Breaking the ice
Fracture angles with viscous-plastic sea ice rheologies

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ECCOMAS YIC 2021 — 2021-07-07 – MS18 – 17h15

Motivation

We observe deformation lines in the Arctic sea ice, called the *Linear Kinematic Features* or **LKFs**.

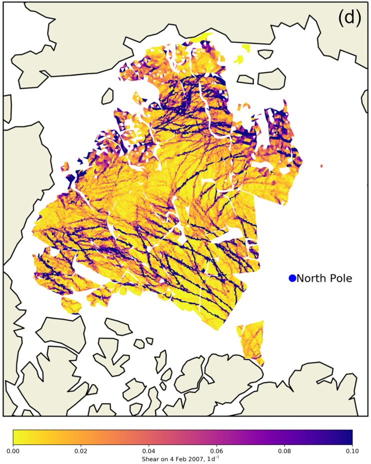

Figure: Shear Deformation — From Rampal et al. (2019) — under CC-BY license.

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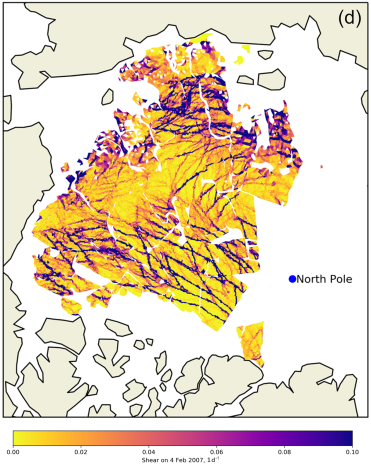
LKFs influence

- Exchange of Energy and Moisture
- Creation of new ice → in leads
- Creation of thick ice → in ridges

→ **Influence the mass balance**



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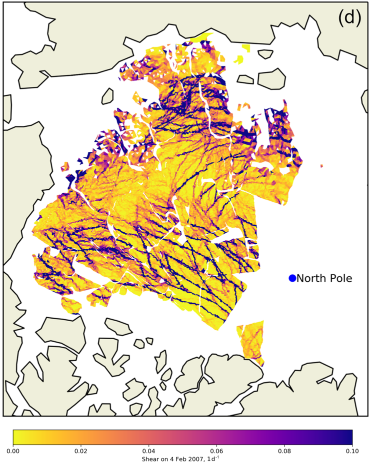
One (of the possible) metric

The LKFs intersection angles, or their half angles, called fracture angles



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Models and observation disagree on LKFs intersection angles

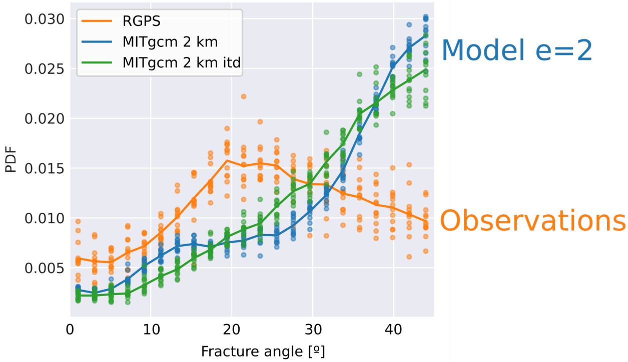

Figure: PDFs of LKFs half-intersection angles — Derived from Hutter and Losch (2020) – under CC-BY license.

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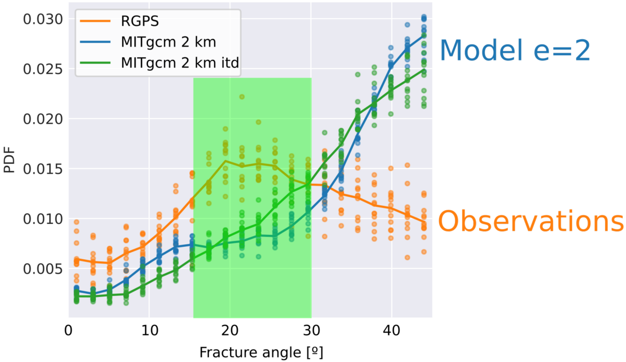


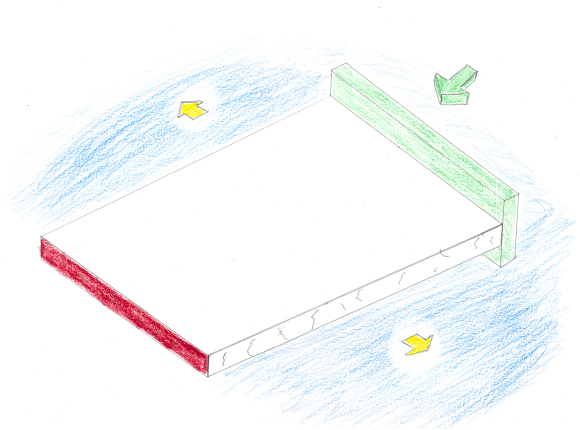
Figure: PDFs of LKFs half-intersection angles — Derived from Hutter and Losch (2020) – under CC-BY license.

