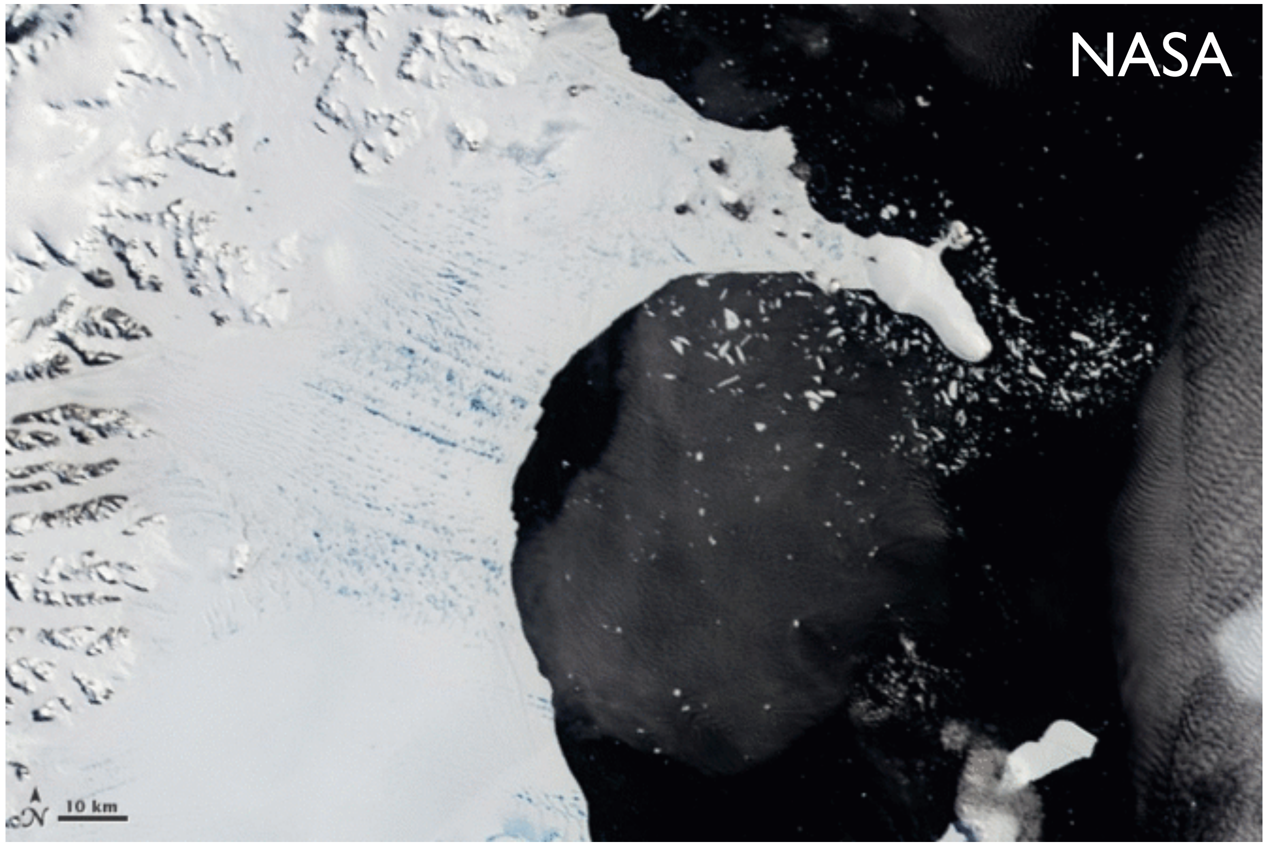


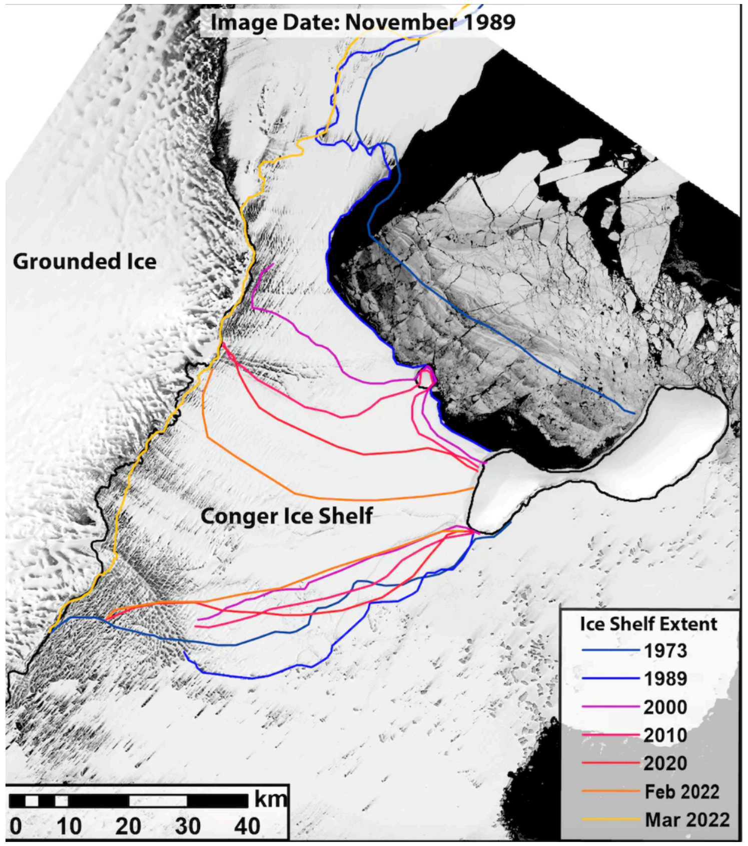
DeConto and Pollard, 2016



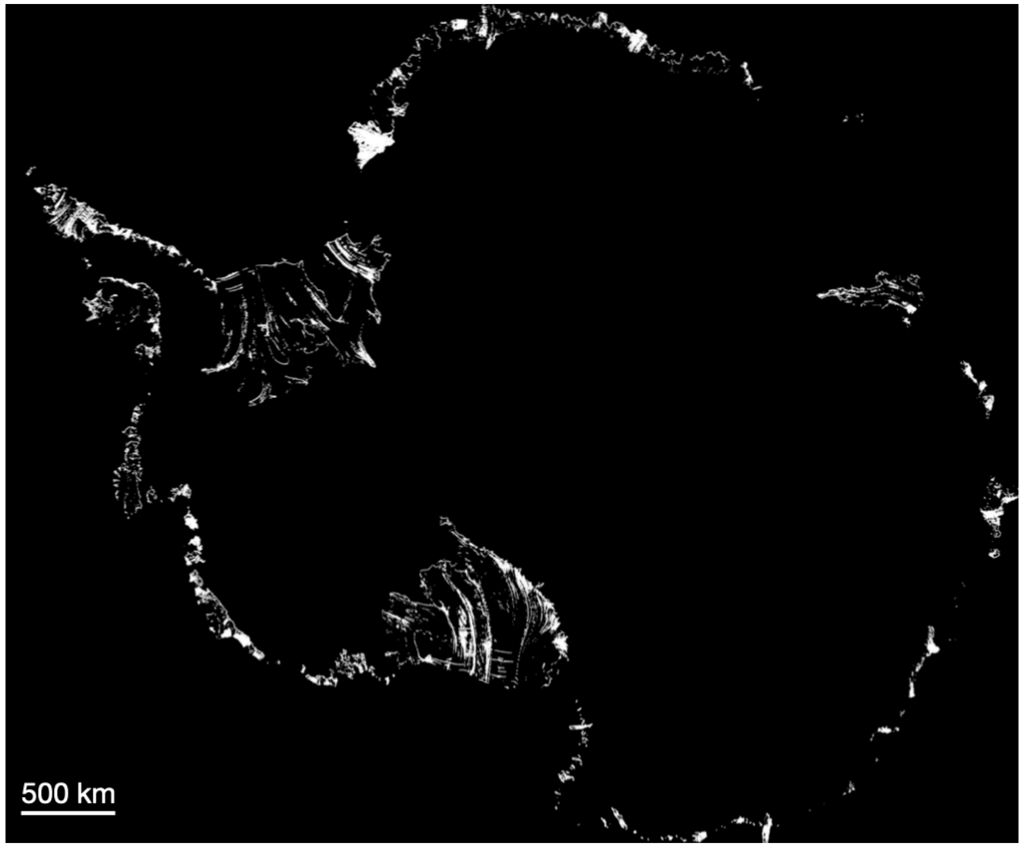


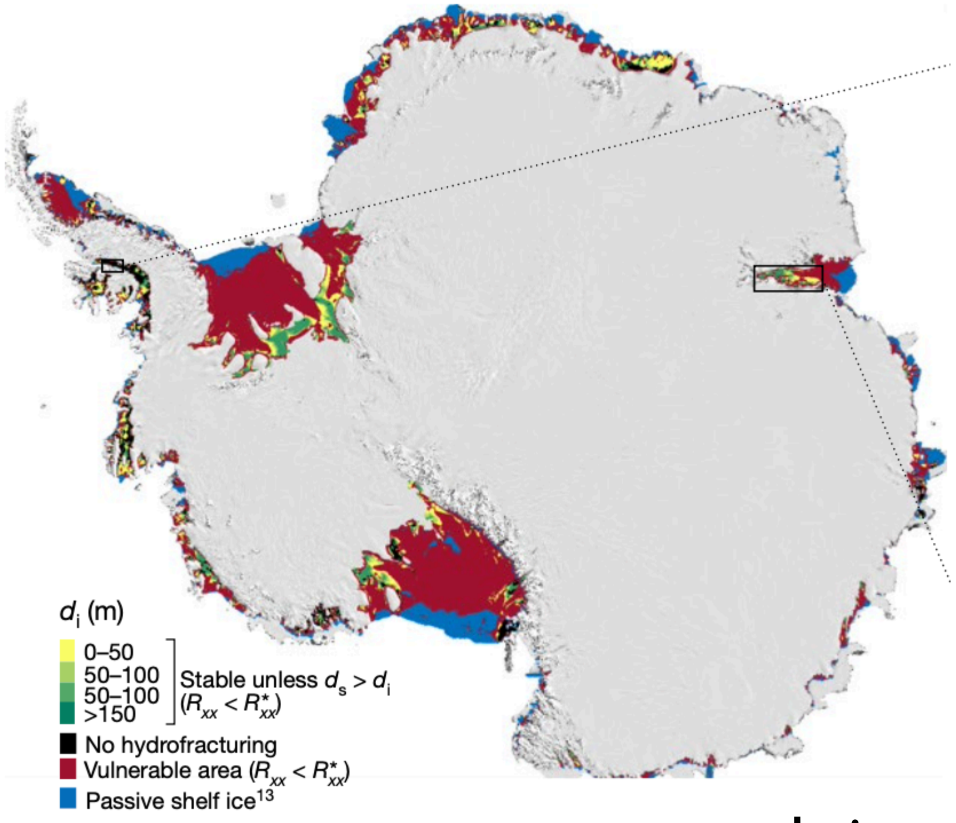
MICI questioned, but still ice shelf collapse still real possibility





Bertie Miles

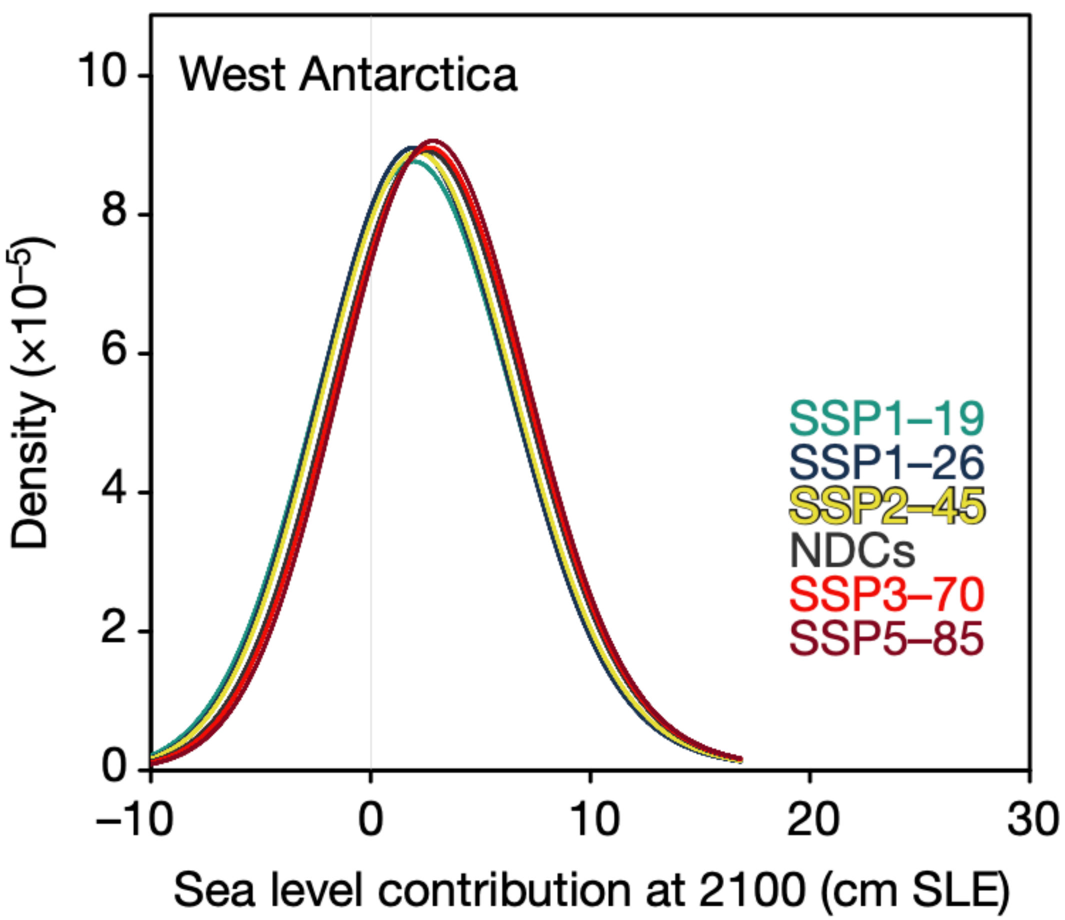




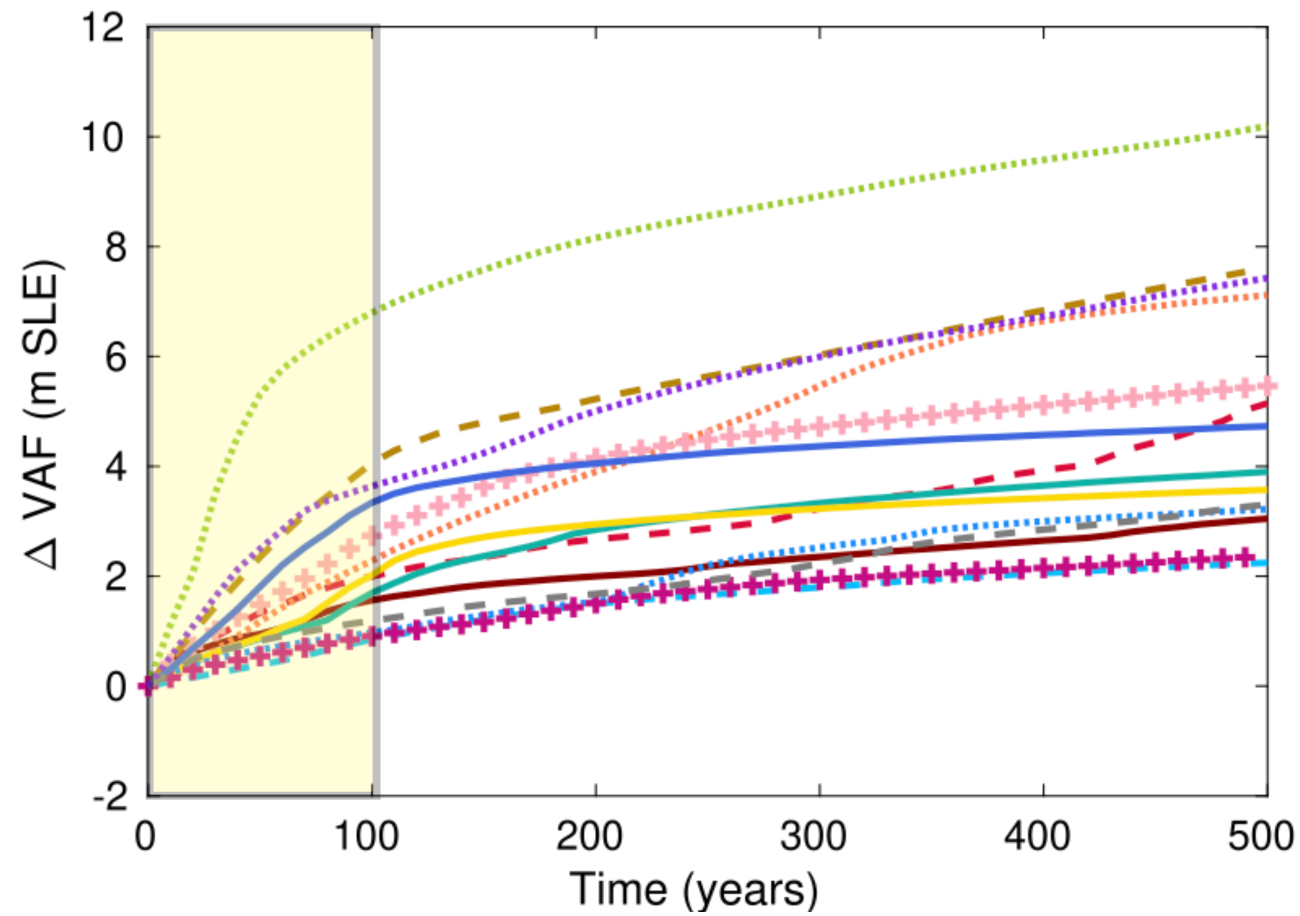
Lai et al. , 2020

When ice shelves collapse — the biggest uncertainty in SLR projections?

