ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR-
UND MEERESFORSCHUNG

Characterising the regional glaciological context for relevance for IceCube-Gen-2

Olaf Eisen, Daniela Jansen, Steven Franke,

Ilka Weikusat, Frank Wilhelms

Alfred Wegener Institute

Bremerhaven, Germany

IceCube-Gen2 Polar Science Workshop

15 January 2021

HELMHOLTZ
GEMEINSCHAFT

Motivation

For IceCube Gen2:

- What does ice stratigraphy look like?

  (around IceCube Gen2 at South Pole (Ant) but also at RNO-G pilot site in Greenland)

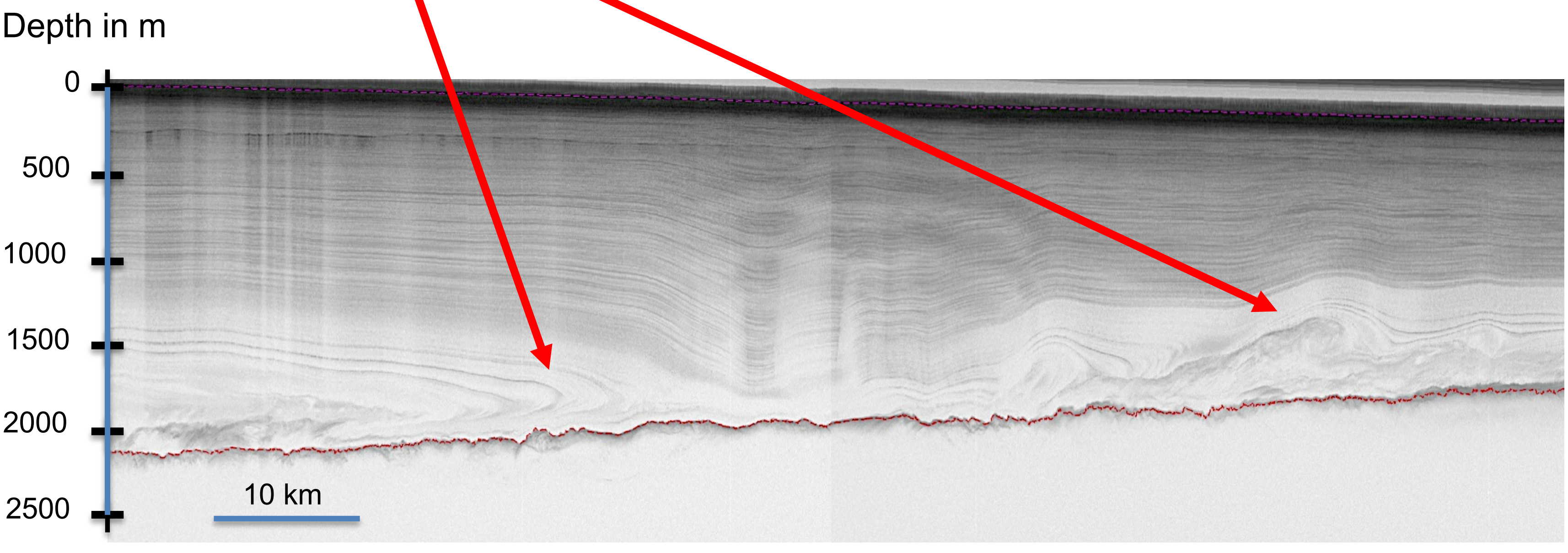
For Glaciologists

- Properties of ice
- Properties of basal interface (not this talk)
- Upscaling to regional scale

Internal layering

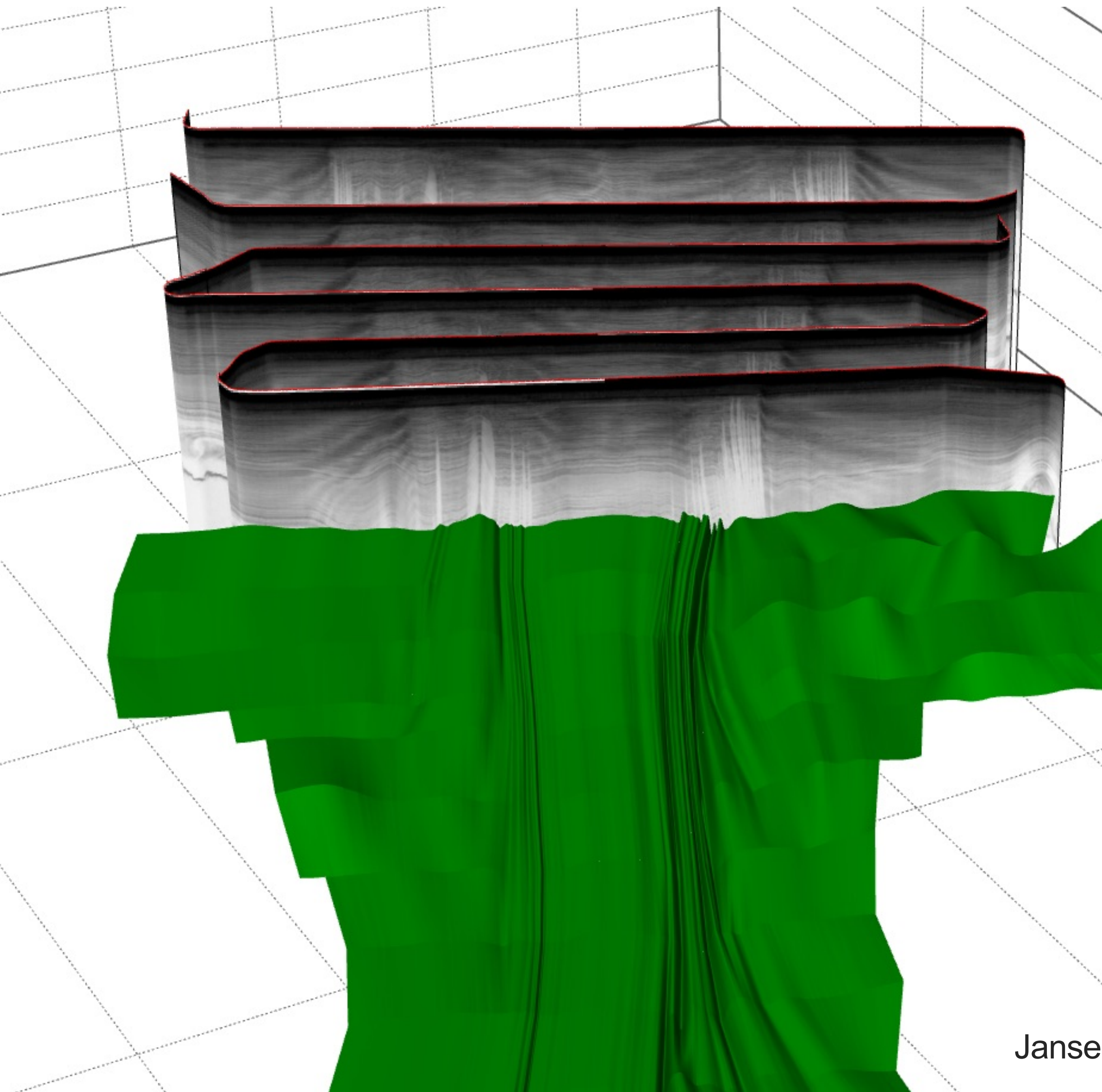
Impurities vary with age of ice (deposition)

