# 3D characteristics of snow bands and implications for surface snowfall in Northeast Winter Storms


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NC STATE UNIVERSITY

# Terminology

- Use term “snow” for precipitation-sized ice particle that is large enough to fall in still air
  - Distinct from cloud-sized ice
  - “age of snow” - time since snow particle first attained precipitation-size

- “microphysical pathway” sequence of d(mass)/dt changes a snow particle undergoes as a function of the sequence of environments it falls through along its path through the storm

# Big picture takeaways from multi-year winter storm observations

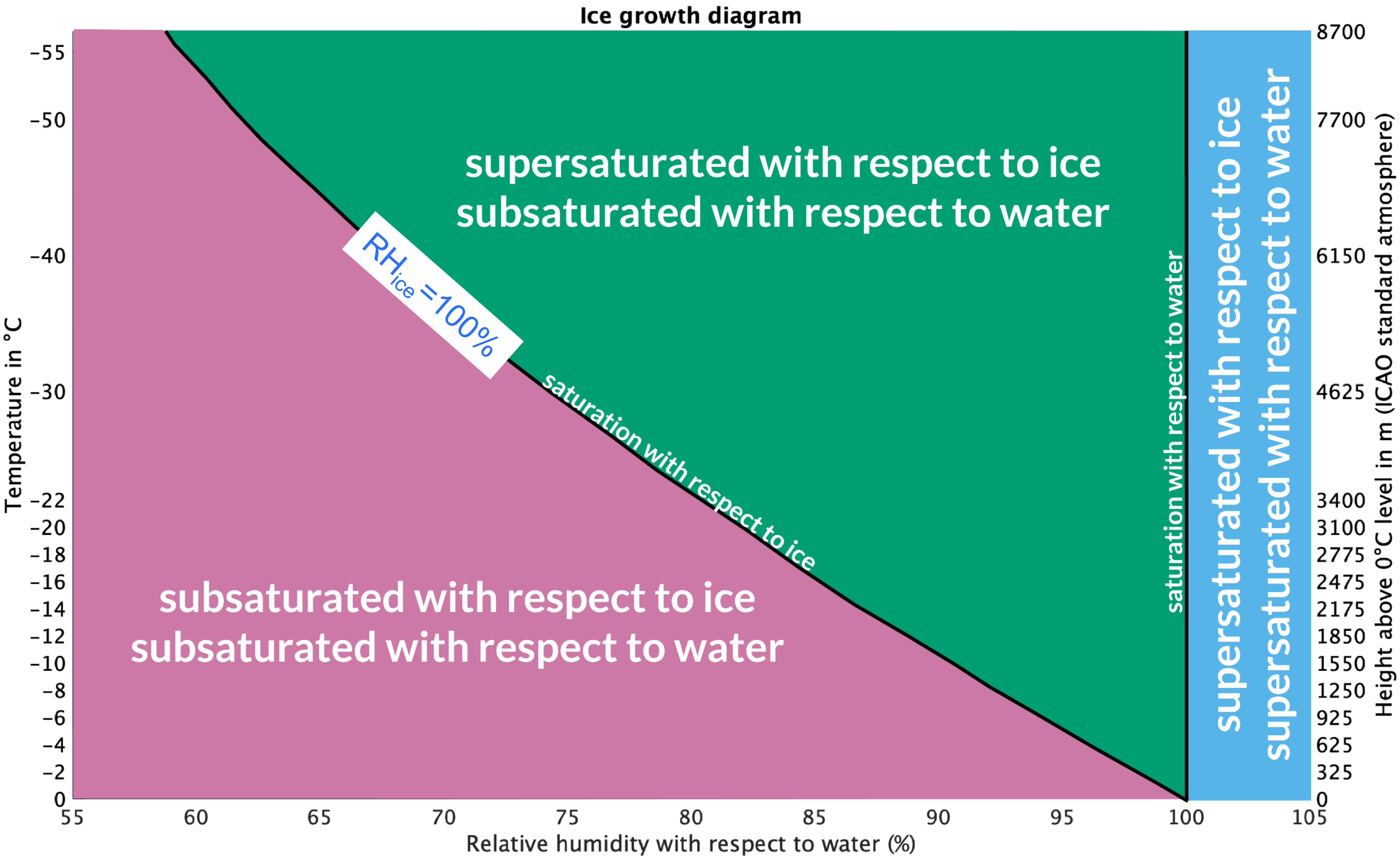
## Low correlation between enhanced Z in “snow bands” detected on regional scanning radar and hourly surface snow rates

**Usually observe coincident mixtures of snow particle shapes and degrees of riming**

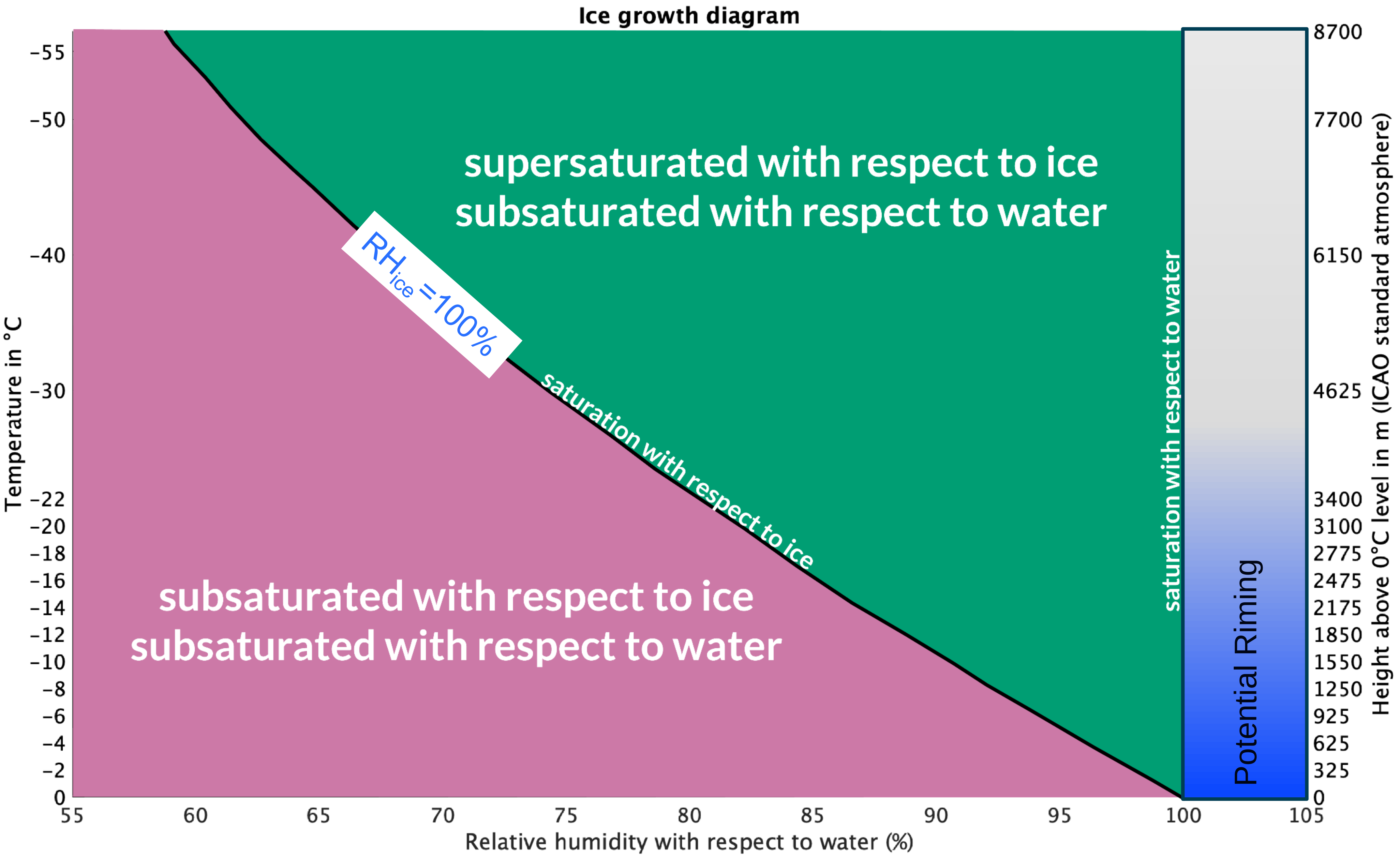
- Mixtures yield varying distributions of shapes, sizes, and densities in the same volume which complicate interpretations and retrievals of snow rate

**In the 1-2 hours that it takes a precipitation-sized ice particle to fall from near cloud top to the surface, 3d ice streamers originating in generating cells are tilted and smeared**

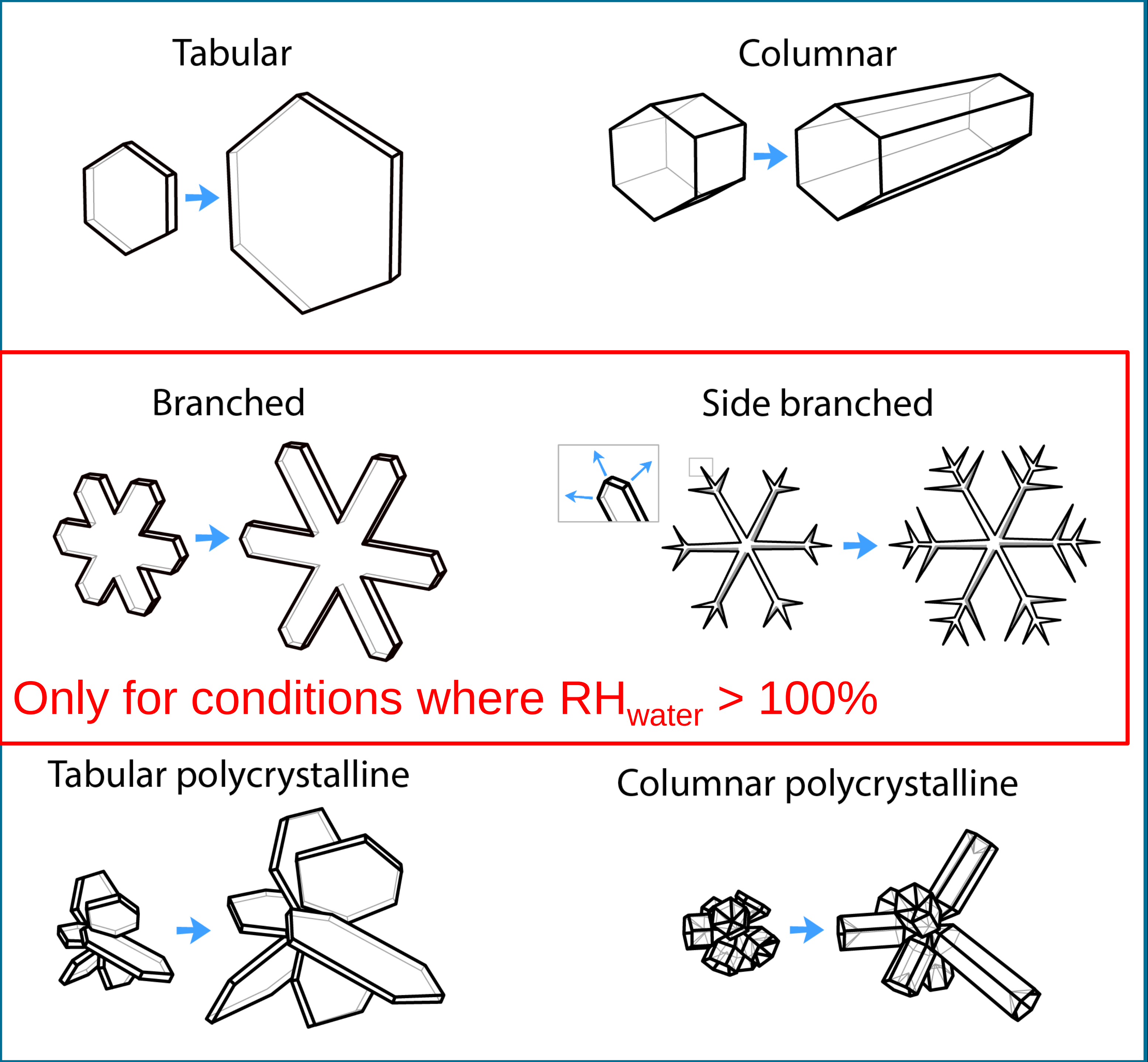
- Lack of vertical column continuity in local enhancements in radar Z




Hueholt et al. (2022)




Hueholt et al. (2022)



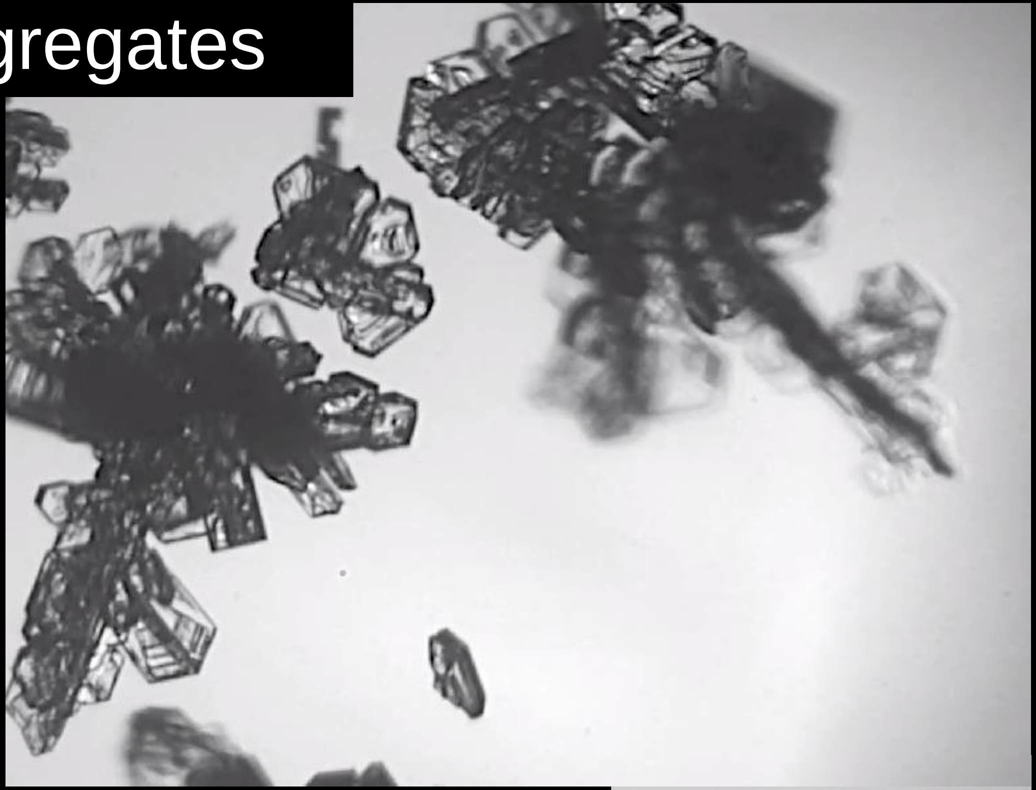

# Ice growth forms

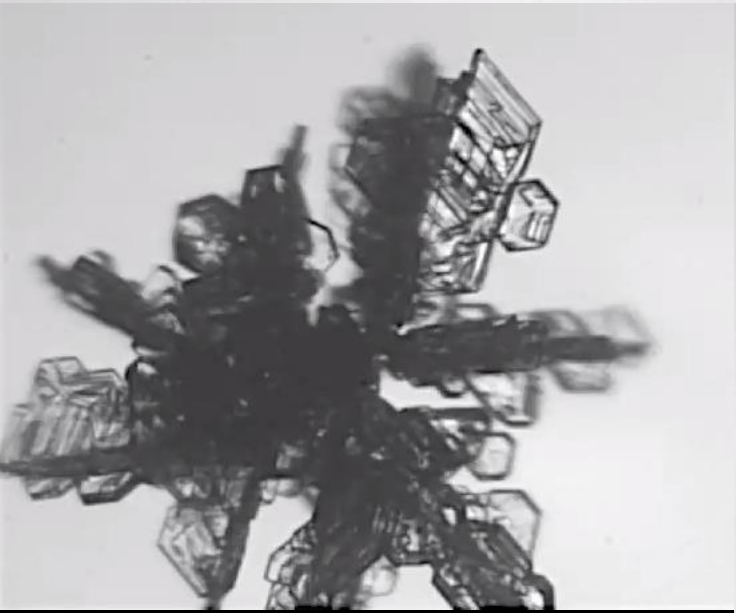
Ice growth form depends on air temperature **and** vapor content of air.

As particles fall and temperature and vapor content of environmental air changes, growth type can change.