Edwards et al. 2021 — CMIP

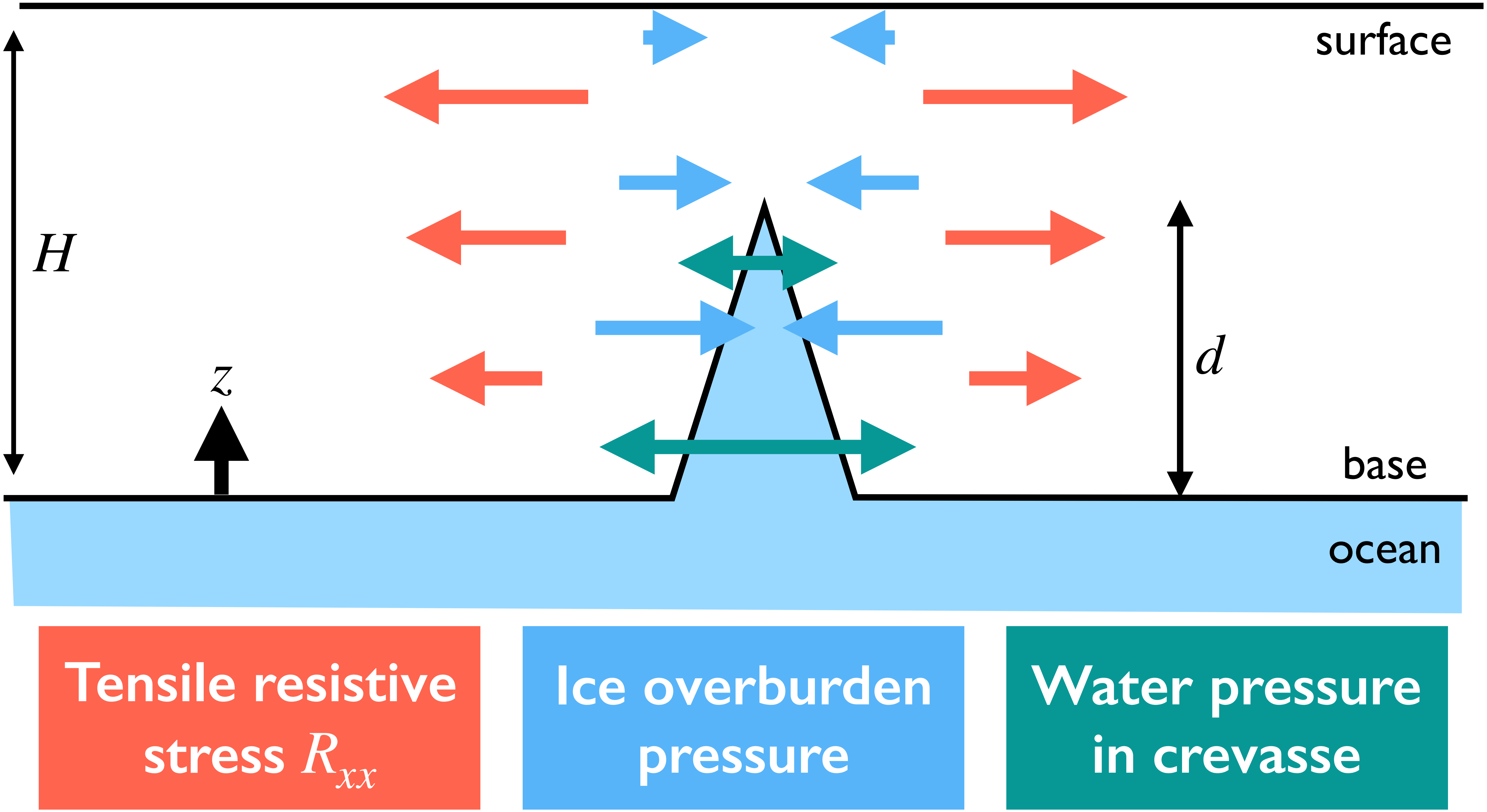


Sun et al. 2020 — ABUMIP (no ice shelves)



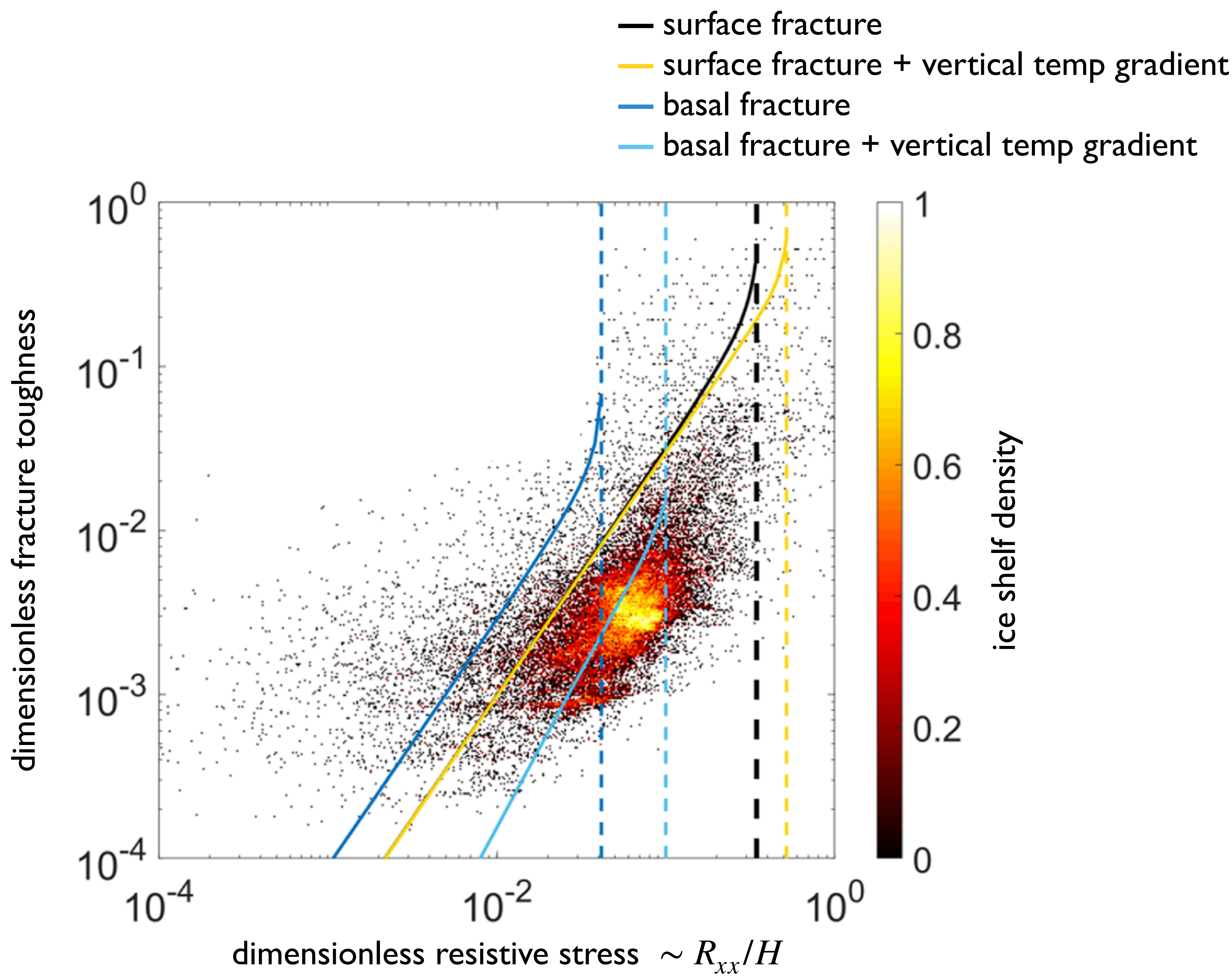
What is SLR by 2100? → Which ice shelves collapse before 2100 and when?

Lai et al. results based on LEFM

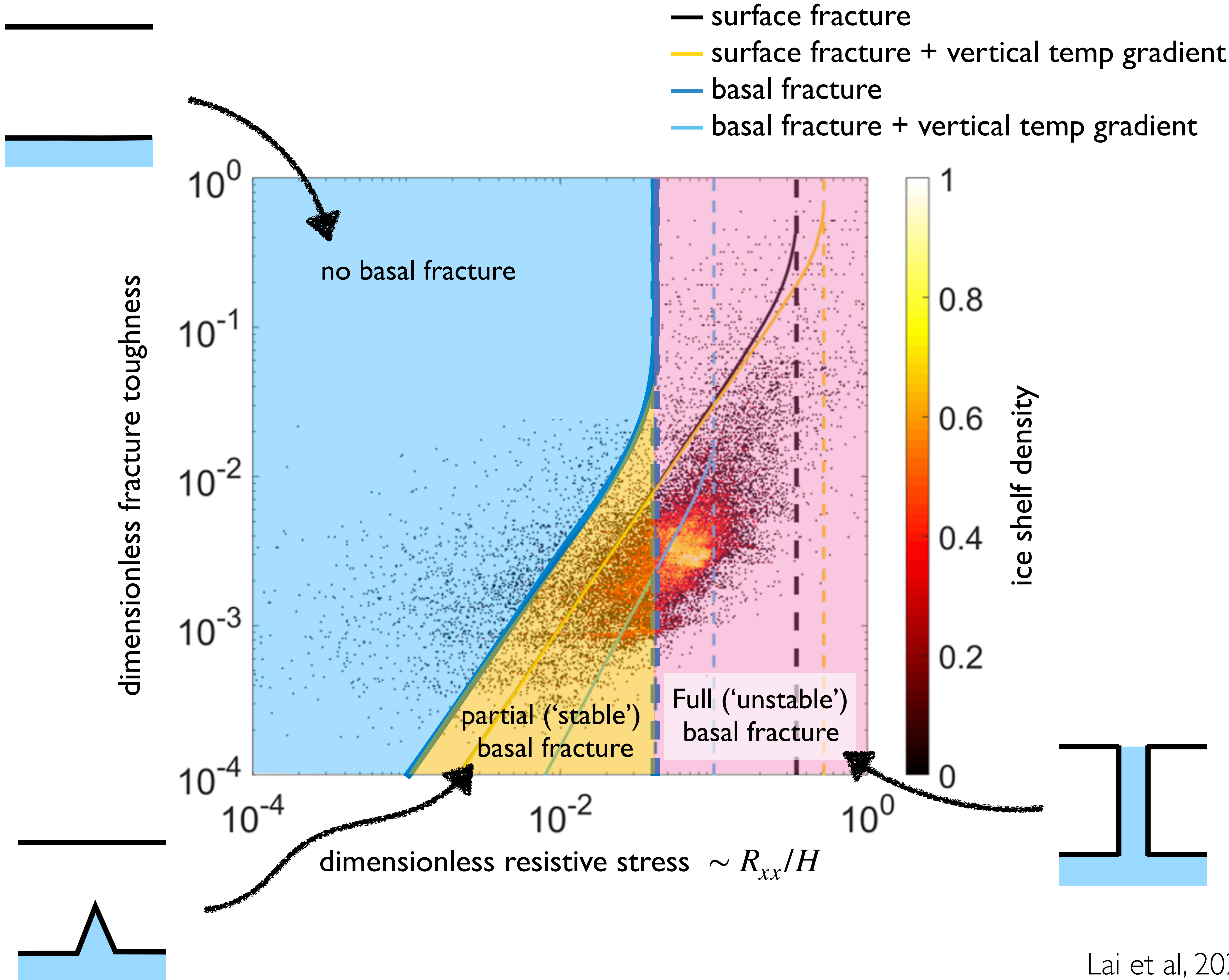


Stress intensity = tensile resistive stress + water pressure + ice overburden

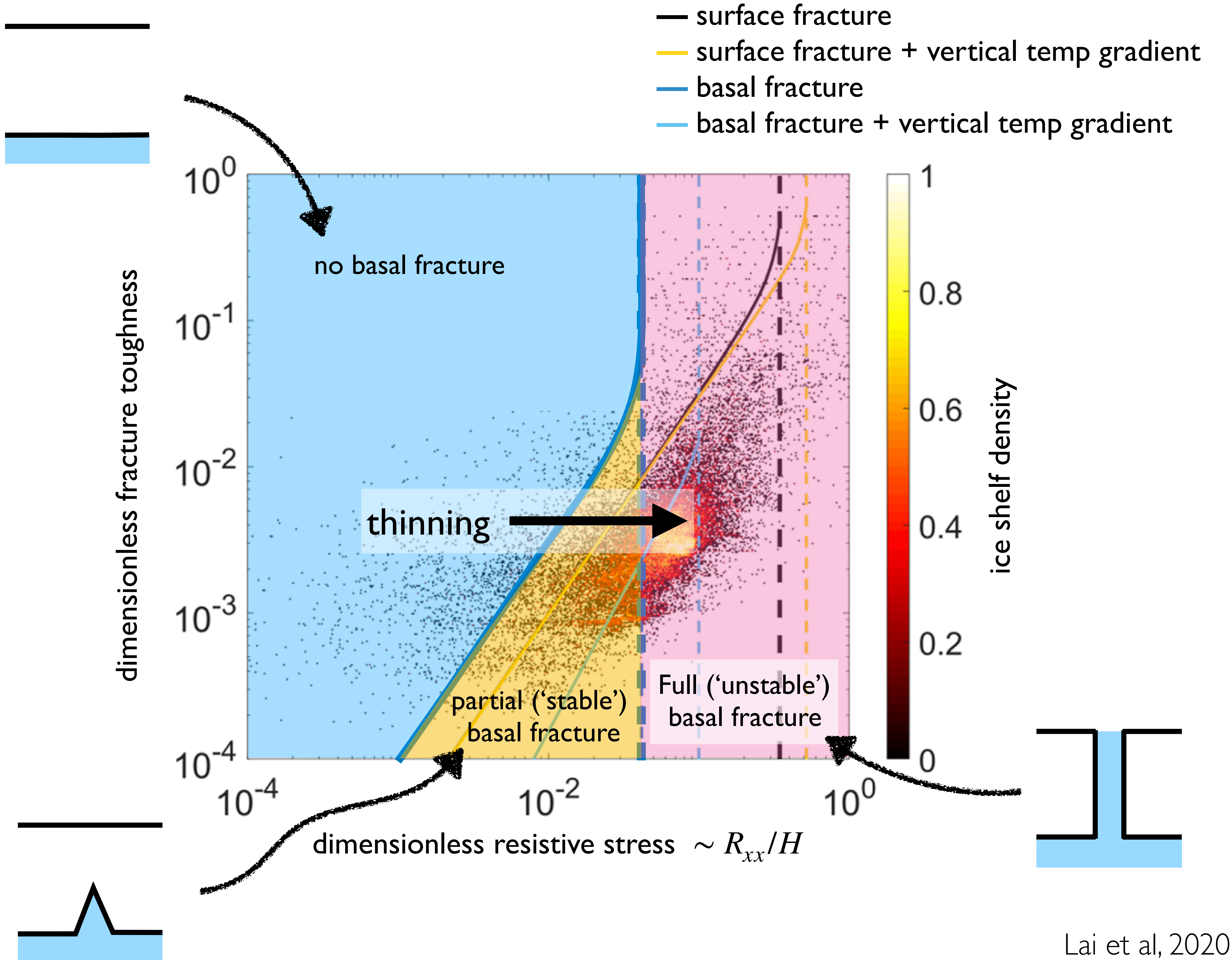
Crevasse depth set by **stress intensity** = **ice fracture toughness** $F \approx$ 150 MPa