- extrapolate from ice cores (Ant & Grl.)
- disturbed integrity problematic



Jansen et al., 2016

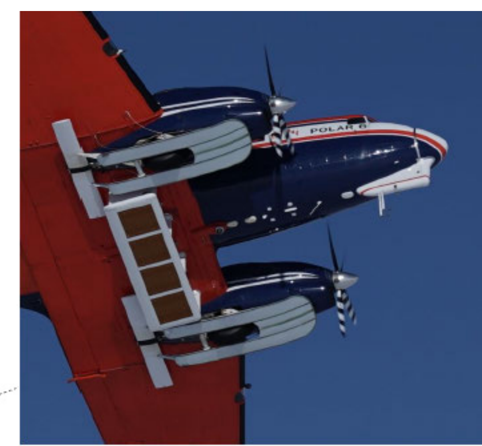
Internal layering



High-resolution internal layering

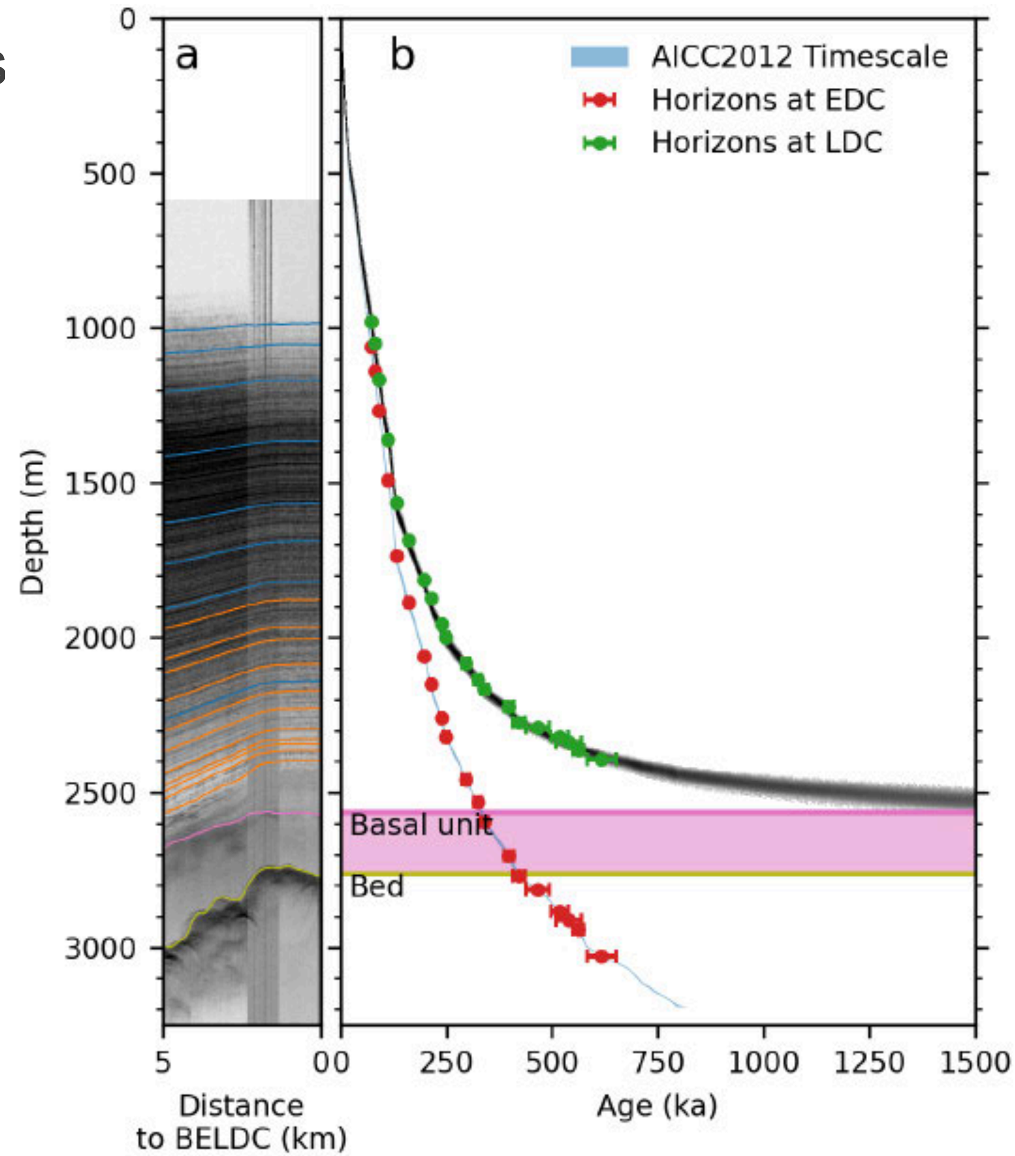
-> distribution of impurities by extrapolation from ice cores

Jansen et al., 2019



Disturbed layering & basal ice

- Basal units of ice sheets highly disturbed and anisotropic
- Depending on depth: influence on IceCube?
- Gen2: use array to characterise regional properties



Lilien et al., TCD, 2020

Radar Physics – a birefringent medium

ice 1h: anisotropic crystal, effects on

- rheology ("softness" of ice)
- radar velocity:

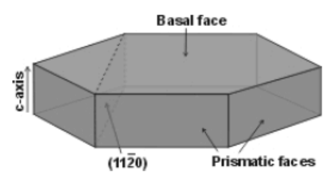
$$c = \frac{c_0}{\sqrt{\varepsilon'}}$$

$$\varepsilon'_{||} - \varepsilon'_{\perp} \approx 1\%\varepsilon', \qquad \varepsilon' \approx 3.1 - 3.2$$

- seismic velocity:

$$v^s_{||} - v^s_{\perp} \approx 100\ \mathrm{ms}^{-1} \approx 5\% v^s, \qquad v^s \approx 1900\ \mathrm{ms}^{-1}$$

