PHYSICALLY-BASED RADAR RETRIEVAL ALGORITHMS FOR SWE ESTIMATION

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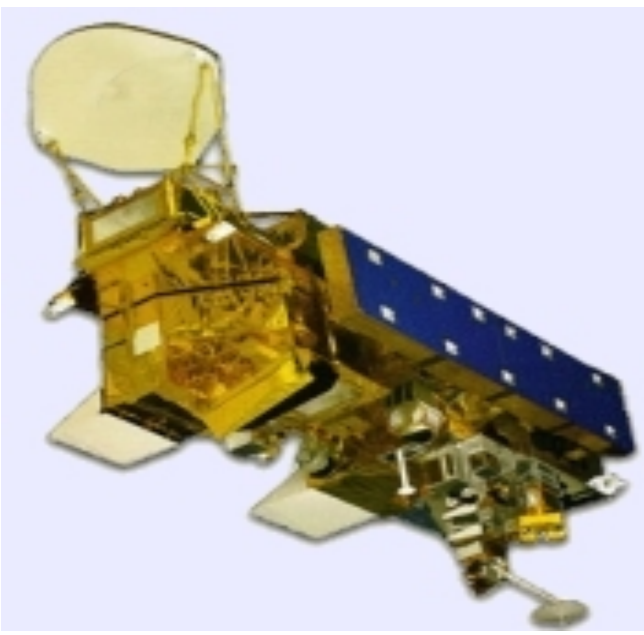
SnowEx Workshop, August, 2017

Near Grand Mesa site 53W

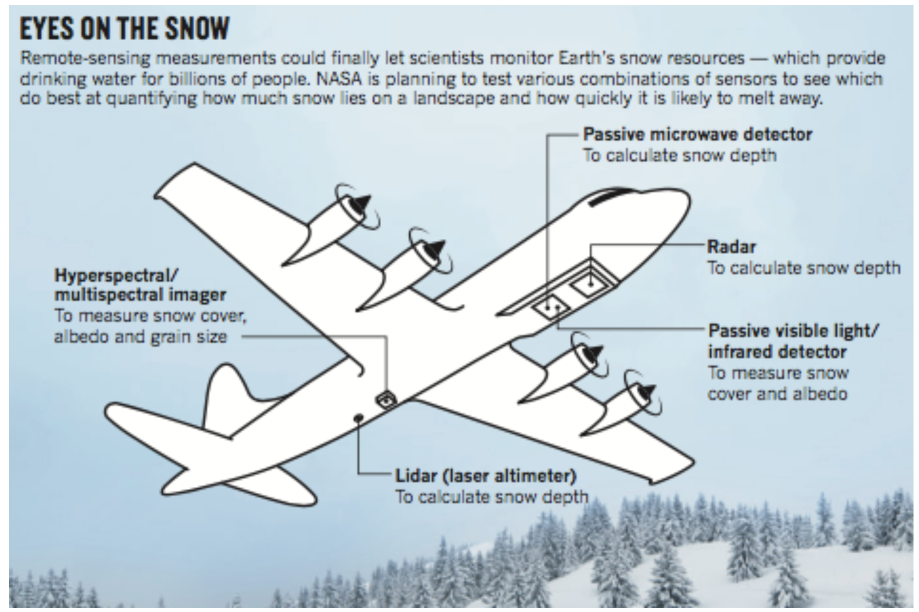
The Ohio State University

BYRD POLAR AND CLIMATE RESEARCH CENTER

IN PURSUIT OF PHYSICALLY BASED ALGORITHMS



e.g. AMSR-E



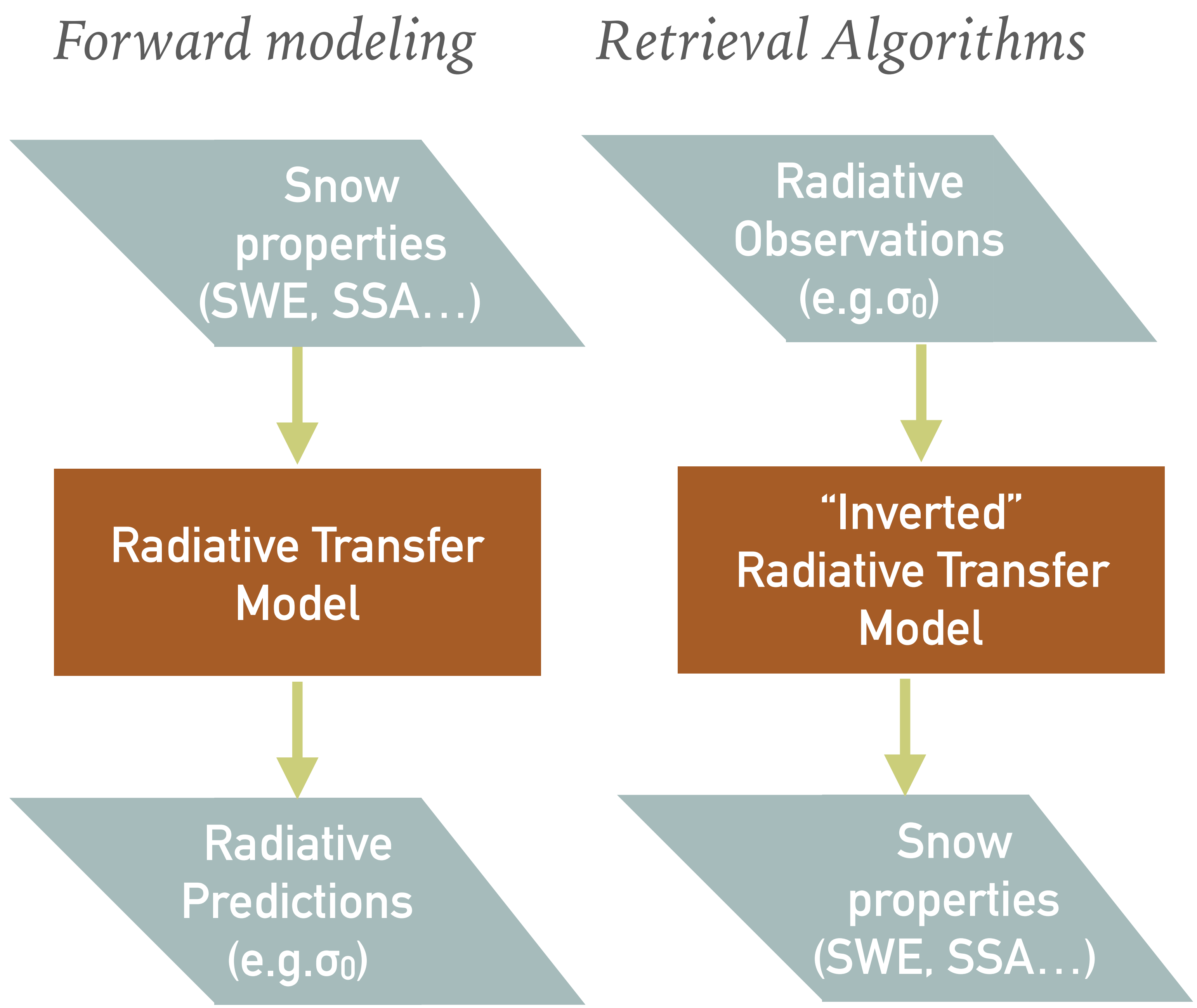
e.g. SnowEx

e.g. SodRad @ NoSREx

SWE retrieval algorithm applicable ***across scales*** *from field to space that faithfully represents all important* ***physics*** *of the retrieval problem, with known and validated* ***accuracy****, for both active & passive microwave measurements, suitable for design of future satellite missions.*

THE RETRIEVAL CHALLENGE

- Radiative transfer models (RTMs) predict microwave observables given snow properties and are now forced by measurable parameters e.g. specific surface area (SSA)
- Inverting RTMs is complex:
  - Many unknowns: depth, density, SSA…
  - Snow is a layered medium
  - Soil substrate properties significantly impact measurement



THE RETRIEVAL HYPOTHESIS

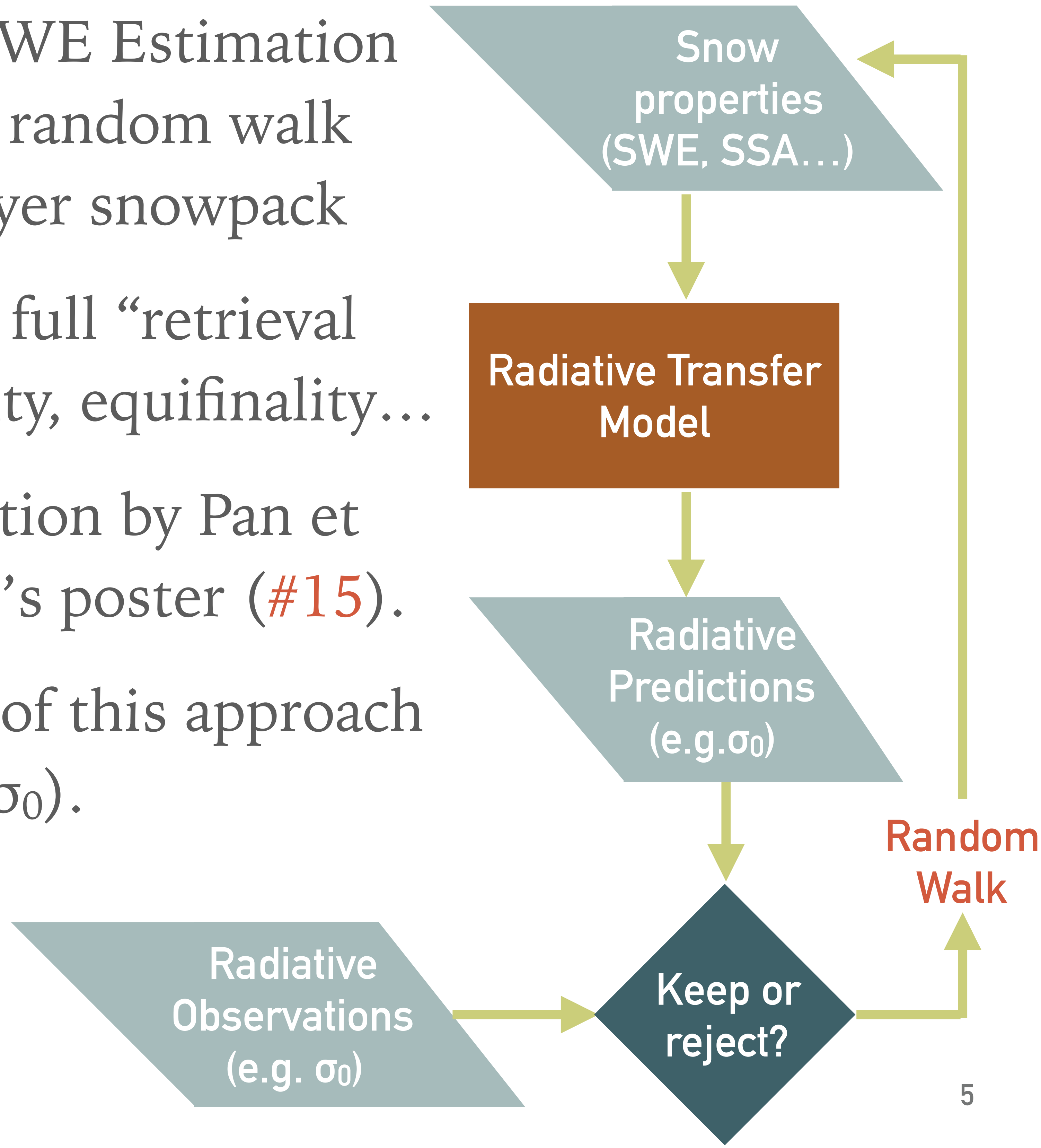
Physically-based retrievals should work!