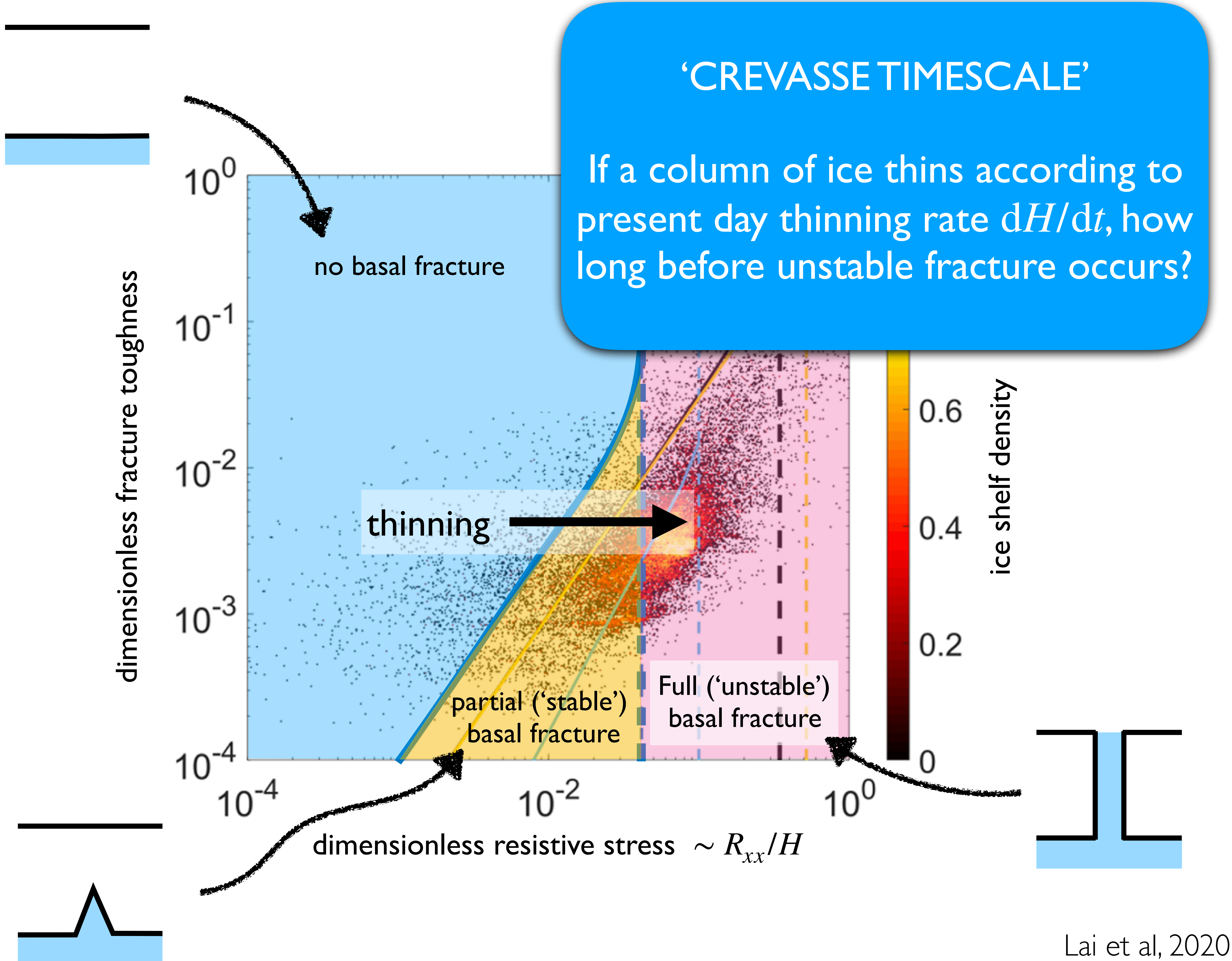
Lai et al, 2020

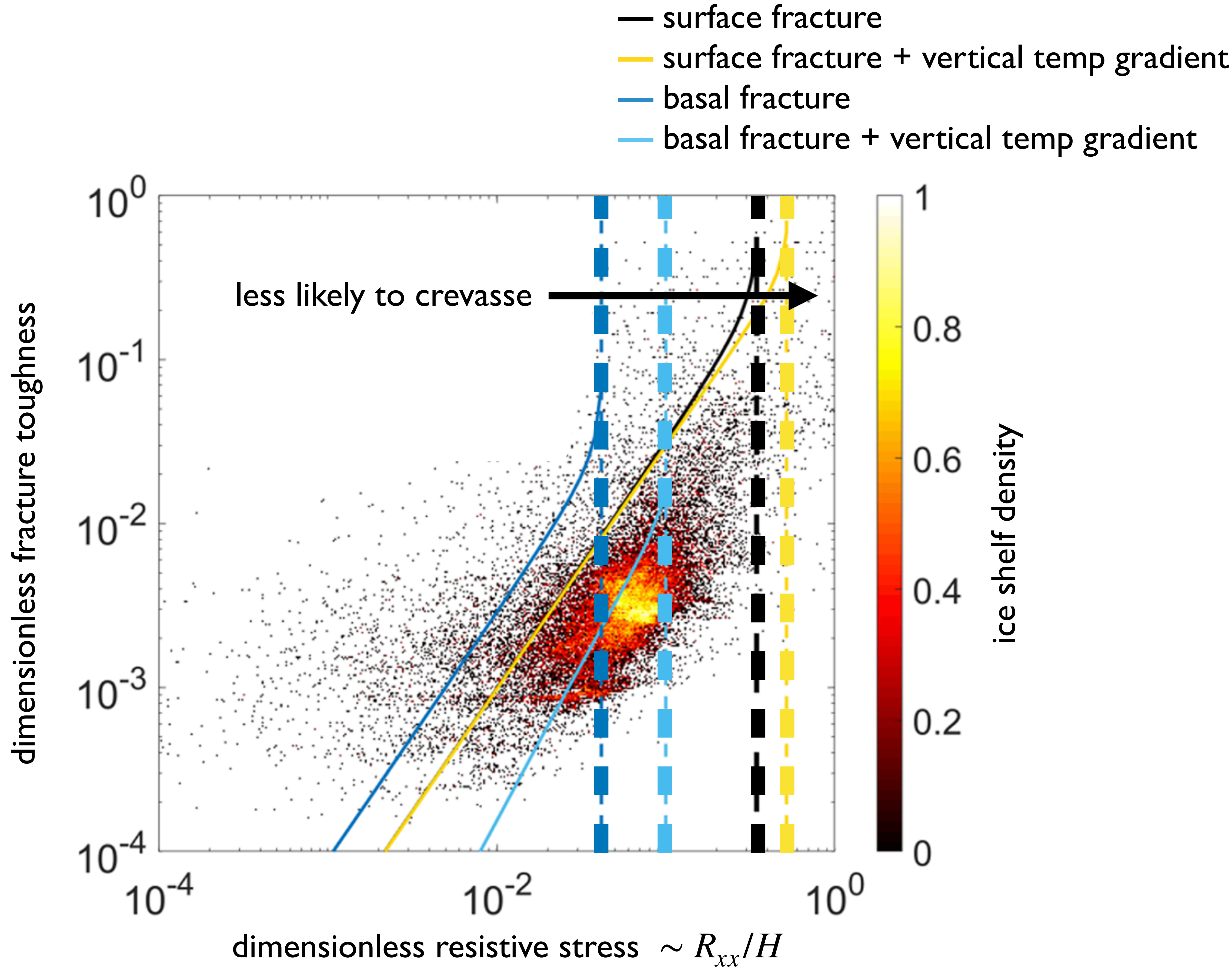


Lai et al, 2020



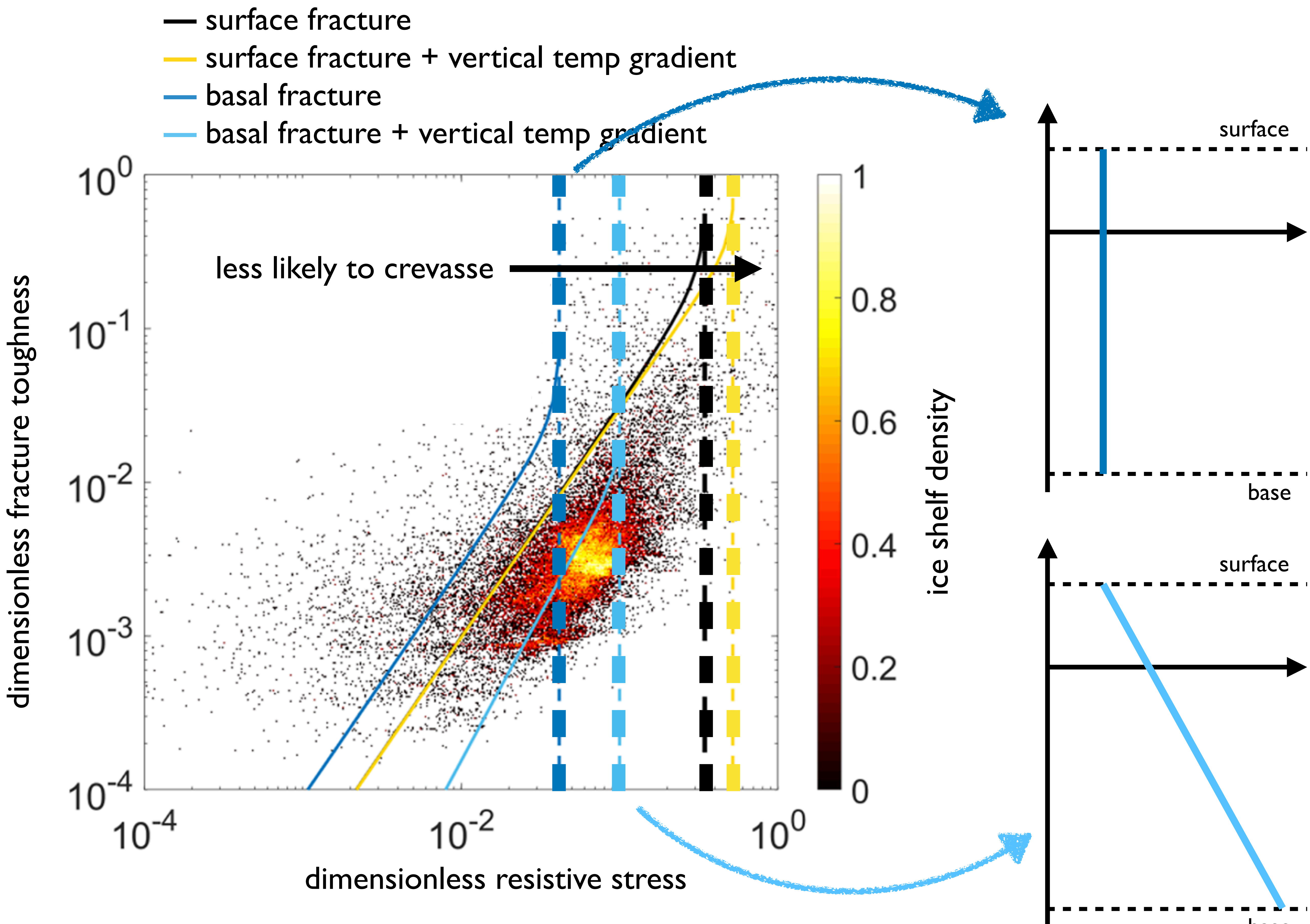
surface fracture
surface fracture + vertical temp gradient
basal fracture
basal fracture + vertical temp gradient
no basal fracture
thinning
partial ('stable') basal fracture
Full ('unstable') basal fracture
dimensionless fracture toughness
dimensionless resistive stress $\sim R_{xx}/H$
ice shelf density
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-4}
10^{-2}
10^{0}
1
0.8
0.6
0.4
0.2
0
Lai et al, 2020


‘CREVASSE TIMESCALE’
If a column of ice thins according to present day thinning rate $\mathrm{d}H/\mathrm{d}t$, how long before unstable fracture occurs?
no basal fracture
thinning
partial (‘stable’) basal fracture
Full (‘unstable’) basal fracture
dimensionless fracture toughness
dimensionless resistive stress $\sim R_{xx}/H$
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-4}
10^{-2}
10^{0}
ice shelf density
0
0.2
0.4
0.6
Lai et al, 2020



(1) surface crevasses less likely than basal crevasses(!)
(2) temperature profile really matters

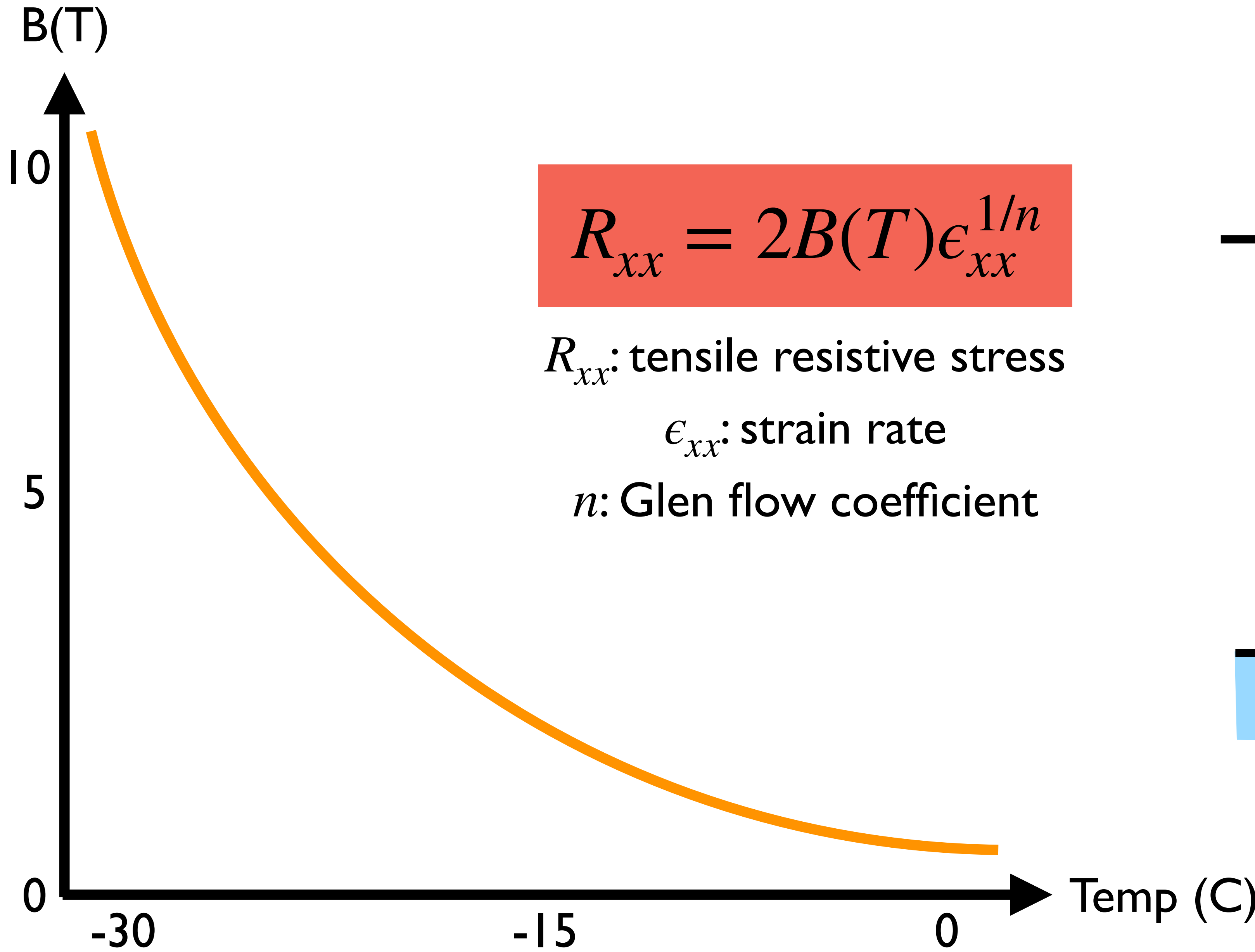
Lai et al, 2020



warmer ice less likely to crevasse!?

Lai et al, 2020

Why is warmer ice less likely to crevasse?

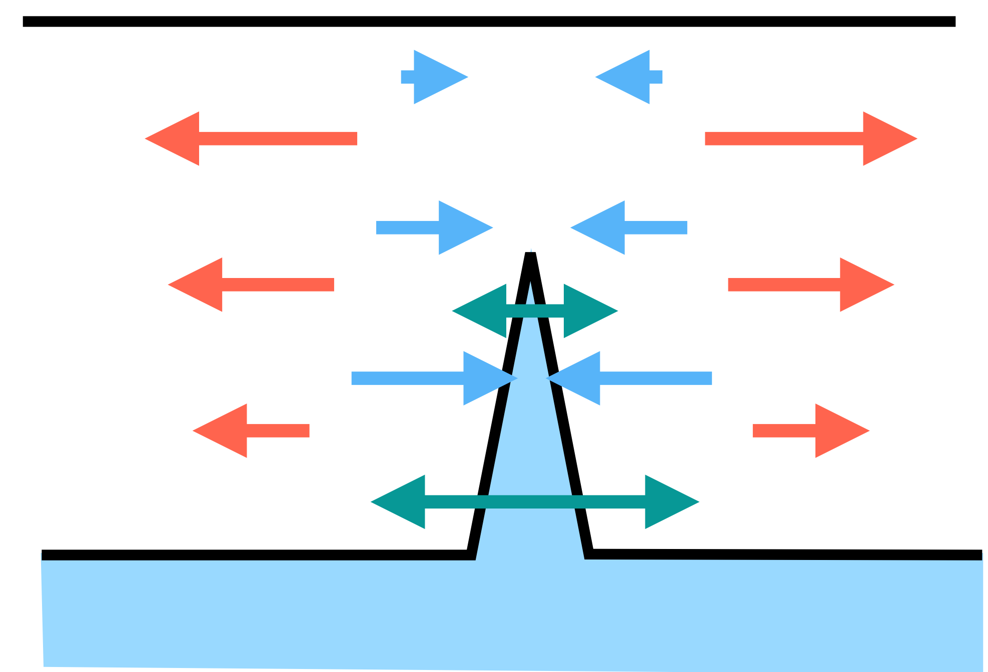


$$R_{xx} = 2B(T)\epsilon_{xx}^{1/n}$$

R_{xx}: tensile resistive stress

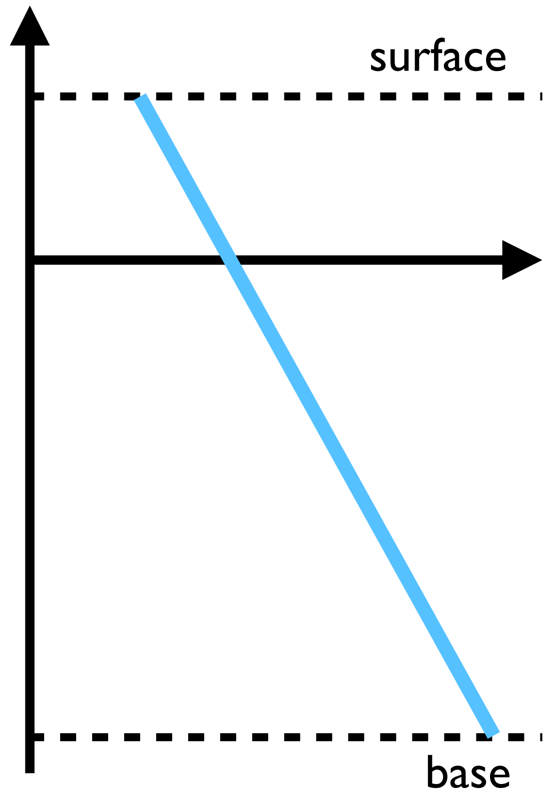
ϵ_{xx}: strain rate

n: Glen flow coefficient



~ order of magnitude variation in viscosity across expected range of temperatures