Hueholt et al. (2022, BAMS)

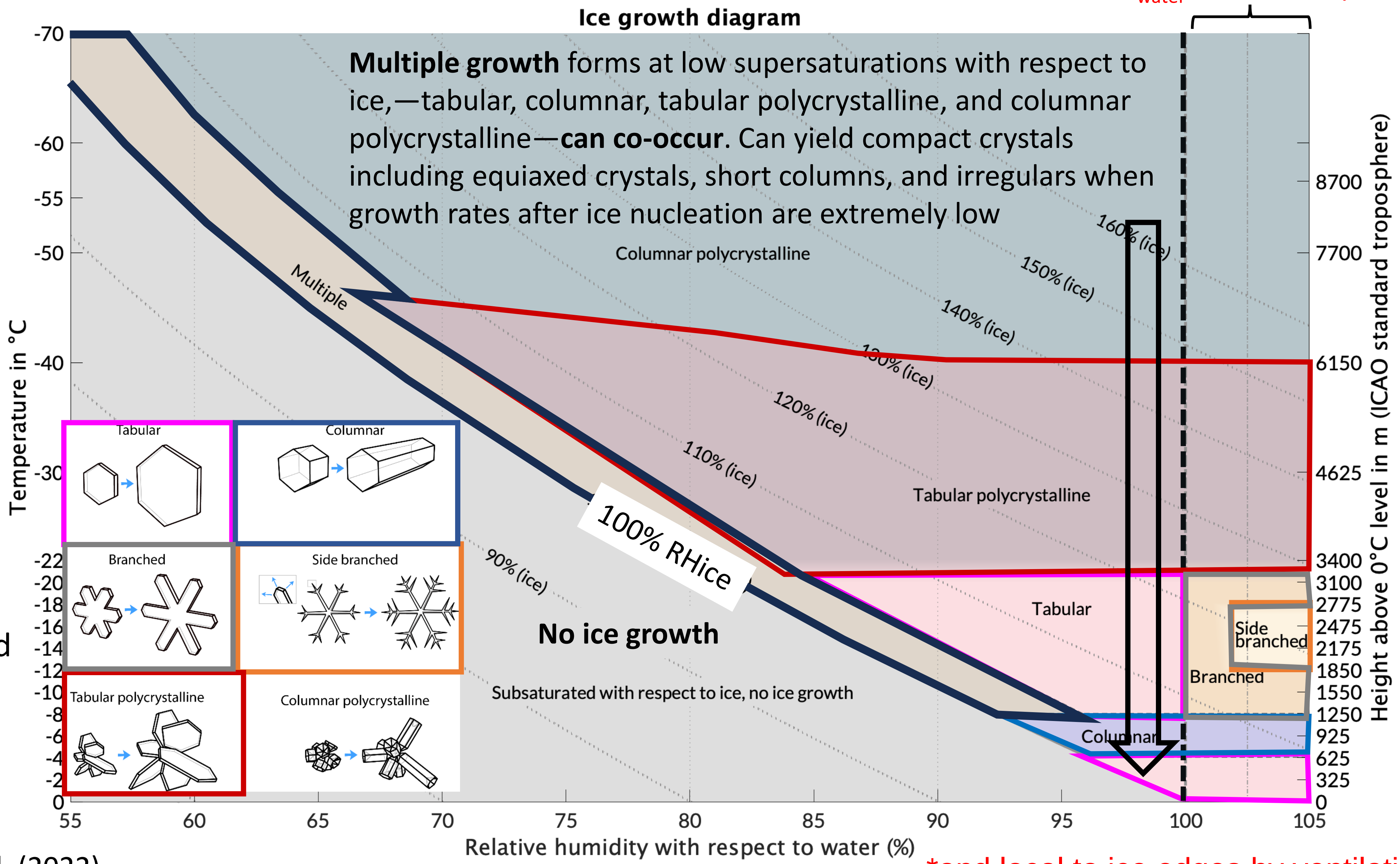
# Polycrystaline natural ice, Polycrystals ≠ Aggregates





PHIPS images courtesy of M. Schnaiter, KIT

Ambient $RH_{water}$ > 100% in updrafts*

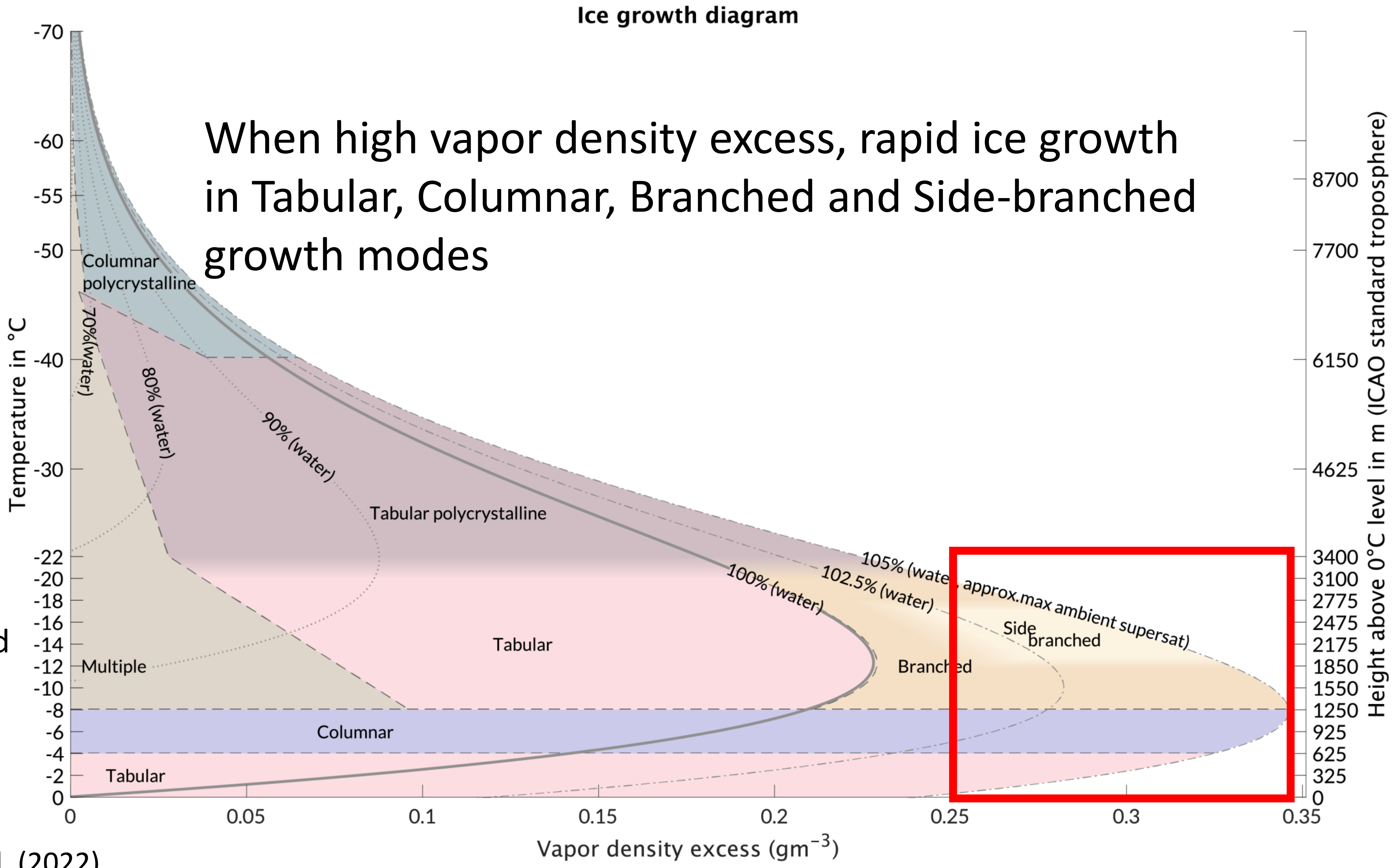



Revisualized diagram based on established science

Hueholt et al. (2022)

*and local to ice edges by ventilation

When high vapor density excess, rapid ice growth in Tabular, Columnar, Branched and Side-branched growth modes

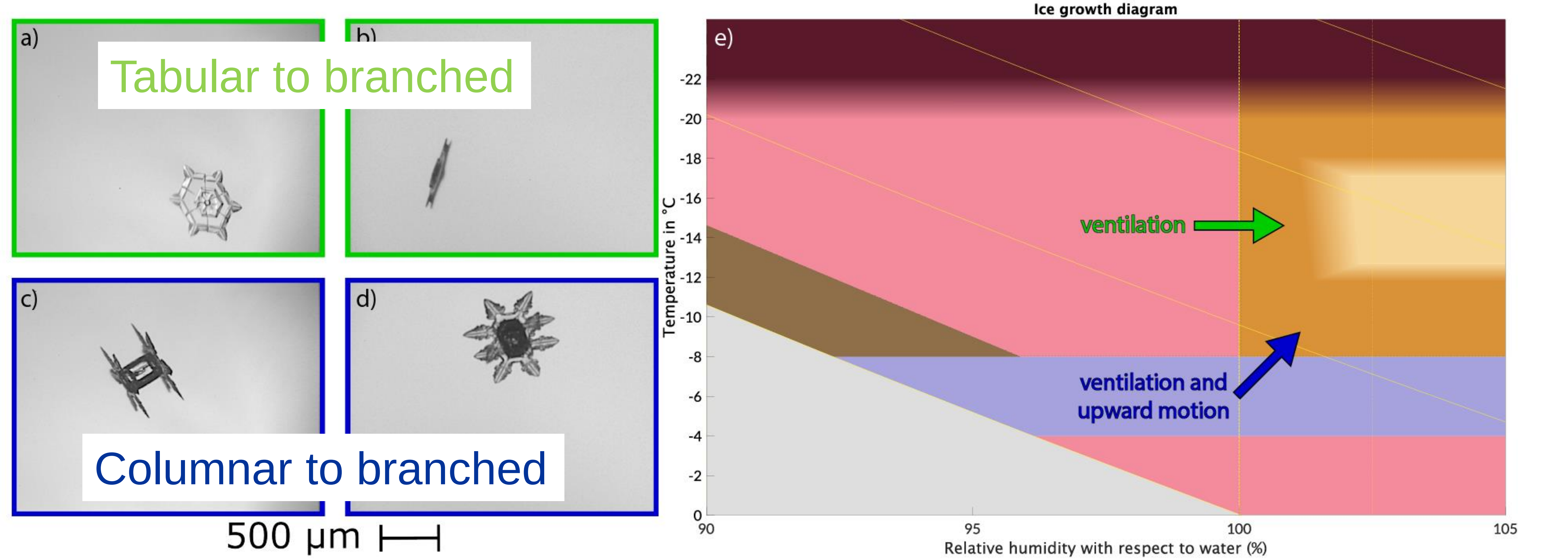



Revisualized diagram based on established science

Hueholt et al. (2022)

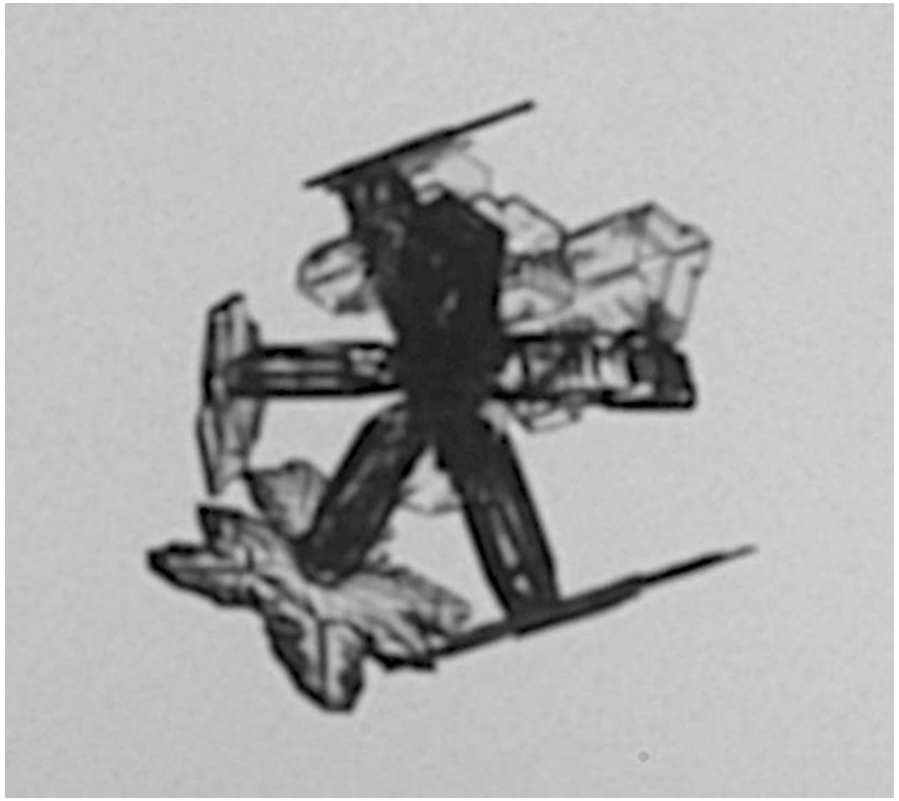
# Often get sequences of ice growth in different environments

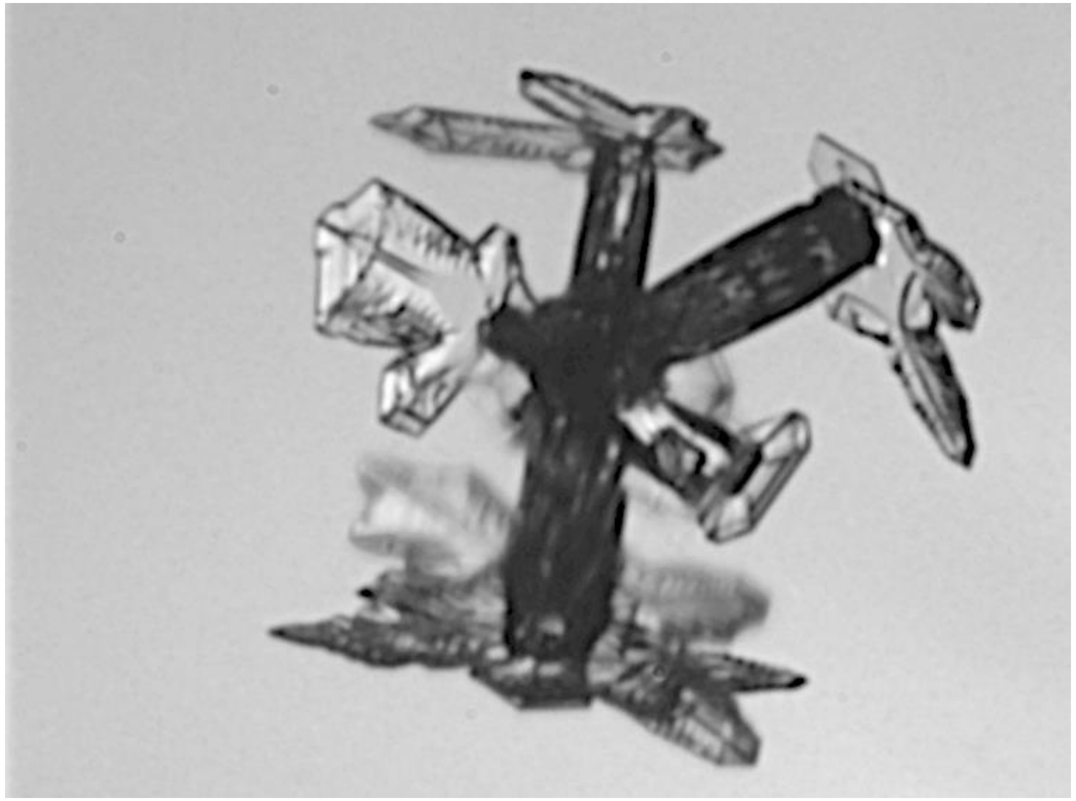
Same color outlines two views of the same particle




Hueholt et al. (2022)

# Sequential growth as particle falls to surface can yield complex 3D particles



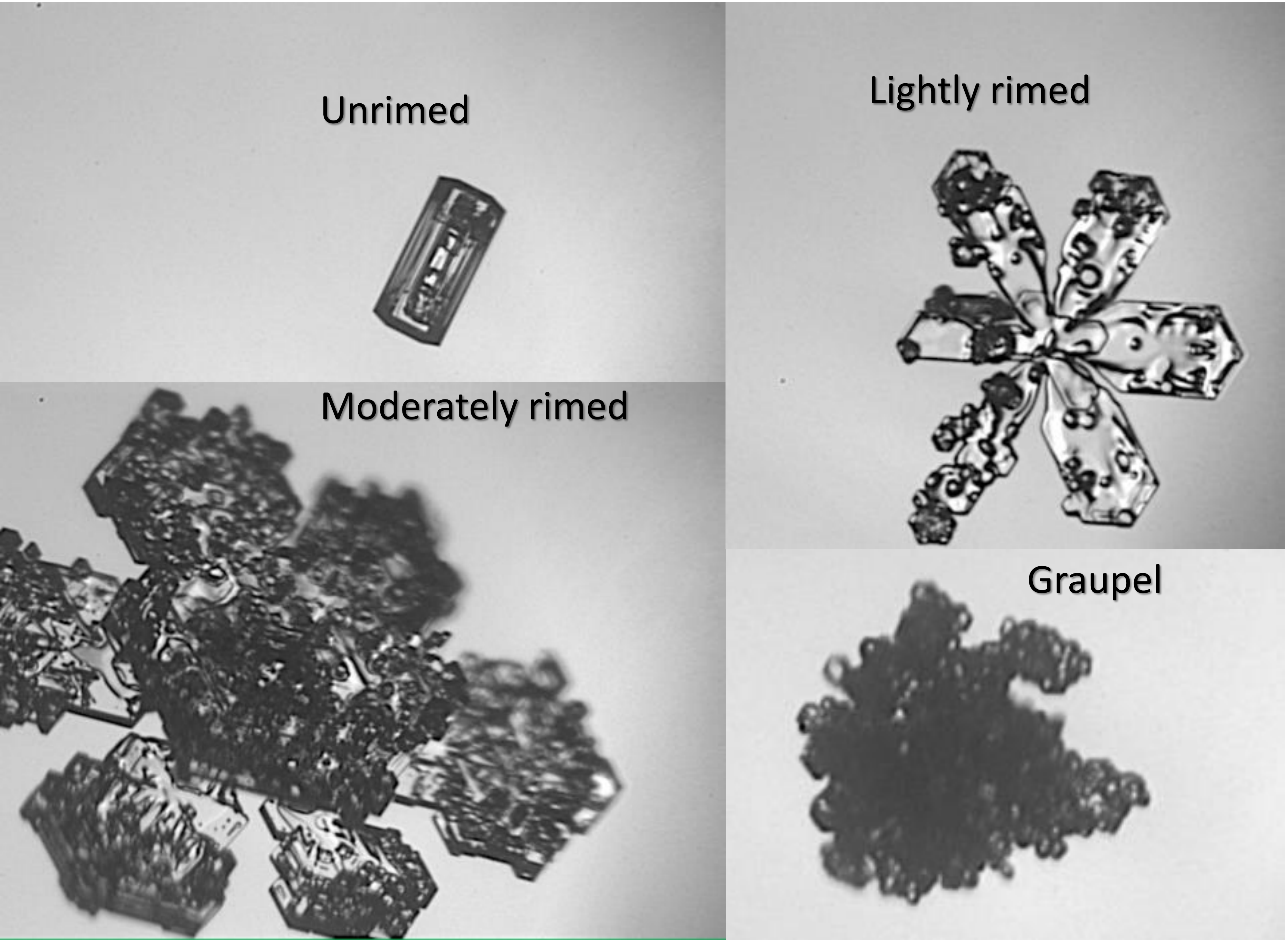


NASA IMPACTS PHIPS images,

2 views of the same particle

initial columnar polycrystalline growth followed by tabular growth then branched growth