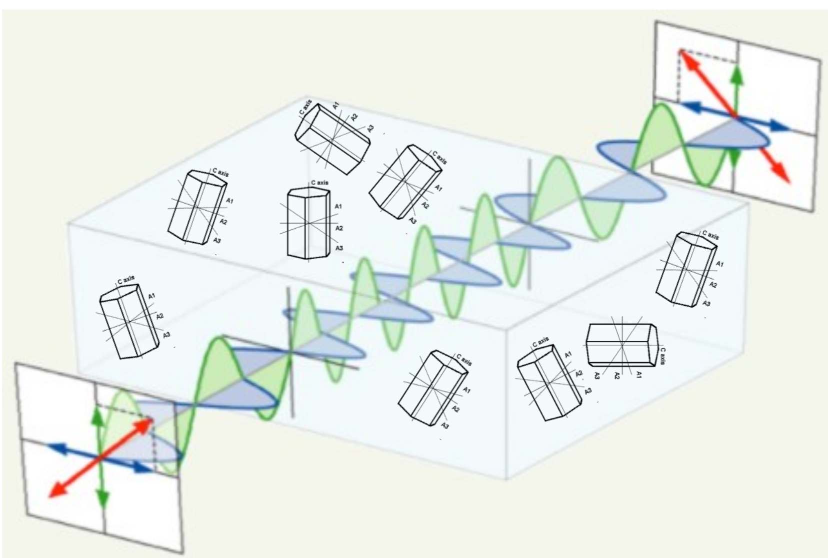
$$v^p_{||} - v^p_{\perp} \approx 100\ \mathrm{ms}^{-1} \approx 3\% v^p, \qquad v^p \approx 3900\ \mathrm{ms}^{-1}$$

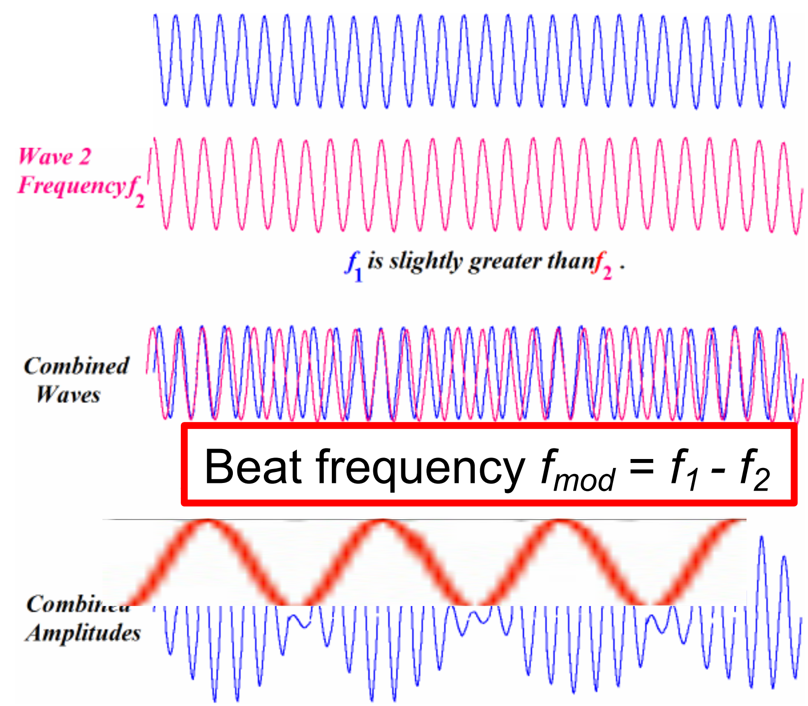


Interference of radar waves travelling with slightly different **velocities**:

$$\Delta\varepsilon' = \varepsilon'_{||} - \varepsilon'_{\perp} = 0.034$$

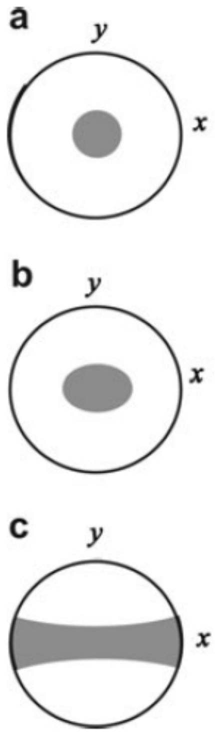
$$\Delta c = (1.6995 - 1.6903)\ 10^8\ \mathrm{m/s} = 0.54\%\ c_0$$





Theory: Fujita et al. (2006) on ice

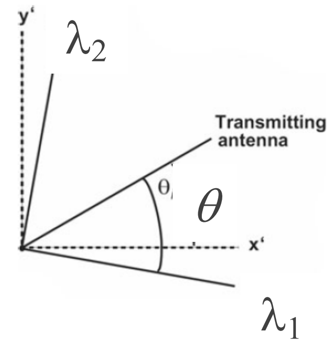
Bulk properties of polycrystals:

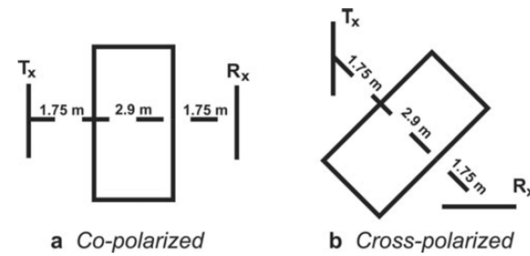


$$|\varepsilon'_x - \varepsilon'_y| \cong 0$$

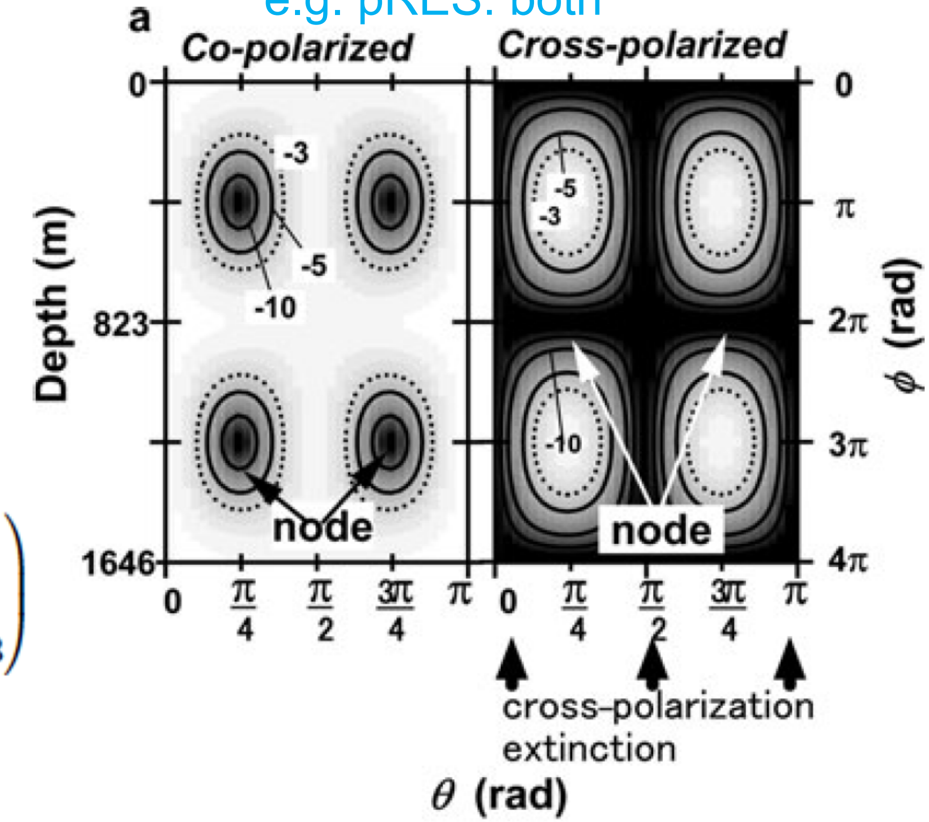
$$\Delta\varepsilon' \gg |\varepsilon'_x - \varepsilon'_y| > 0$$