Stress intensity = tensile resistive stress + water pressure + ice overburden

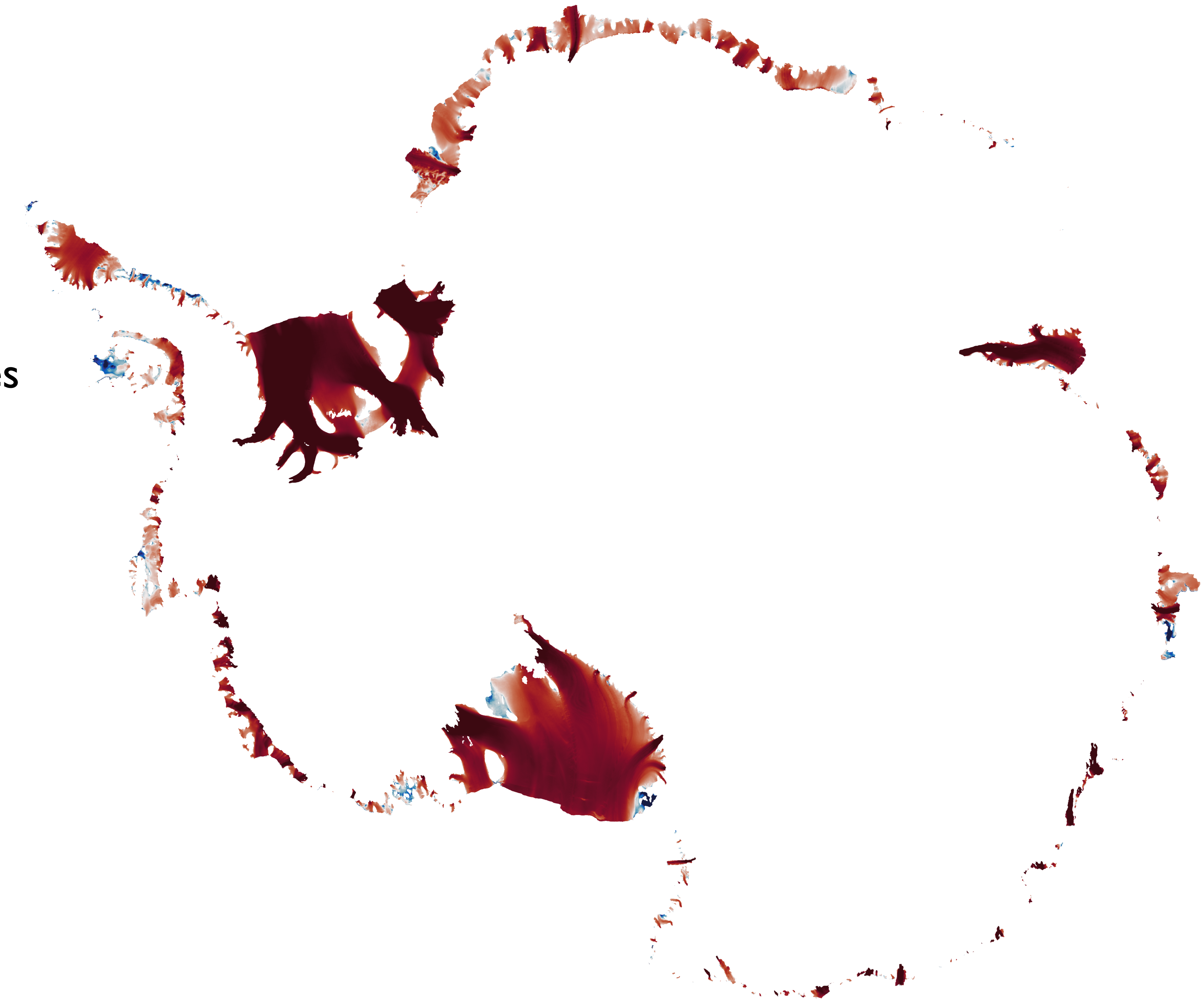


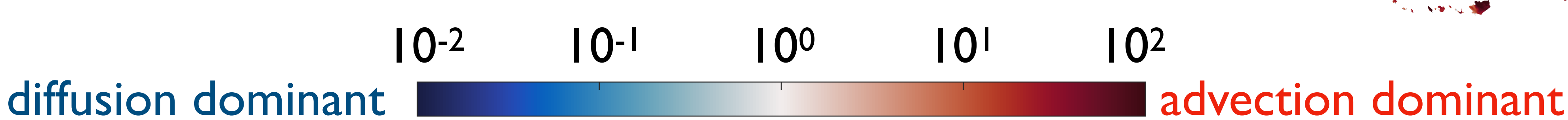
Linear profile based on diffusion dominated heat transfer…

$$\cancel{\mathbf{u}\,.\,\nabla} T = \nabla\,.\,(\kappa \nabla T)$$

…but really advection dominates

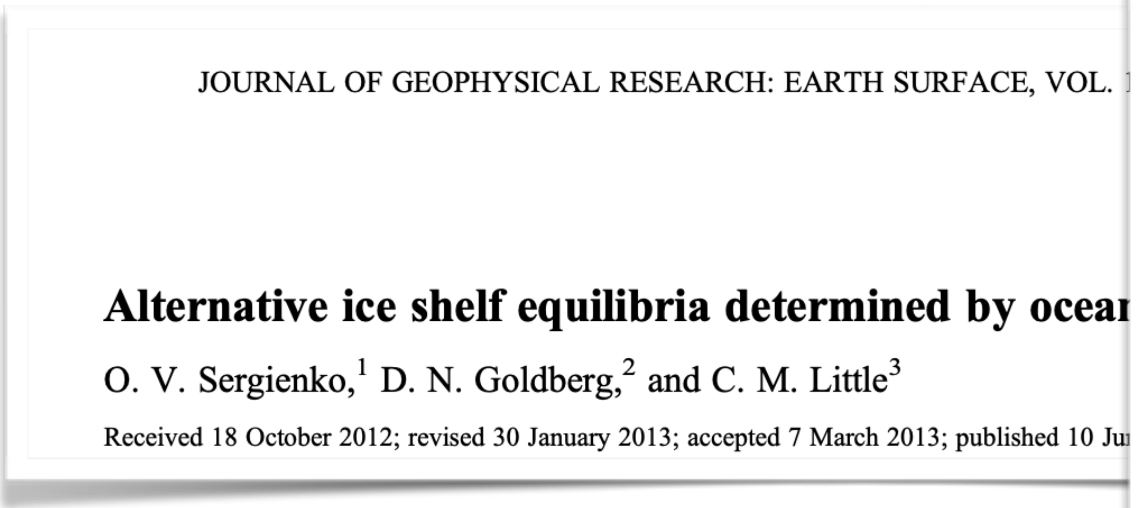
$$\mathrm{Pe} = \frac{H^2\,|\,\mathbf{u}\,|}{L\kappa_i}$$





Flowline description of ice shelf temperature (Sergienko et al. ,2013)

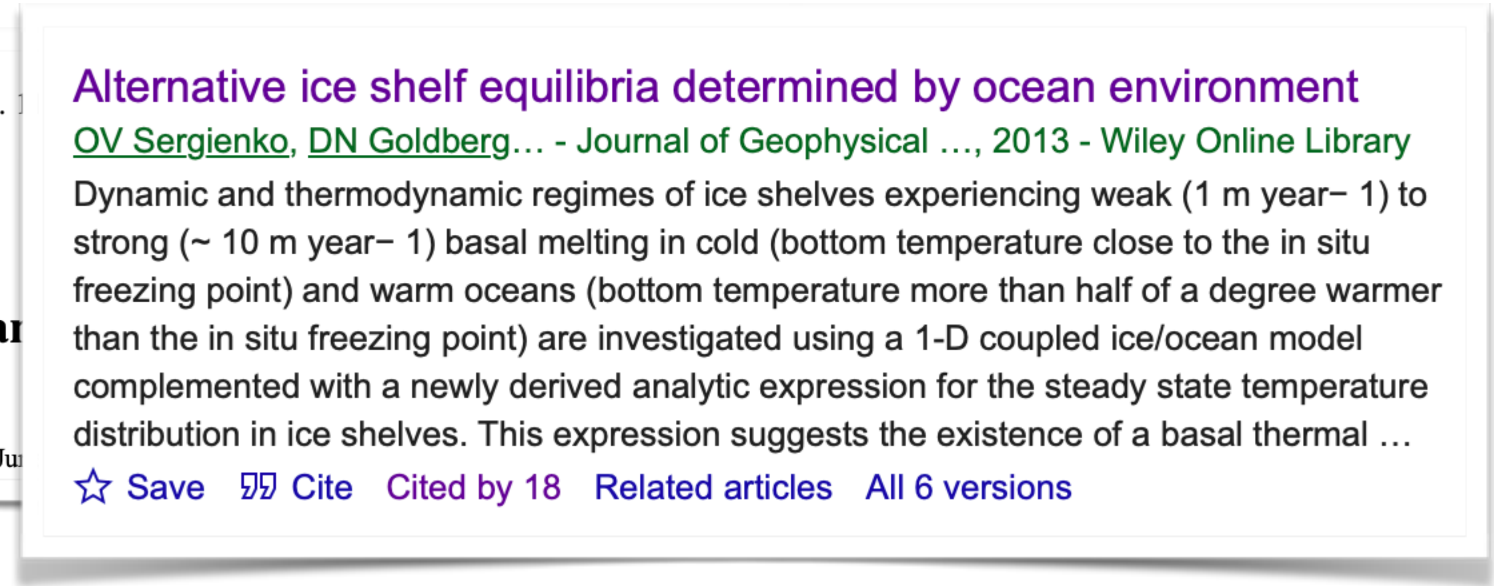
appropriate for advection dominant flow


JOURNAL OF GEOPHYSICAL RESEARCH: EARTH SURFACE, VOL.

Alternative ice shelf equilibria determined by ocean

O. V. Sergienko,[1] D. N. Goldberg,[2] and C. M. Little[3]

Received 18 October 2012; revised 30 January 2013; accepted 7 March 2013; published 10 Ju


Alternative ice shelf equilibria determined by ocean environment

OV Sergienko, DN Goldberg… - Journal of Geophysical …, 2013 - Wiley Online Library

Dynamic and thermodynamic regimes of ice shelves experiencing weak (1 m year− 1) to strong (~ 10 m year− 1) basal melting in cold (bottom temperature close to the in situ freezing point) and warm oceans (bottom temperature more than half of a degree warmer than the in situ freezing point) are investigated using a 1-D coupled ice/ocean model complemented with a newly derived analytic expression for the steady state temperature distribution in ice shelves. This expression suggests the existence of a basal thermal …

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along flow line co-ordinate

basal temperature (freezing)

$$T(x,\zeta) = T_g\left[\xi(x,\zeta)\right] + \left\{T_f(x) - T_g\left[\xi(x,\zeta)\right]\right\} \exp\left(-\frac{\dot{m}H}{\kappa}\zeta\right)$$

Grounding line temperature advected downstream

diffusive part, restricted to boundary layer of width $\ell = \frac{\kappa}{\dot{m}H}$

dimensionless vertical co-ordinate

Flowline description of ice shelf temperature (Sergienko et al. ,2013)

along flow line co-ordinate

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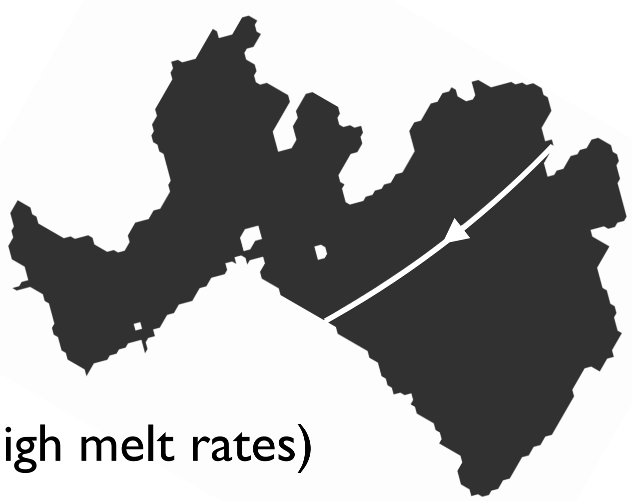
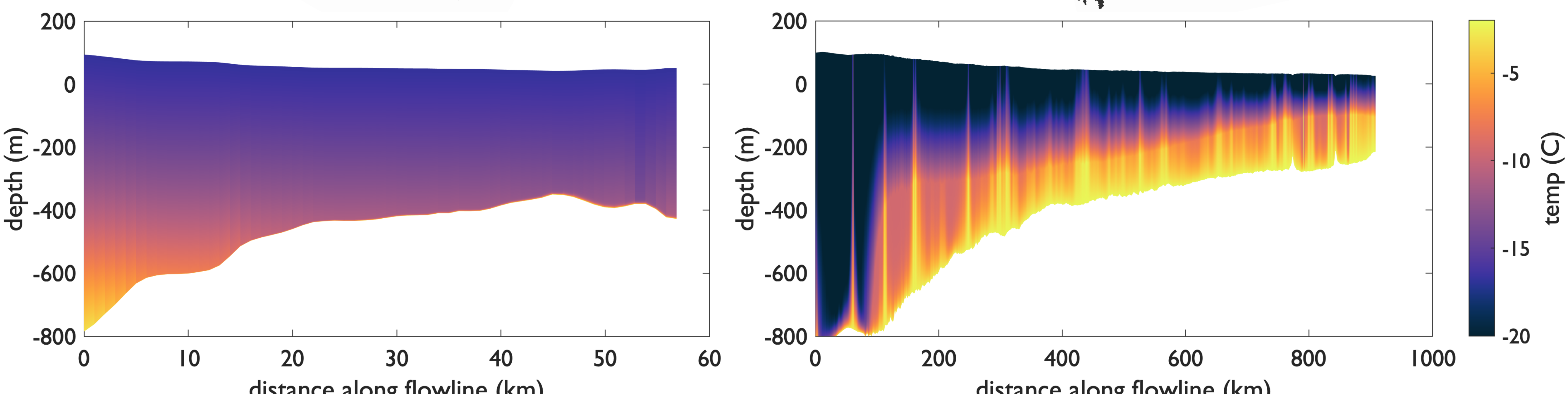
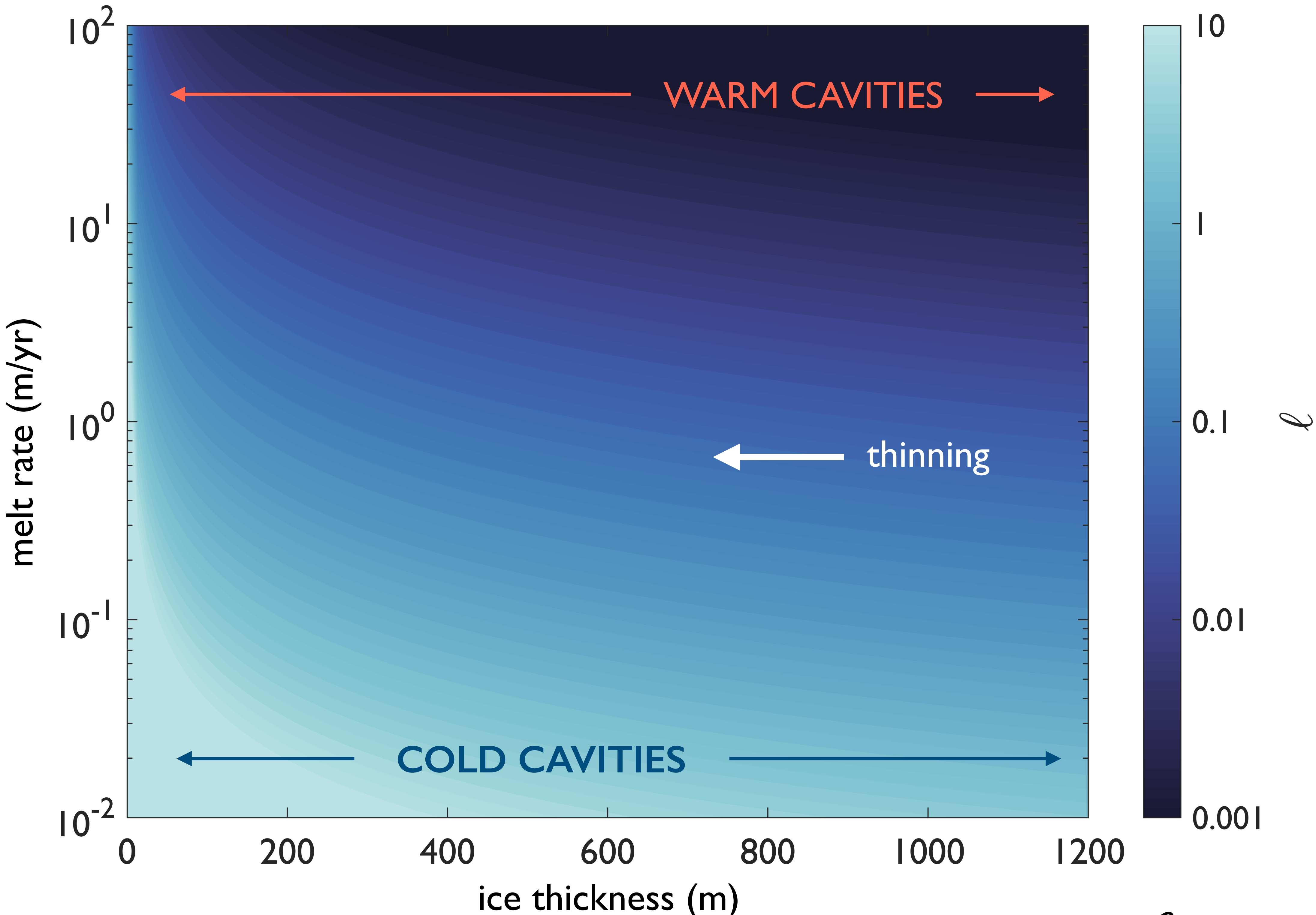


Pine Island (high melt rates)

Ross (low melt rates)