Goals

We want

- to link the sea ice models to the angles
- to know how to create smaller angles in sea ice models
- to reproduce the LKFs patterns in sea ice dynamical models

Idealized experiment. . .



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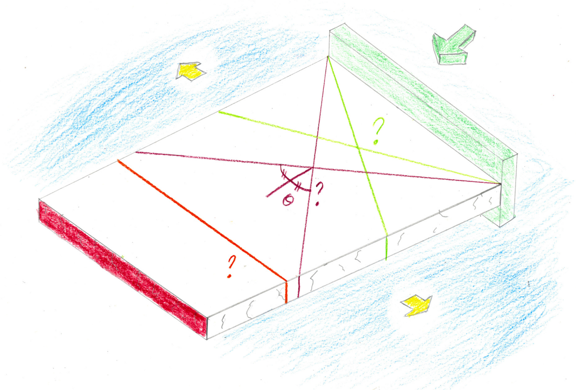

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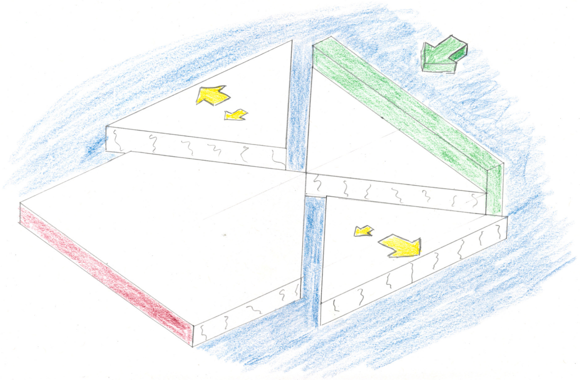
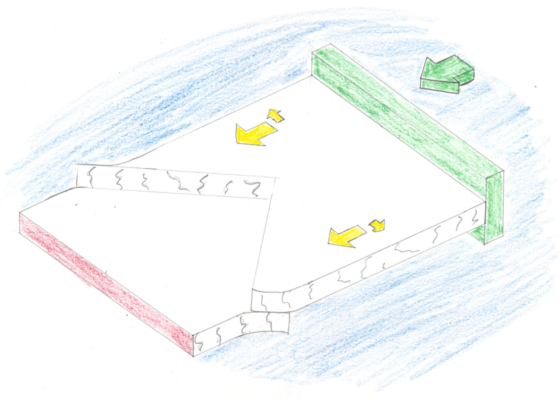
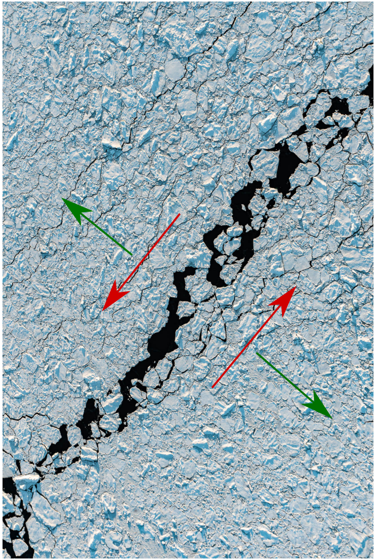


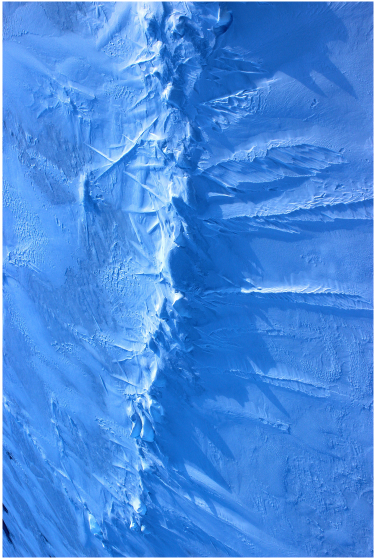
Idealized experiment. . .