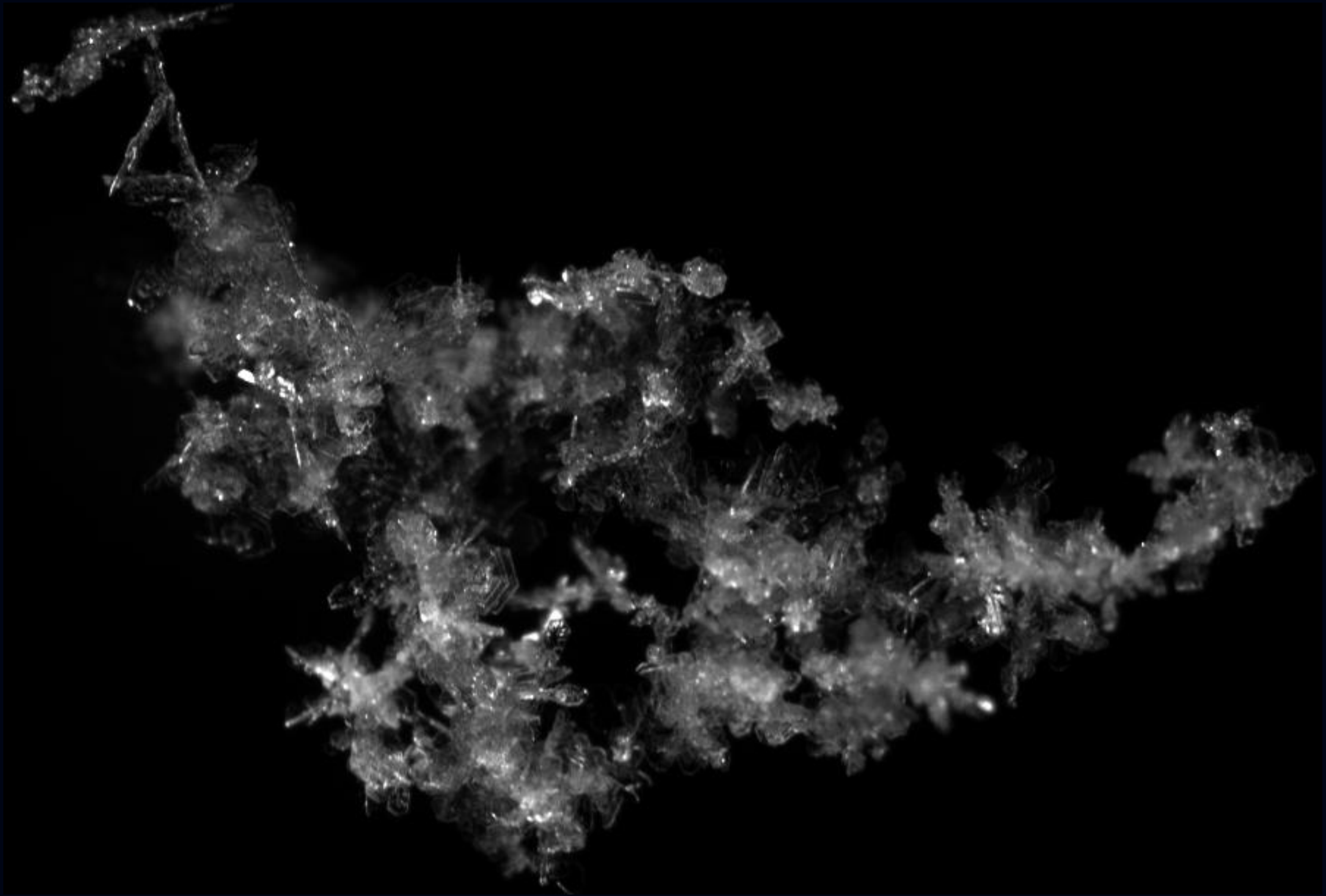
# Different degrees of riming




NASA IMPACTS field project
PHIPS data (Schnaiter)

# Graupel


Surface Observations from Multi-Angle Snowflake Camera (NCSU)



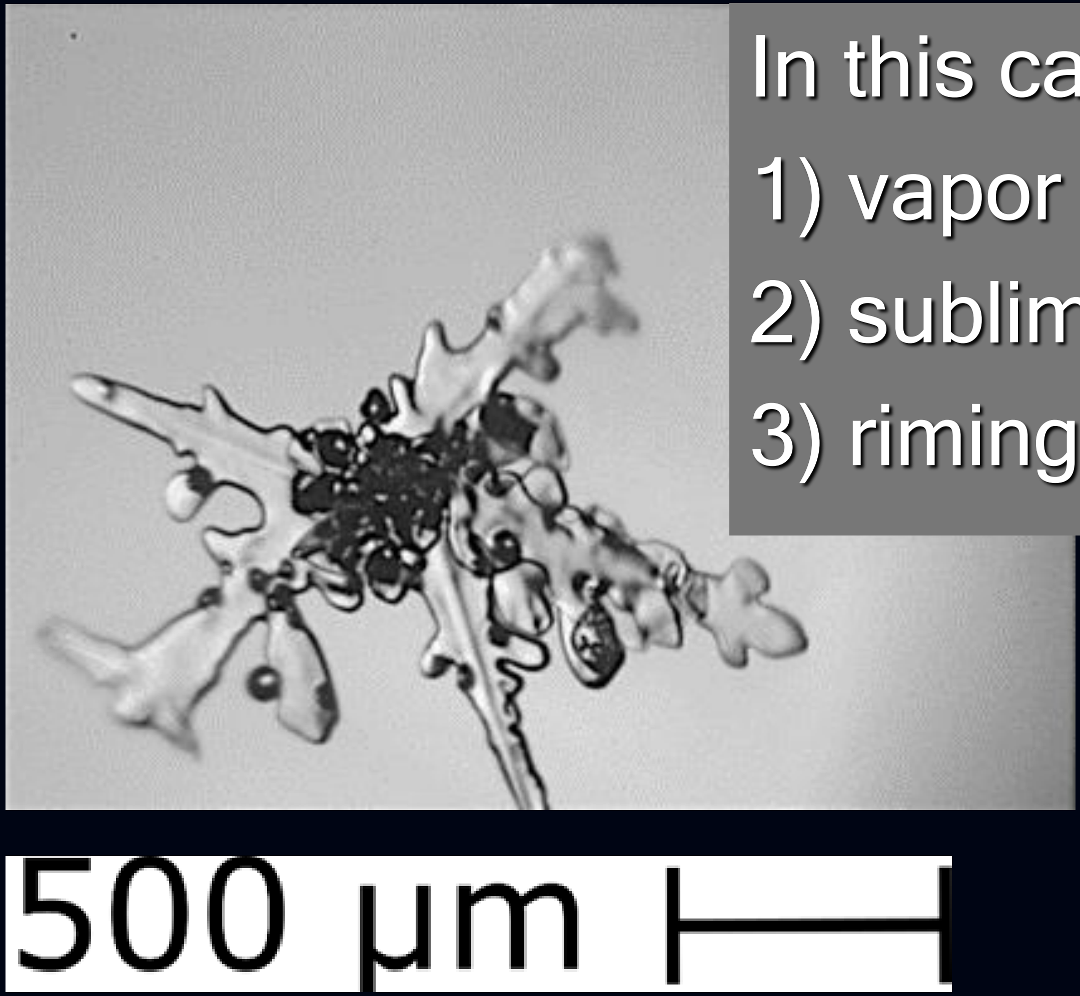
Aggregation- collection of ice particles > 0.2 mm diameter, yields jumbles of multiple individual ice particles called aggregates)

Often includes ice particles with different shapes

2015 01 24 07 42 00, max diameter 17.8 mm, fall speed 1.33 m/s

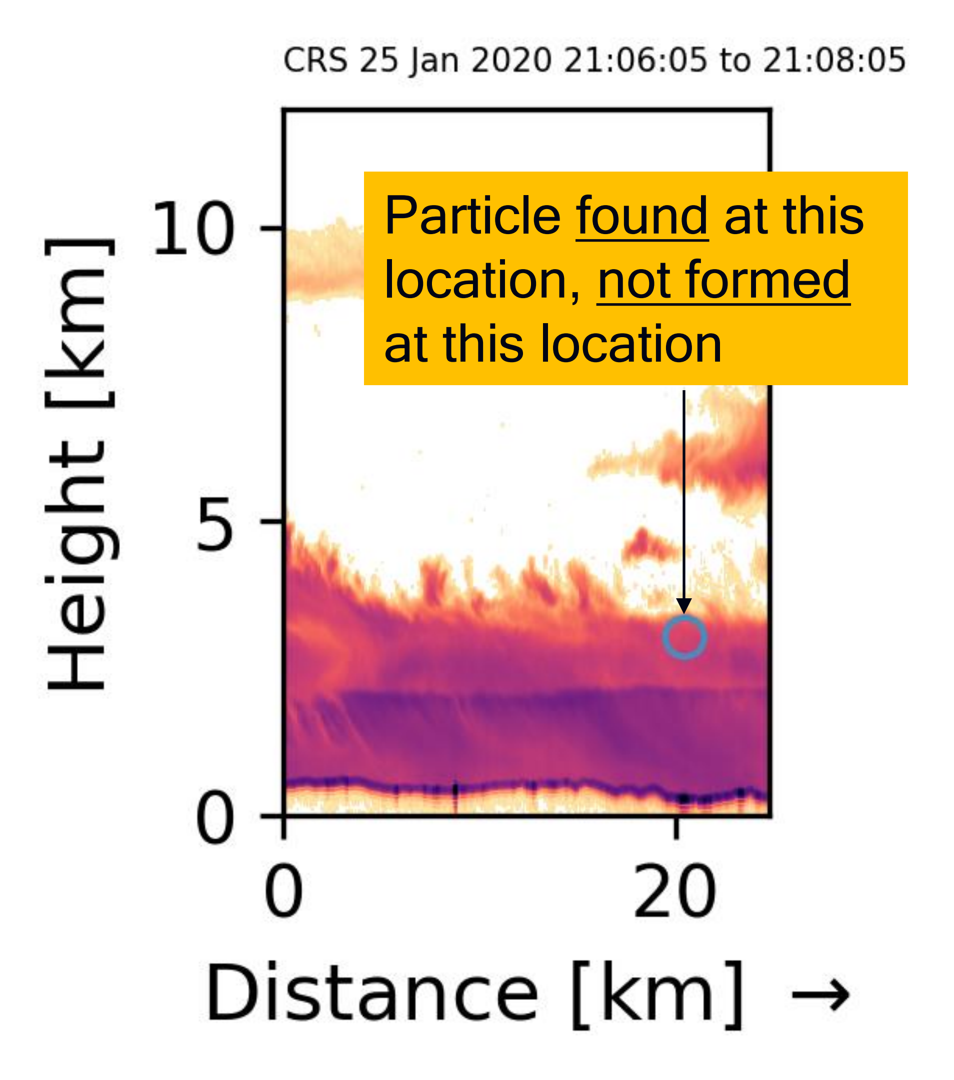
# Time-integrated state of individual snow particles