(thick ice) high melting: low ℓ
→ little temperature correction



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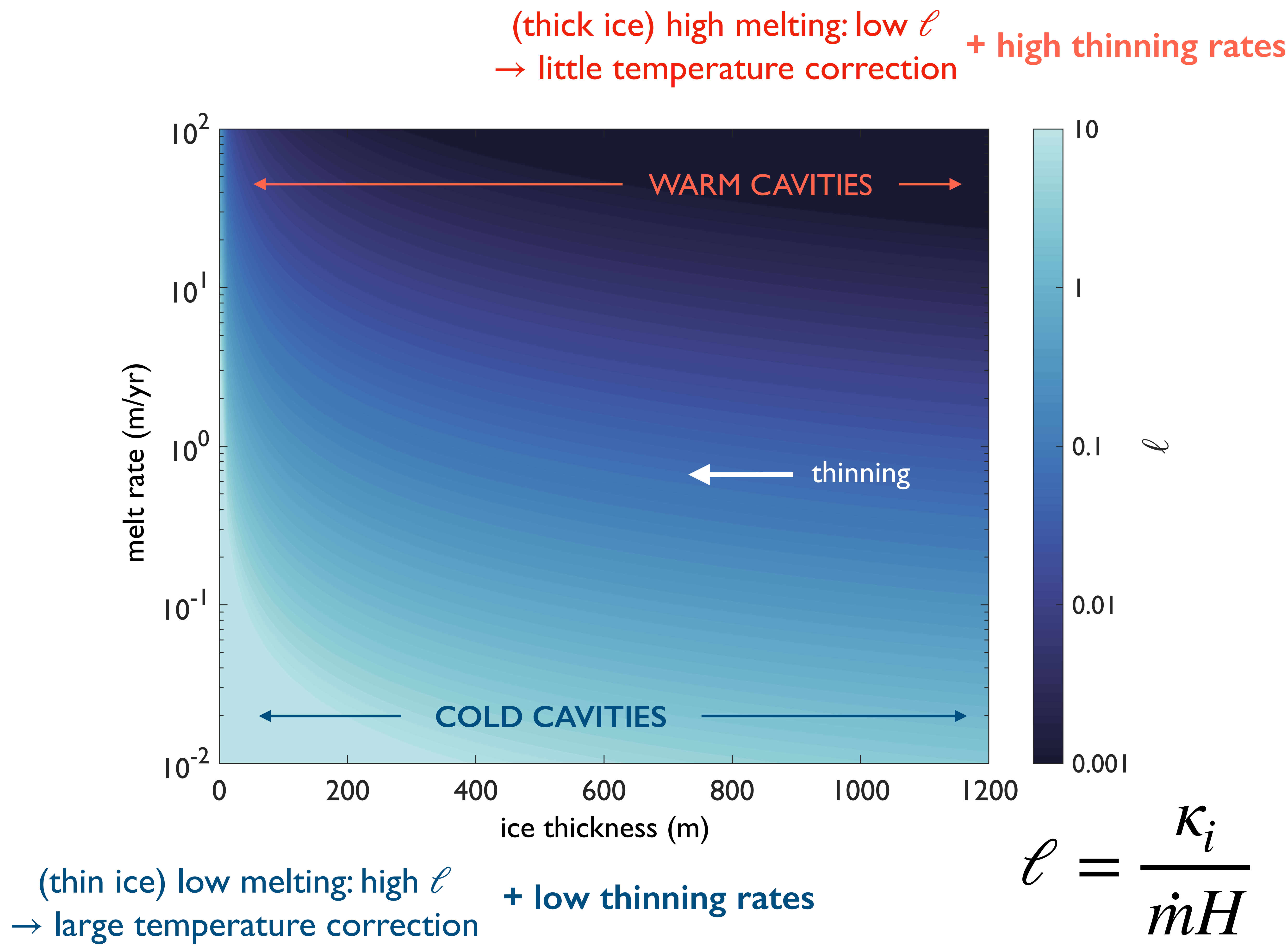
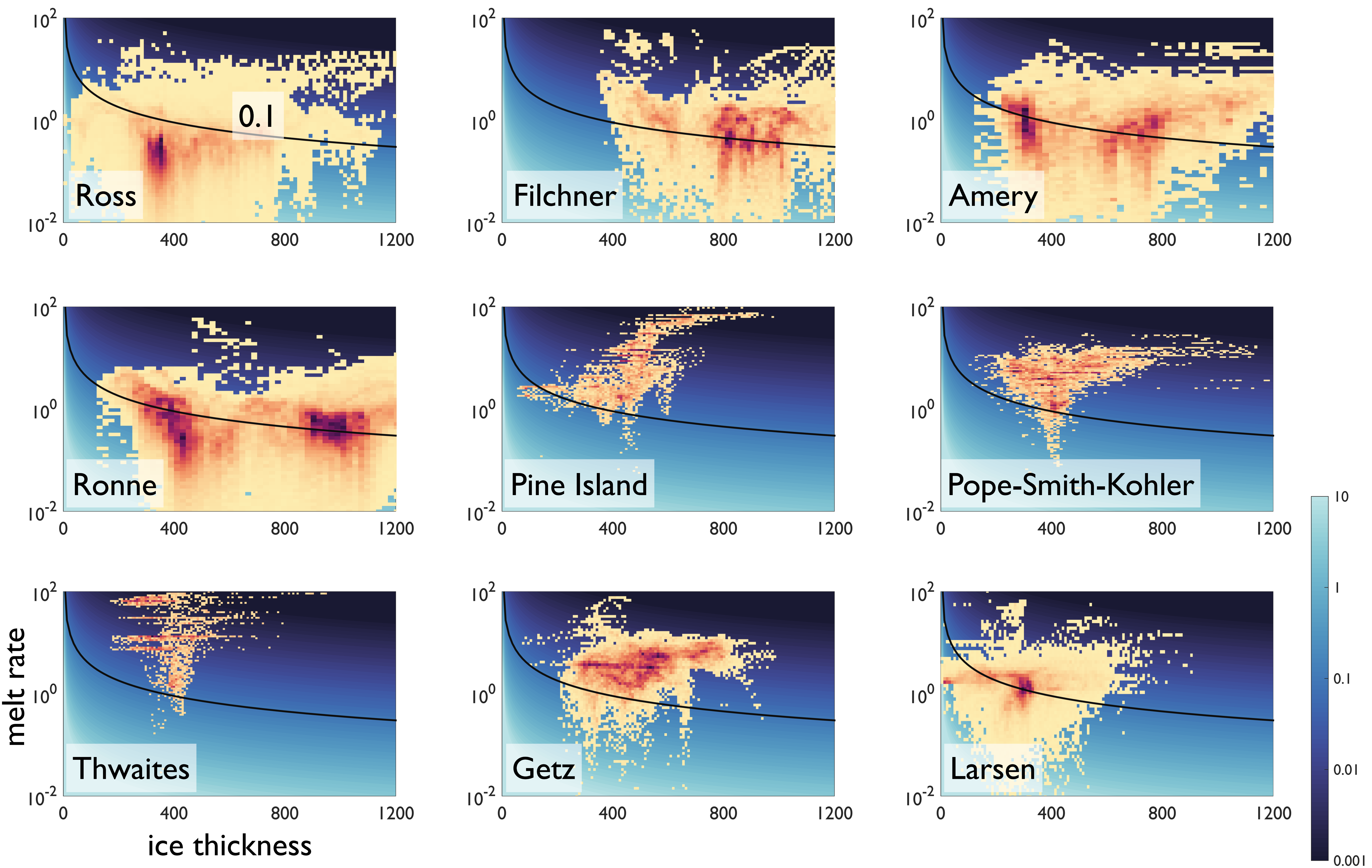
$$\ell = \frac{\kappa_i}{\dot{m}H}$$



$$\ell = \frac{\kappa_i}{\dot{m}H}$$

What does cold/warm cavity mean?



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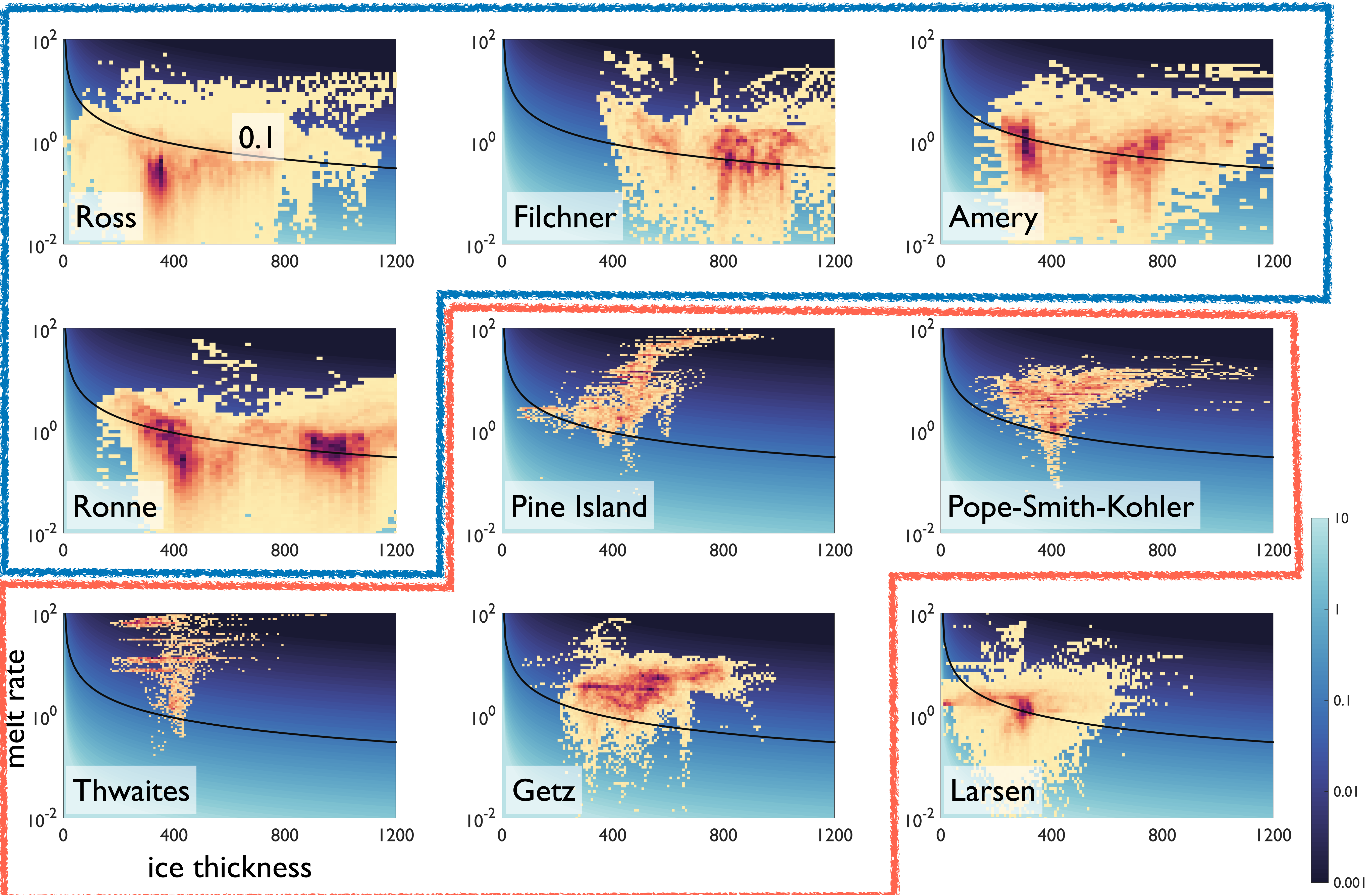
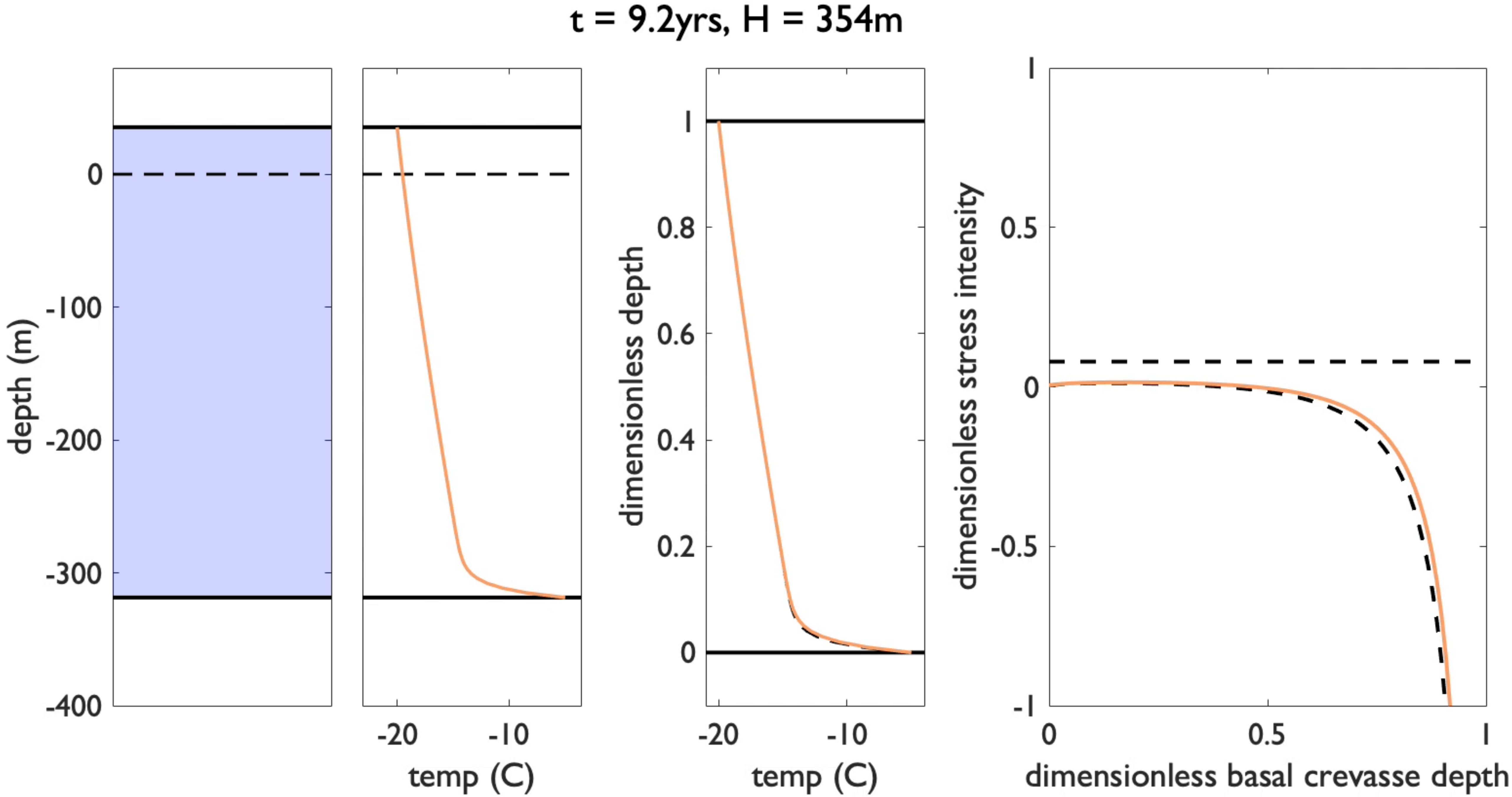


'Crevasse timescale'