. . . which we can observe on the field.



Credit: Lukas Piotrowski



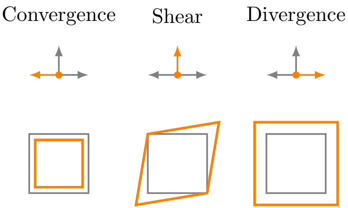
Credit: Grace Shephard (distributed via imaggeo.egu.eu) CC-BY-NC

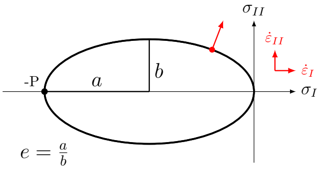
Viscous-Plastic (VP) sea ice model

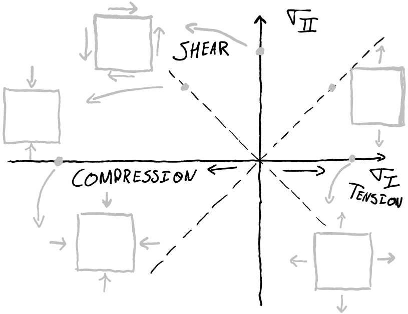
The *de facto* standard — the most widely used — sea ice rheological model today

2 Components

- Yield curve: Stresses in plastic failure
  - Viscous inside the yield curve
- Flow rule: Deformation at failure







Theory of fracture angles

- **Coulomb Angle** θ_C (Coulomb, 1773):

  The fracture angle depends on the slope of the yield curve F.

$$\theta_C = \frac{1}{2} \arccos\left(-\frac{\partial \sigma_{\mathrm{II},F}}{\partial \sigma_{\mathrm{I}}}\right)$$

- **Roscoe Angle** θ_R (Roscoe, 1970):

  The fracture angle depends on the flow rule (Plastic potential G)

$$\theta_R = \frac{1}{2} \arccos\left(-\frac{\partial \sigma_{\mathrm{II},G}}{\partial \sigma_{\mathrm{I}}}\right)$$

- **Arthur Angle** θ_A (Arthur et al., 1977):

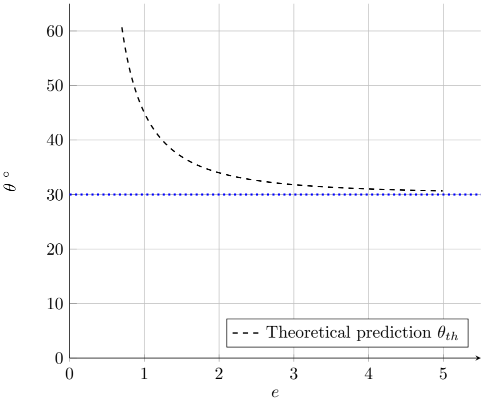
  The fracture angle is the mean of θ_C and θ_R.

Note: with a normal flow rule, then $\theta_C = \theta_R = \theta_A$

Elliptical yield curve with normal flow rule

Ringeisen et al. (2019)

- Angle follow the theory
- Flow rule is coupled to the yield curve
- Does not allow for angles $< 30^\circ$



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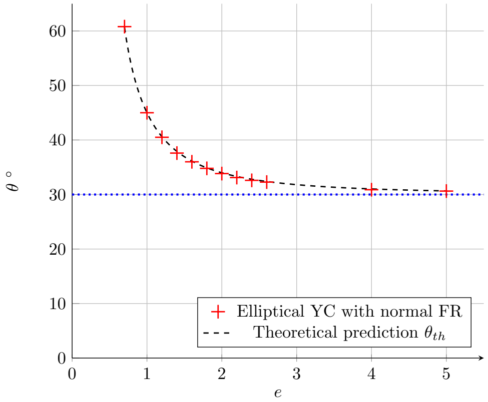