## --everything that happened to particle prior to observation



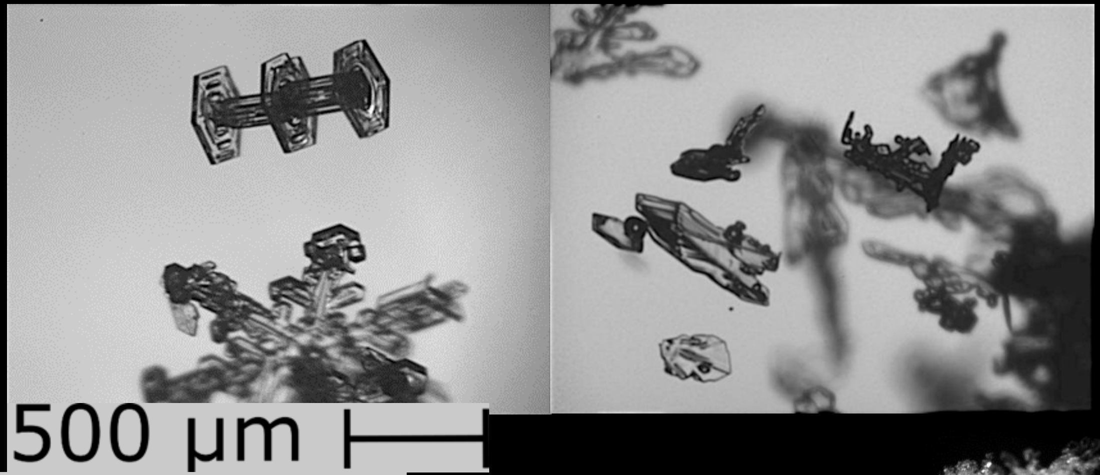

In this case,

1) vapor deposition
2) sublimation
3) riming

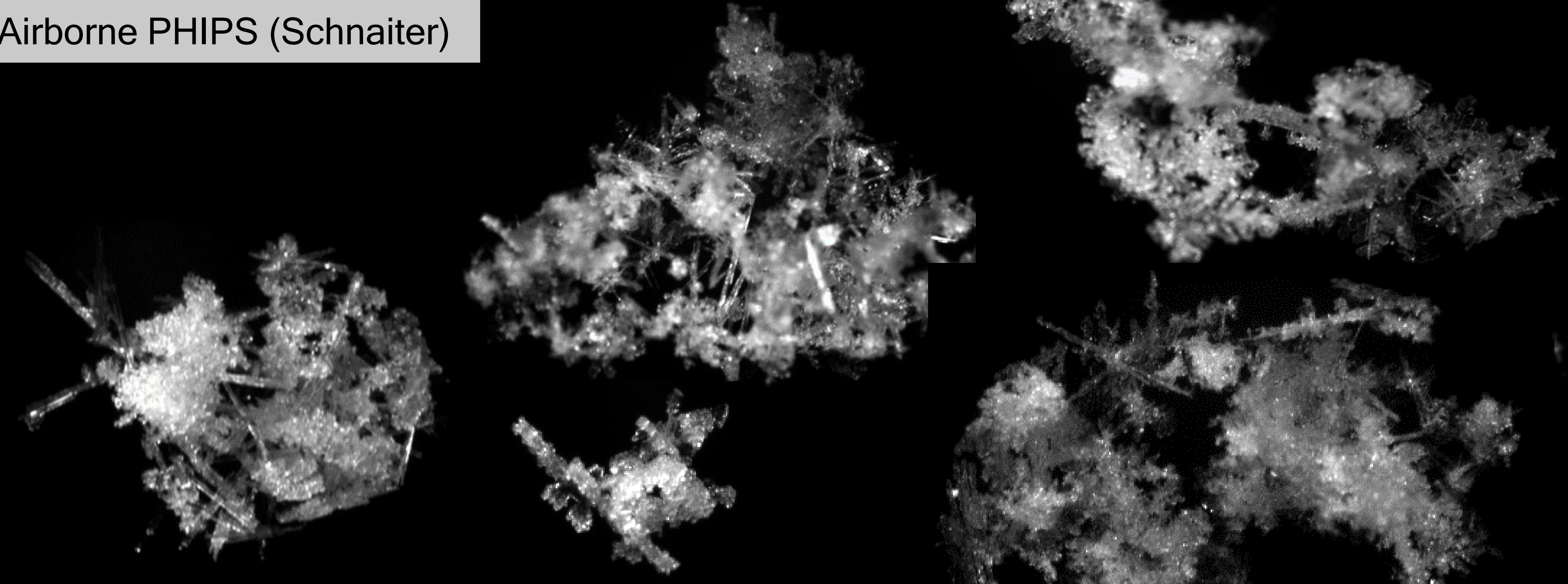


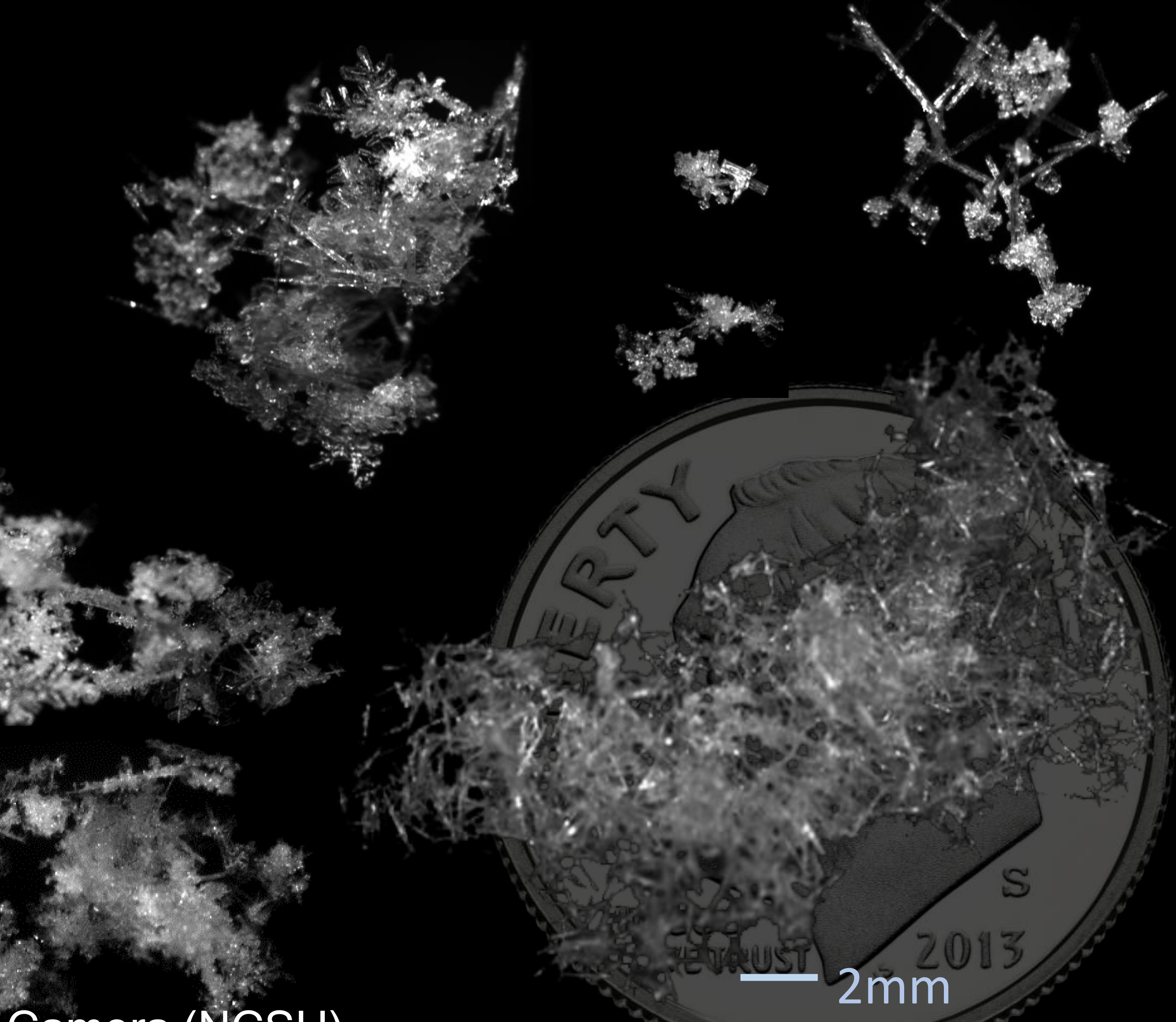

NASA IMPACTS field program PHIPS particle image (Schnaiter) and ER-2 Cloud Radar (McLinden, Li)

# Time-integrated state of set of particles that end up in the same volume--Snow particles that initially formed separately often get mixed together



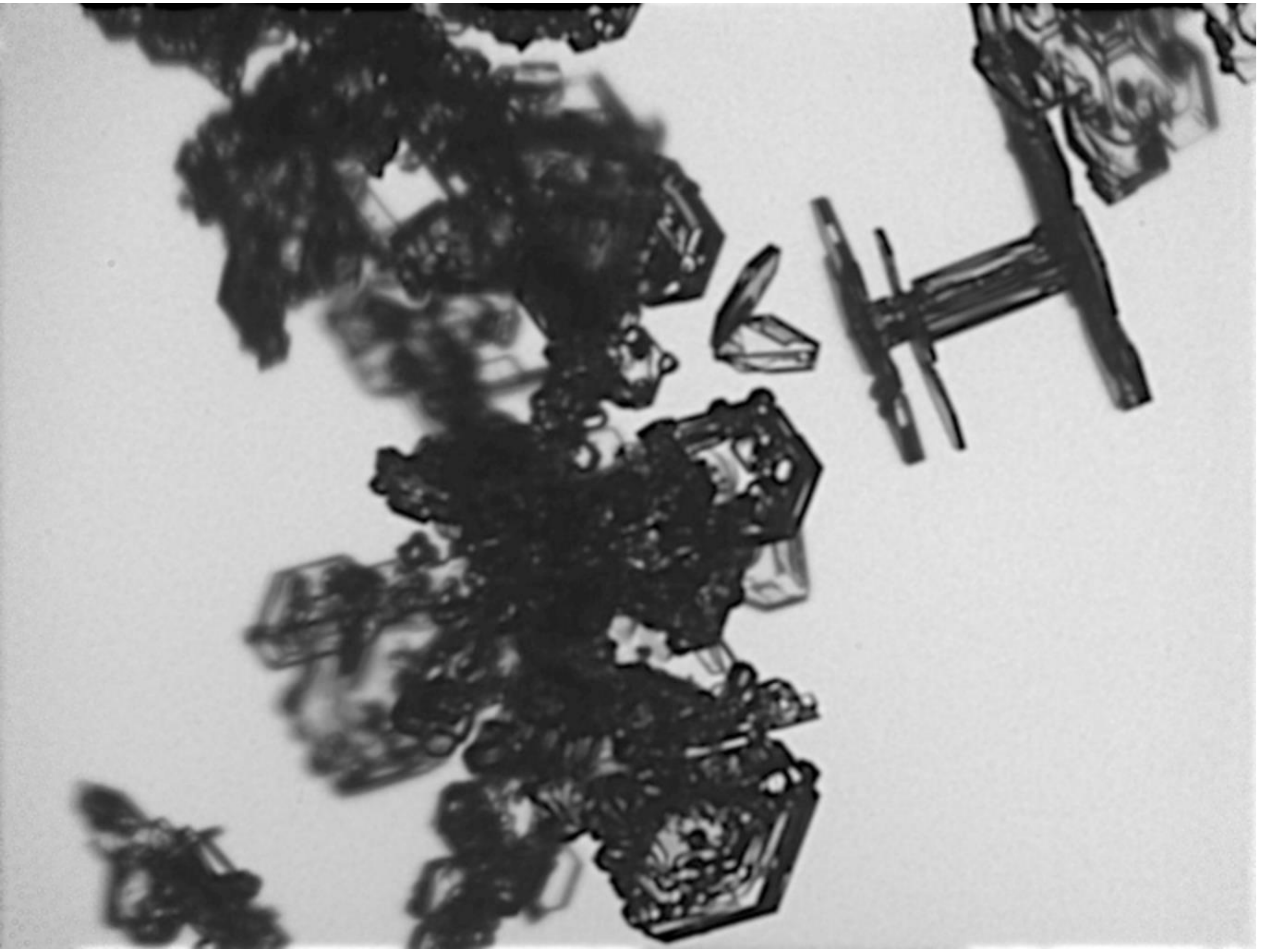

Airborne PHIPS (Schnaiter)



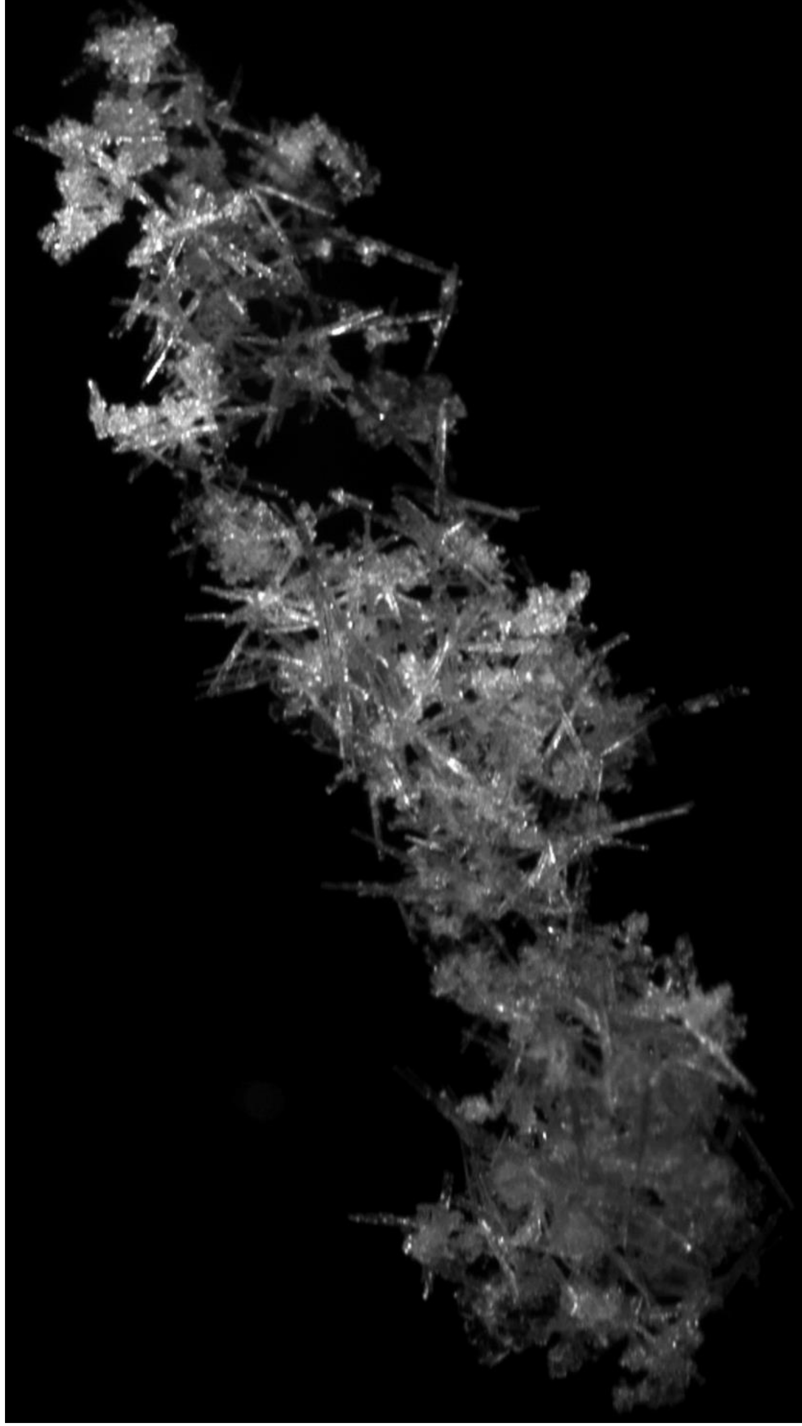



Surface Observations from Multi-Angle Snowflake Camera (NCSU)

# Particles with different shapes and degrees of riming often co-occur in the same volume

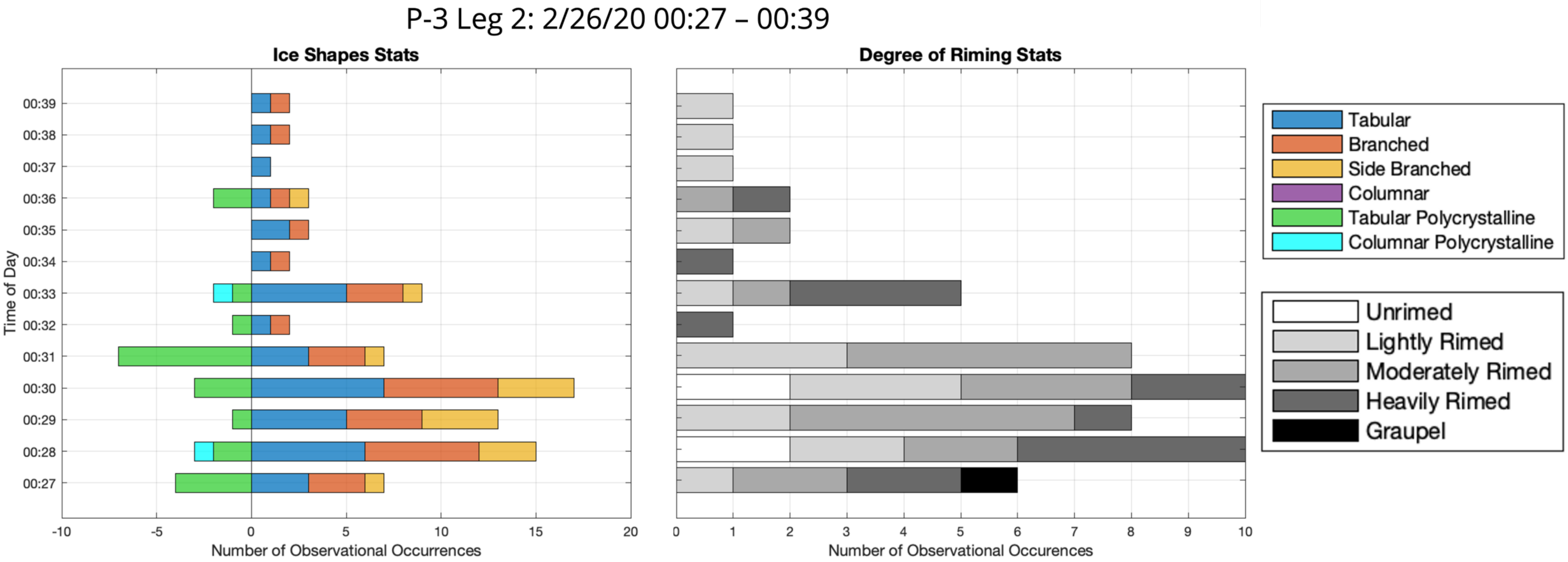


Airborne PHIPS (Schnaiter)



Surface snowflake camera (NCSU)

# Mixtures of shapes and degree of riming based on airborne PHIPS ice particle images, minute by minute

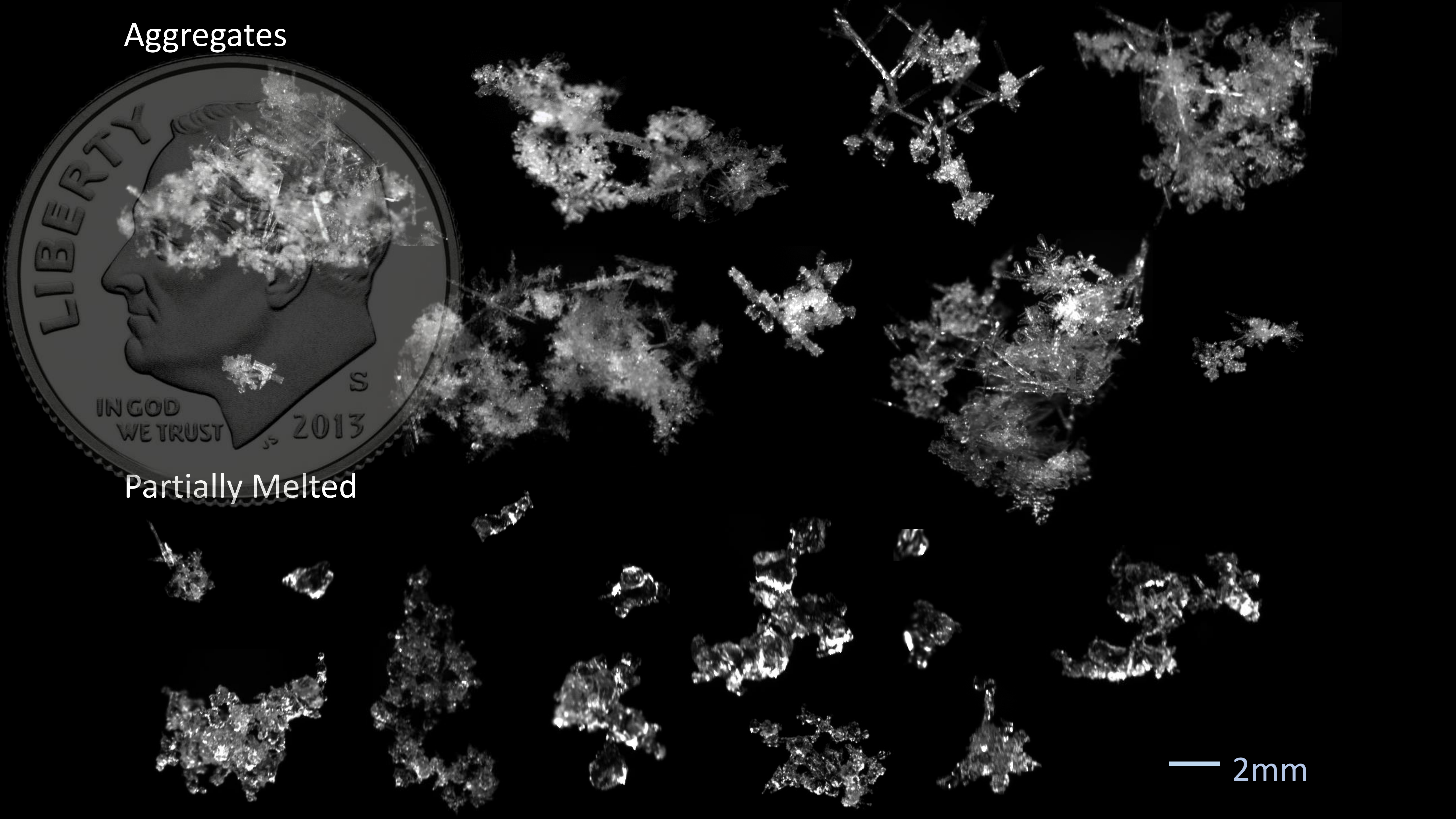



Near cloud-top flight leg sample for NASA P-3 closely coordinated with NASA ER-2

# Processes that change reflectivity (Z)

In snow, changes in Z do not necessarily mean changes in mass per unit volume

| Process | Change to IWC/LWC | Change to radar reflectivity |
|---|---|---|
| Riming | **Increase** | **Increase** |
| Vapor Deposition | **Increase** | **Increase** |
| Collision-Coalescence | **Increase** | **Increase** |
| Condensation | **Increase** | **Increase** |
| Aggregation | *No change* | **Increase** |
| Melting | *No change* | **Increase** |
| Evaporation | **Decrease** | **Decrease** |
| Sublimation | **Decrease** | **Decrease** |
| Freezing | *No change* | **Decrease** |
| Fragmentation | *No change* | **Decrease** |
| Raindrop Breakup | *No change* | **Decrease** |