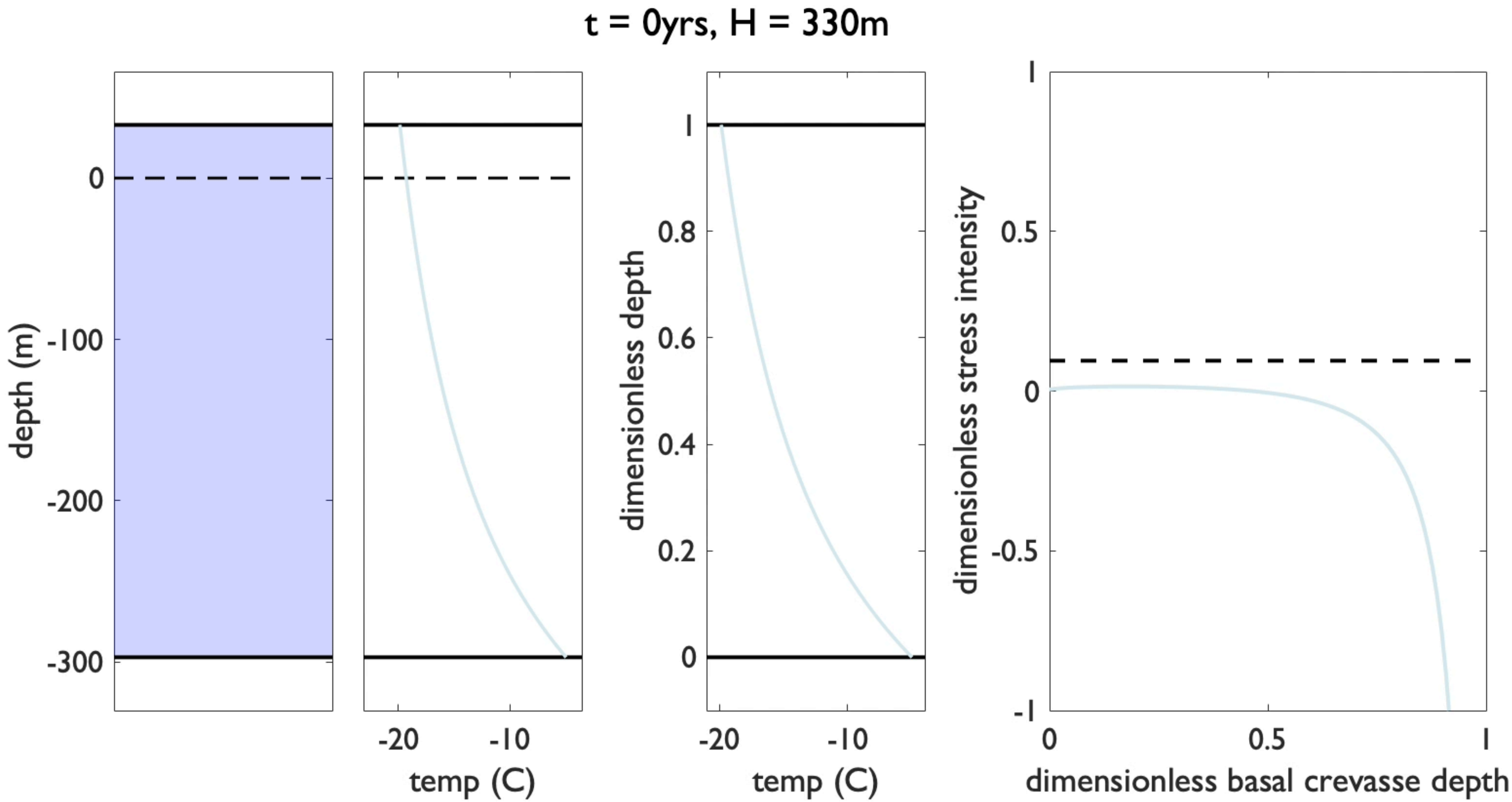


high melt rate → little *absolute* change in temp profile

Crevasse timescale $\tau \approx 38$ years

No melt change (dashed): $\tau_0 \approx 36$ years

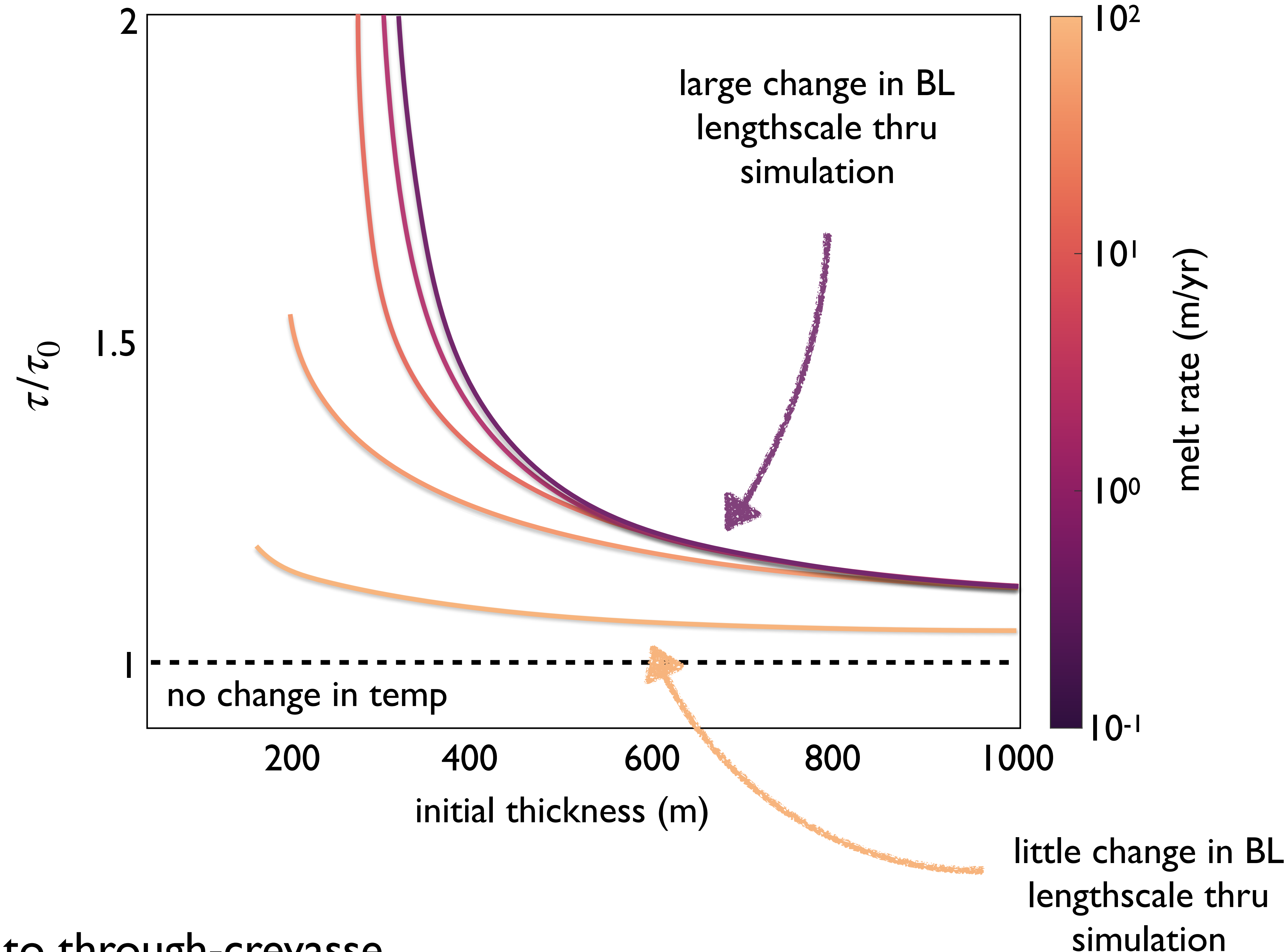
‘Crevasse timescale’



low melt rate → large *absolute* change in temp profile

Crevasse timescale $\tau \approx 308$ years

No melt change (dashed): $\tau_0 \approx 200$ years



τ: time to through-crevasse

τ_0: time to through-crevasse if temp profile does not change

COLD WATER (LOW MELT RATE)
CAVITY ICE SHELVES

- Low thinning rates (high τ_0)
- Large adjustment temp profile (high τ/τ_0)
- Low strain rates (high τ)

WARM WATER (HIGH MELT RATE)
CAVITY ICE SHELVES

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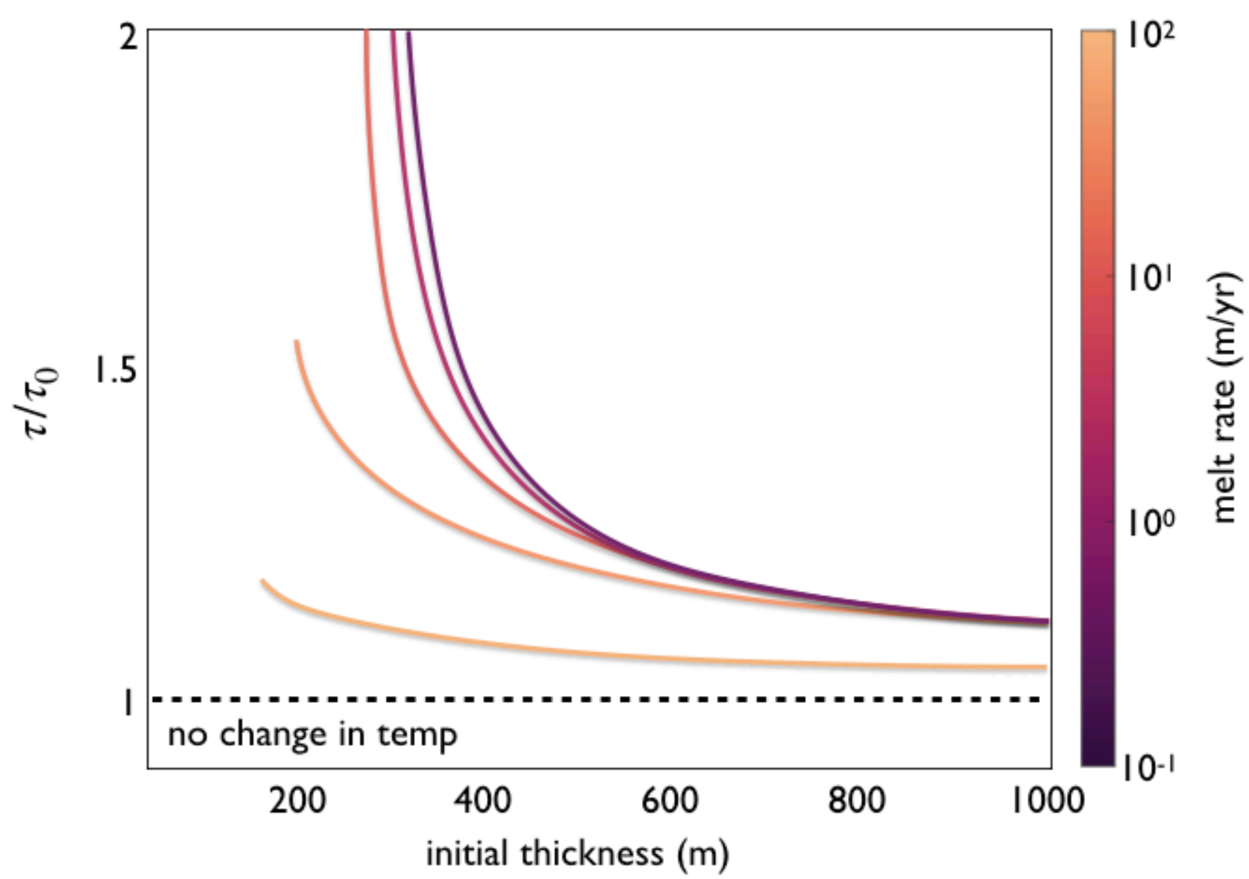
- Large adjustment temp profile(high τ/τ_0)
- High strain rates (low τ)

EXPECT LARGE DIFFERENCE IN
'CREVASSE TIMESCALE'



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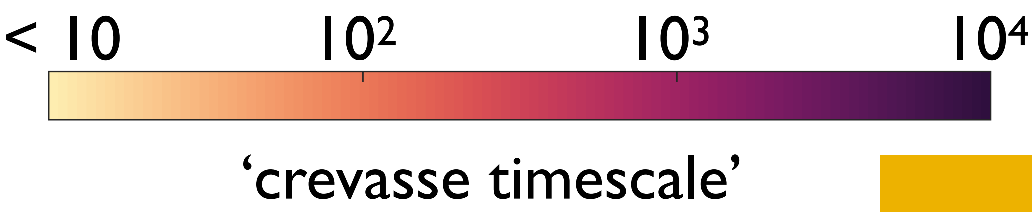

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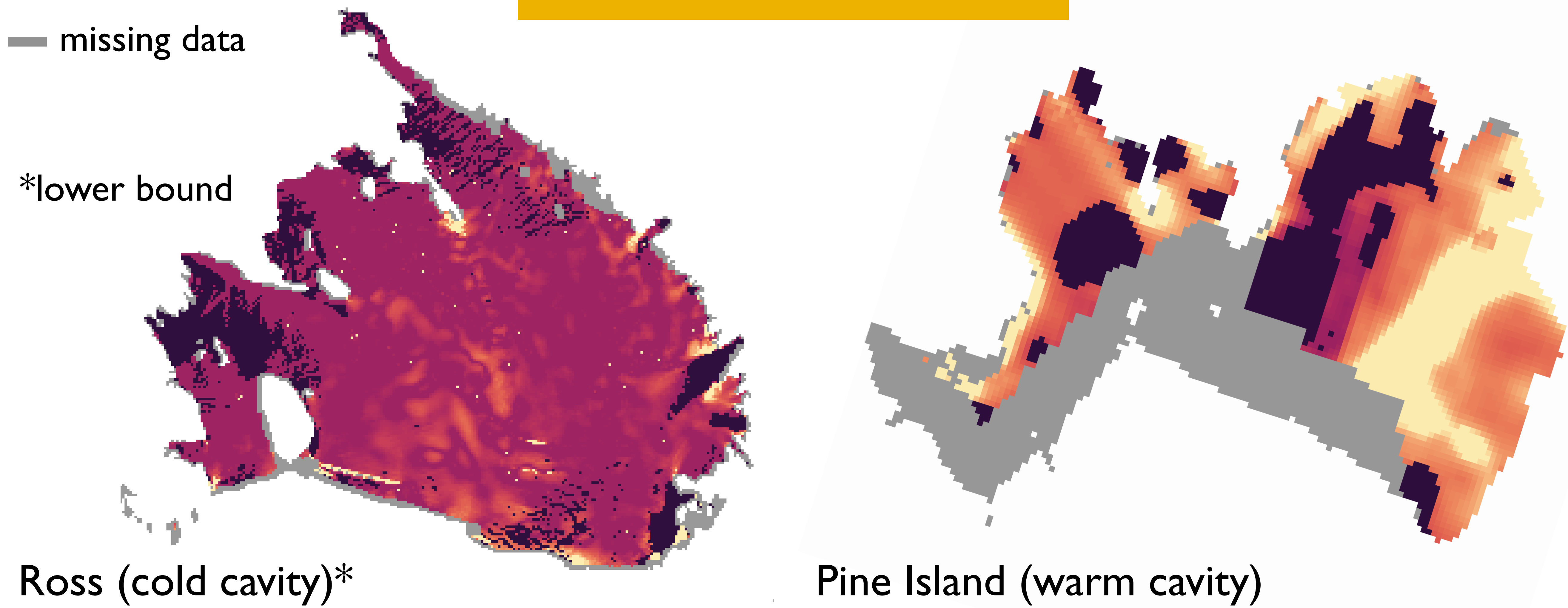
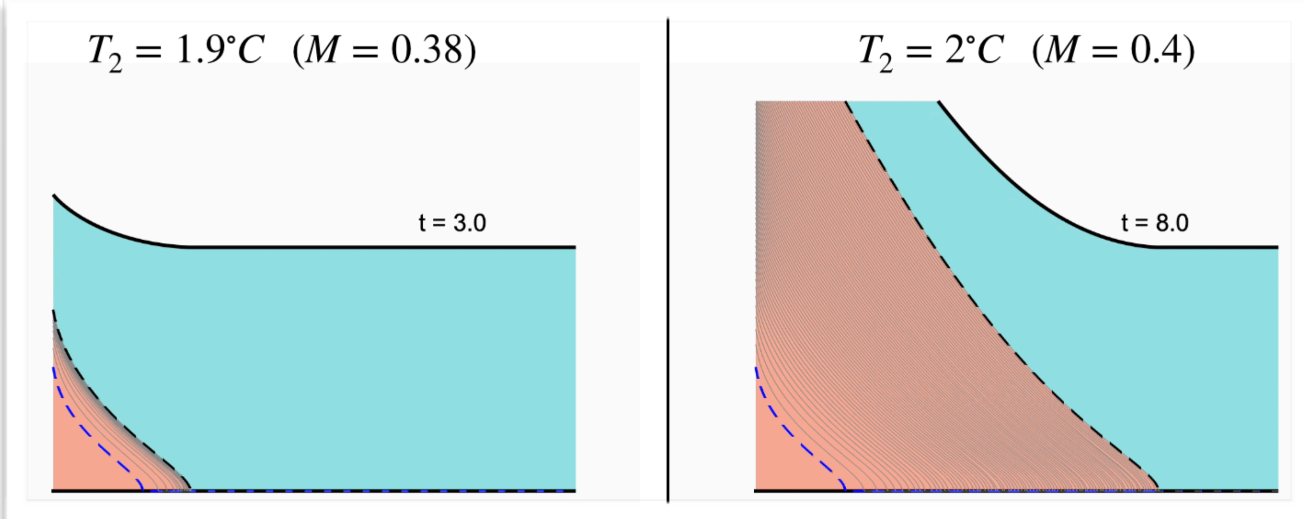
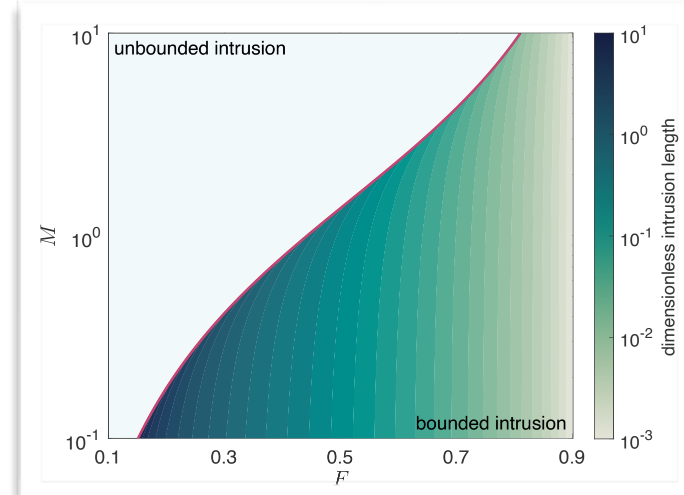


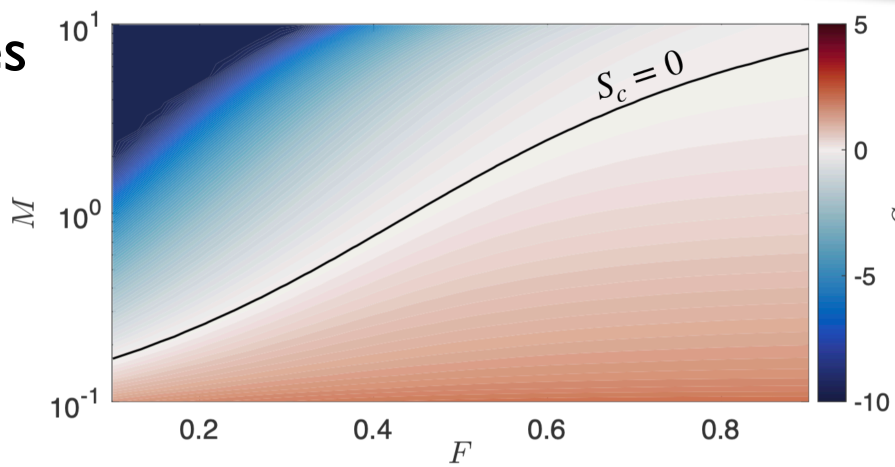
Melt feedback result in grounding zone tipping points



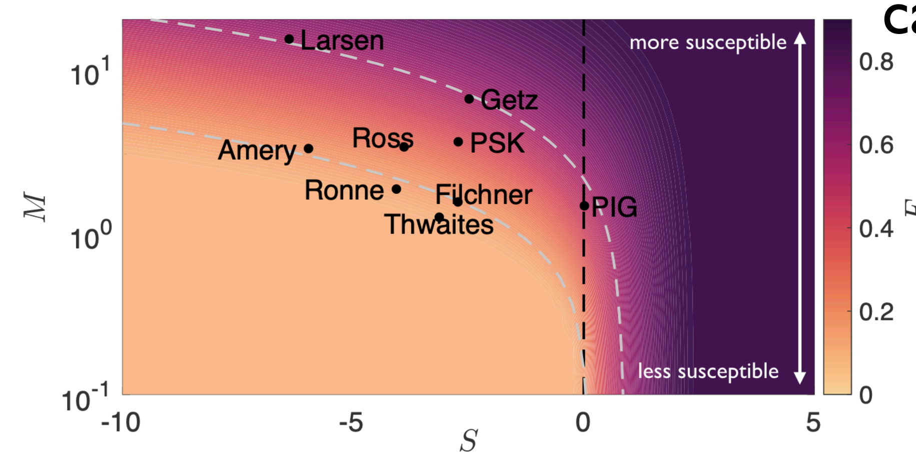
Tipping point is 'generic'