$$\Delta\varepsilon' > |\varepsilon'_x - \varepsilon'_y| > 0$$





e.g. pRES: both



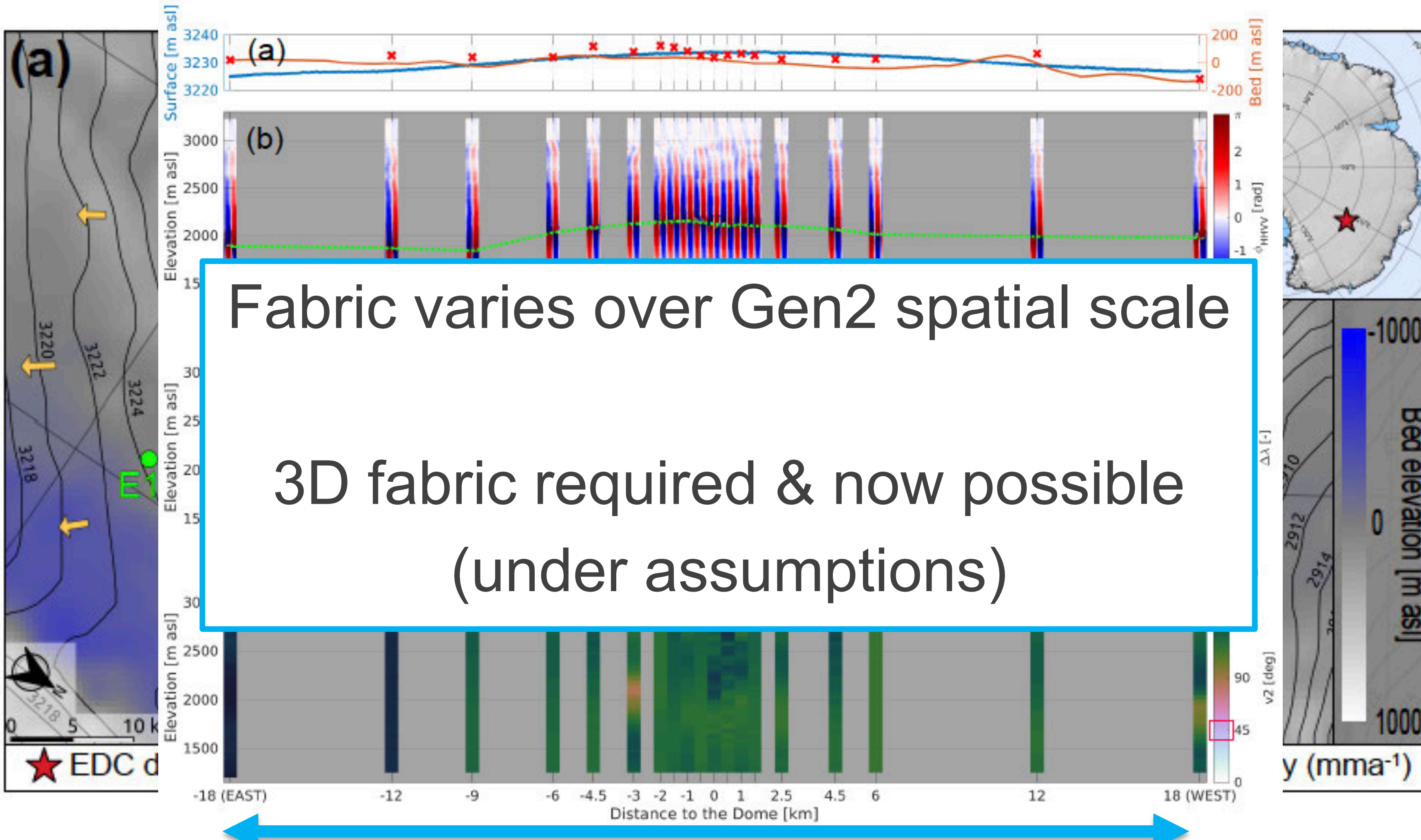
Bulk properties related to single crystals:

$$\epsilon'(z) = \begin{pmatrix} \epsilon'_x & 0 & 0 \\ 0 & \epsilon'_y & 0 \\ 0 & 0 & \epsilon'_z \end{pmatrix} = \begin{pmatrix} \epsilon'_\perp + \Delta\epsilon'\lambda 1 & 0 & 0 \\ 0 & \epsilon'_\perp + \Delta\epsilon'\lambda 2 & 0 \\ 0 & 0 & \epsilon'_\perp + \Delta\epsilon'\lambda 3 \end{pmatrix}$$

$\Delta\varepsilon' = \varepsilon'_{\|} - \varepsilon'_{\perp} = 0.034$ (for a single crystal)

Fabric anisotropy radar I: polarimetry

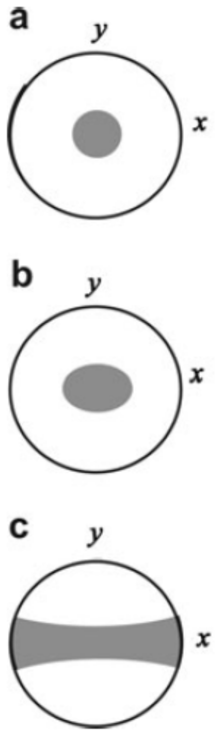
Multiple point measurement (pRES)



Ershadi et al., TCD, 2021

Theory: Fujita et al. (2006) on ice

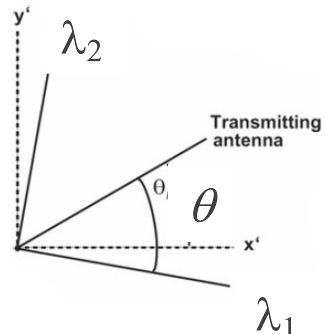
Bulk properties of polycrystals:

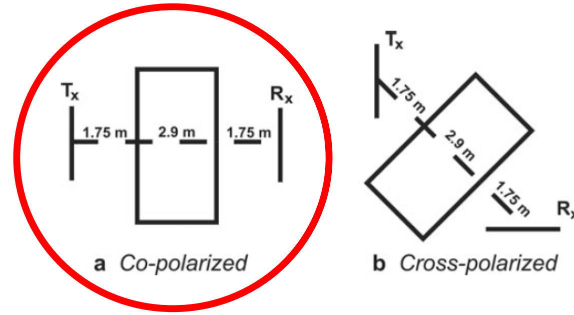


a: $|\varepsilon'_x - \varepsilon'_y| \cong 0$

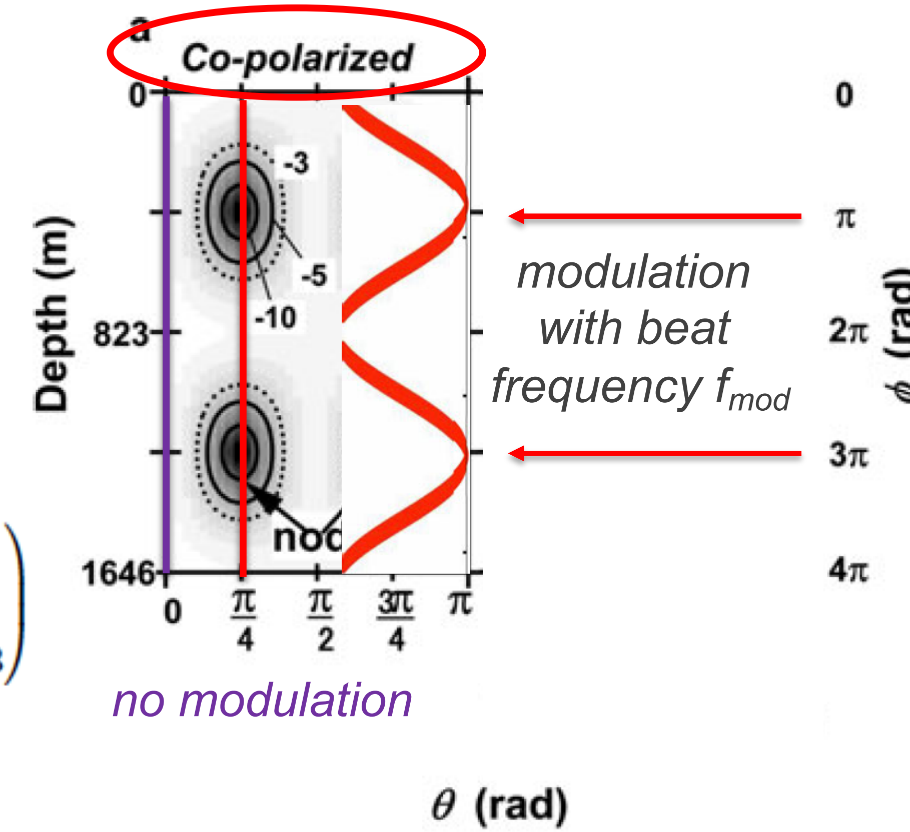
b: $\Delta\varepsilon' \gg |\varepsilon'_x - \varepsilon'_y| > 0$

c: $\Delta\varepsilon' > |\varepsilon'_x - \varepsilon'_y| > 0$





typical airborne data



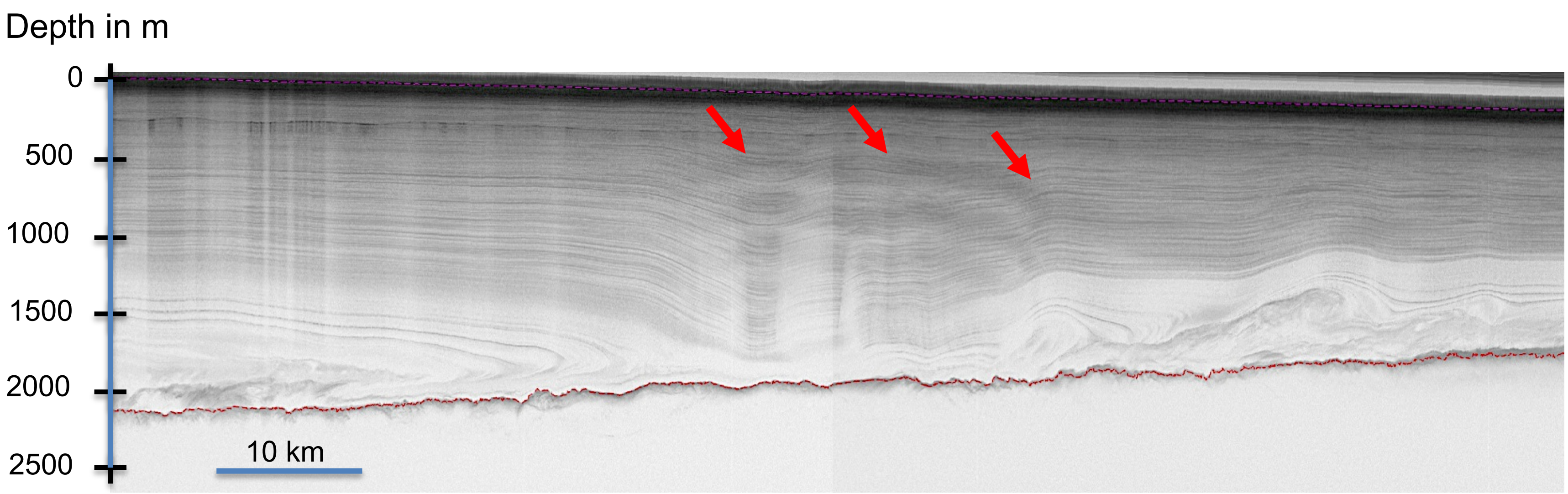
Bulk properties related to single crystals:

$$\epsilon'(z) = \begin{pmatrix} \epsilon'_x & 0 & 0 \\ 0 & \epsilon'_y & 0 \\ 0 & 0 & \epsilon'_z \end{pmatrix} = \begin{pmatrix} \epsilon'_\perp + \Delta\epsilon'\lambda 1 & 0 & 0 \\ 0 & \epsilon'_\perp + \Delta\epsilon'\lambda 2 & 0 \\ 0 & 0 & \epsilon'_\perp + \Delta\epsilon'\lambda 3 \end{pmatrix}$$

$\Delta\varepsilon' = \varepsilon'_{||} - \varepsilon'_\perp = 0.034$ (for a single crystal)