When they don't work:

1. Bring in more *a priori* information
2. Improve radiative transfer model precision
3. Ensure adequate sensitivity to SWE, given SNR

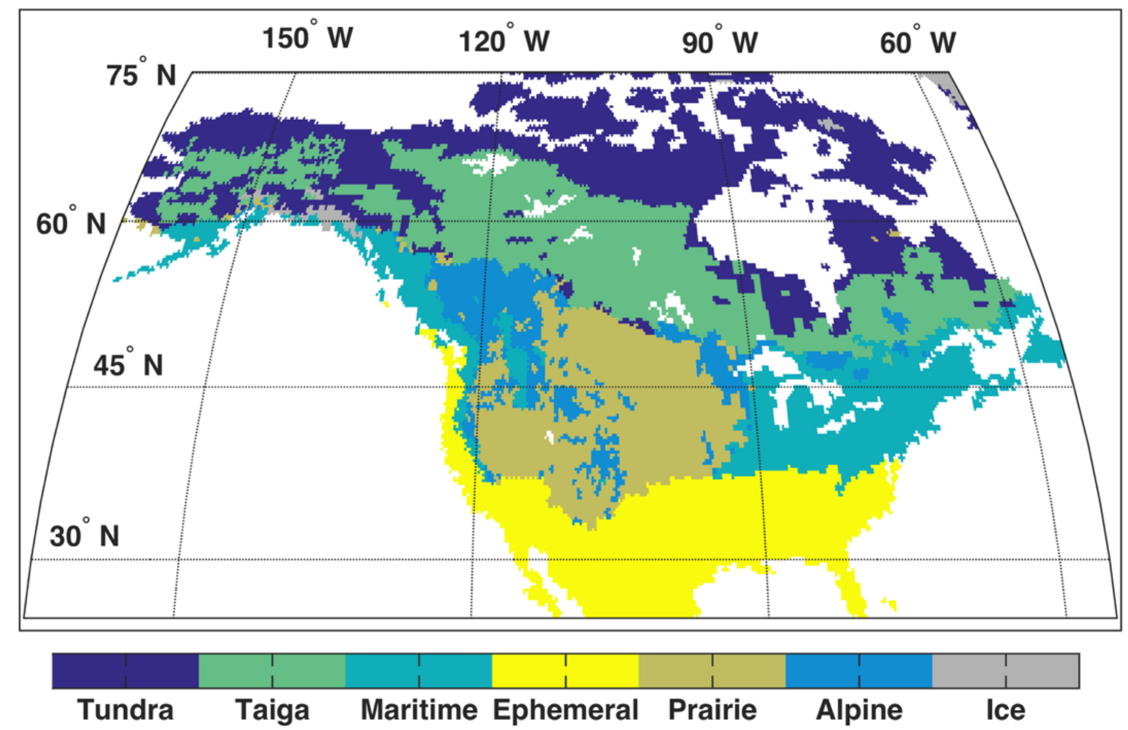
THE BASE-R ALGORITHM: BACKGROUND

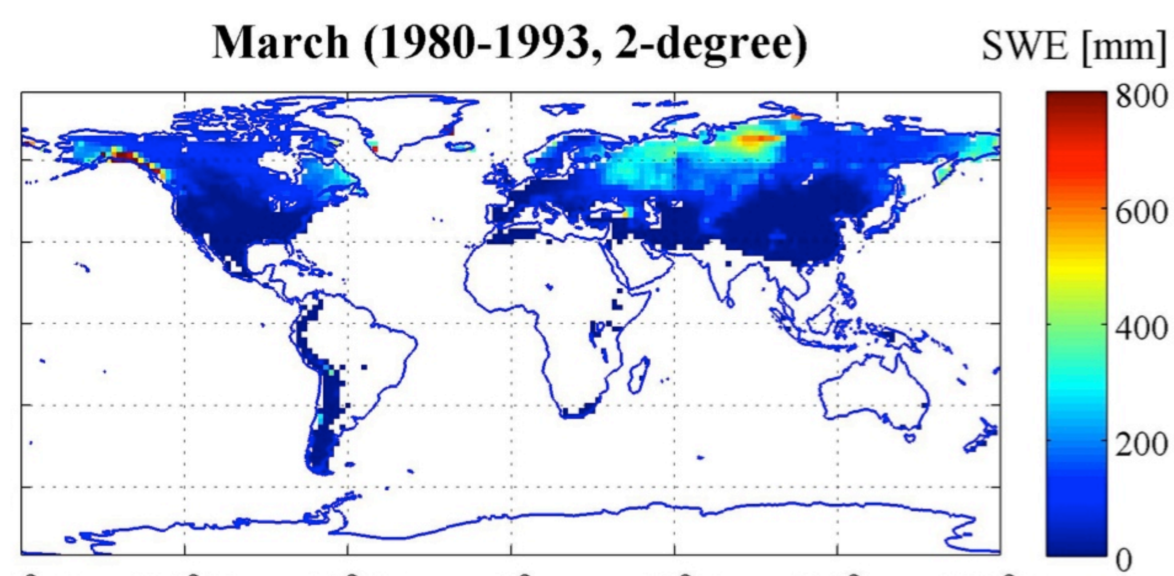
- Bayesian Algorithm for SWE Estimation with radar (BASE-R) is a random walk algorithm for multiple-layer snowpack
- Iterative evaluation gives full "retrieval pdf", including uncertainty, equifinality…
- Passive microwave validation by Pan et al. RSE, 2017. See Jinmei's poster (#15).
- BASE-R is an adaptation of this approach using radar backscatter (σ_0).



BASE-R IMPLEMENTATION

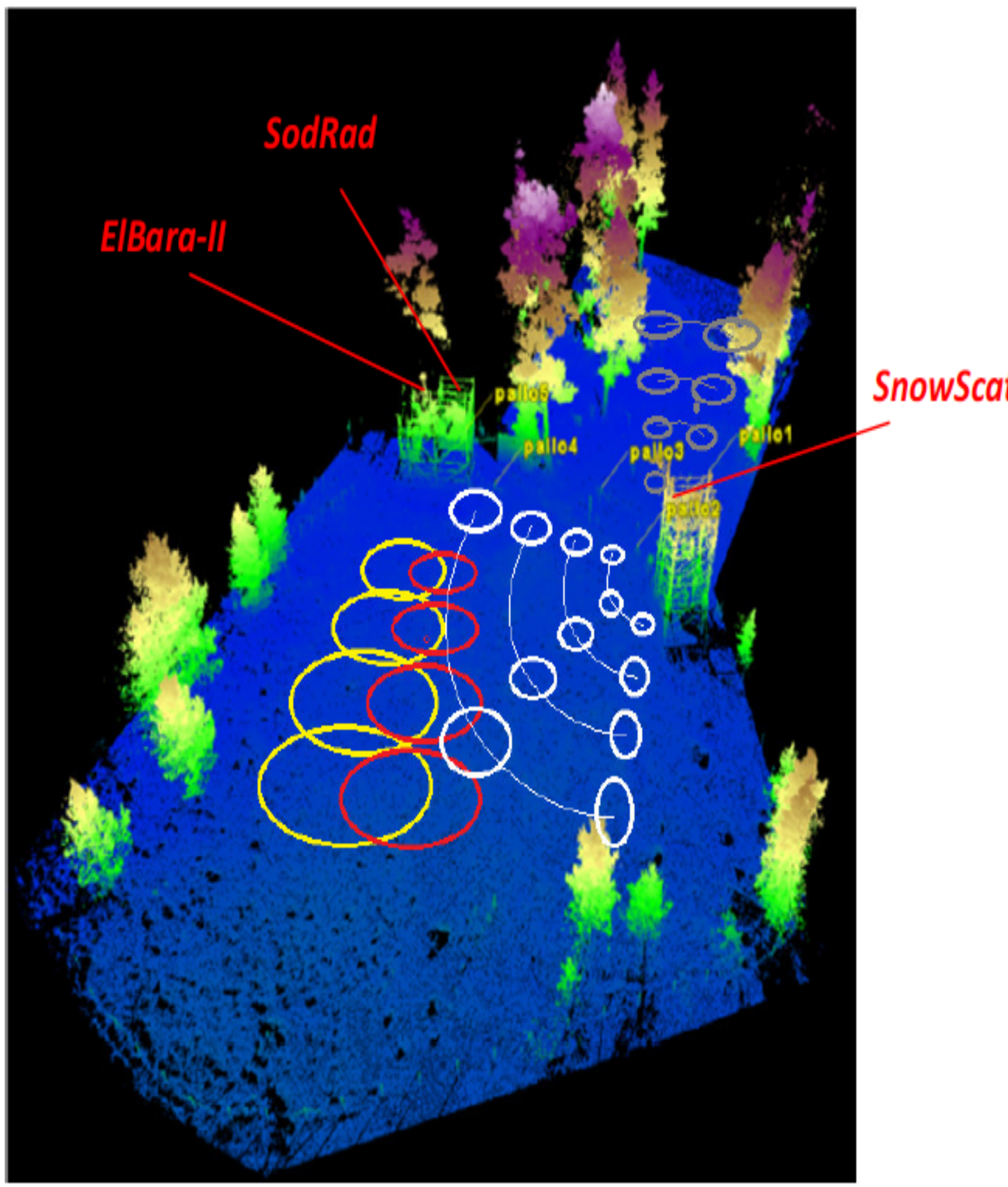
- For each snow layer, BASE-R estimates density, grain size autocorrelation length, temperature, layer thickness. Also soil moisture, roughness and temperature
- First guess / prior info: global SWE climatology (VIC), Sturm density. Assume large grain size uncertainty.
- Easy to objectively add better site-specific prior information if available (e.g. from modeling, past snowpits, etc.)
- Radiative transfer model: MEMLS3&a (Proksch et al., 2015) for snow + modified Mironov for soils





Pan et al., 2017

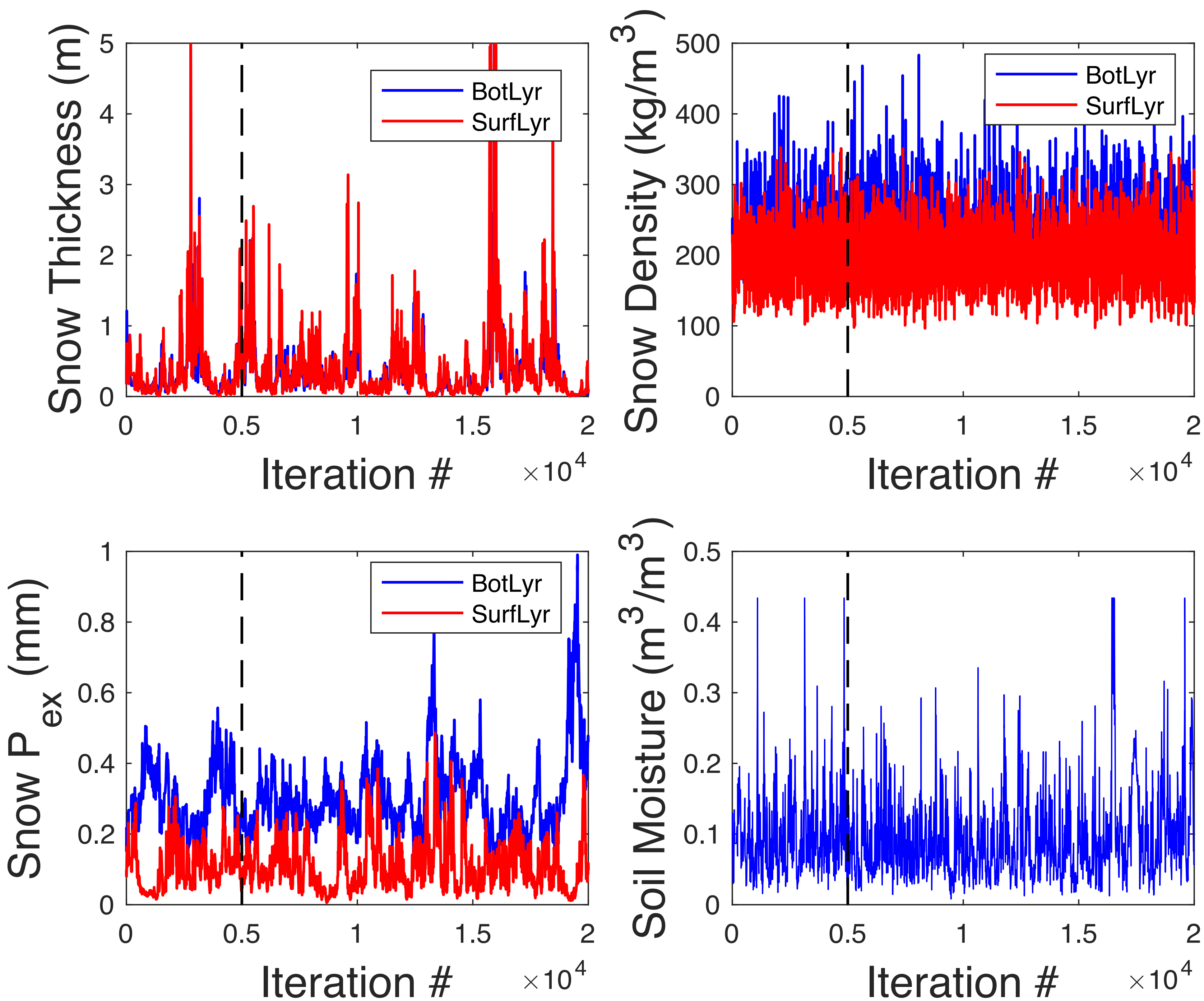
BASE-R: VALIDATION EXPERIMENT WITH NOSREX