Aggregates
LIBERTY
IN GOD
WE TRUST
2013
S
Partially Melted
2mm

# Mapping from volumetric water content to radar reflectivity has much larger uncertainty in snow compared to rain

| | Rain | Snow |
|---|---|---|
| **Density of individual particles** | Constant | *Varies* with degree of riming and aggregation |
| **Mass to shape relationship of individual particles** | Well defined | *Varies* depending on microphysical pathway |
| **Mass per unit volume to equivalent backscatter (shape, size, number)** | Well defined if can assume exponential-like particle size distributions | *Varies* with different mixtures of snow with different shapes, riming, and aggregation properties |

100 m scale aircraft observations from SNOWIE (Idaho) project

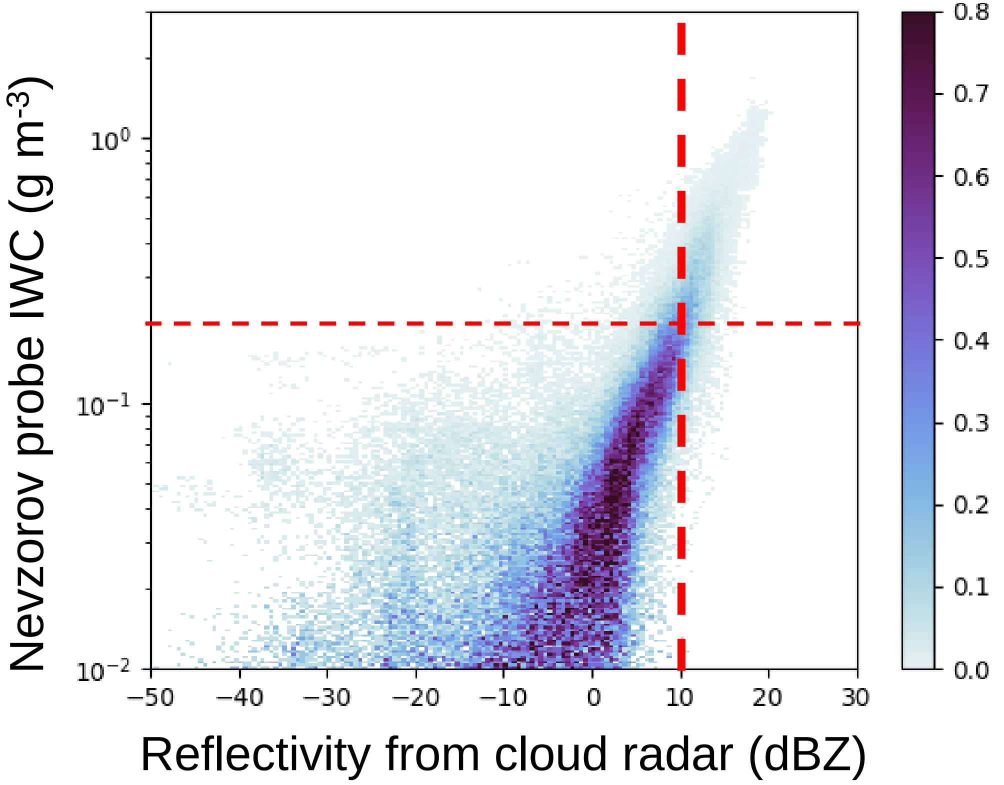
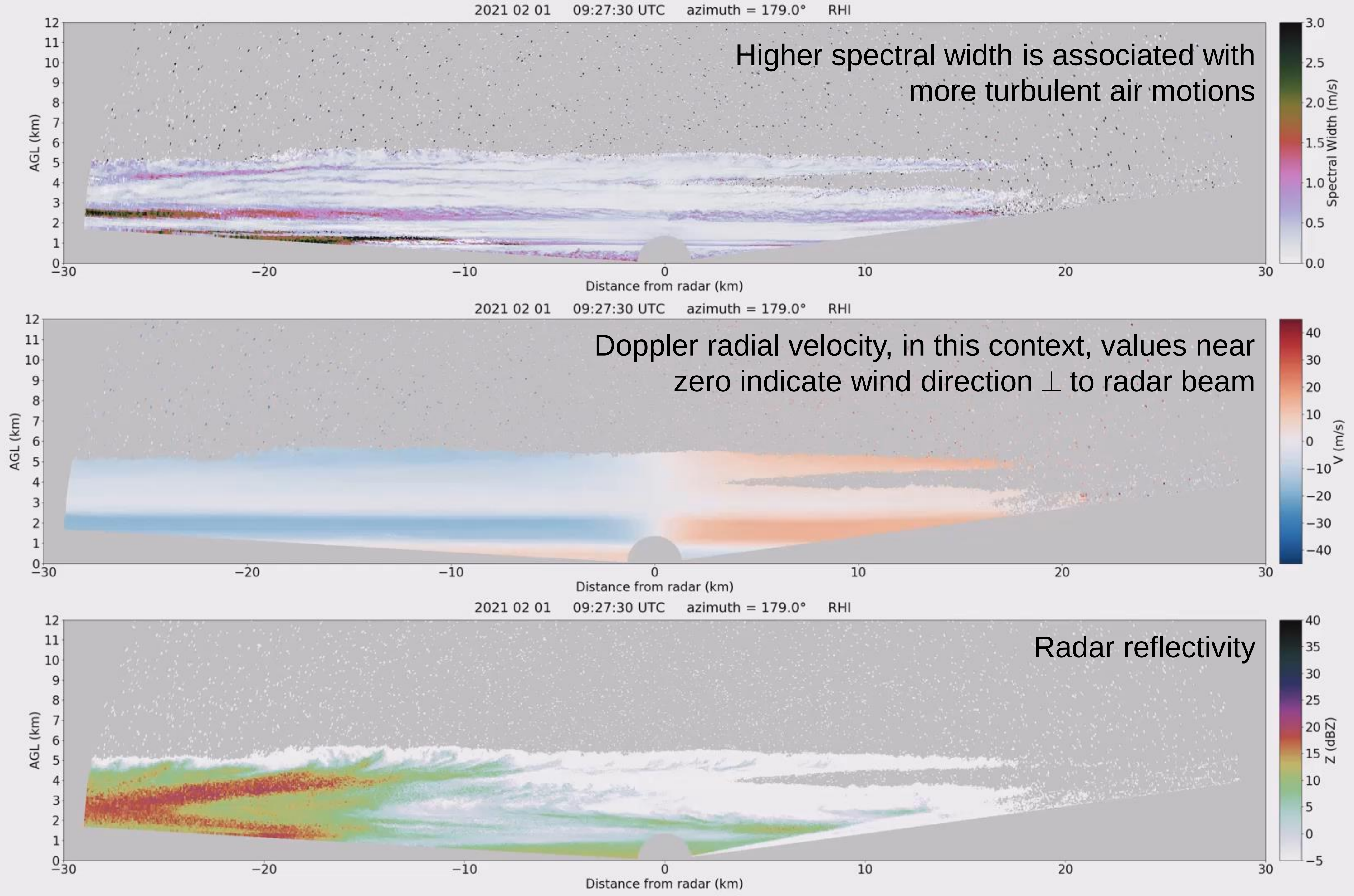


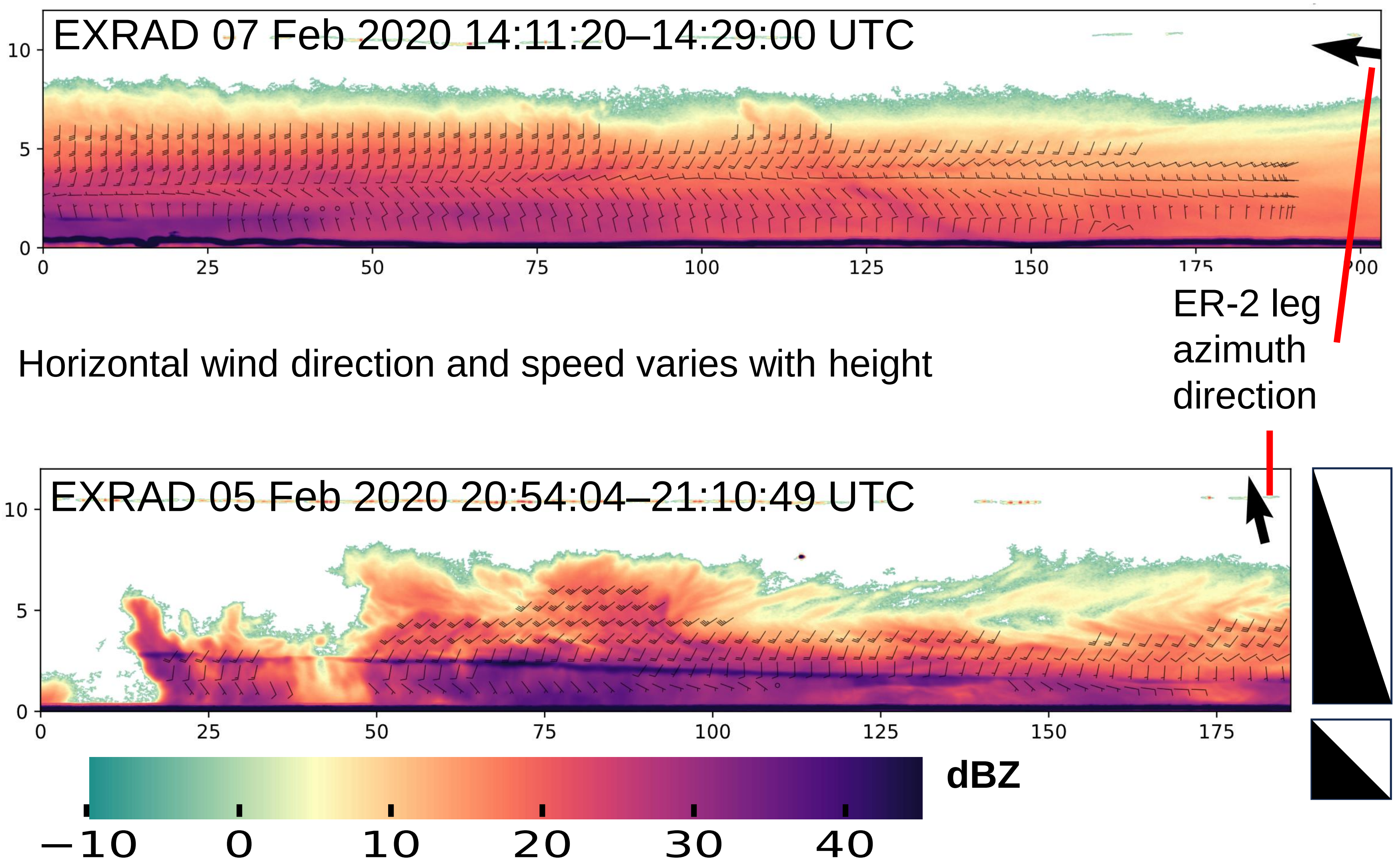

Figure adapted from Zaremba et al. (2023, JAMC)




Stonybrook University KASPR radar RHI sequence from 1 Feb 2021 (1:1 aspect ratio)

KASPR data courtesy of Mariko Oue and Pavlos Kollias

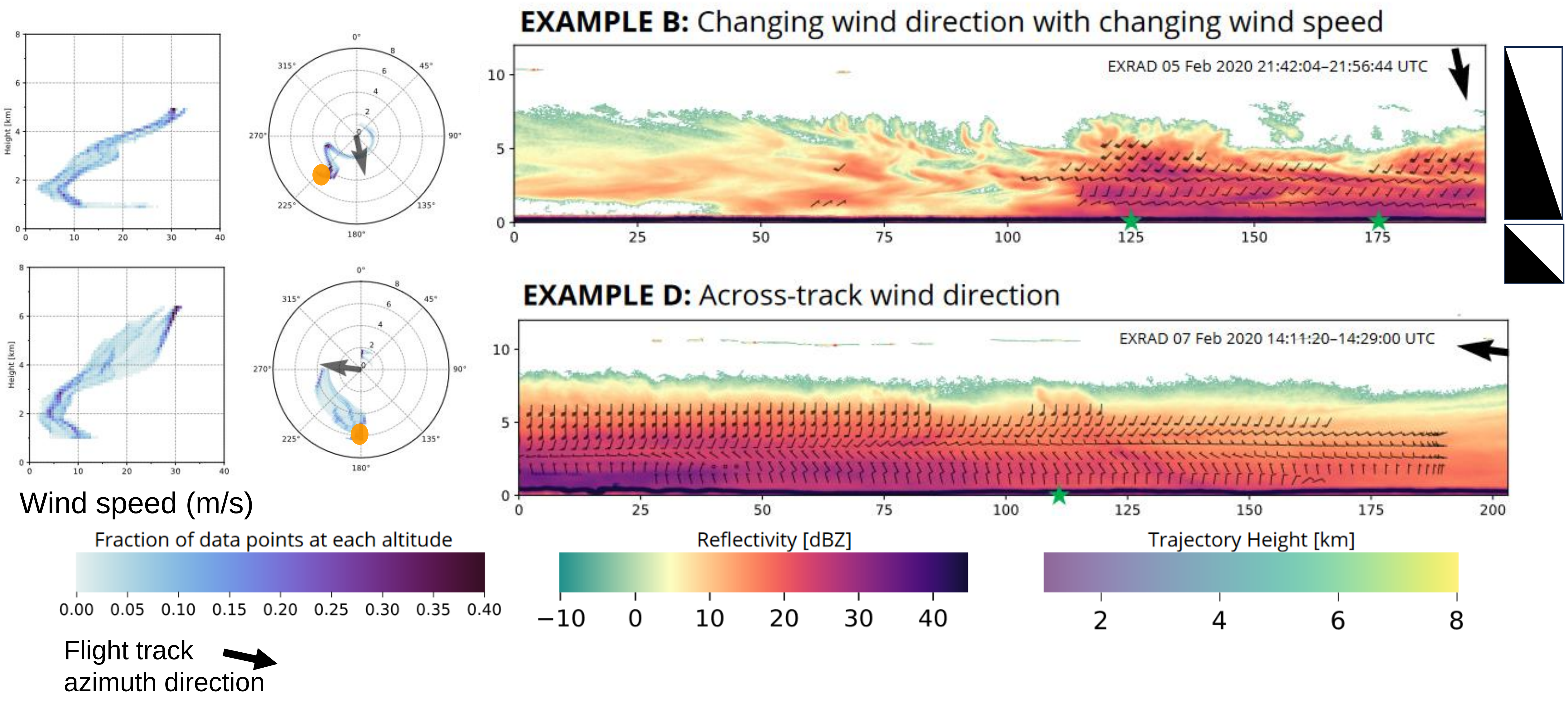
# Snow falls slowly ~1± 0.5 m/s, takes ~67 min to fall 4 km




*Layers with snow have fair amount of time for integrated properties to accumulate*

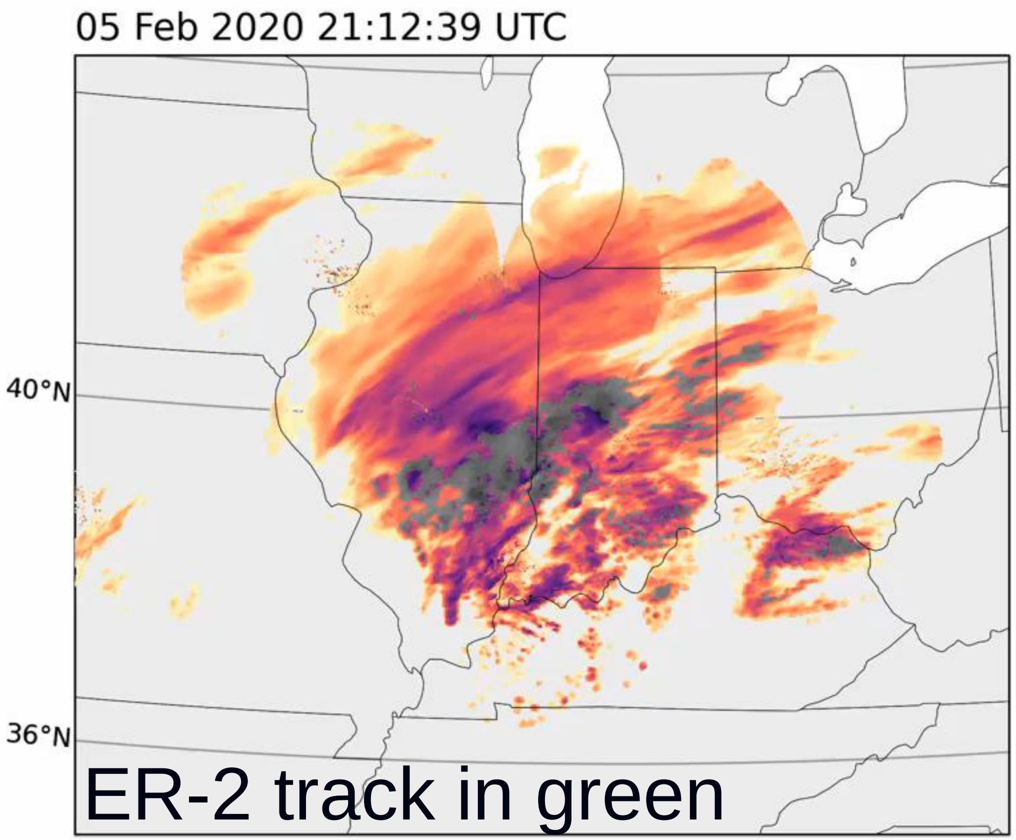
NASA ER-2 X-band radar (McLinden, Li) with VAD winds overlaid (Helms)