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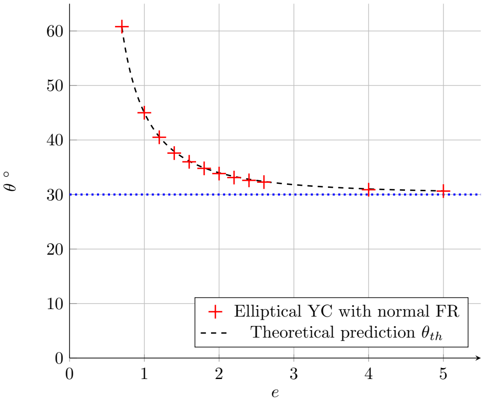
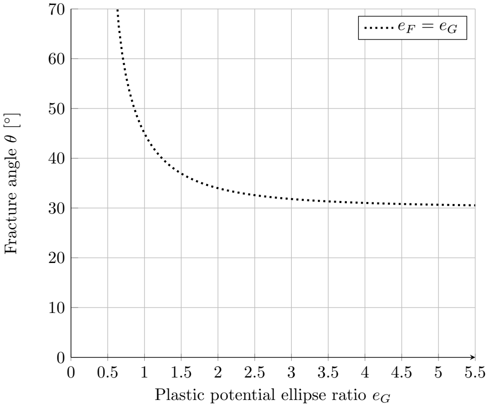


Elliptical yield curve with non-normal flow rule



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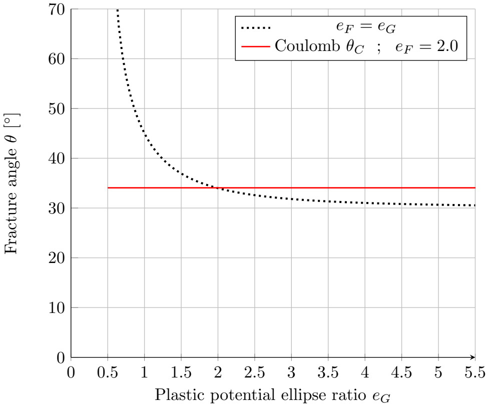

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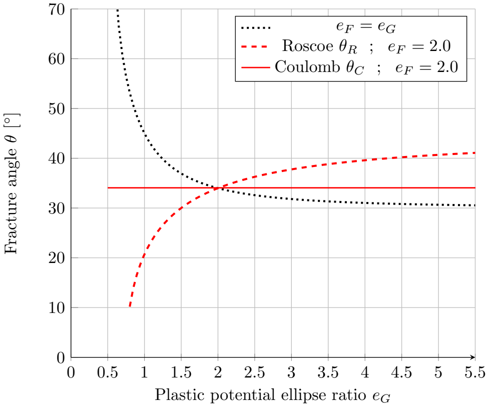

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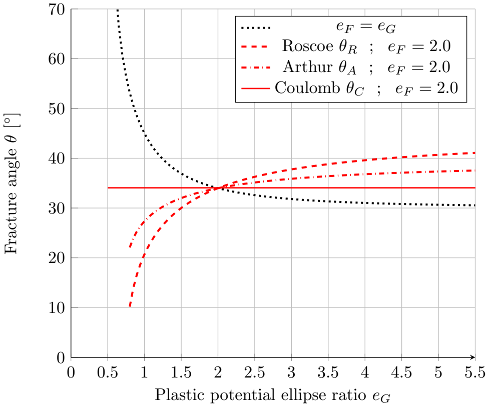

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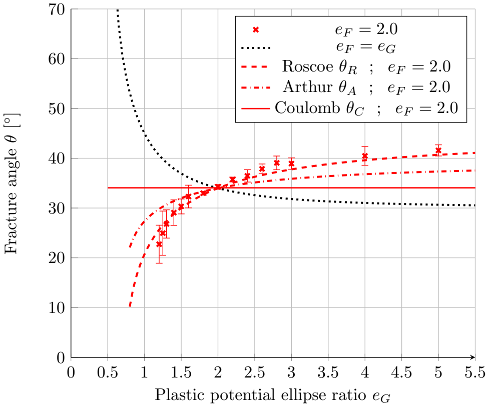

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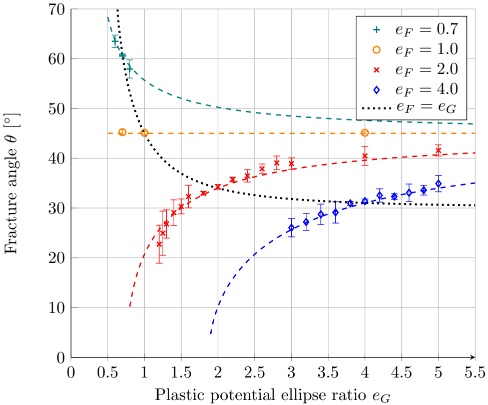
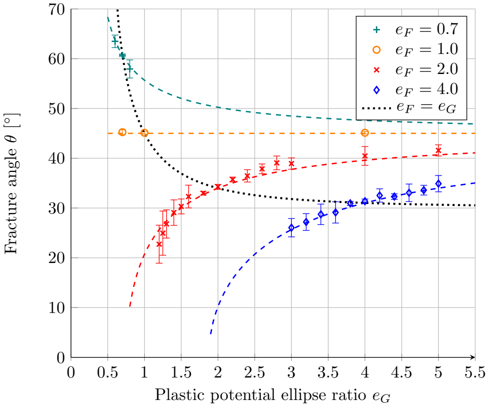