Fabric anisotropy radar II: beats

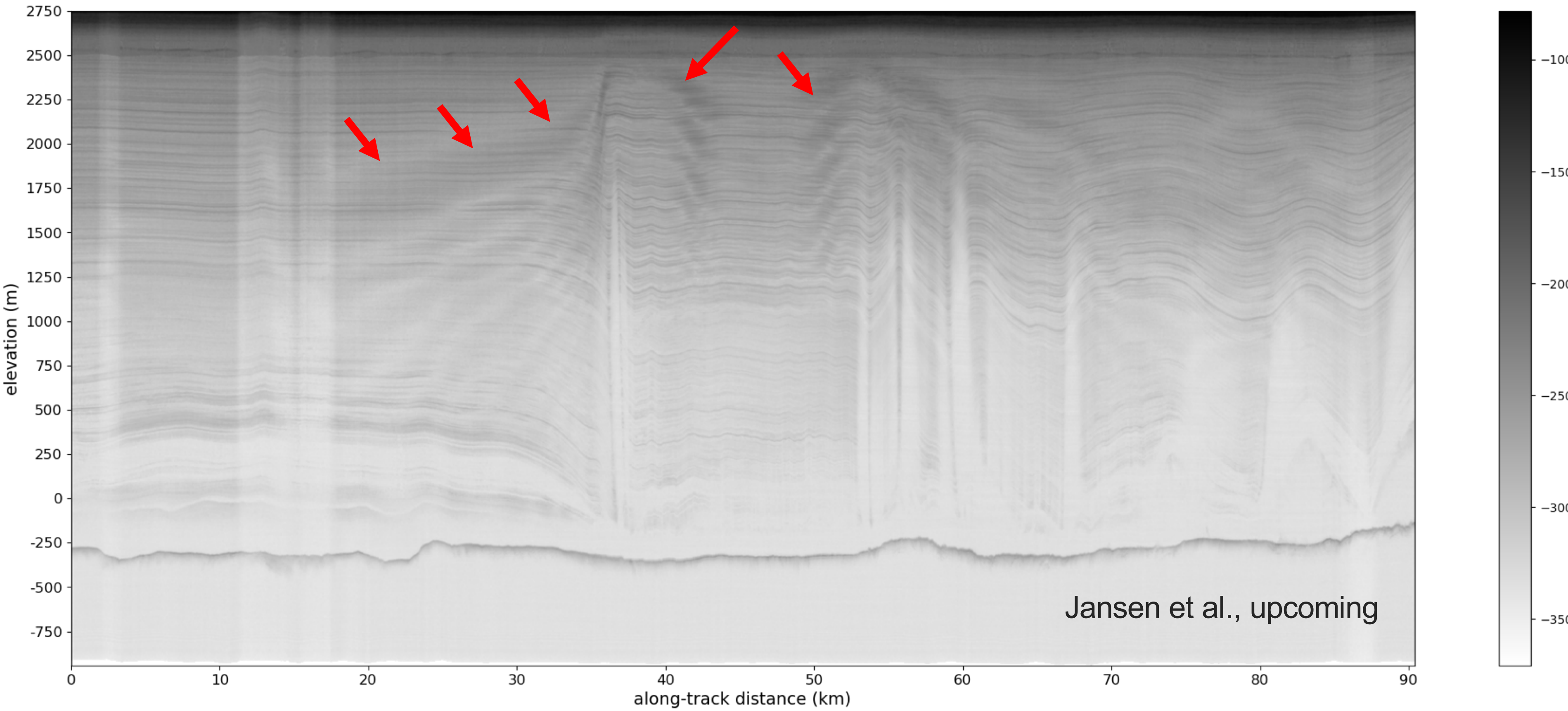
Horizontal anisotropy from amplitude modulation in co-polarized data



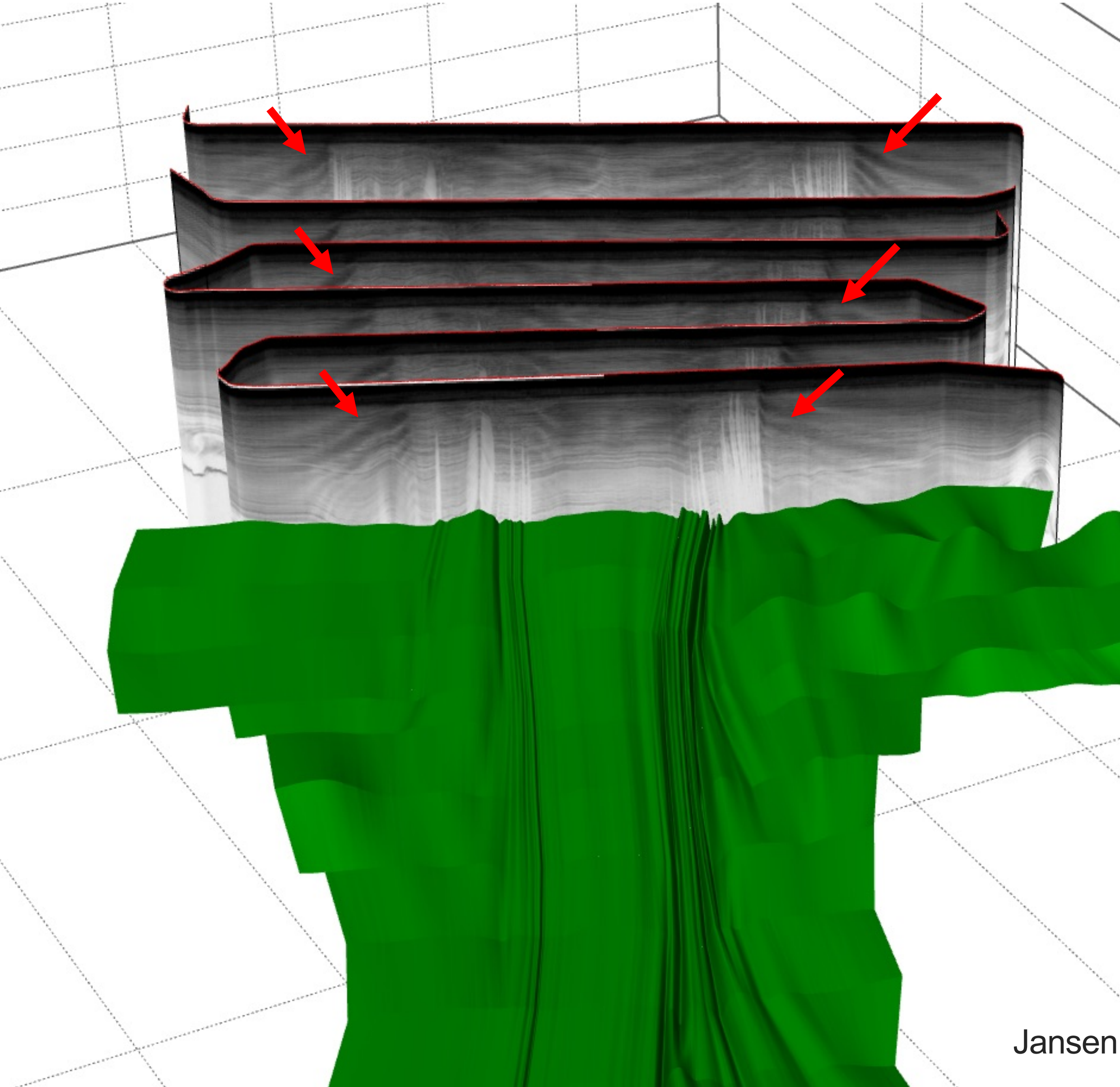
Jansen et al., 2016

Fabric anisotropy radar II: beats

Horizontal anisotropy from amplitude modulation



Fabric anisotropy radar II: beats



Strong amplitude modulations in all across-flow radargrams

Jansen et al., 2019

Fabric anisotropy radar II: beats

Phase difference ϕ of ordinary and extraordinary wave causes modulation (Fujita et al., 2006)

$$\phi = \frac{4\pi f}{c_0} \int_z^0 (\sqrt{\epsilon'_x} - \sqrt{\epsilon'_y}) dz + (\Delta\phi_x + \Delta\phi_y),$$

$$= \frac{4\pi f}{c_0} \int_z^0 \frac{\Delta\epsilon(z)}{2\sqrt{\bar{\epsilon}}} dz$$