# Commonly see wind speed and direction changes with height which can advect ice particles > 50 km in horizontal from origin generating cell

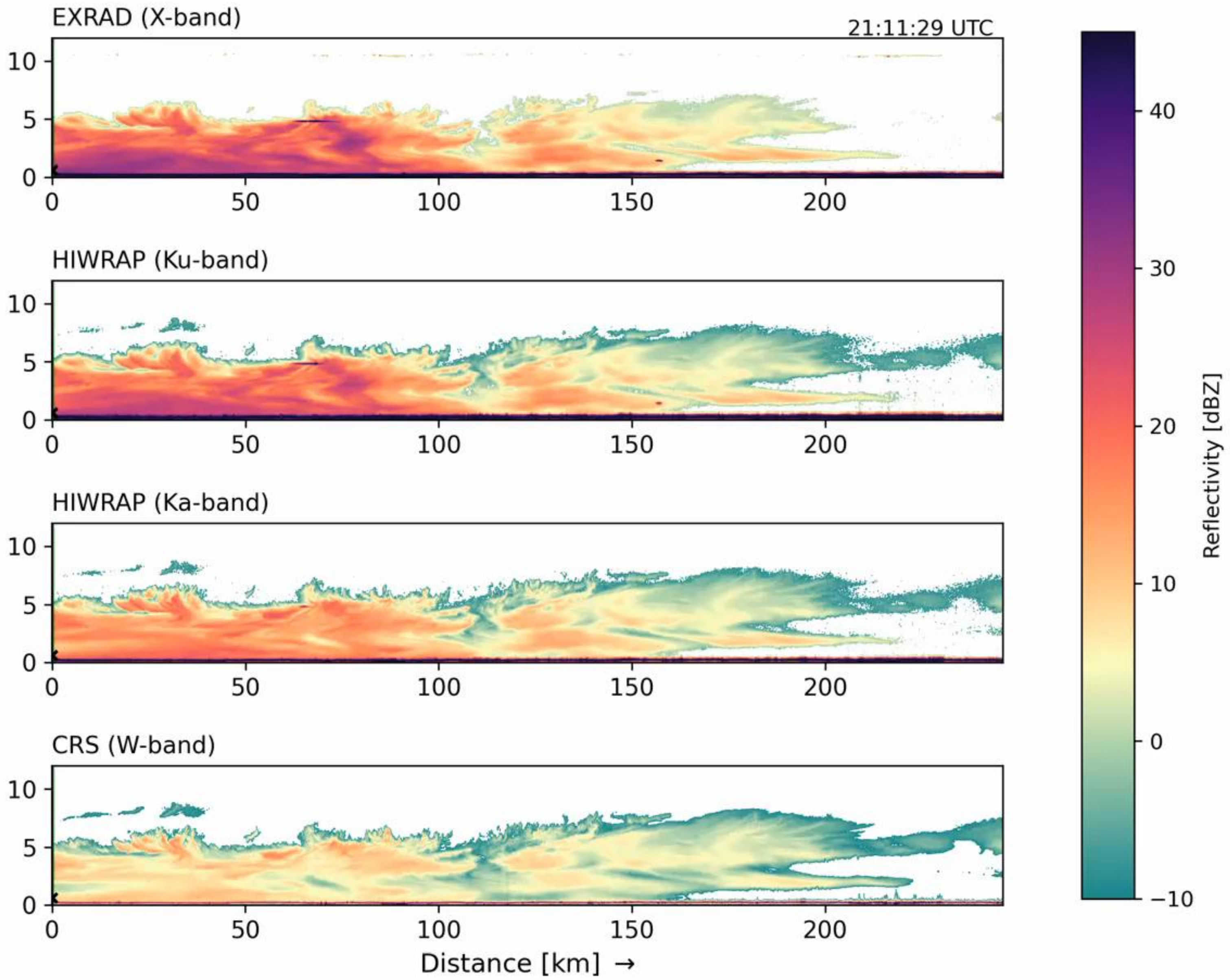



NASA ER-2 X-band radar (McLinden, Li) with VAD winds overlaid (Helms)

# Illustration of vertical structures associated with horizontal Z features

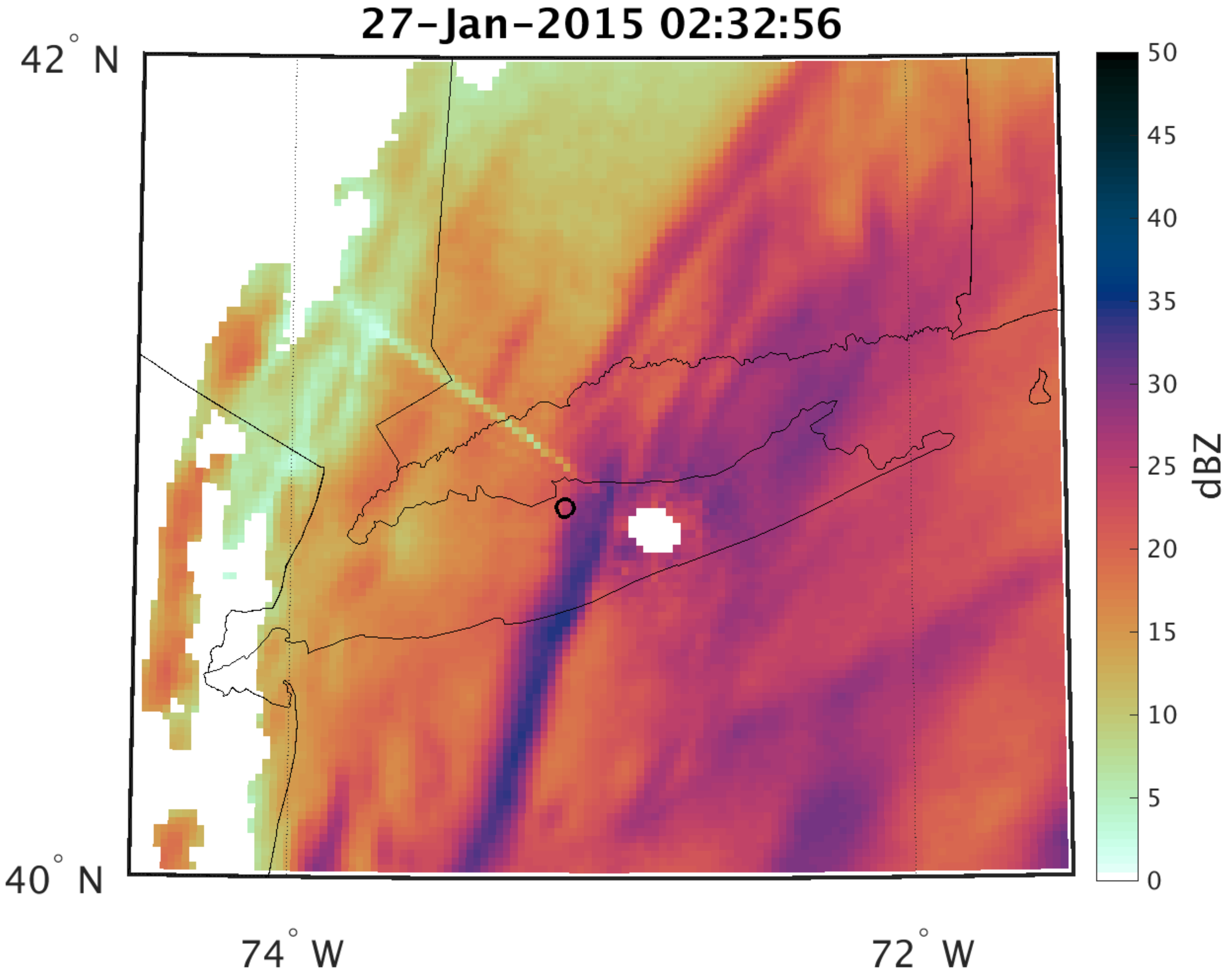



NEXRAD regional map with low $RHO_{HV}$ values (melting regions) in gray scale




x indicates altitude of NEXRAD data used in map based on lowest elevation angle, when radars overlap uses max Z

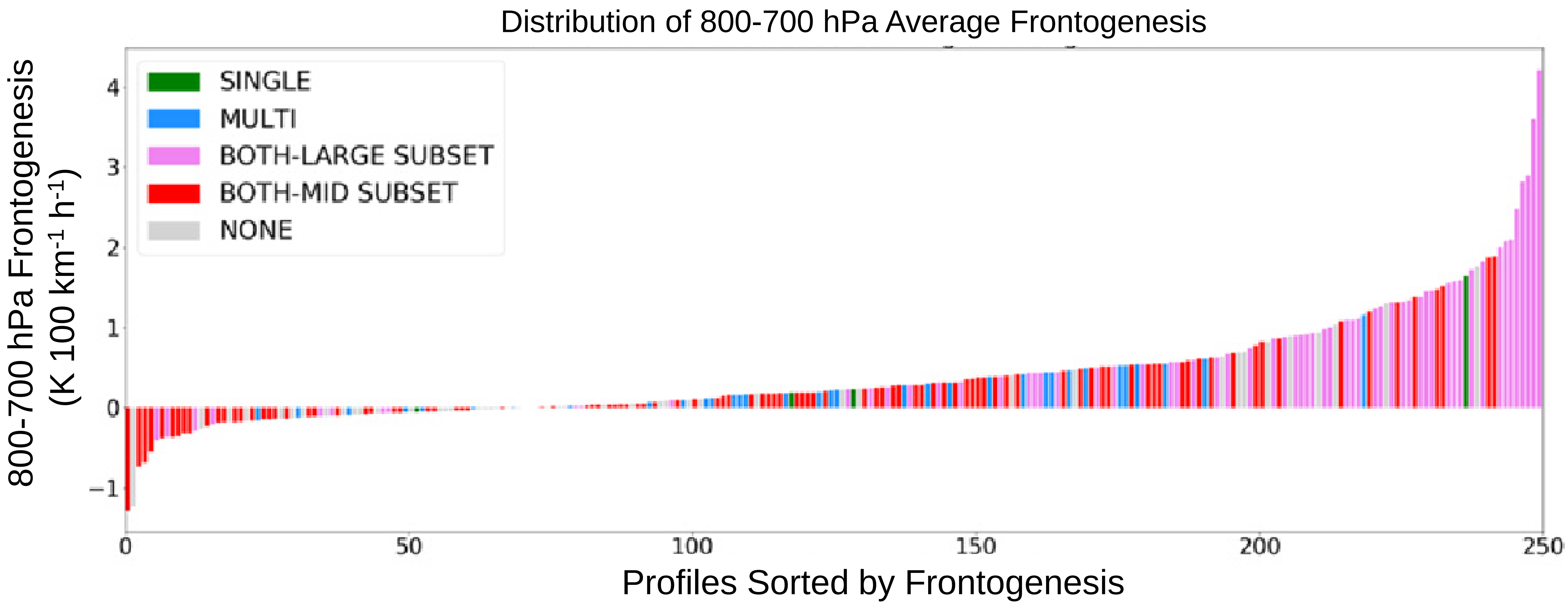
NASA ER-2 radar (McLinden, Li)




# Winter storm mesoscale bands in radar reflectivity

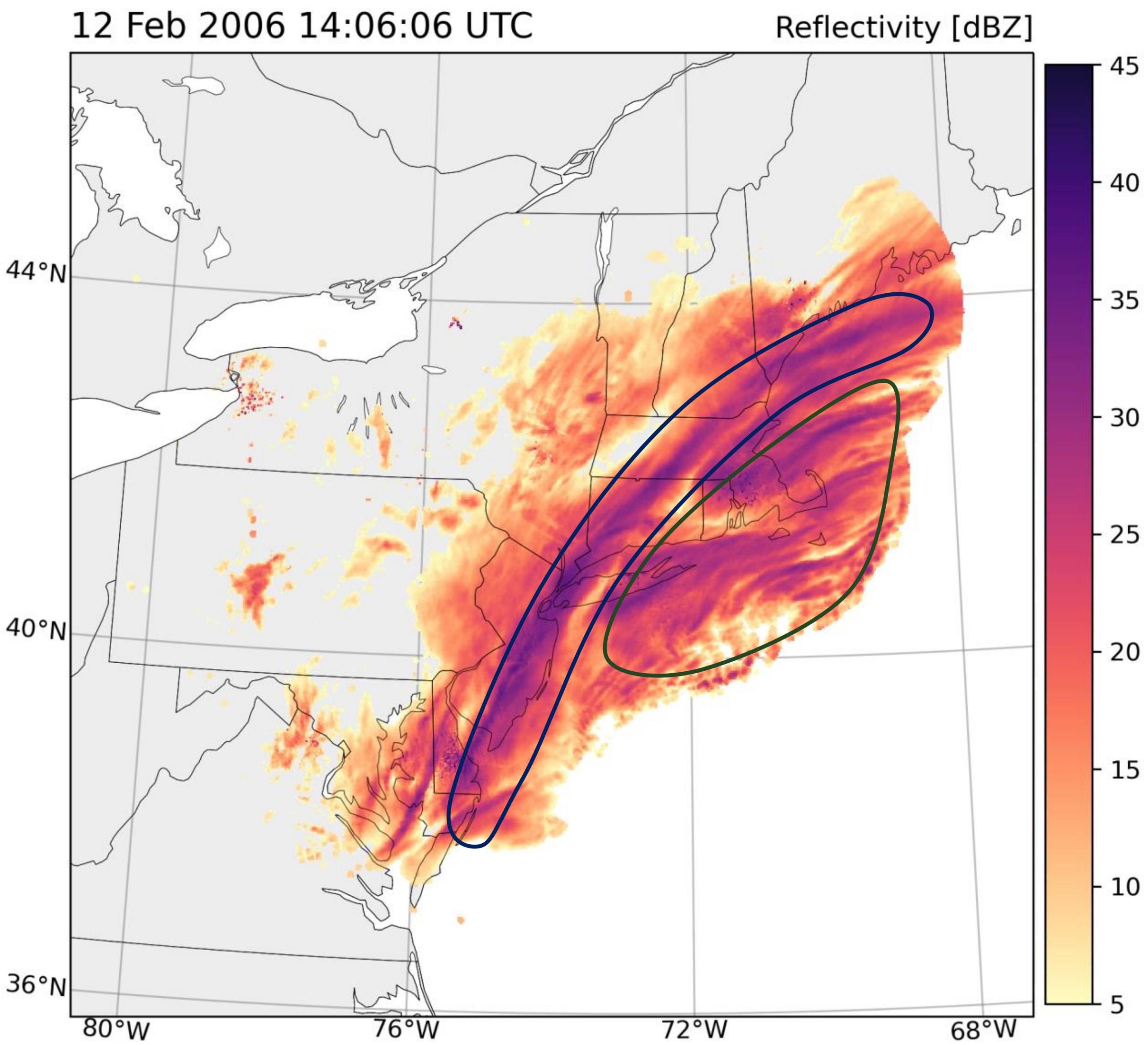
- **Unlike warm season convective lines**
- Some (esp. longer bands) are associated with strong frontogenesis
- Appear as transient features in a fluid rather than static entities moving with the mean flow
- Better defined as local enhancements to dBZ field than as a fixed dBZ threshold

Ganetis et al (2018) analysis of data from 108 cool season storms (1996-2016). Strong frontogenesis increases the likelihood of a single band forming, but these long bands as well as shorter multibands also frequently occur in environments of weak frontogenesis to frontolysis



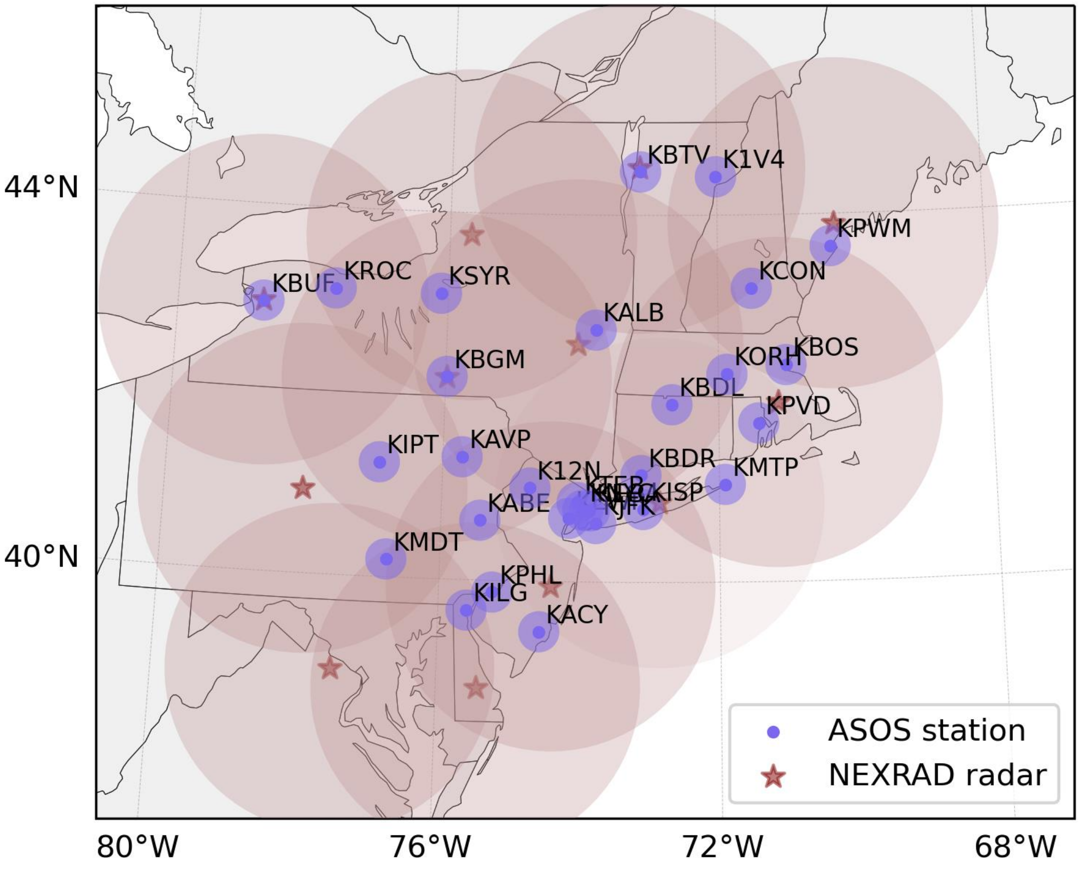

Ganetis et al. (2018)