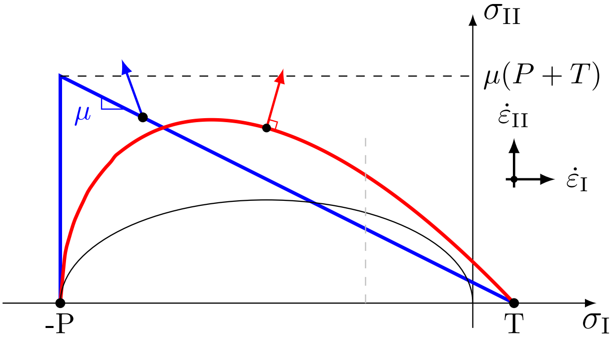
Elliptical yield curve with non-normal flow rule

Ringeisen et al. (2021)

- Angles follow Roscoe theory θ_R
- Poorer numerical convergence
- Allows for angles $< 30^\circ$



Alternative yield curves

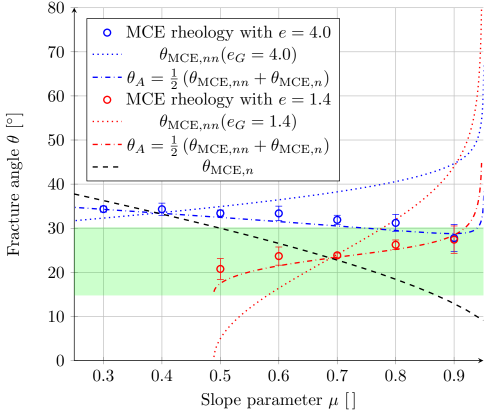


Ip et al. (1991) — Zhang and Rothrock (2005)

Mohr-Coulomb yield curve with non-normal flow rule

Ringeisen et al. (2021, in prep)

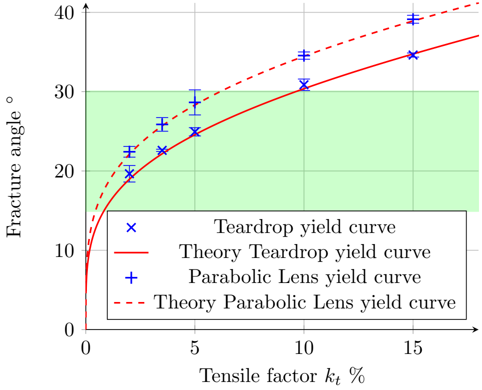
- Formulation is important Ip et al. (1991)
- Angles follow the Arthur angles θ_A
- Allows for angles $< 30°$



Teardrop and Parabolic Lens yield curves – normal flow rules

Ringeisen et al. (2021, in prep)

- Correspond to the theory
- Flow rule is coupled to the yield curve
- Allows for angles $< 30°$



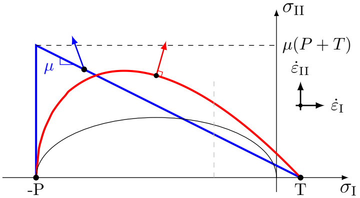
Summary — Contact me for more info

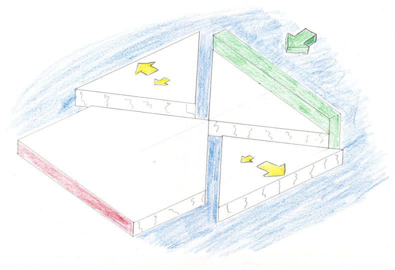
Deformation lines in sea ice

- Intersection angles are larger in models than observed.
- → Viscous-Plastic rheological model

VP yield curves — Flow rules

- Elliptical — normal and non-normal
- Mohr–Coulomb (MC) — non-normal
- Teardrop — normal flow rule





Idealized numerical experiment

- Some rheologies allow for smaller angles
- MC creates fractures with Arthur angles

- Investigating rheologies is necessary
- Next step: test in pan-arctic setups
  - Not only uni-axial compression

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