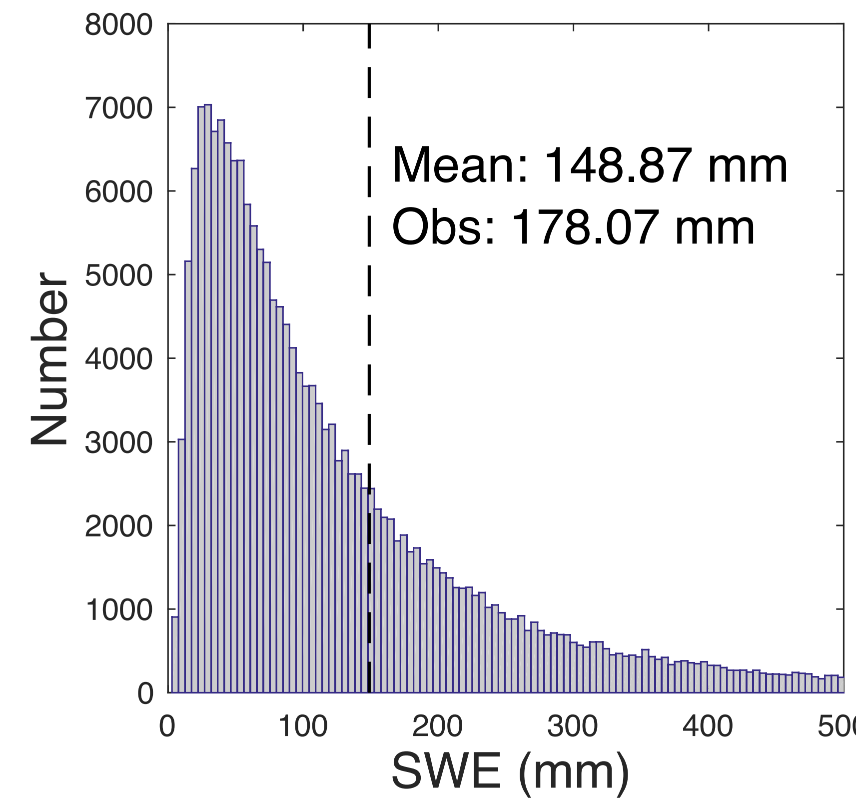


NoSREx: Lemmetyinen et al., 2016

- Nordic Snow Radar Experiment (NoSREx) data from Sodankyla, Finland (67°22' latitude).
- Taiga snow, typical peak accumulation ~200 mm SWE
- Continuous in situ radar observations with weekly snowpits
- Four years of data: Winter 2010-2013. Each year very different
- 10.2, 13.3, 16.7 GHz, vv-pol were used

EXAMPLE BASE-R RESULTS: SODANKYLA, MARCH 23, 2012

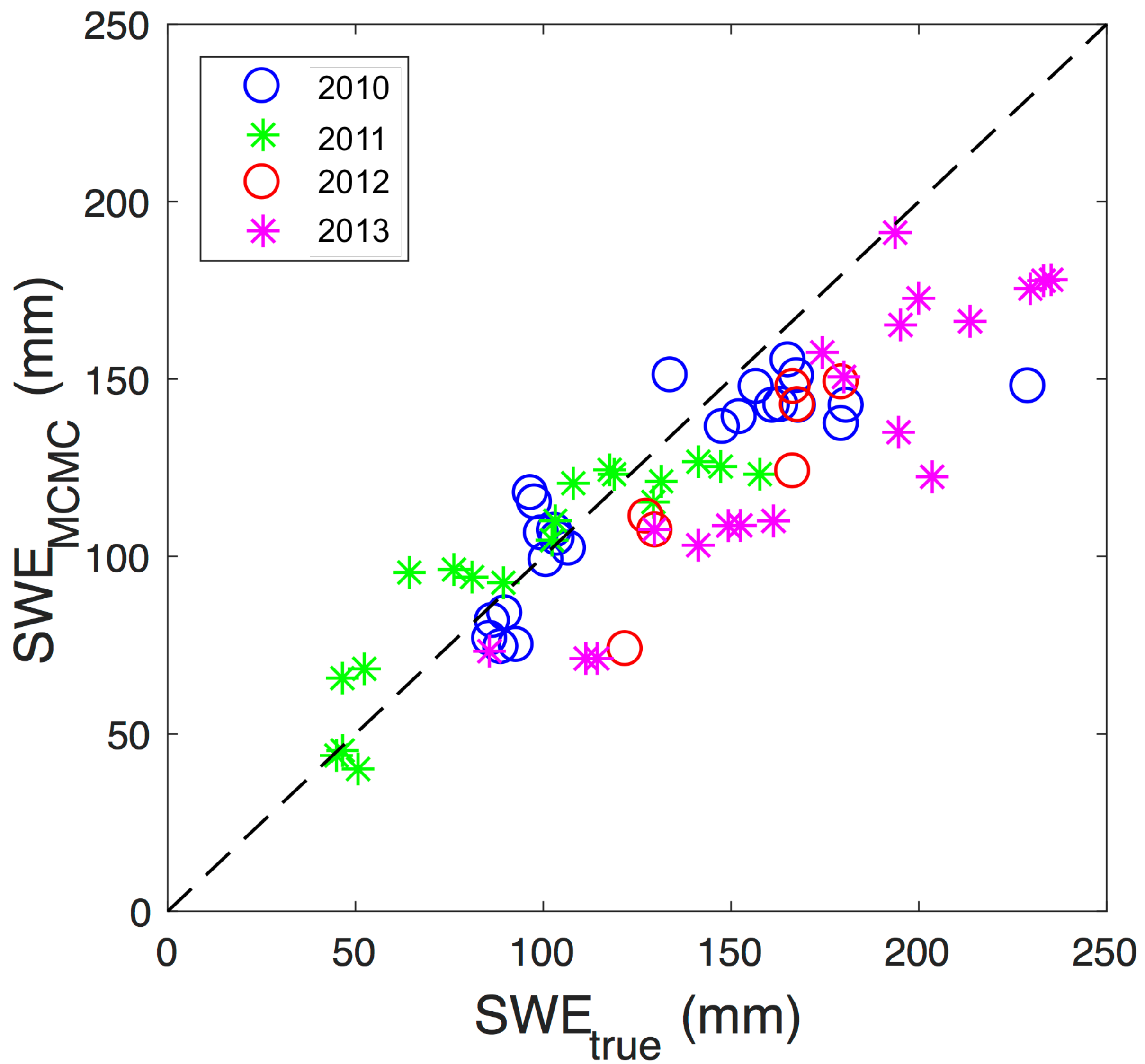


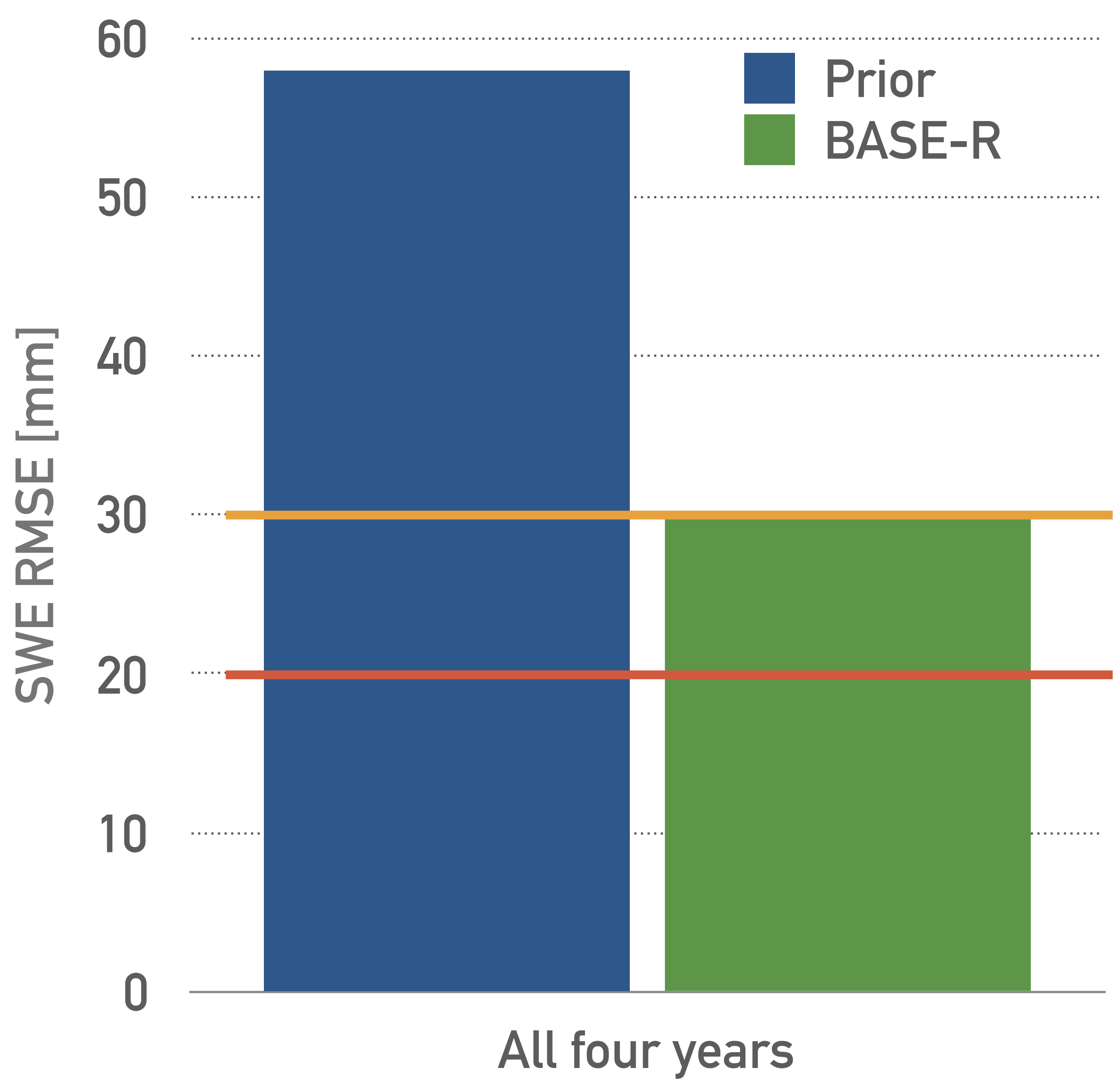


Estimate & uncertainty summarized from "retrieval PDF"