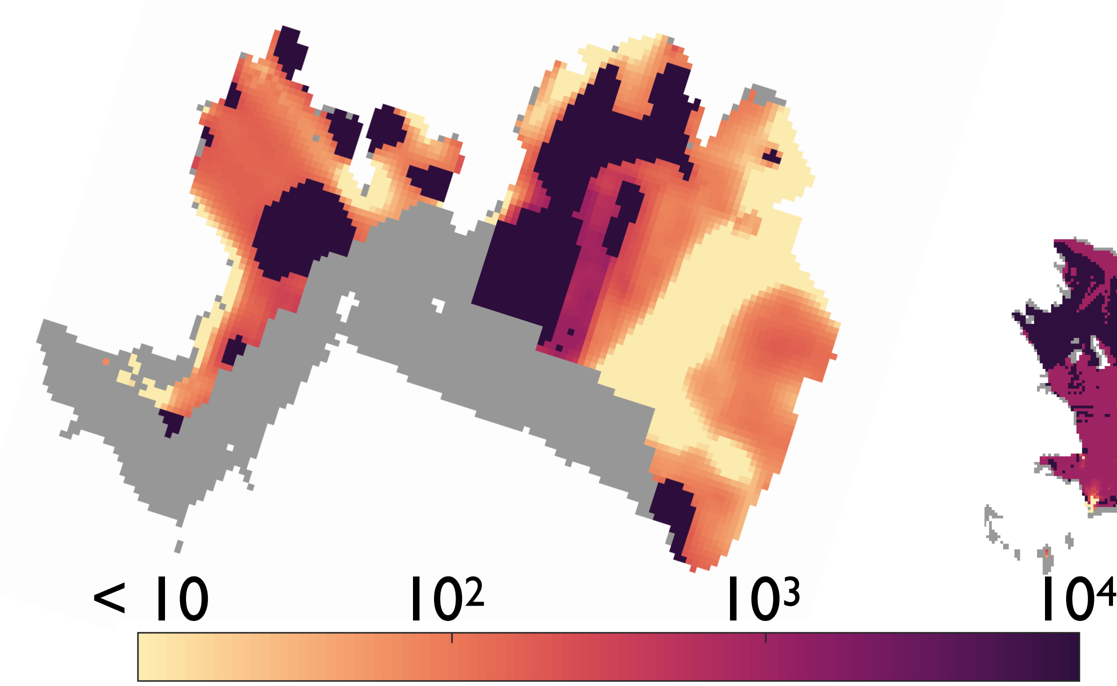
Prograde slopes vulnerable, retrograde enhanced



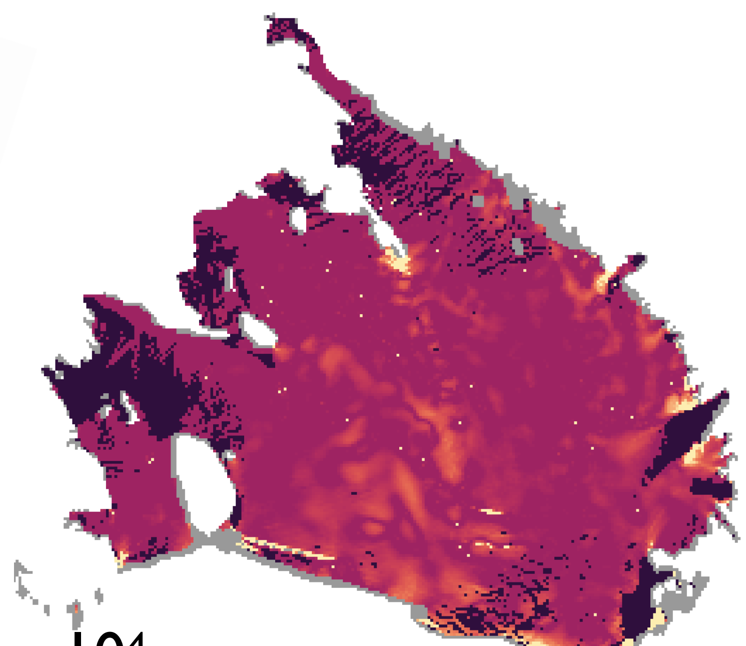
Cold and warm cavity shelves susceptible

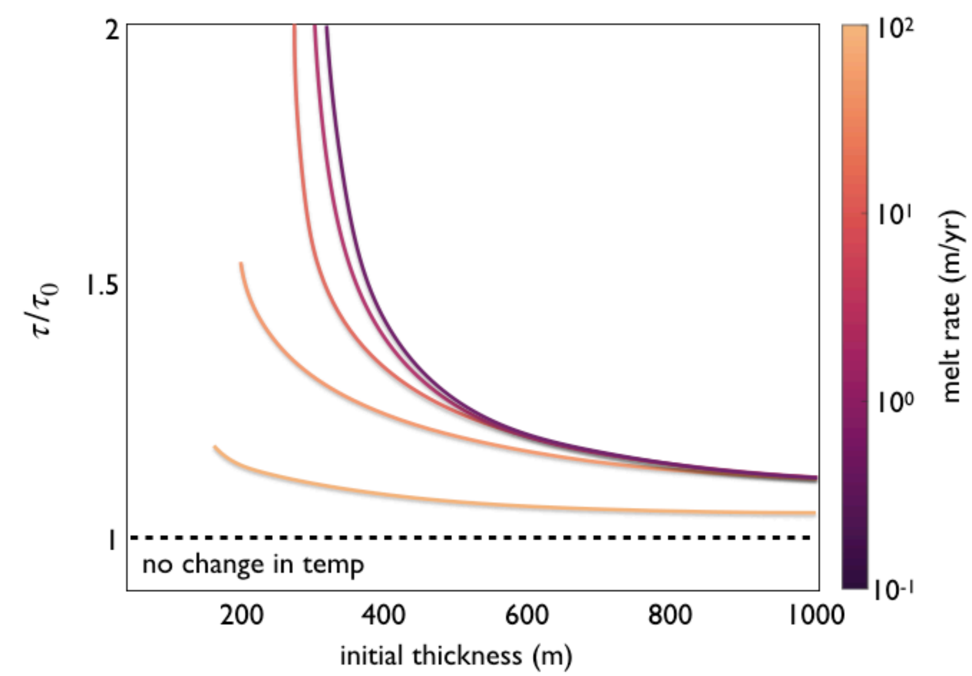


Very different 'collapse' timescales for cold and warm water ice shelves



Temp profile change, thinning and strain rates all contribute





‘Sensitivity boosting’ in ice sheets: tipping points and time-scales

Alex Bradley with Ian Hewitt and C. Yao Lai

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PRINCETON UNIVERSITY
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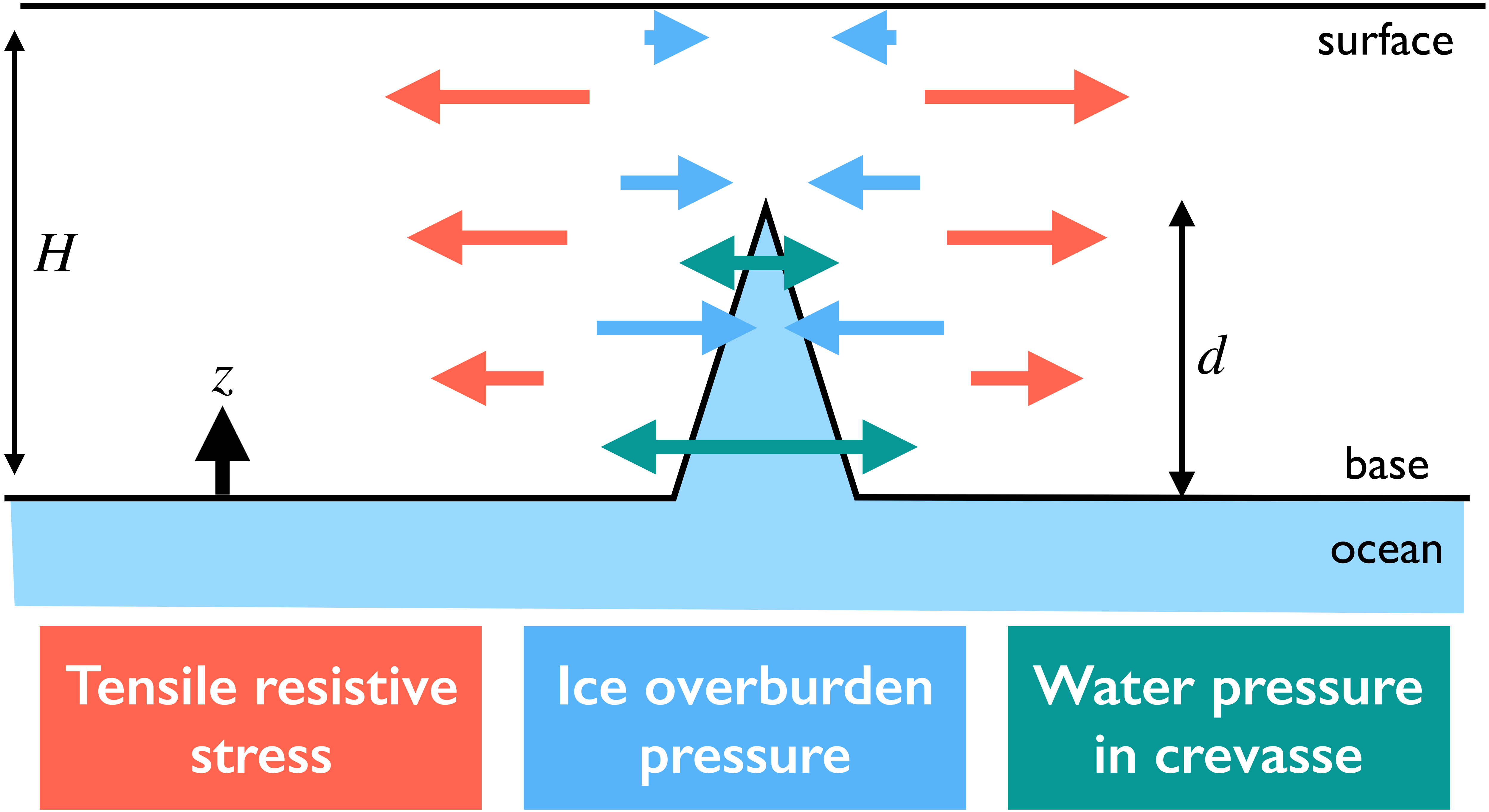
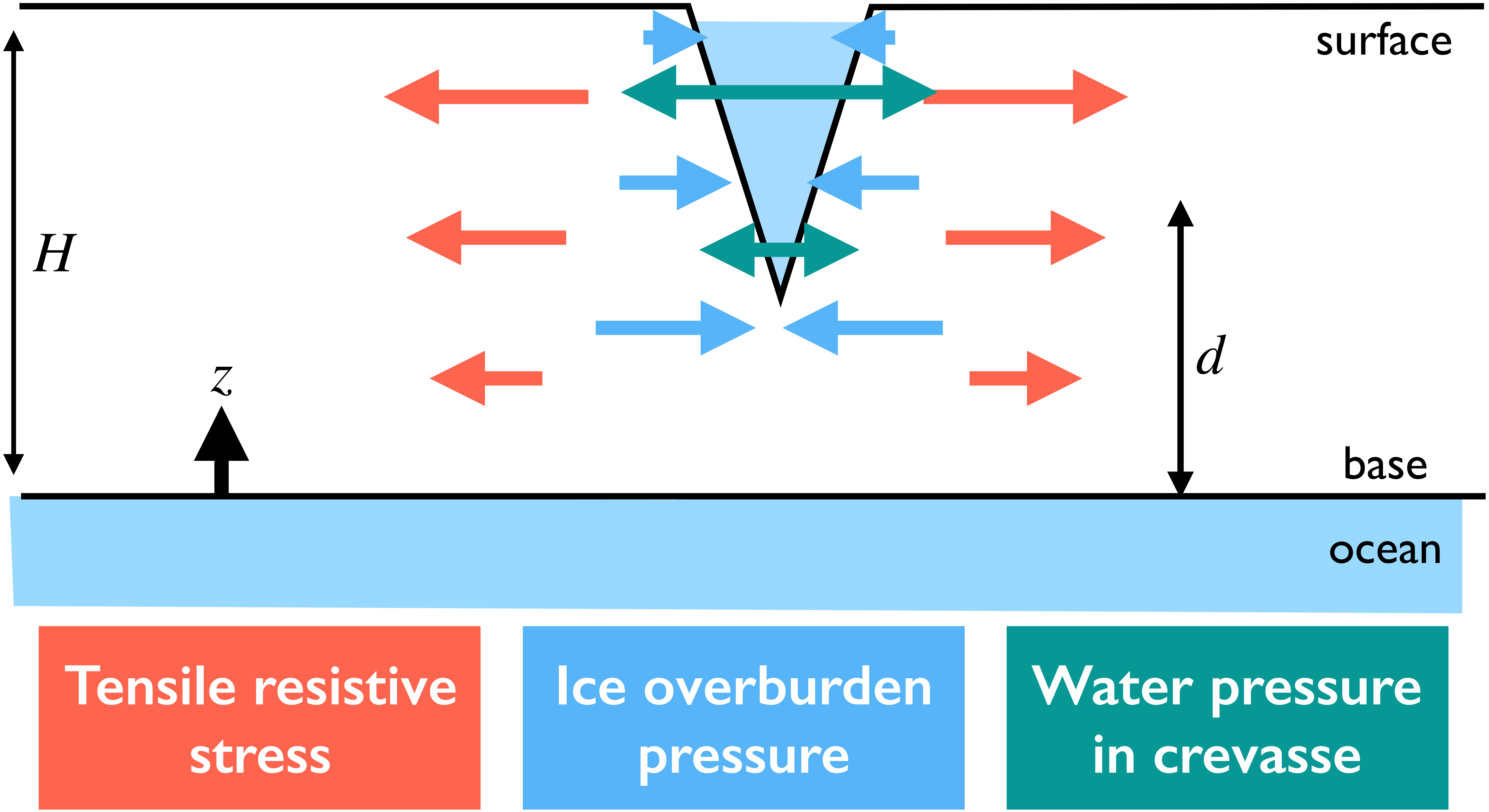
Basal vs surface crevassing?

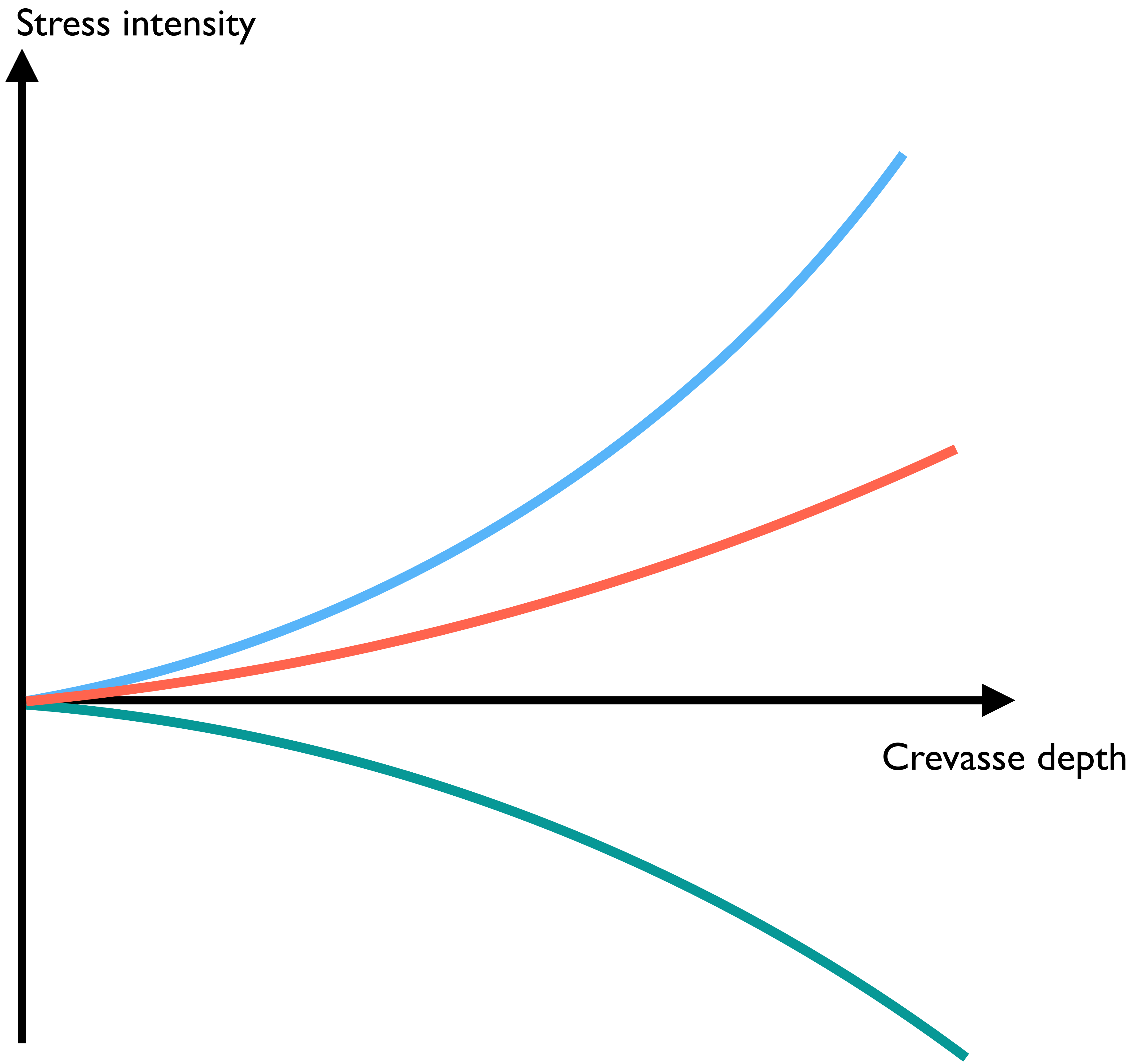


Stress intensity = tensile resistive stress + water pressure - ice overburden

Basal vs surface crevassing?