Taylor expansion (e.g. Jordan et al., 2019)

$$= const \cdot \Delta\lambda\, z$$

assuming vertically constant fabric

(bulk properties of polycrystals)

$$\Delta\epsilon = \epsilon_y - \epsilon_x = \Delta\epsilon'(\lambda_2 - \lambda_1),$$

$$= 0.034\Delta\lambda$$

$$\Sigma_i \lambda_i = 1$$

$$\lambda_3 = 1 - 2\lambda_1 - \Delta\lambda$$

$\Delta\lambda$: horizontal anisotropy

Nodes from destructive interference

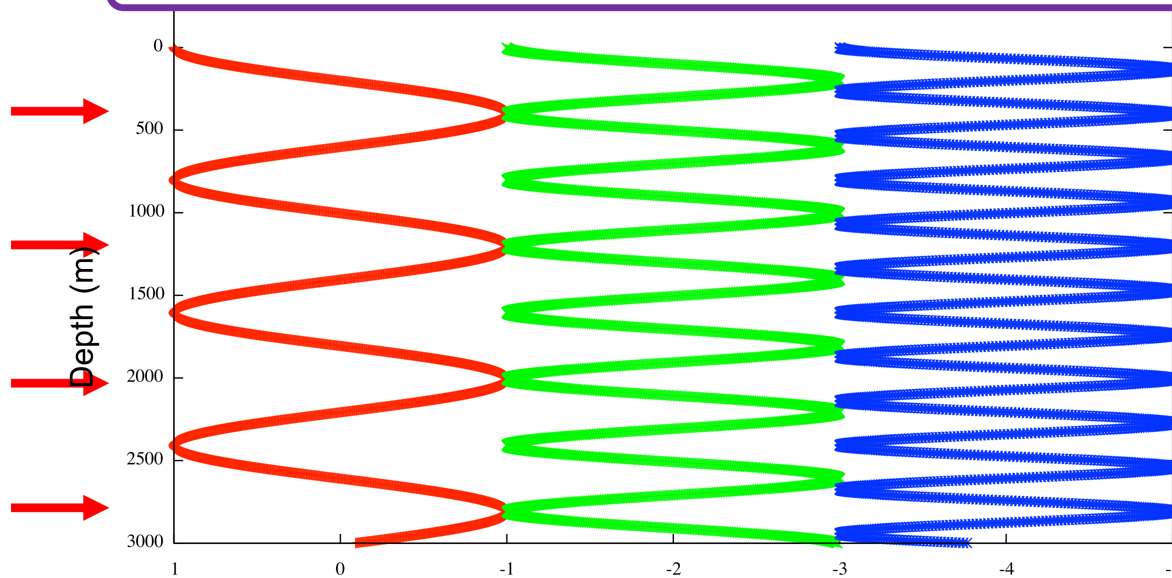
- modulation $A \sim A_0 \cos(\phi)$: minimum for $\phi = (2n-1)\pi$
- wave number: $k = 2\pi$ / wavelength = $2\pi f_{mod}/c$

$$\phi = kz = const \cdot \Delta\lambda z$$

$$\Delta\lambda \sim k \sim f_{mod}$$

forward simulation:

$\Delta\lambda = 0.1$ $\quad \Delta\lambda = 0.2$ $\quad \Delta\lambda = 0.3$



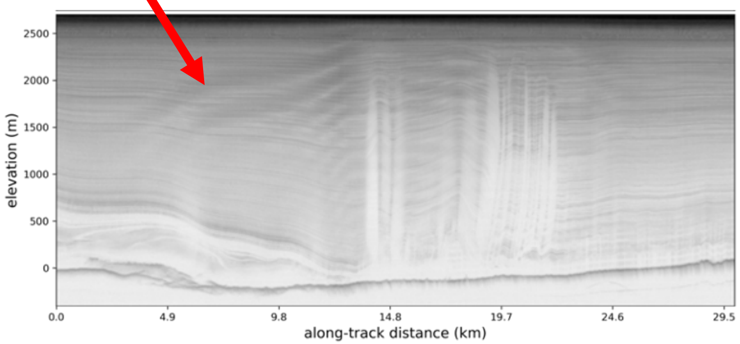
$k / 2\pi = 3.75/3000$ m $\quad = 7.5/3000$ m $\quad = 11/3000$ m

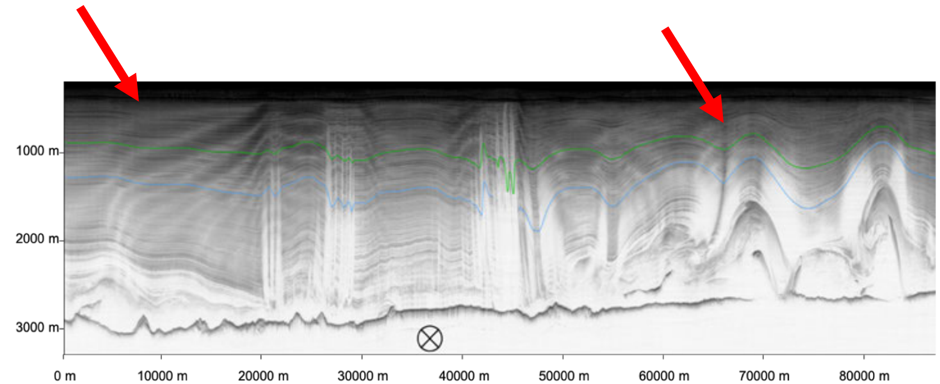
=> $k = 0.0078\ \mathrm{m}^{-1}$ $\quad = 0.015\ \mathrm{m}^{-1}$ $\quad = 0.023\ \mathrm{m}^{-1}$