P_{ex} ~ *snow grain size correlation length*

BASE-R VALIDATION: ACROSS 69 SNOWPITS

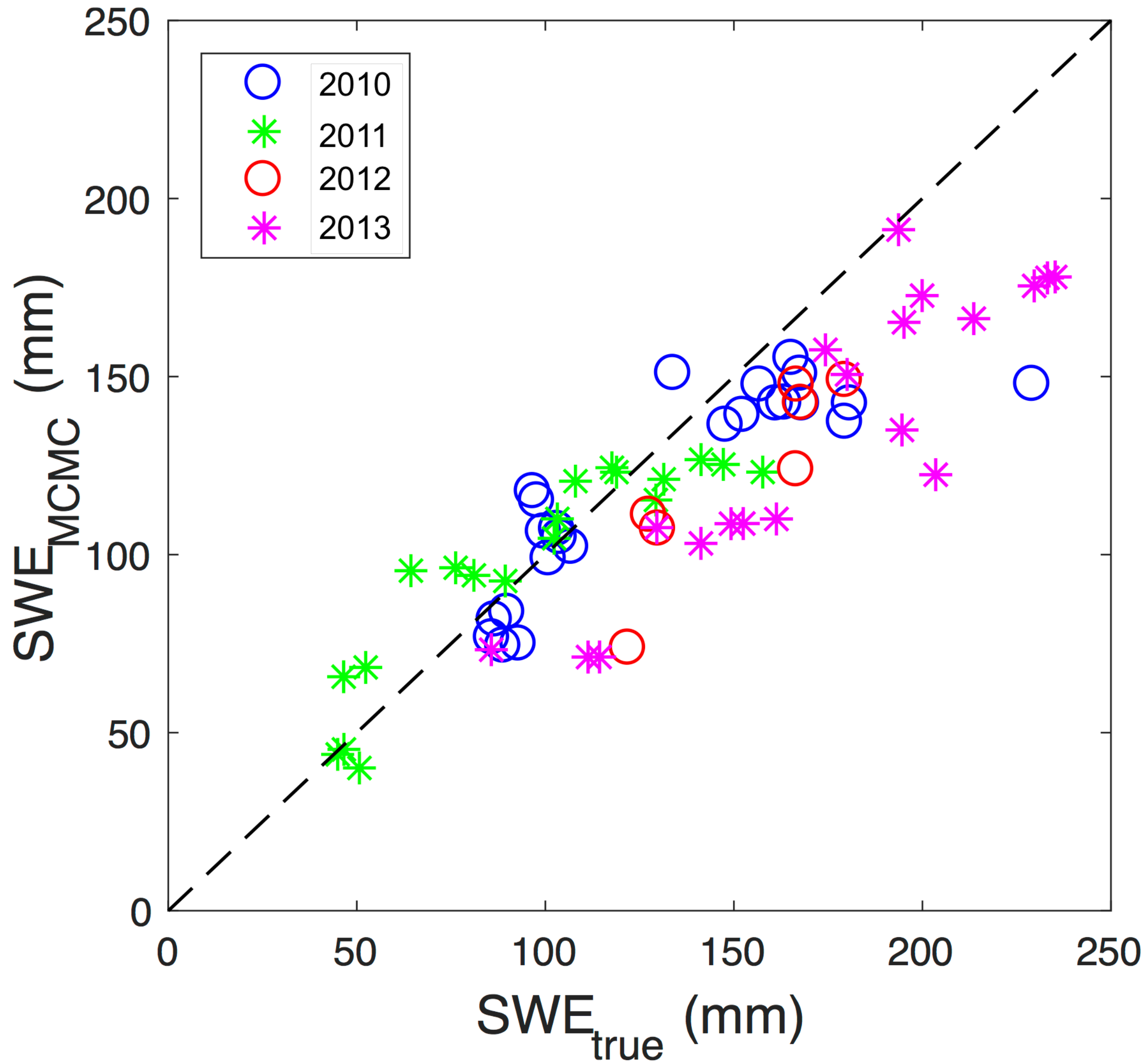


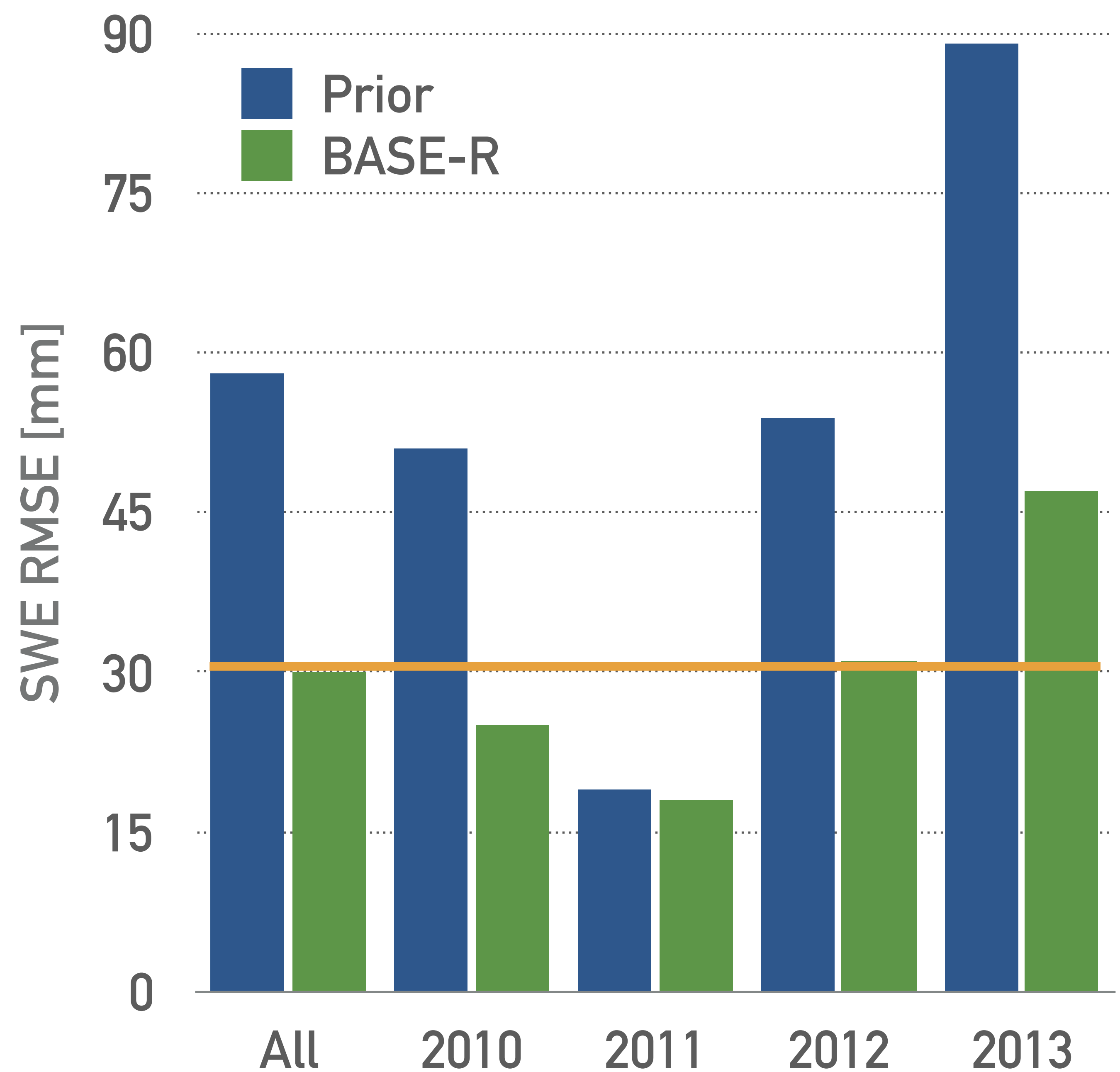


30 mm is the IGOS "threshold" requirement for shallow snow

20 mm is the IGOS "objective" requirement. BASE-R still has 10 mm to go!

BASE-R VALIDATION: PERFORMANCE VARIES ACROSS YEARS



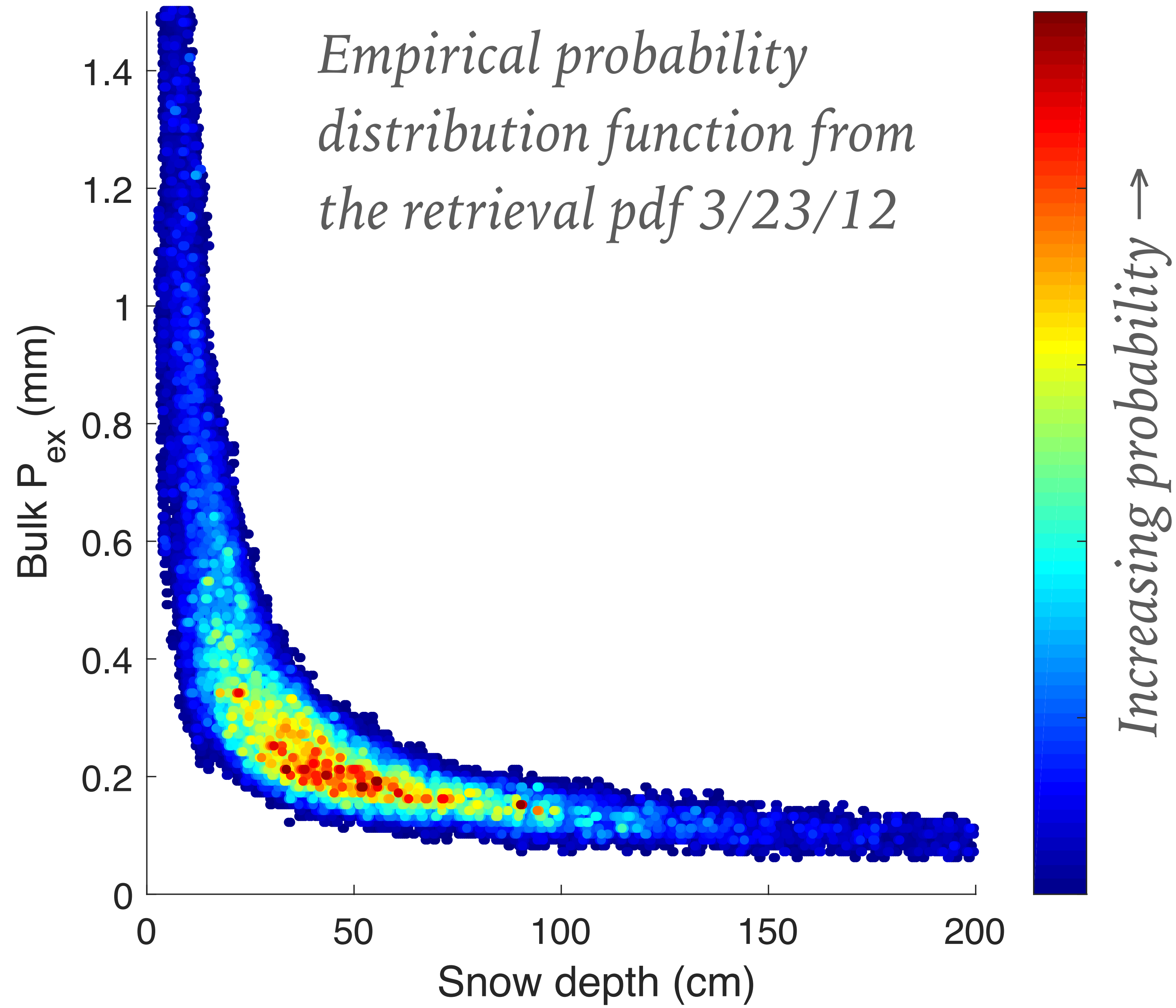


2012: warmest.

2012 & 2013: high measured densities led to SWE underestimation by BASE-R

BASE-R VALIDATION: LIMITATIONS

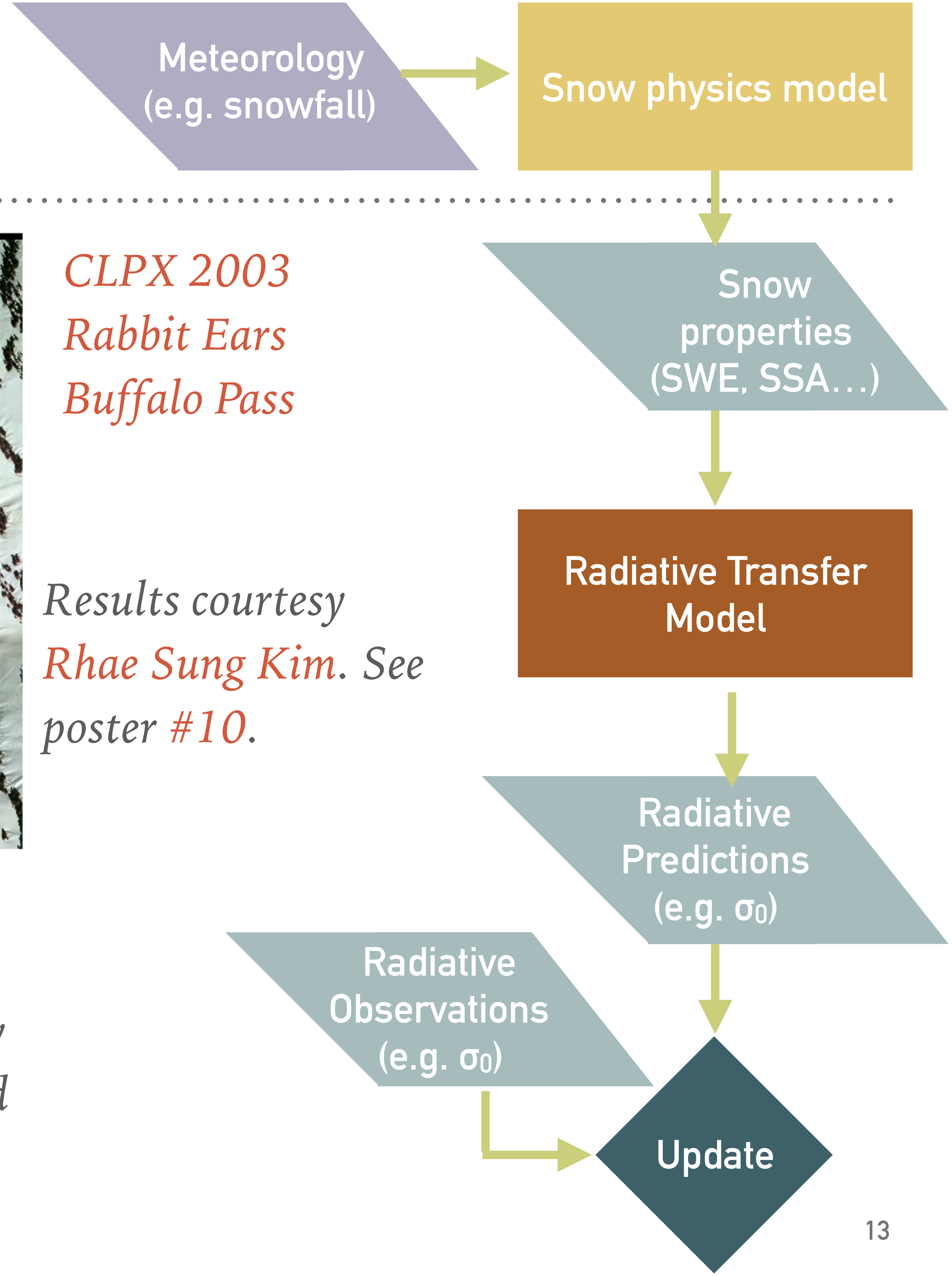
- BASE-R MCMC joint pdf visualization indicates tradeoff between grain size (P_{ex}) and depth
- Snow models could be used to provide additional prior information on grain size (P_{ex})