Stress intensity = **tensile resistive stress** + **water pressure** - **ice overburden**



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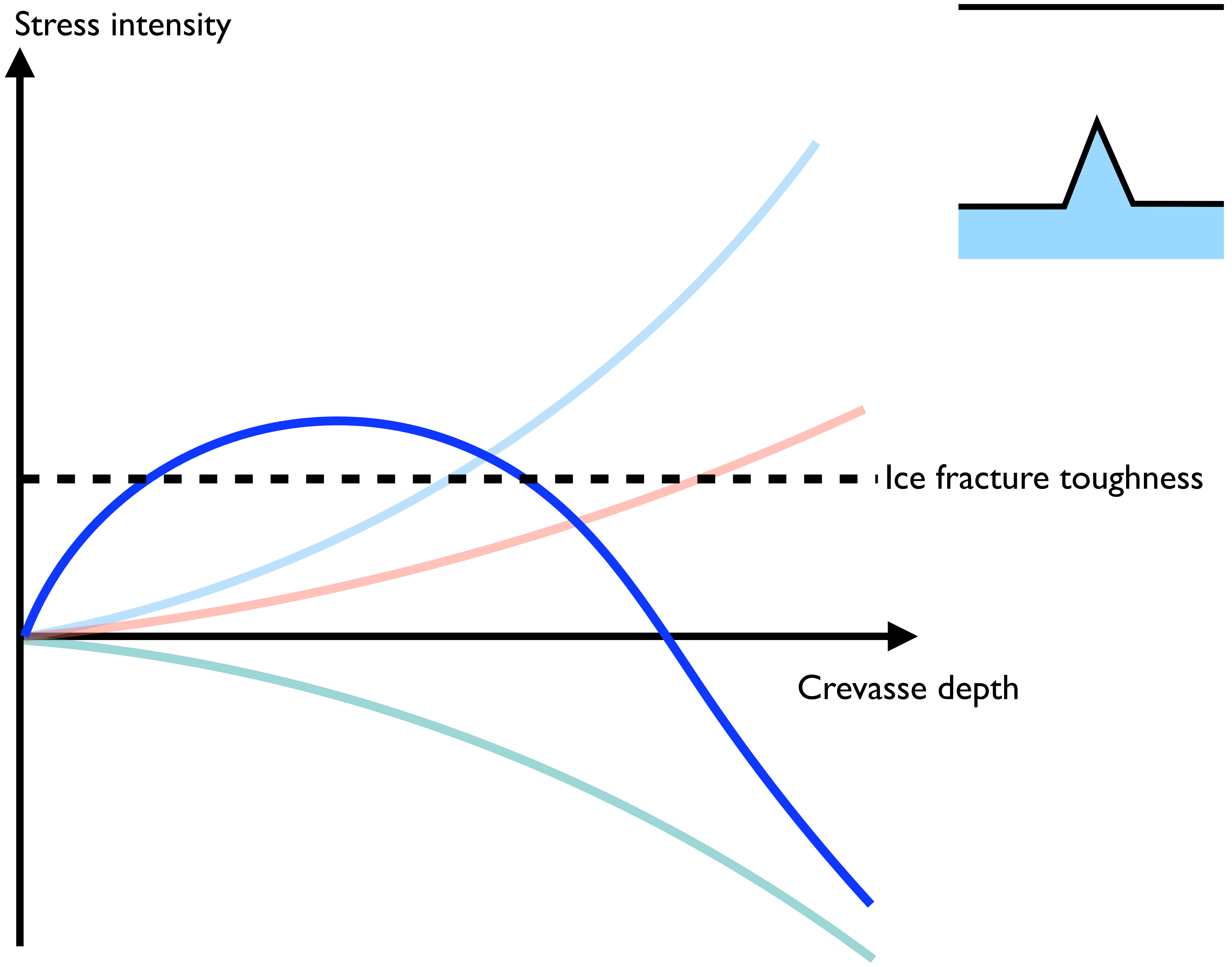

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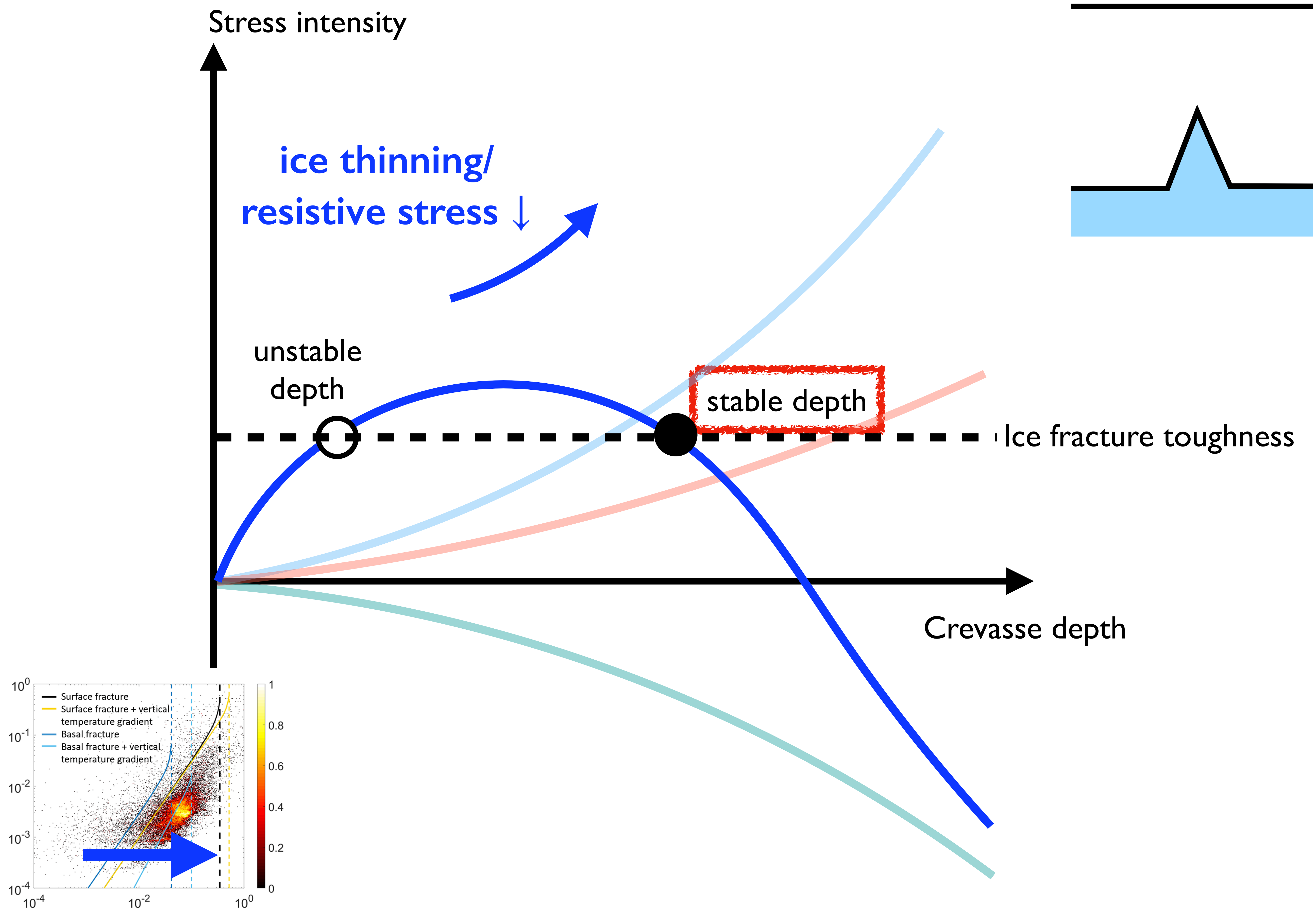

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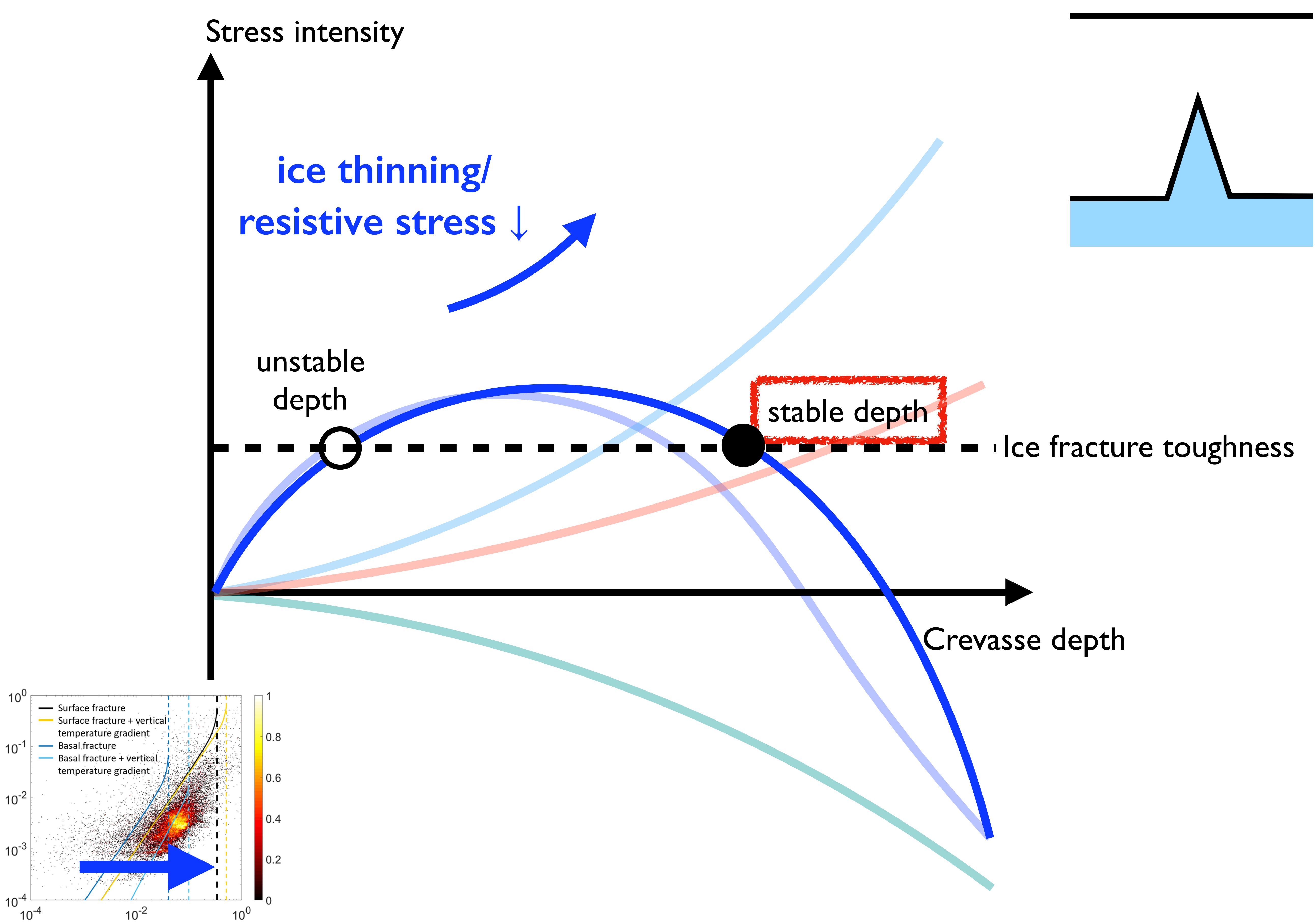

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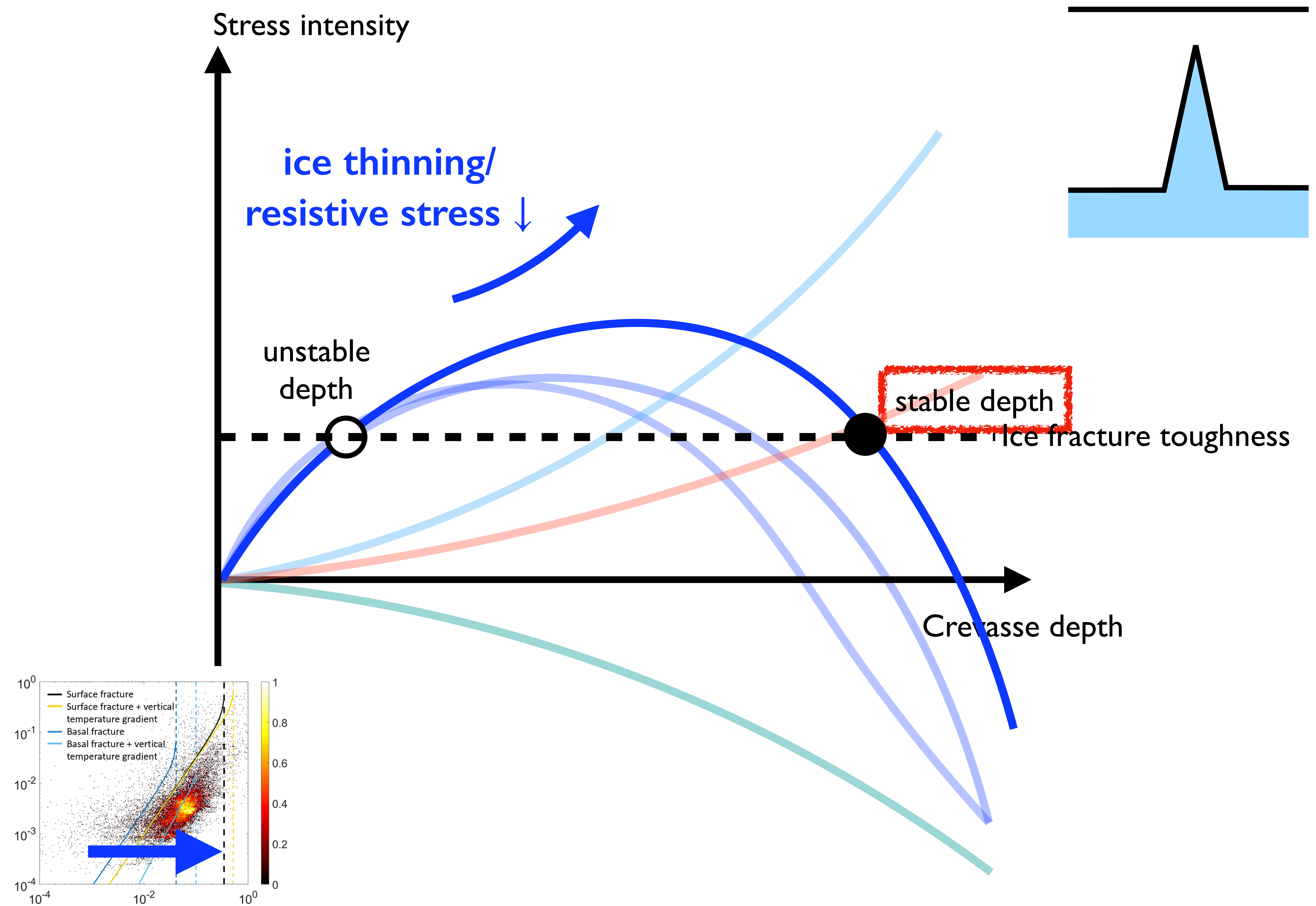

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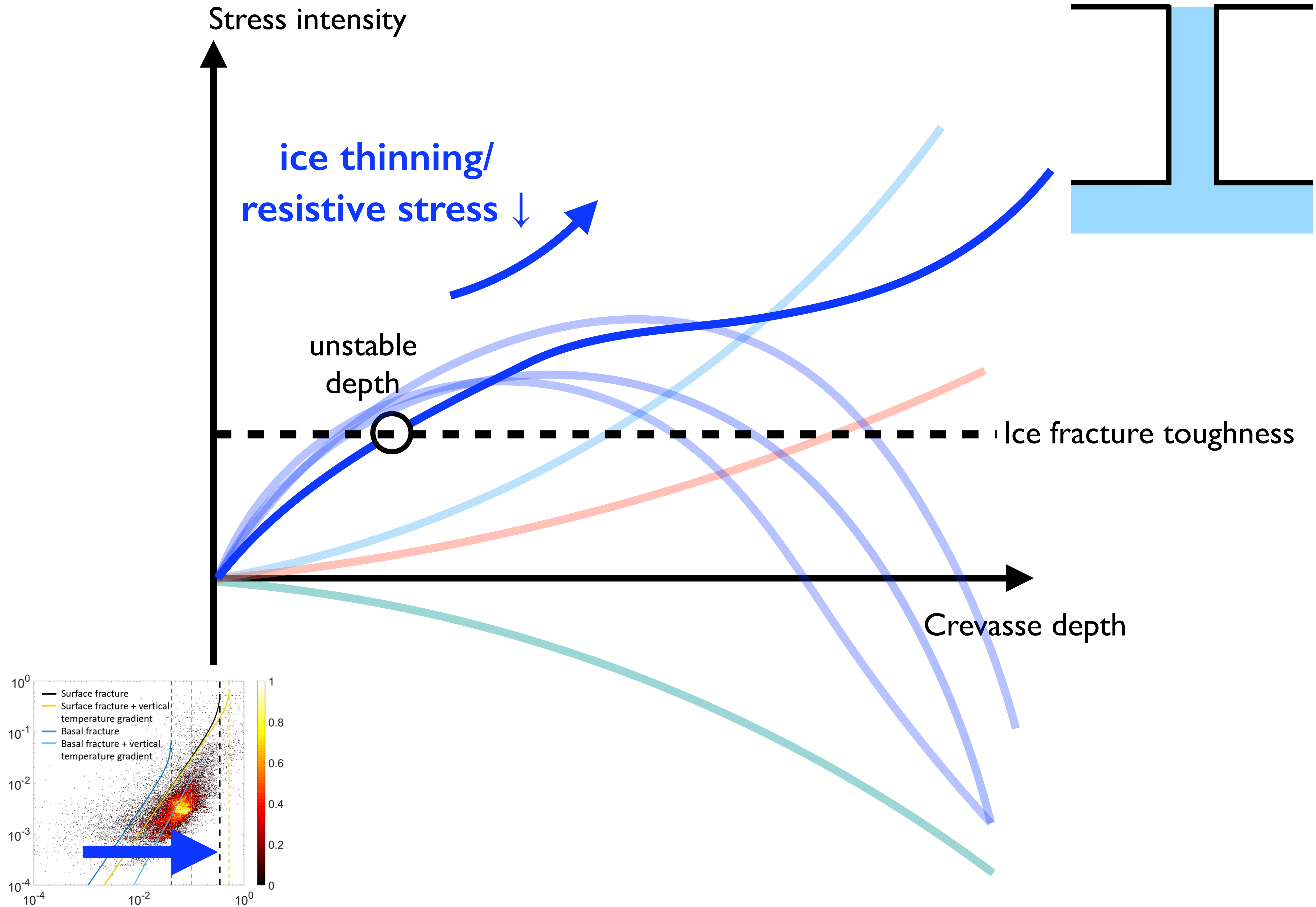

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