$\Delta\lambda = 0.099$ $\quad = 0.192$ $\quad = 0.294$

Fabric anisotropy radar II: beats

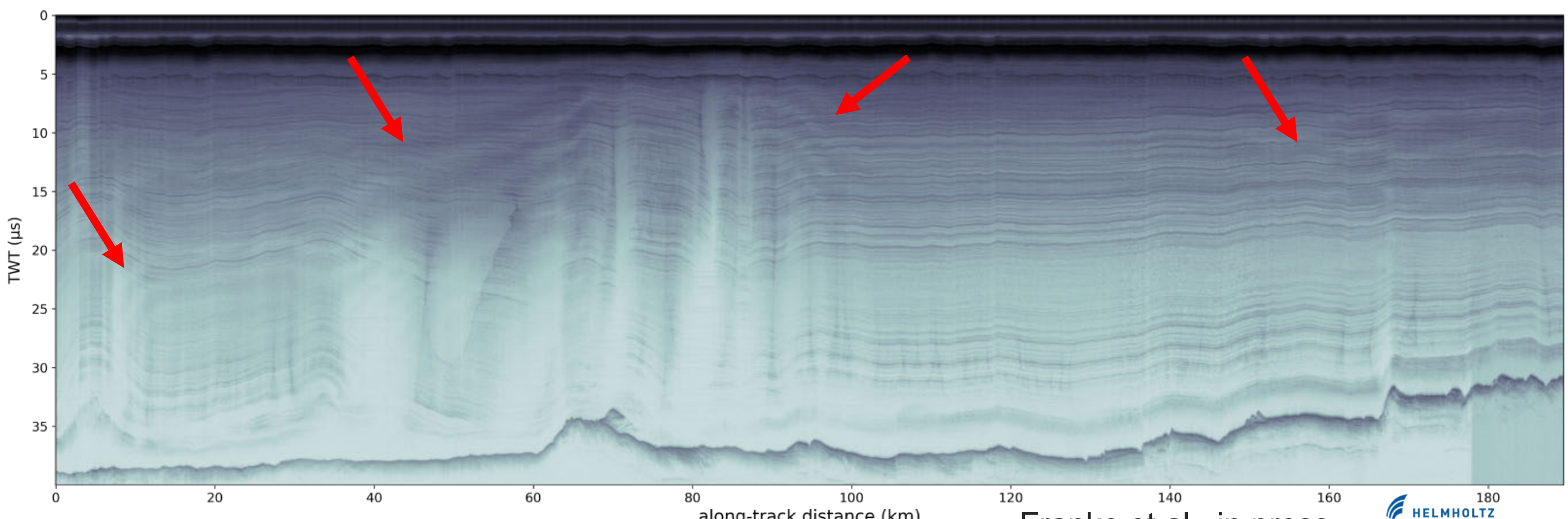
across flow





Jansen et al., upcoming

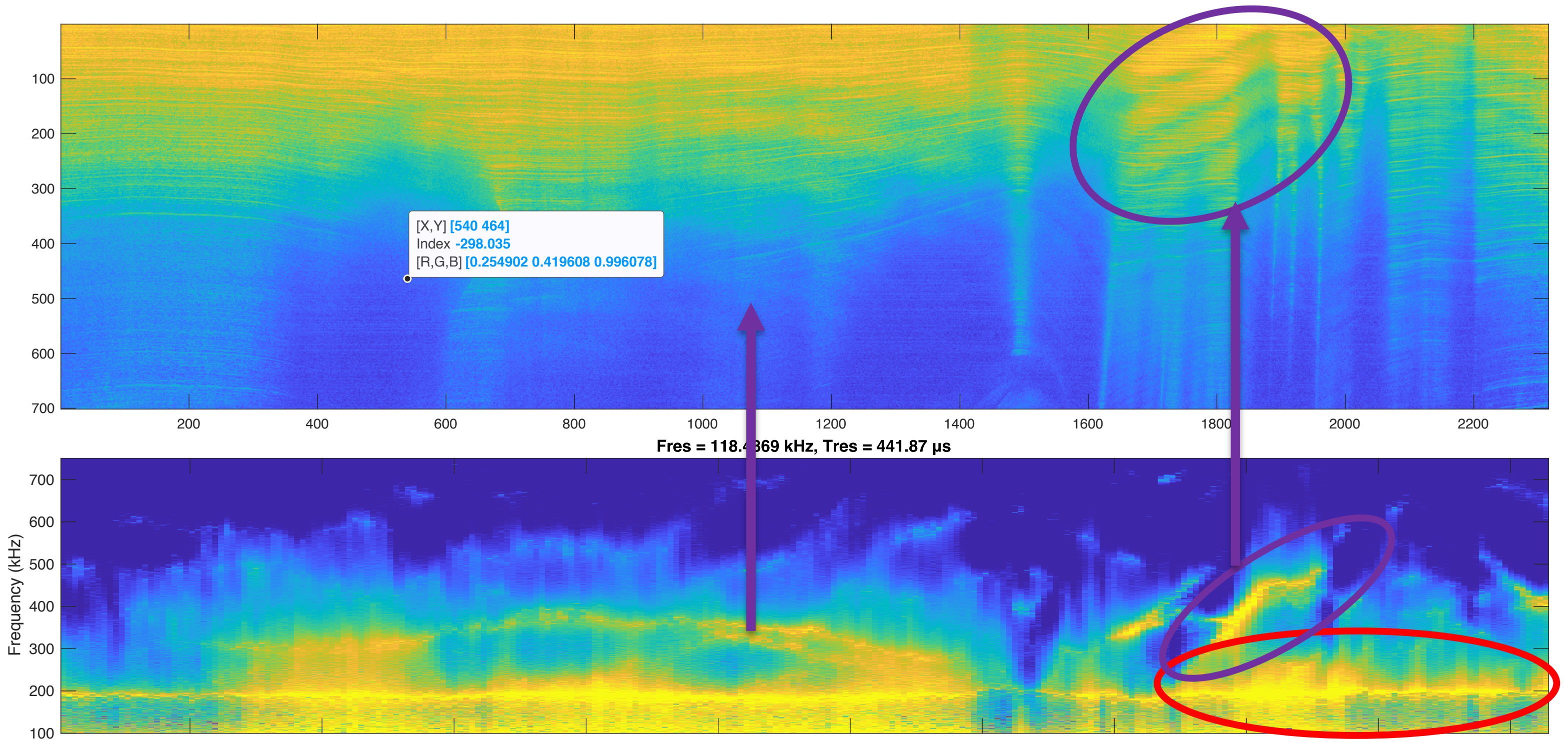
along flow



Franke et al., in press

Fabric anisotropy radar II: beats

Spatial analysis with spectrograms



Conclusion

Internal layering:

- Integrity relevant for IceCube-Gen2 analysis

Radar:

- Cross-pol: full fabric at points (under assumptions)
- Co-pol: strength of horizontal anisotropy $\Delta\lambda = \lambda_2 - \lambda_1$ as function of position
- Complementation: active & passive seismics (not this talk)

Suggestion

- Airborne survey with state of the art systems (SP? RNO-G?)
- Ground-truthing (or airborne) polarimetry (established)
- Use Gen2 radio-detector array for complementation (new)