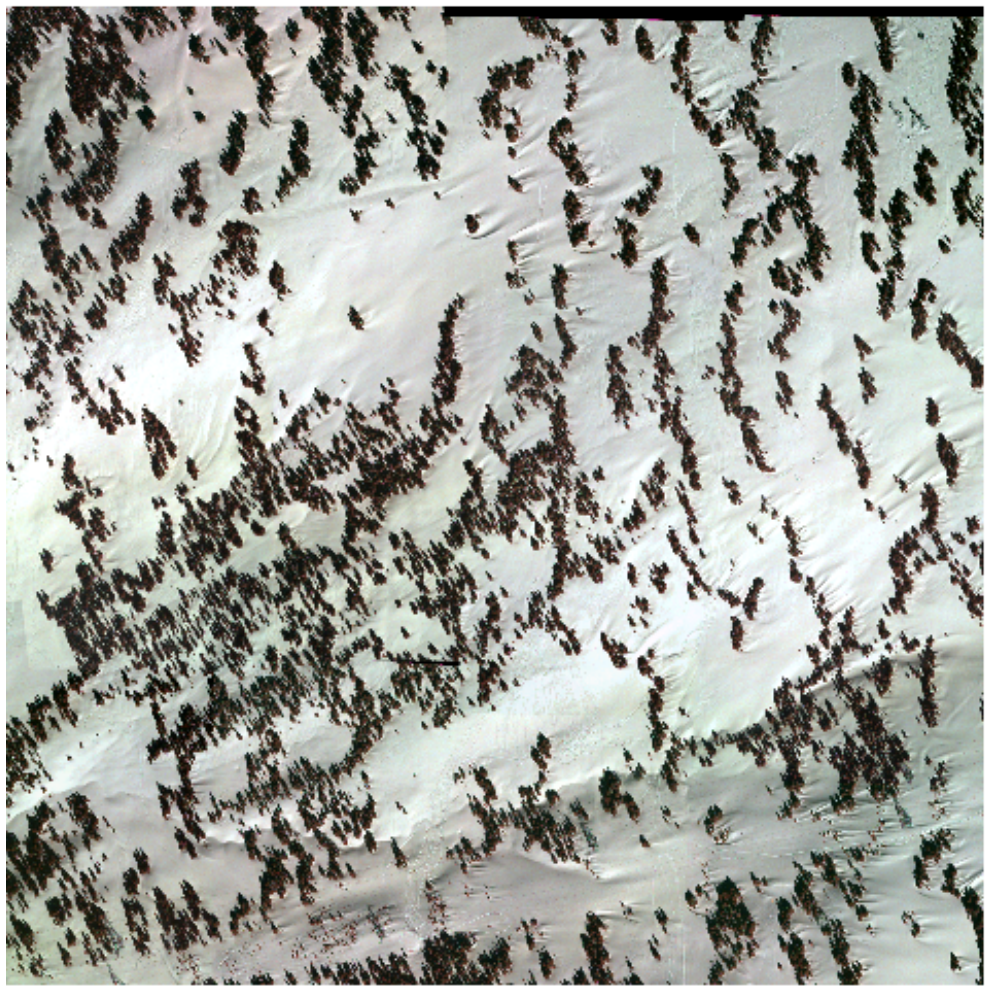


BASE-R: OTHER LIMITATIONS

- Predicted SWE uncertainty in this experiment is very high. This may be because the MEMLS3&a model is relatively low-precision? Switch to DMRT or bicontinuous medium approach
- NoSRex scatterometry had relatively low dynamic range, making observation precision very important. Also not very sensitive to density, and is quite sensitive to soils, and forests. Does not work for wet snow. Highlight need for models!
- Microwave-snow relationships are complex for deep snow… radiance assimilation needed. Dongyue Li et al., *WRR*, 2017

WHAT ABOUT DEEP SNOW?



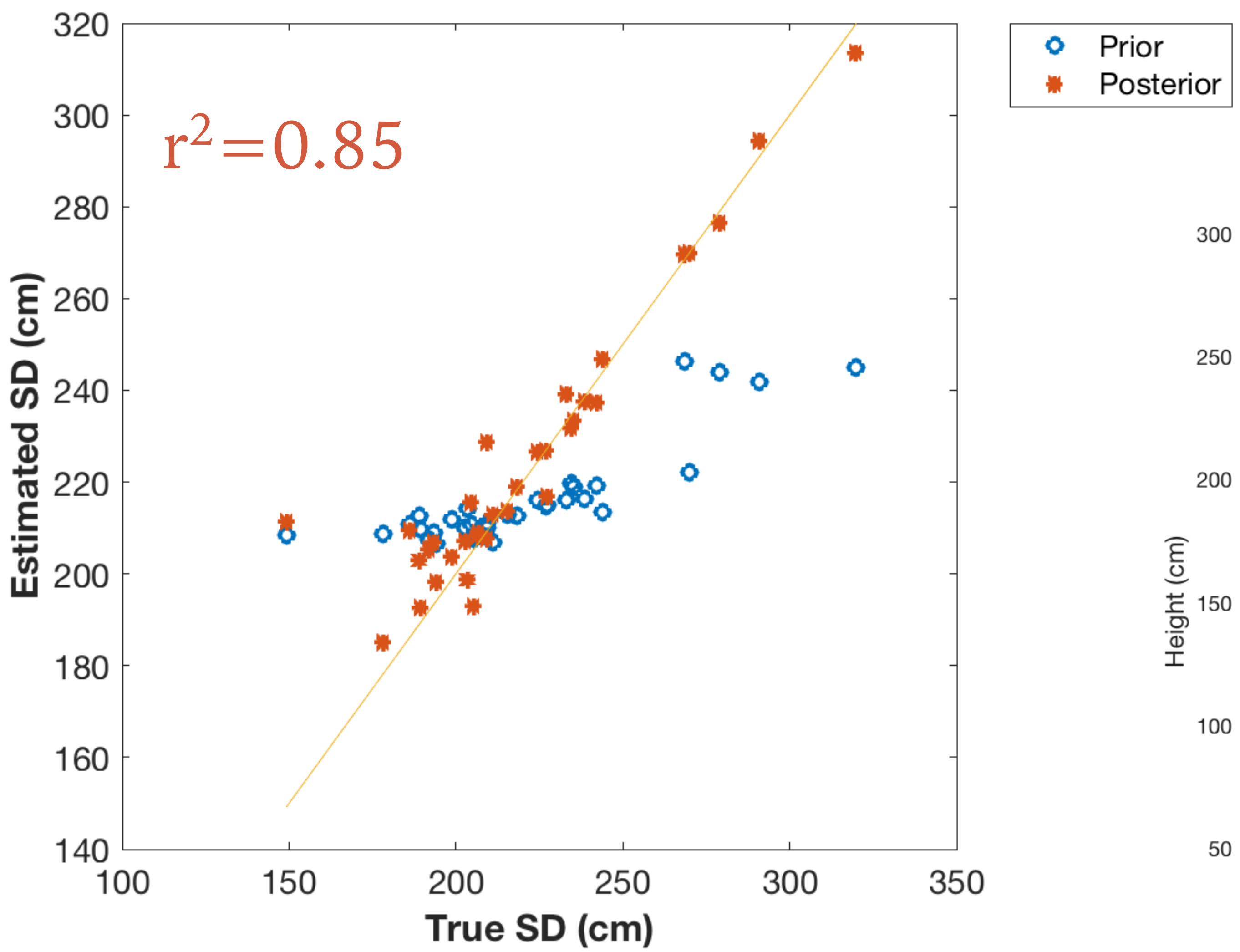


CLPX 2003
Rabbit Ears
Buffalo Pass

Results courtesy Rhae Sung Kim. See poster #10.

CROCUS at 120 m (courtesy Marie Dumont, Meteo France) with ensemble forcing (courtesy Liz Baldo, UCLA). Assimilated airborne 10, 19, 37, 89 GHz.

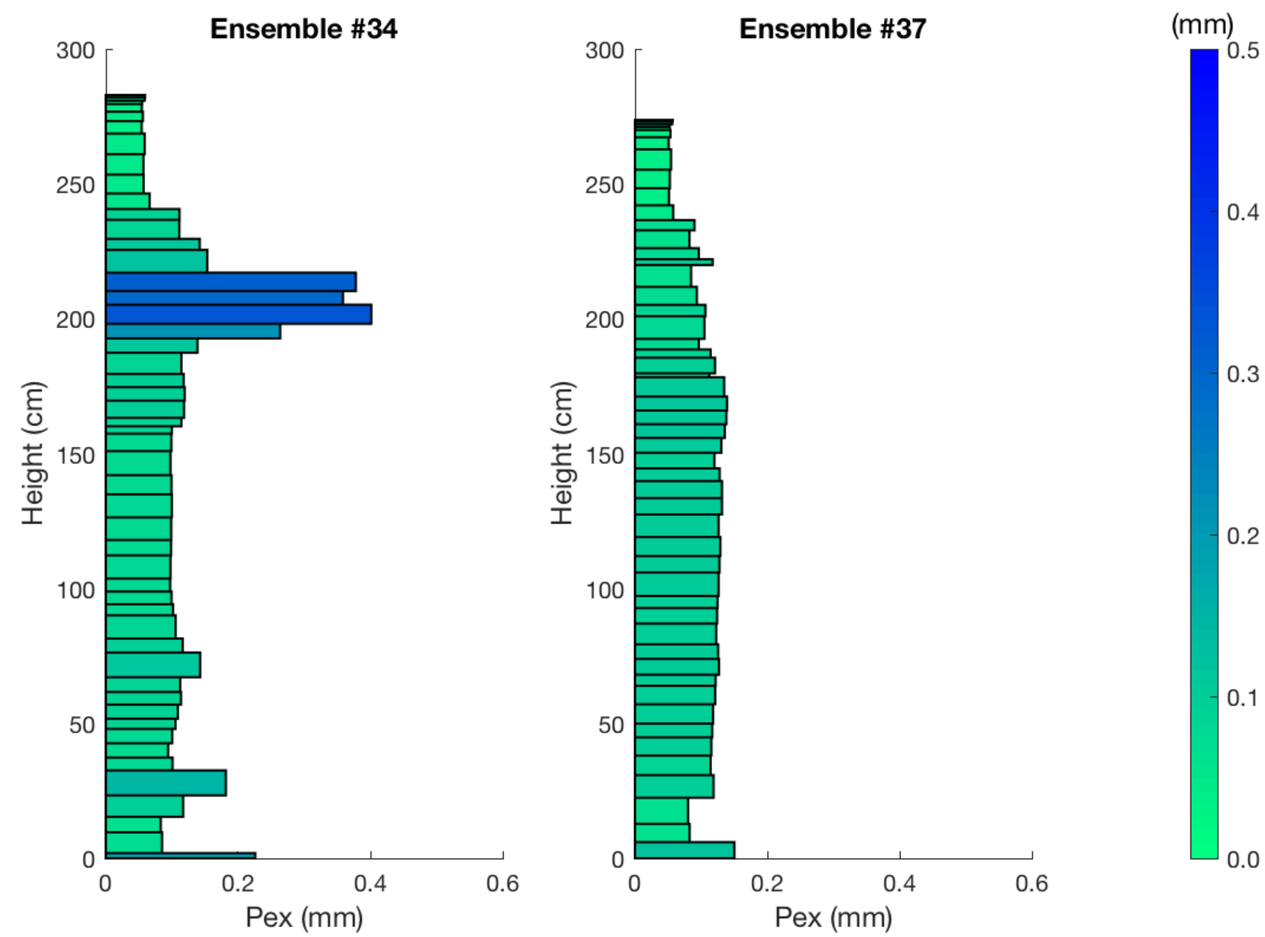
RADIANCE ASSIMILATION WORKS FOR DEEP COLORADO SNOW



Particle filter retrieval for deep mountain snow. Depth RMSE = 13 cm

Results courtesy Rhae Sung Kim. See poster #10.

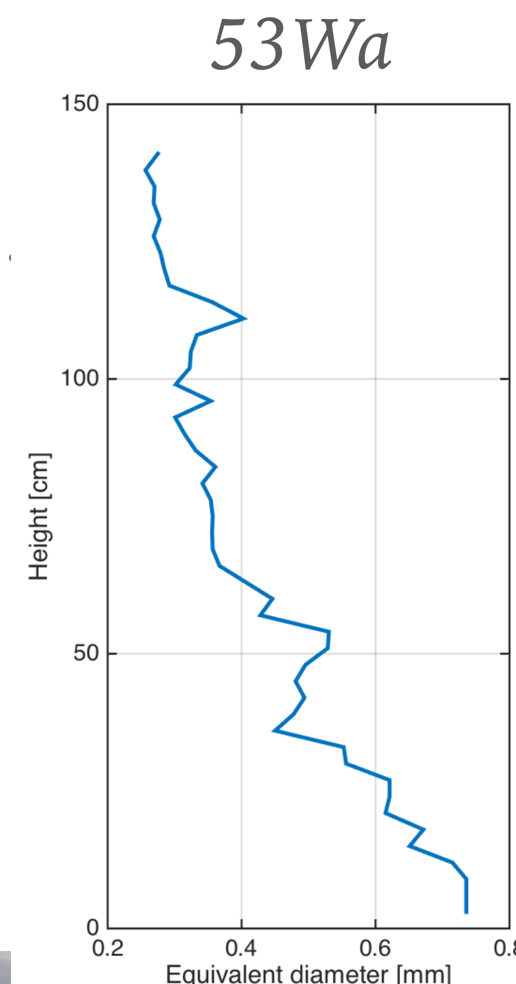
CROCUS simulations for two particles in a single retrieval

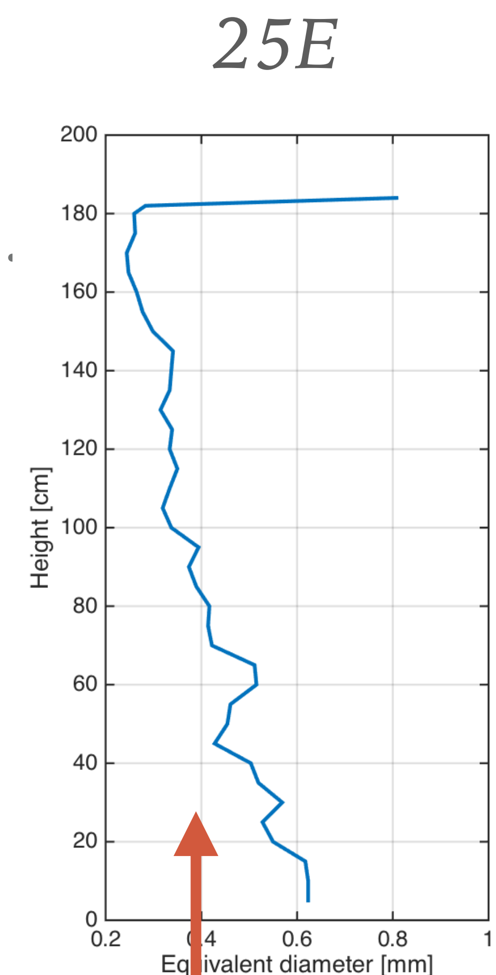


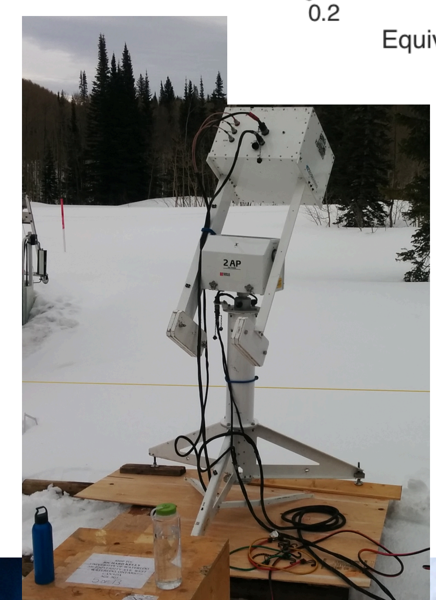
Excursion ~200 cm indicates a melt-refreeze crust possible prior to overflight

SNOWEX & BASE-R PERSPECTIVES

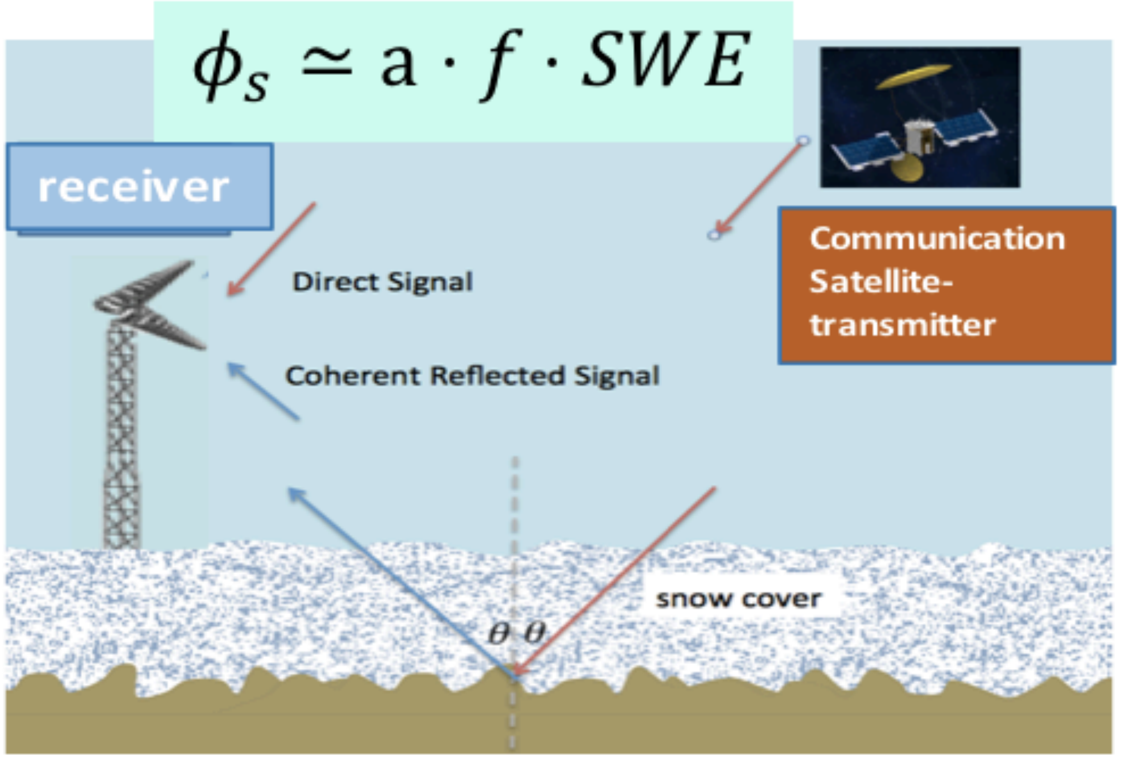
- ➤ Looking forward to microwave working group. Integration with U of M bi-continuous model
- ➤ Run on SnowEx SAR, and collaborator datasets (Trail Vally Creek et al.)
- ➤ Test with in situ scatterometer from Waterloo (A. Thompson & R. Kelly & photo at right; poster #22)
- ➤ Grand Mesa snow is deep! Run BASE-R using CROCUS prior estimate of stratigraphy: models will be key
- ➤ Comparing retrievals to SSA and micropen profiles is crucial! See C. Derksen's talk (this session).





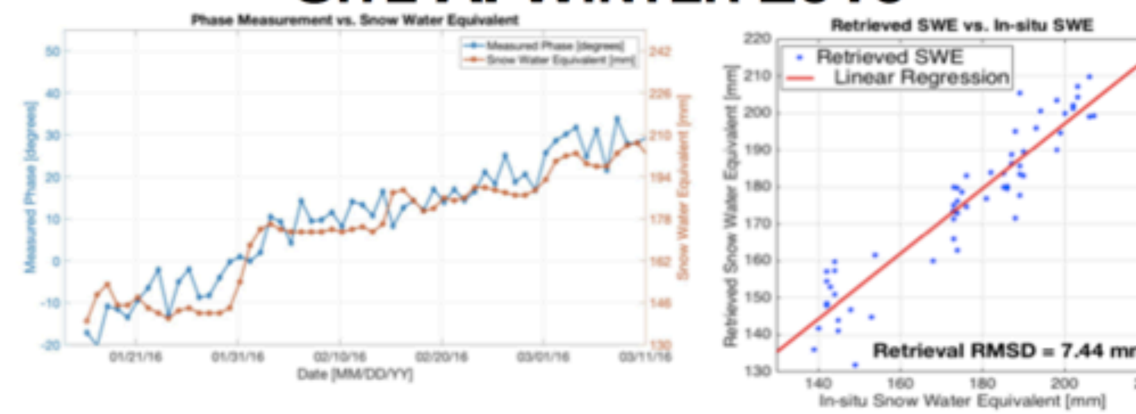


REMOTE SENSING OF TERRESTRIAL SNOW USING P-BAND SIGNALS OF OPPORTUNITY



Satellite of Interest	UHF Follow On/ MUOS

SWE AND PHASE CHANGE SITE A: WINTER 2016



- Excellent correlation between SWE and phase change (0.94)
- RMSD with linear regression is 7.5 mm
- Relationship between phase and SWE from experiment matched theory

Shah, R., Xu, X., Yueh, S., Chae, C. S., Elder, K., Starr, B., & Kim, Y. (2017). Remote Sensing of Snow Water Equivalent Using P-Band Coherent Reflection. IEEE Geoscience and Remote Sensing Letters, 14(3), 309-313. doi: 10.1109/LGRS.2016.2636664

SOOP EXPERIMENTAL SETUP

Site A:
- **Almost no vegetation**
- Installed in Fall 2015
- In Winter 2015-2016: recorded data from 240-270 MHz
- In Winter 2016-2017: recorded data from 254-270 MHz and 360-376 MHz

Site B:
- **Vegetation with trees up to 3 meters**
- Installed in October 2016
- In Winter 2016-2017: recorded data from 254-270 MHz and 360-376 MHz

Key points

Lead: Simon Yueh, JPL

- P-band SoOp technique effective for SWE (dry snow) or snow depth (wet snow) remote sensing
  - Essentially unaffected by snow density, grain size, and stratigraphy
- P-band can penetration vegetation to sense snow under canopy
- Developing drone for airborne survey

ACKNOWLEDGMENTS: FUNDING & DATA

Many thanks to CLPX, NoSREx, SnowEx and other field teams

QUESTIONS?


ADDITIONAL SLIDES
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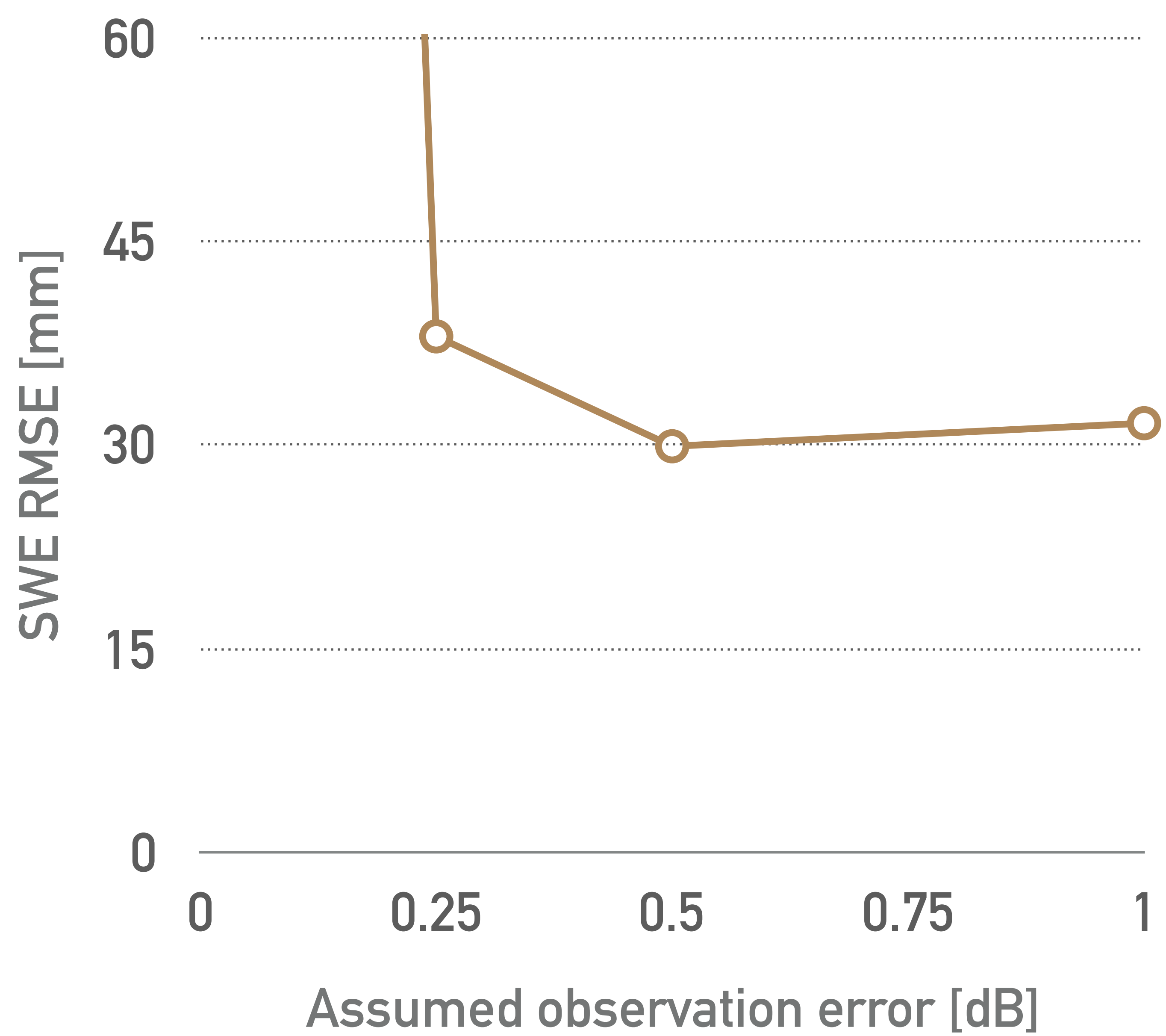
CLIMATE RESEARCH CENTER

BASE-R VALIDATION: OBSERVATION & MODEL ERROR

- Lowering assumed observation+model error too far leads to unrealistic results
- We suspect MEMLS3&a precision is around 0.5 dB
- Searching for a more precise model, including one that handles co-pol

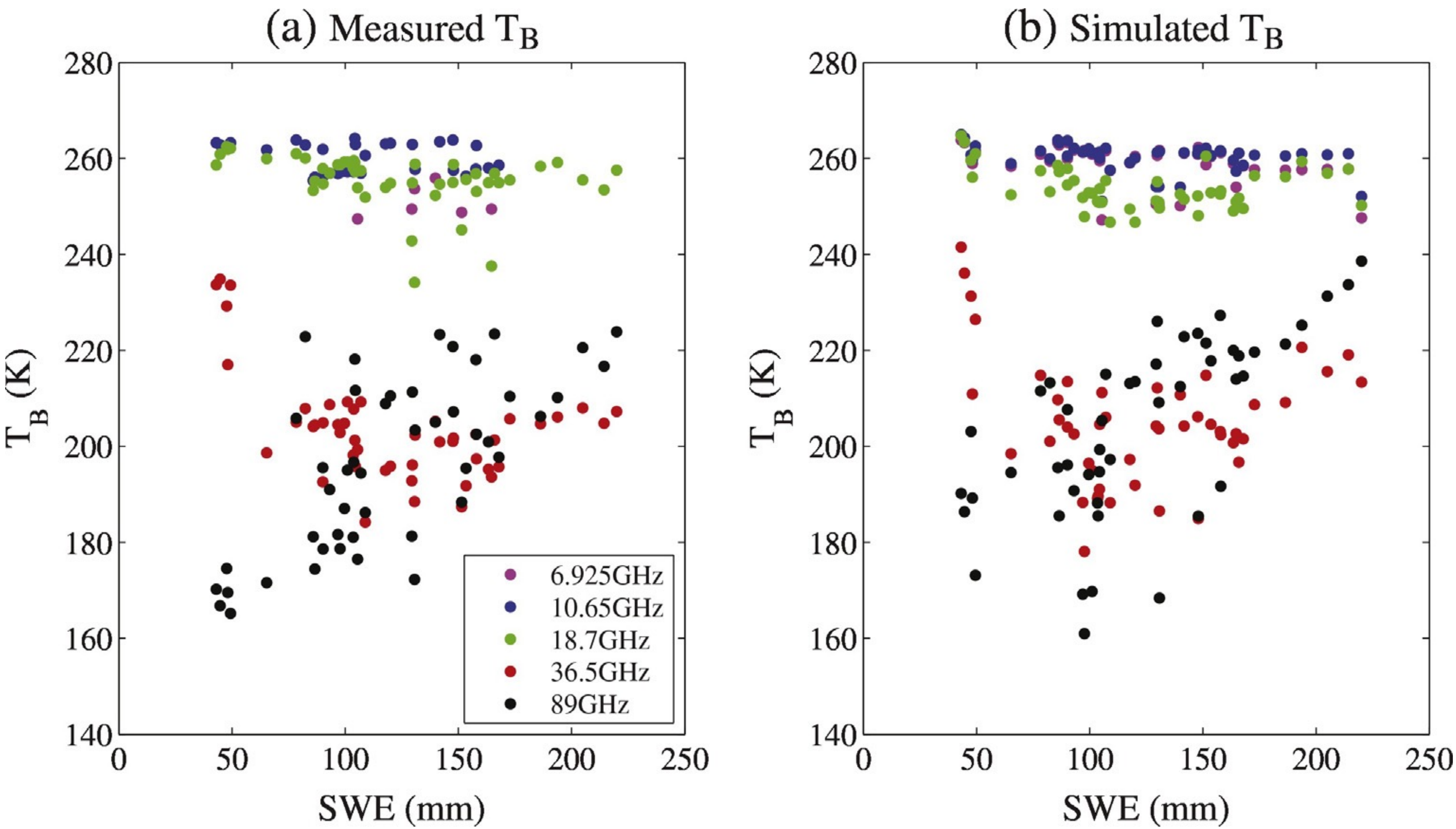
Not shown: estimate explodes (310 mm error) when error assumed to be .1 dB



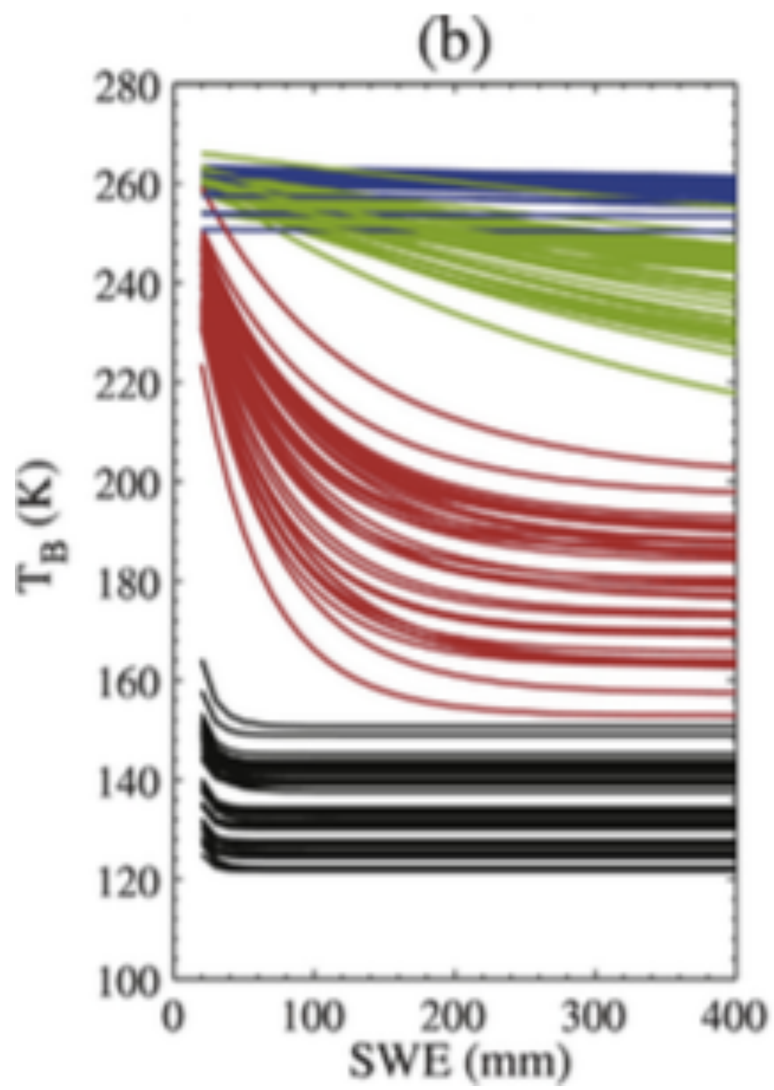
SATURATION (1/4)

- Sometimes, what is implied by “saturation” is that after a given depth, all snow of the same depth has the same radiometric signature
- In that way of thinking, retrieval algorithms cannot function past a saturation depth.
- However, it is simply not true that deep snow all has the same radiometric signature.
- Changes in depth and grain size lead to changes in microwave radiance regardless of depth

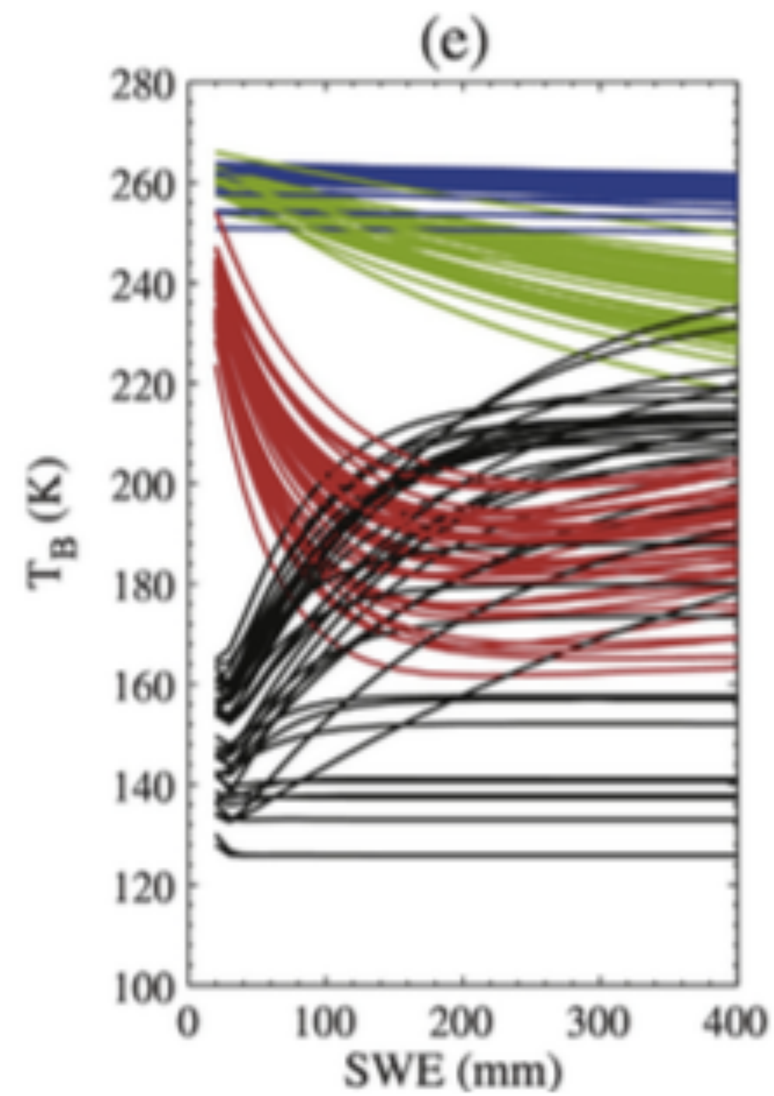
SATURATION (2/4): DATA FROM SODANKYLA



REVISITING SATURATION (3/4)



One layer models "saturate"; they converge to a steady state value as SWE increases



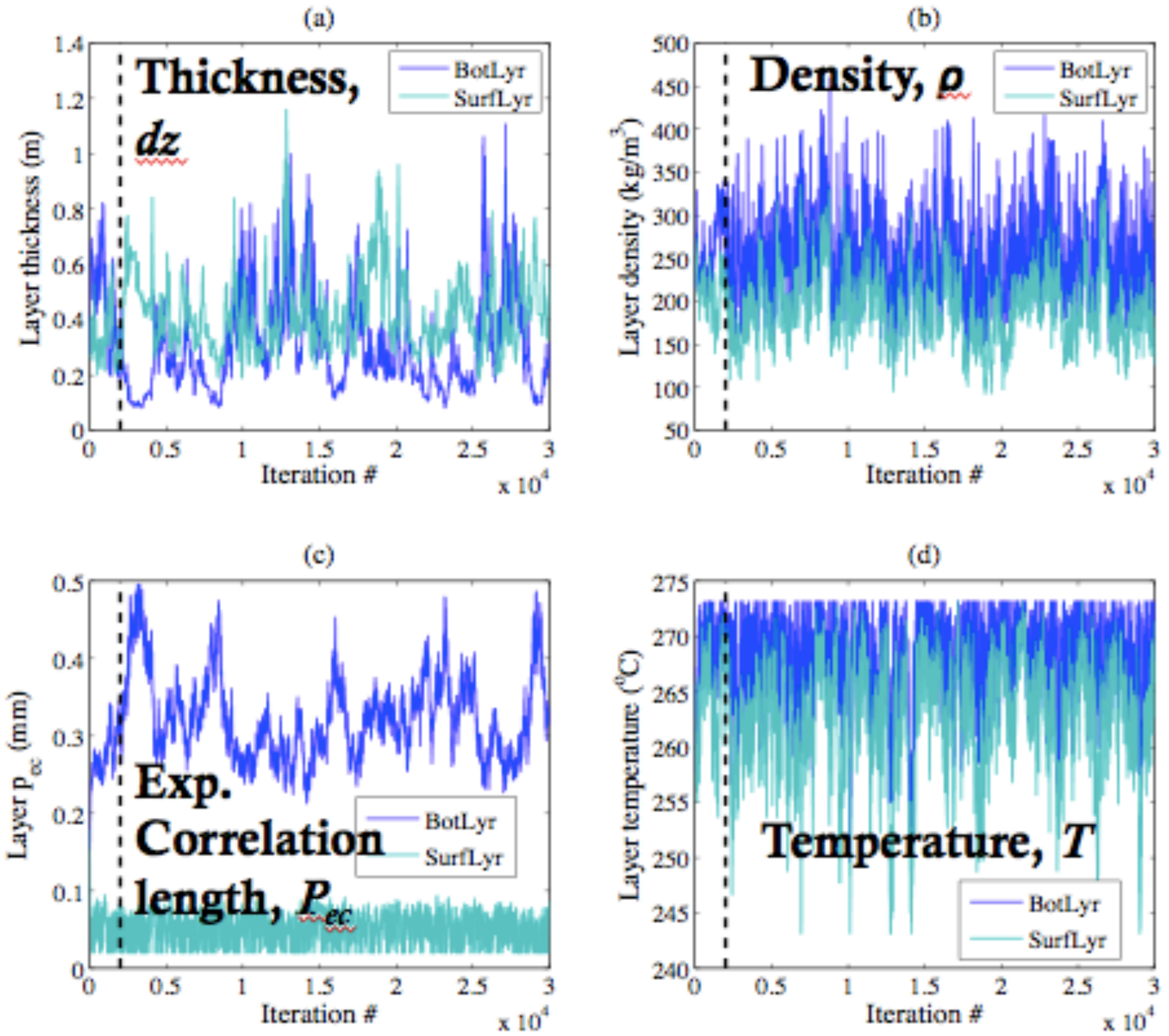
Multi-layer models do not: many studies have noted this. The retrieval is complicated for deep snow, of course!

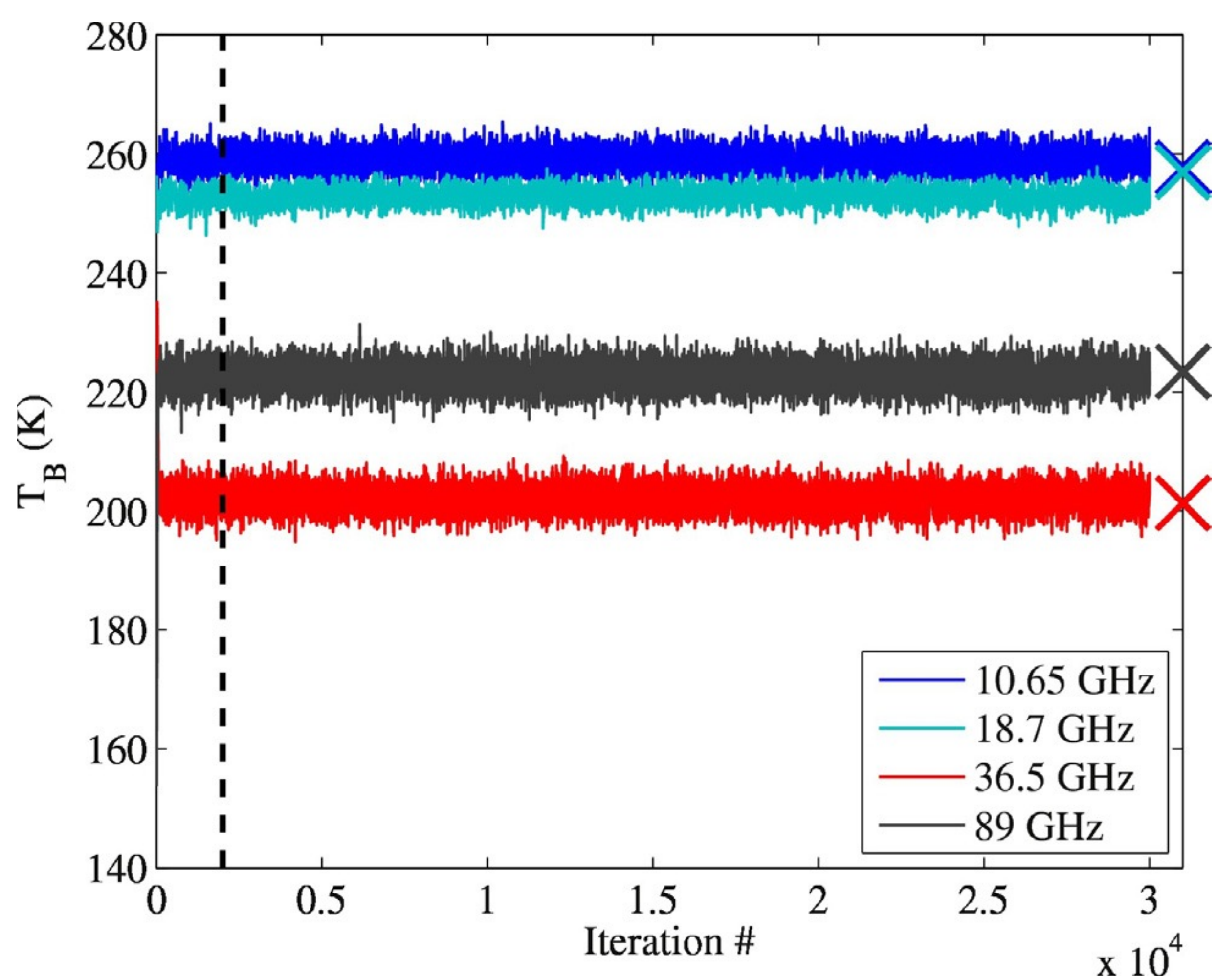
REVISITING SATURATION (4/4)

- How can SWE be retrieved for deep snow in Li et al. (2017)?

1. Due to stratigraphy and vertical grain size variability, saturation only truly applies to a vertically-uniform snowpack. Vertical uniformity rare, especially for deep snow
2. As snow gets deeper, snow-microwave relationships become more complex, however, meaning you need more prior information (i.e. radiance assimilation) for deep snow
3. Li et al. model precipitation bias as a constant*: no storm-to-storm error variability. Thus information early in the year helps correct SWE late in the year.
4. Sub-footprint SWE variability at satellite scale: some parts of the footprint are deeper than others

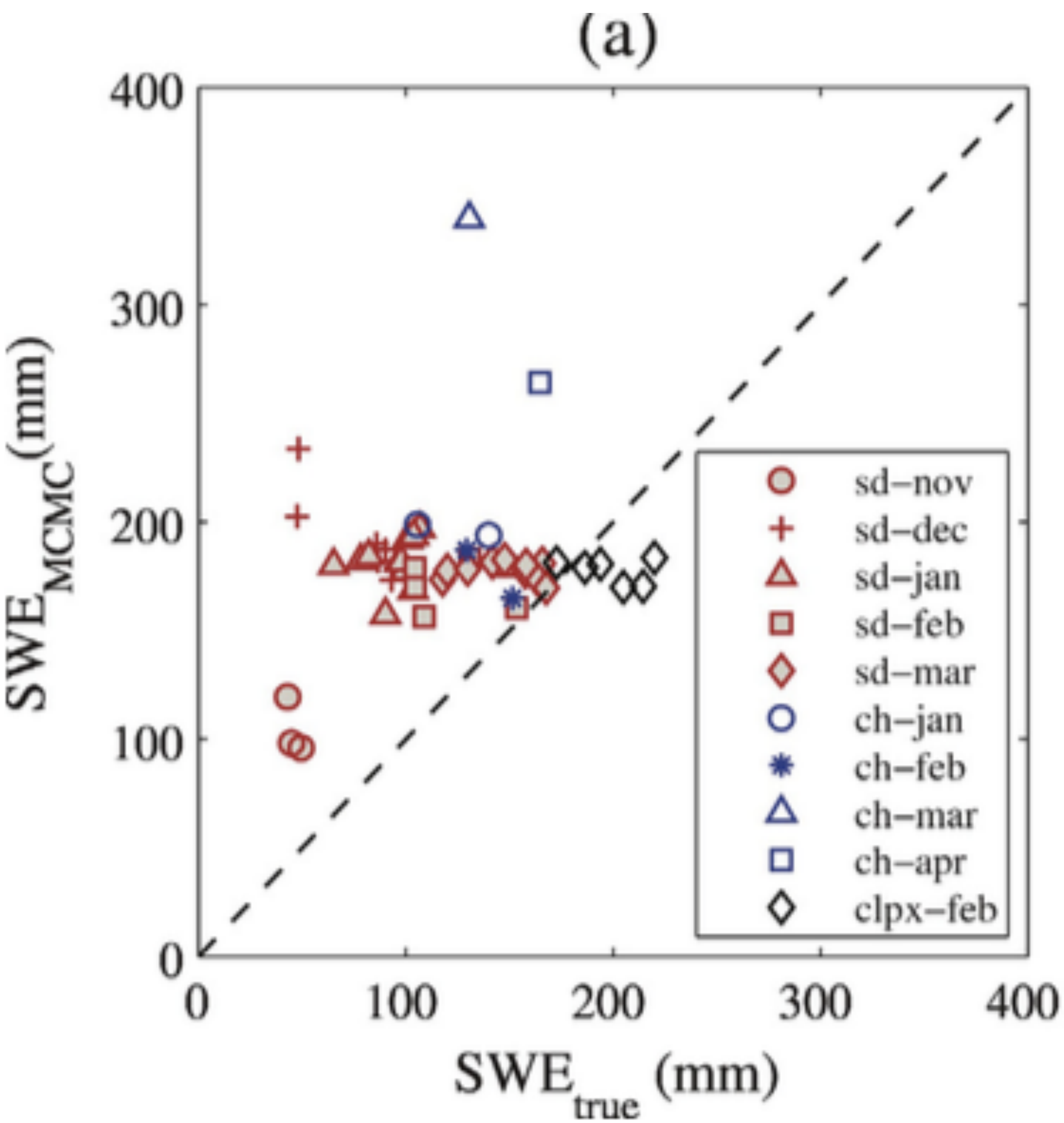
EQUIFINALITY & RETRIEVAL

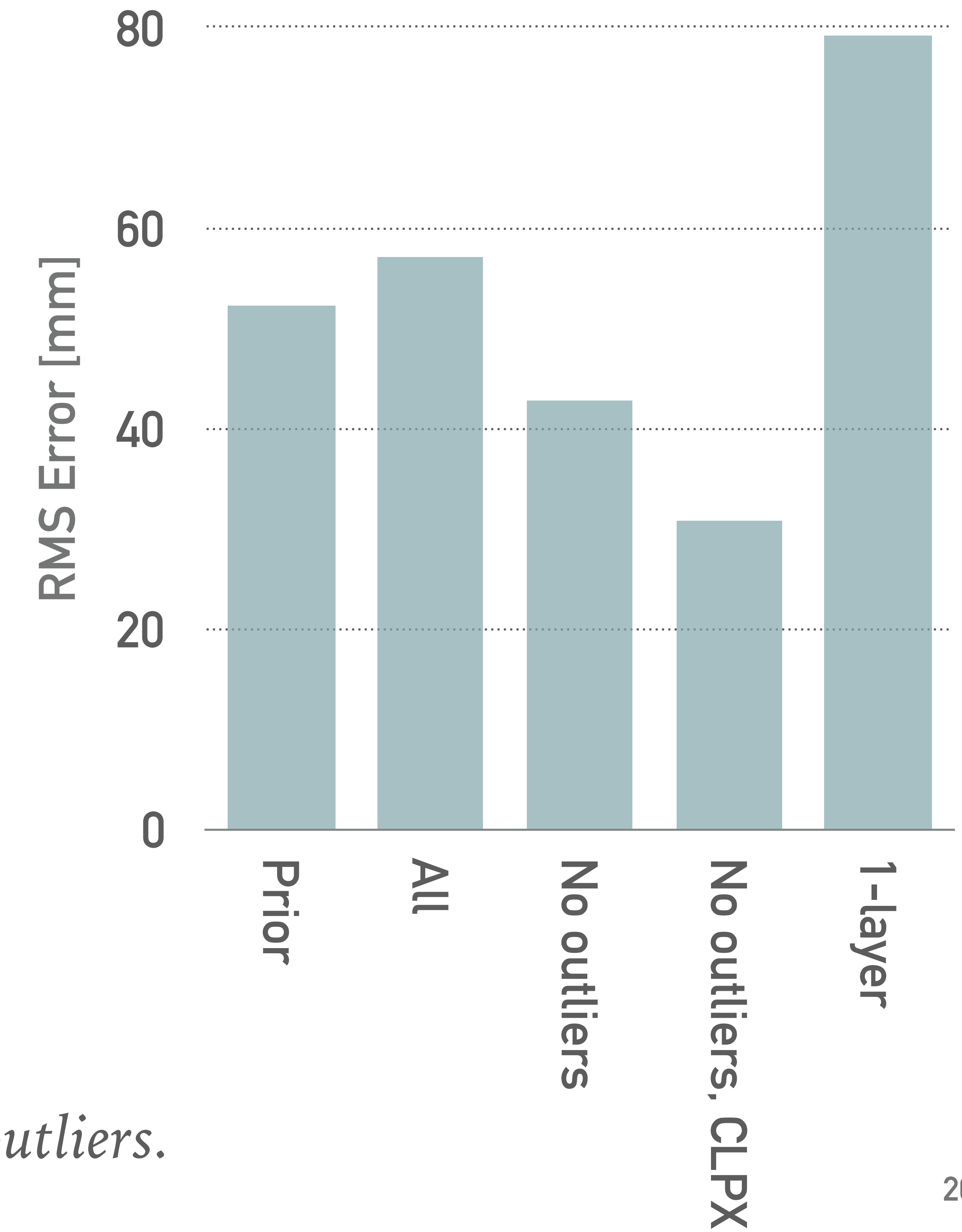




BASE-PM: EFFECT OF STRATIGRAPHY

Pan et al., 2017





1-layer RMSE excludes two Churchill outliers.