# Snow bands and surface snow rates




*To what degree do locally- enhanced reflectivity banded features have an impact on surface snow fall rates?*

# **Data:** Hourly ASOS surface station data (2012-2023)

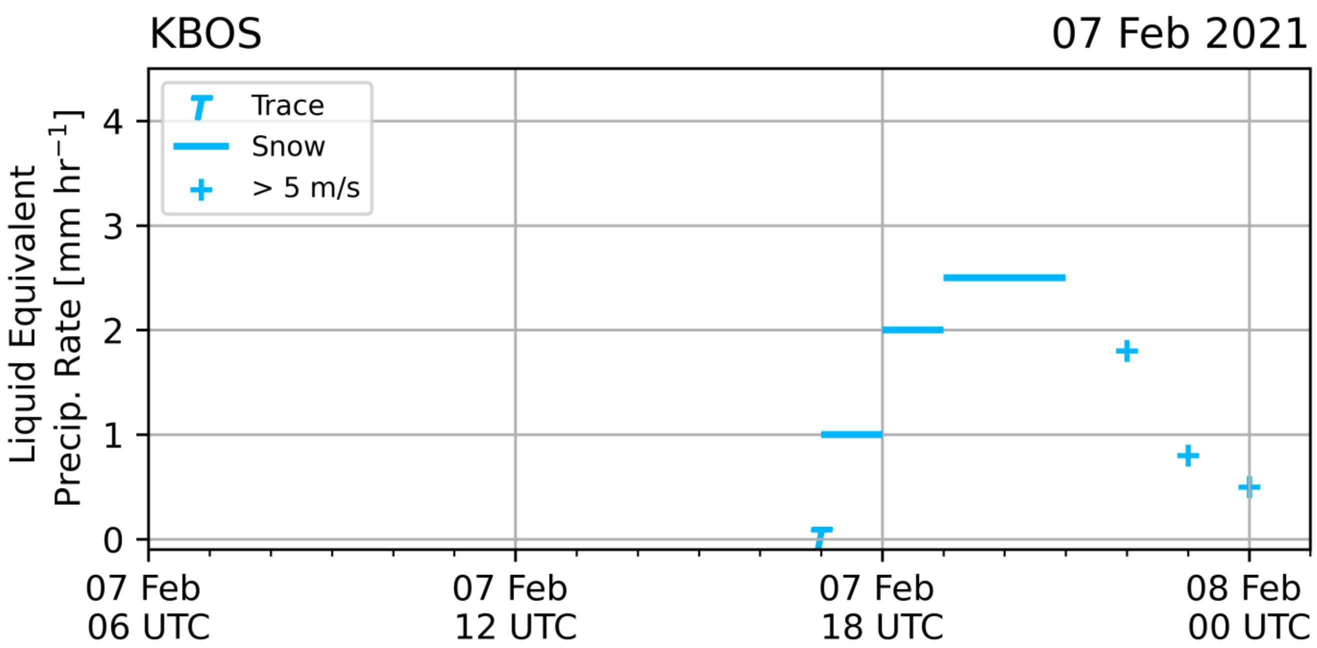



***ASOS stations*** ***with 25 km radius range***

*NEXRAD stations with 200 km range ring*

1 sample = 1 hour at 1 ASOS station

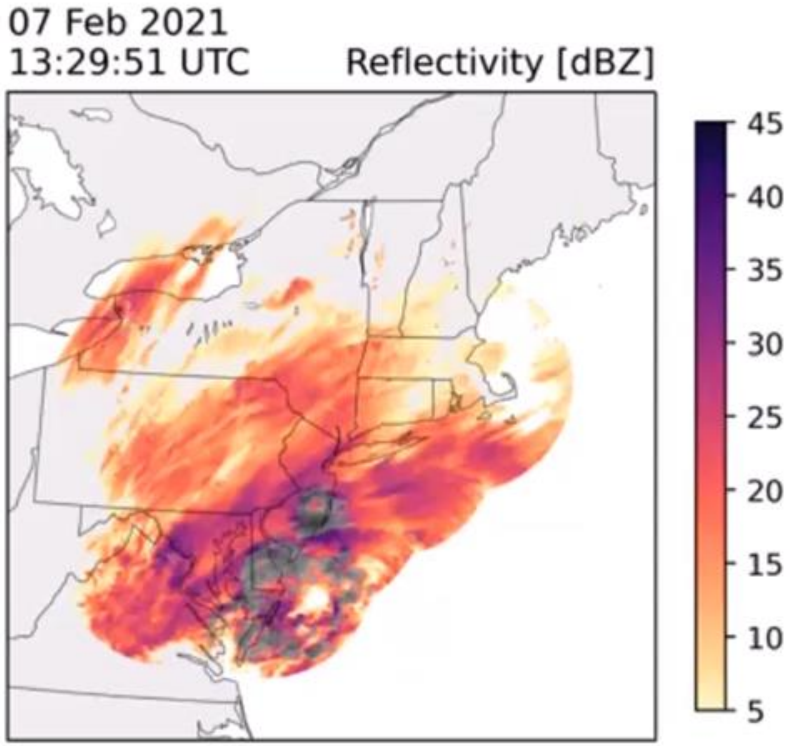
**17,486** total samples over 29 stations and 264 storm days



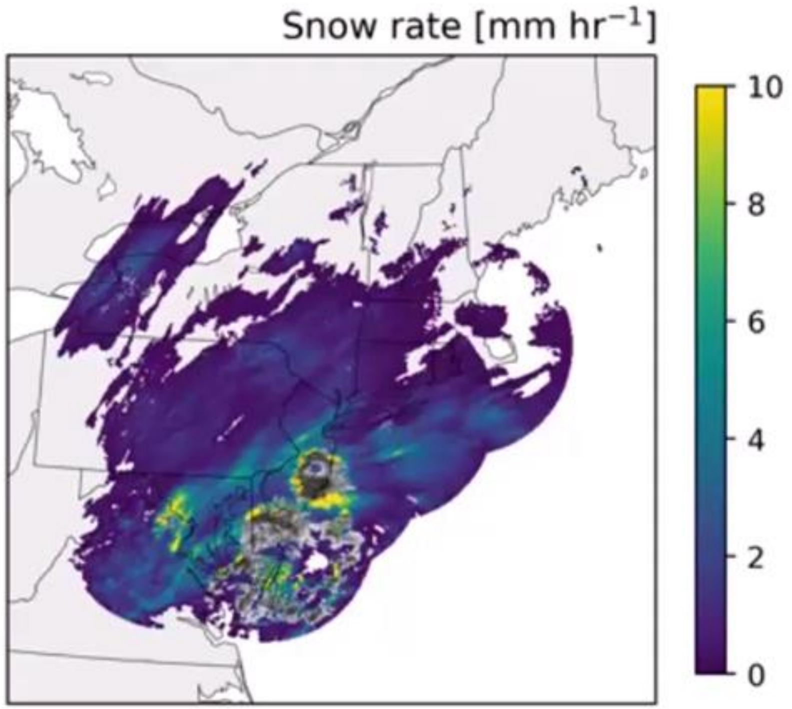

Criteria:

- Must have reported snow for at least 4 hours
- Only using snow observations with wind speed < 5 m $s^{-1}$ *(removes ~40% of observations)*
- Only using stations with AWPAG weighing gauges with wind shields for best LWE measurements of frozen precipitation

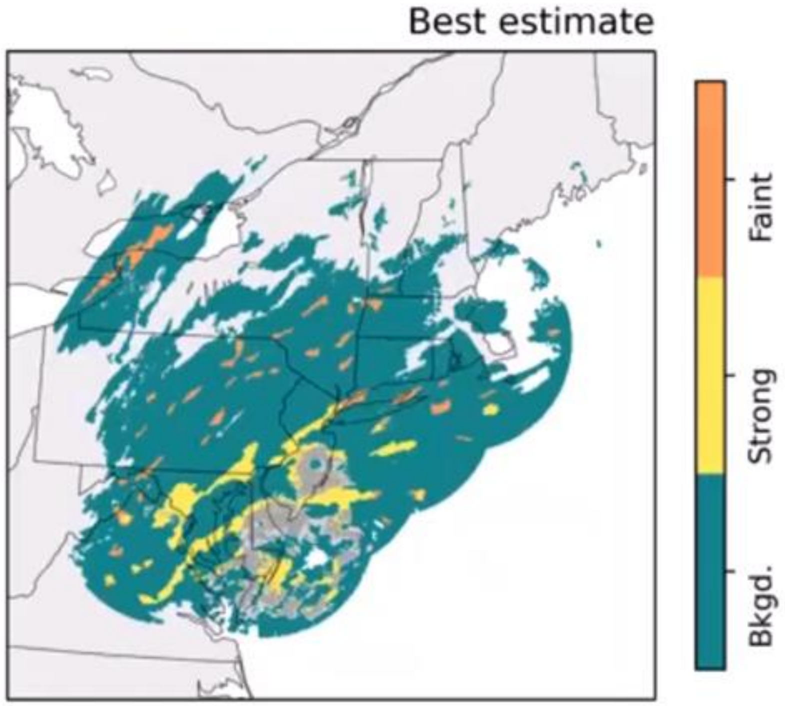
# **Data:** NEXRAD regional radar maps




**Radar Reflectivity [dBZ]**
melting and mixed precip regions removed from analysis *Tomkins et al. (2022)*




**Snow Rate [mm hr$^{-1}$]**
Rescaled Z to better represent snow field using following equation:
$Z_e = 57.3\ S^{1.67}$
*Rasmussen et al. (2003)*



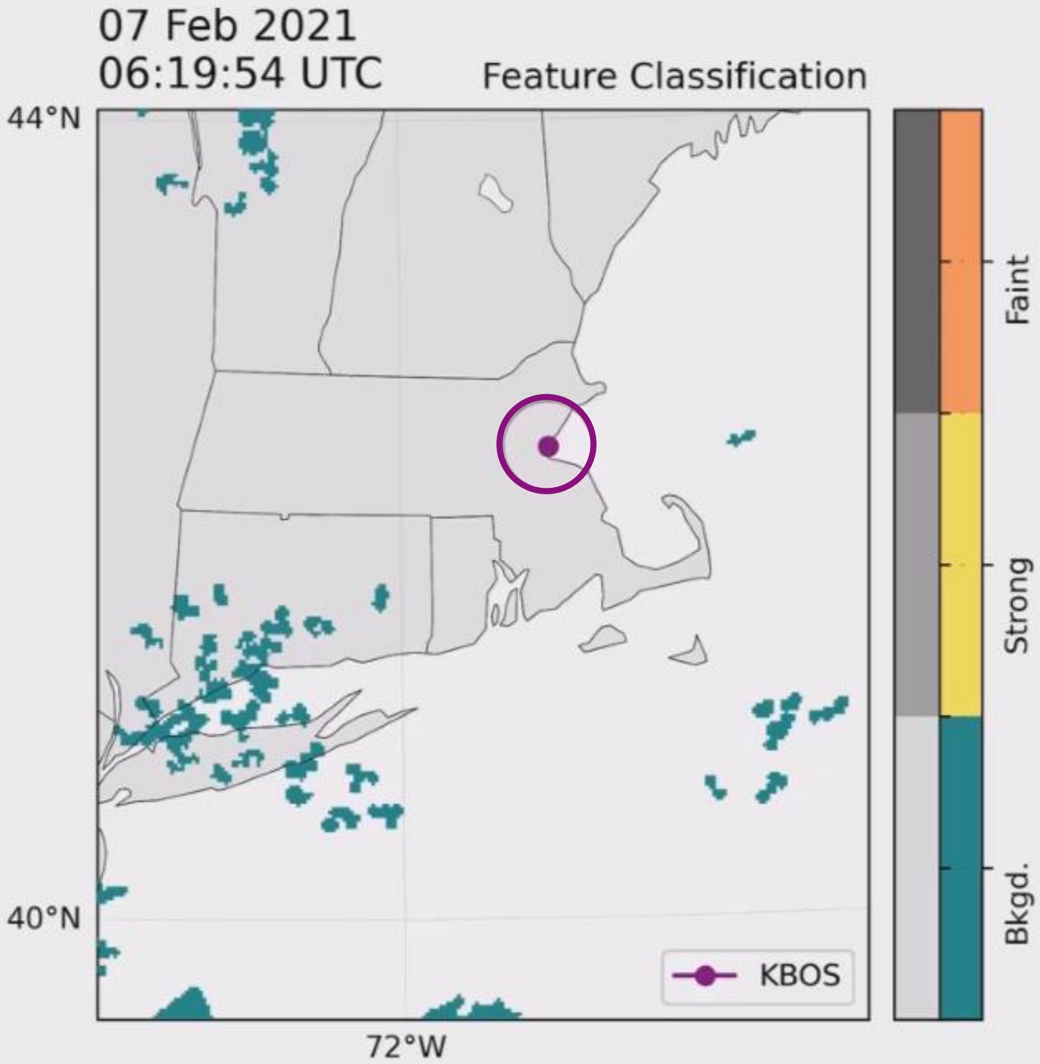

**Objective Feature Detection for snow bands**
*Tomkins et al. (2023)*

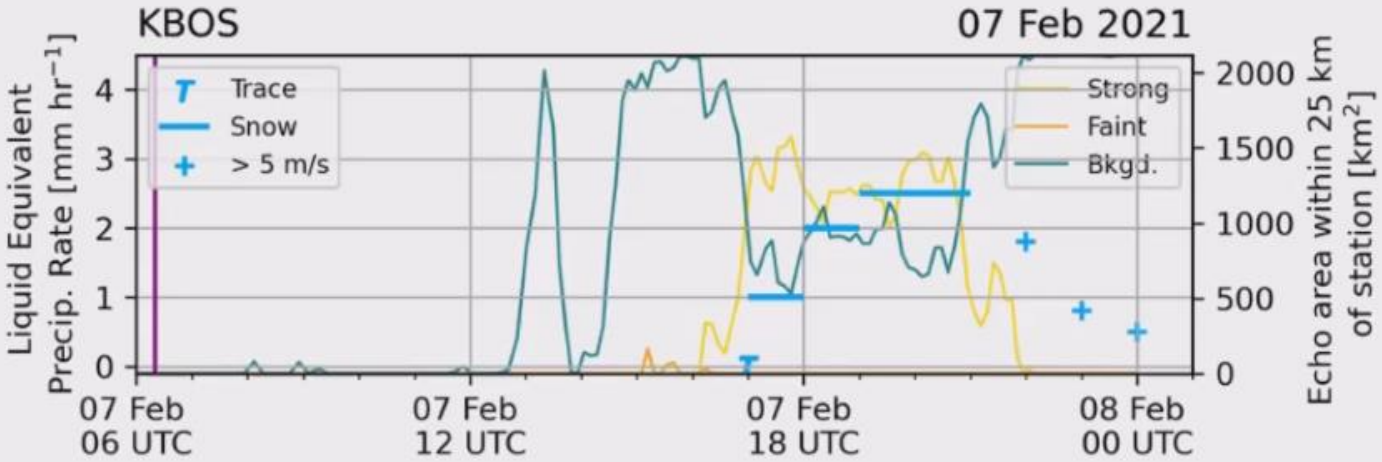
**Faint**: not very distinct features
**Strong**: very distinct features
**Background**: echo surrounding objects

netCDF files for all regional composites between 1996-2023 available on Dryad (open-source data repository) soon

- 1996-2012 *(pre dual-pol)* DOI: **10.5061/dryad.zcrjdfnk6**
- 2012-2023 *(post dual-pol)* DOI: **10.5061/dryad.rbnzs7hj9**

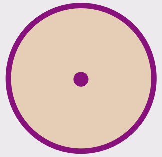
# **Methods:** Combining ASOS hourly surface station data and feature detection regional radar maps



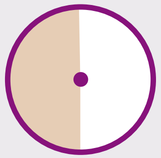




**Area * Time fraction**

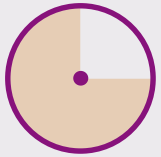
Fraction of 0.5 could be obtained many ways, including:



**100% coverage** of 25 km radius circle for **30 minutes**

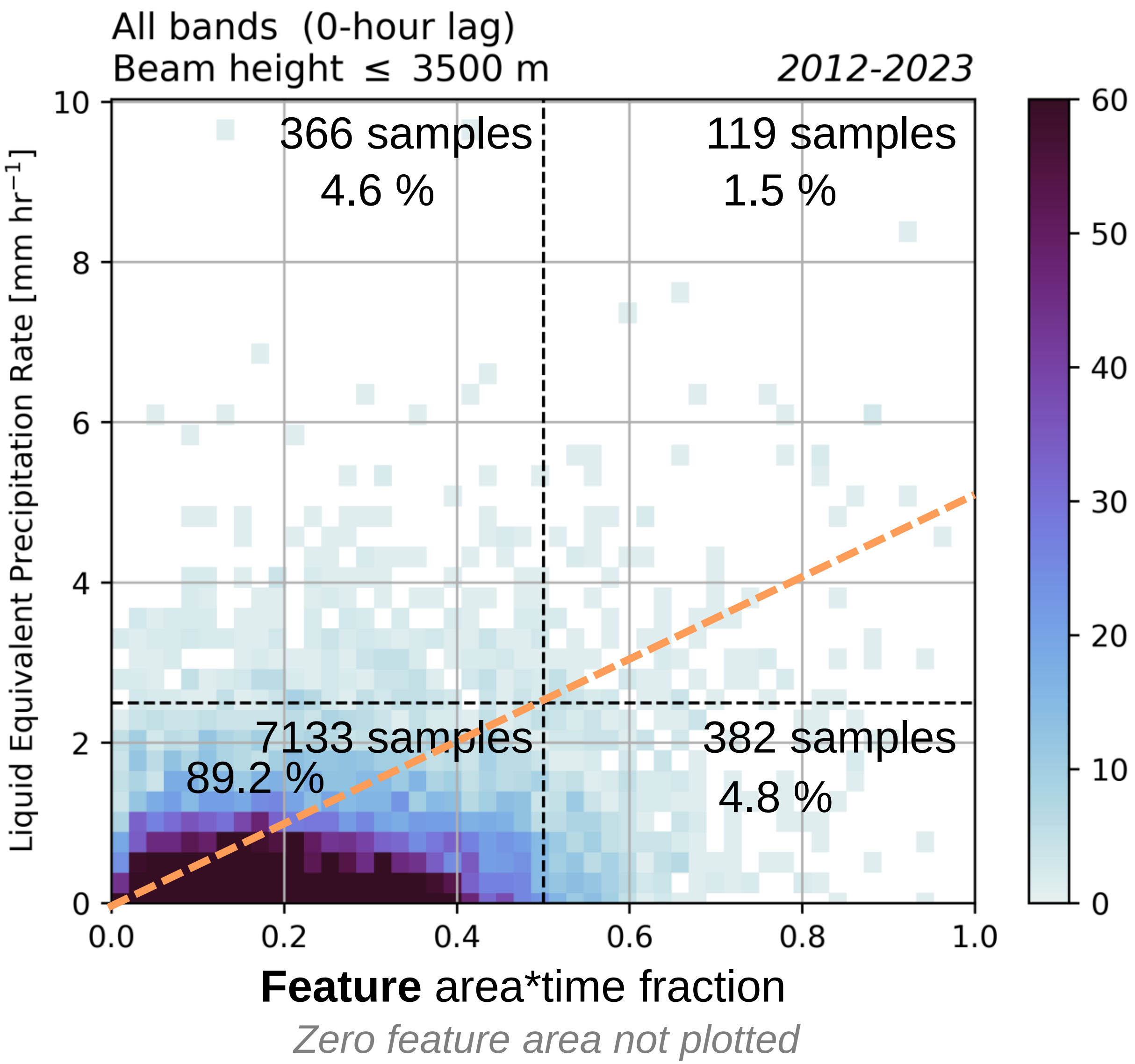


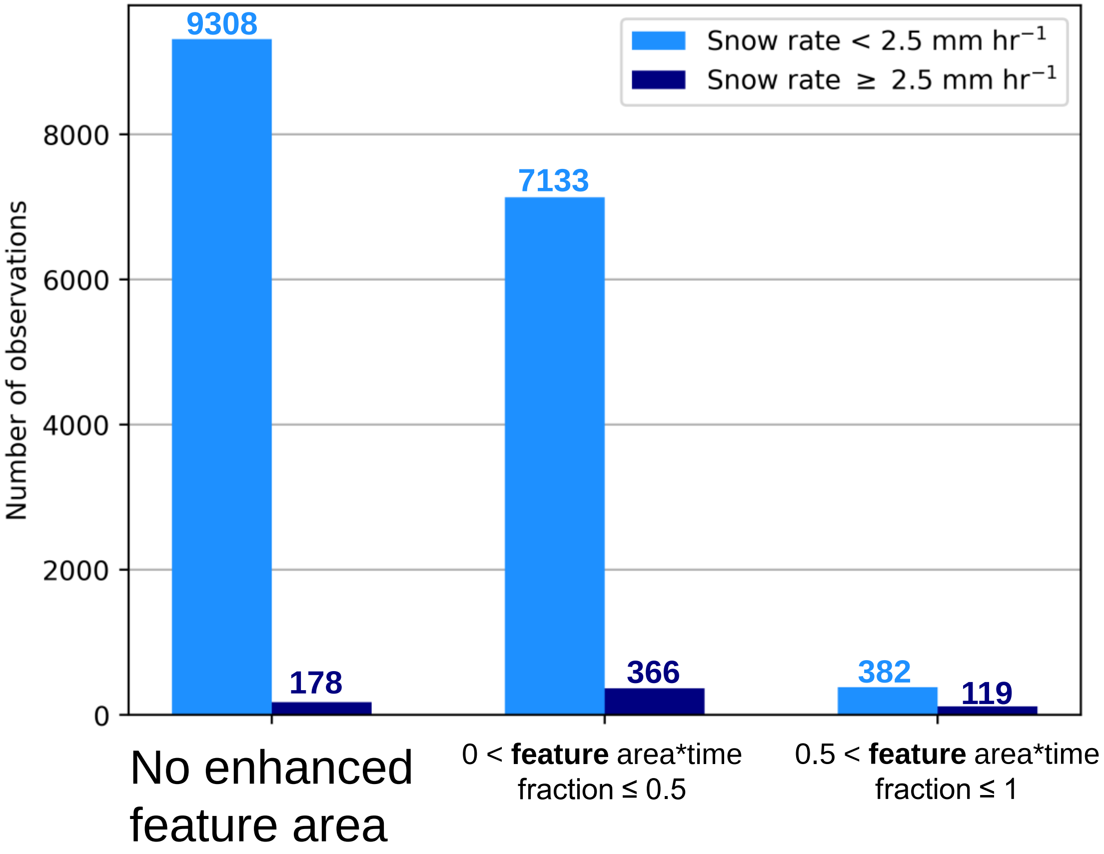
**50% coverage** of 25 km radius circle for **1 hour**



**75% coverage** of 25 km radius circle for **40 minutes**

# Most of the time, locally enhanced reflectivity is associated with low snow rates.

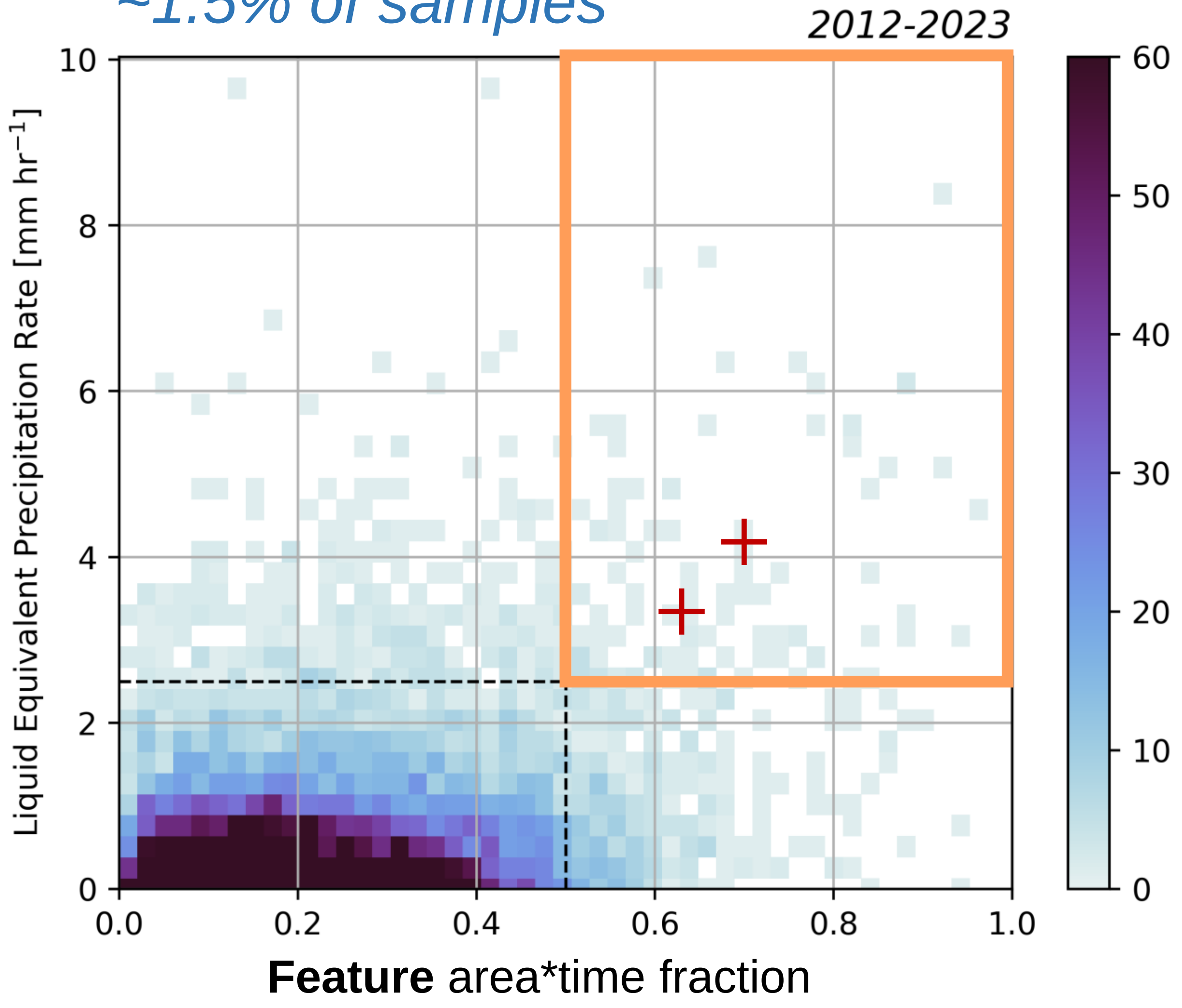


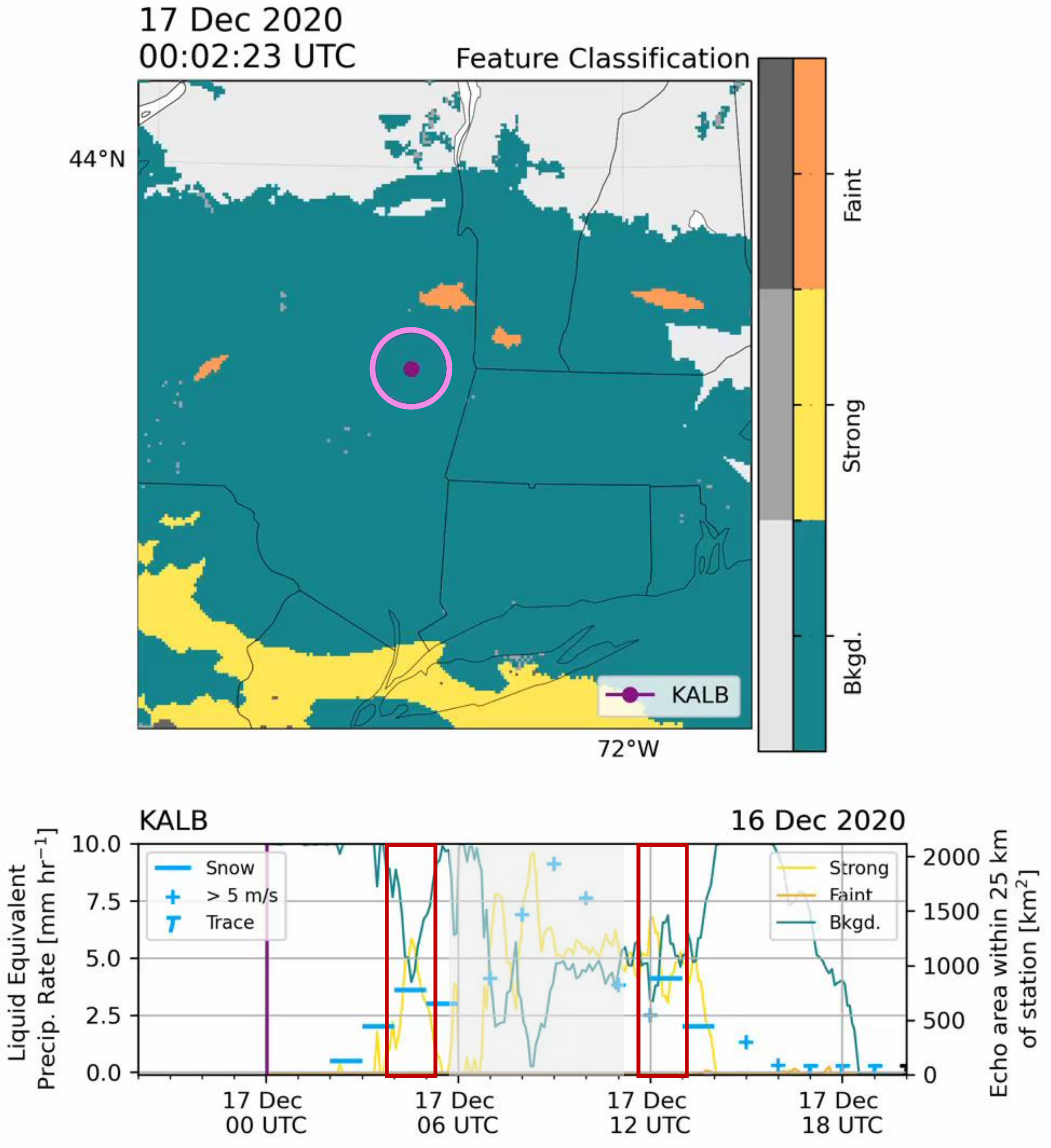



# Example:

## High feature area, heavy snowfall

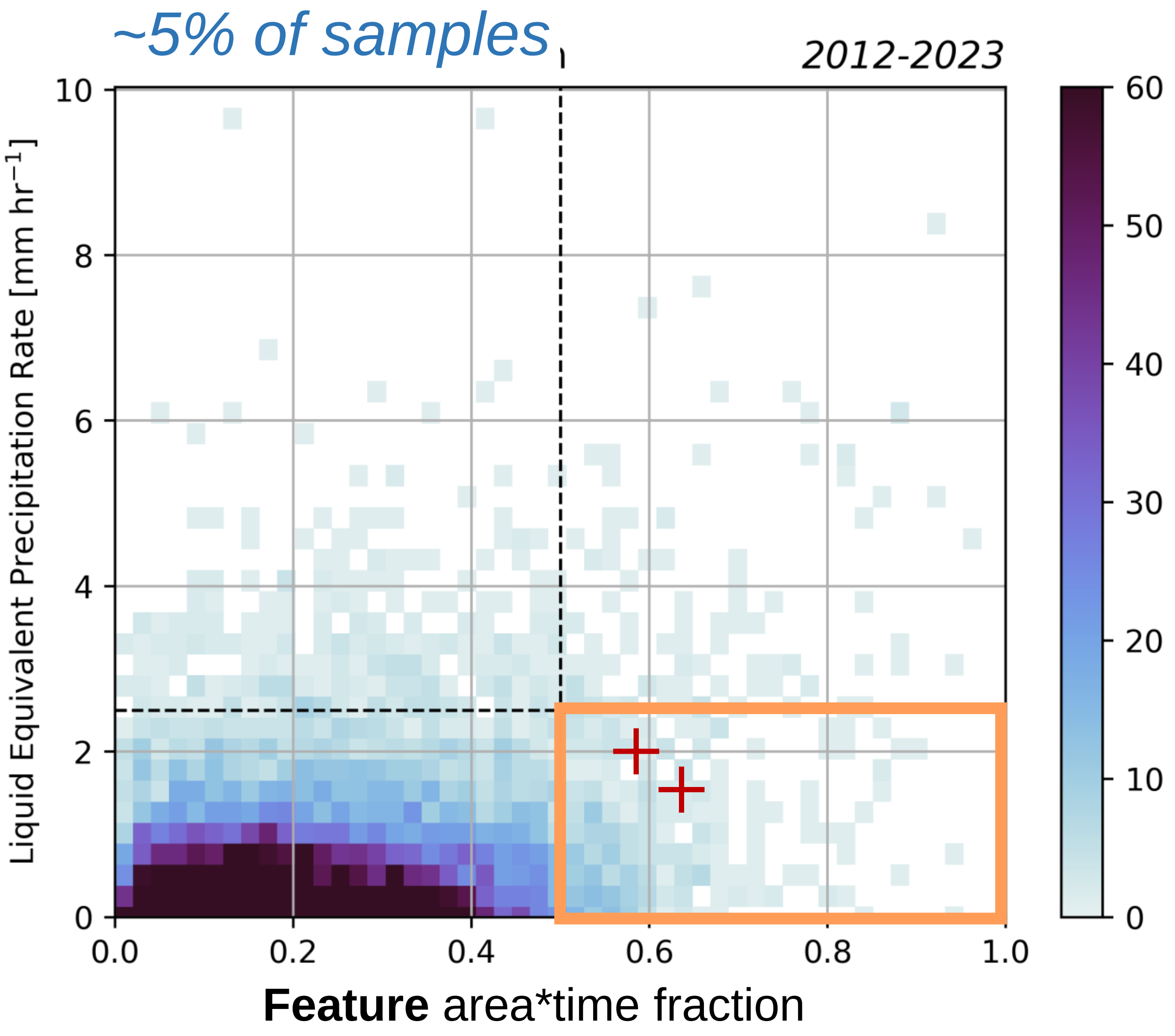
*~1.5% of samples*

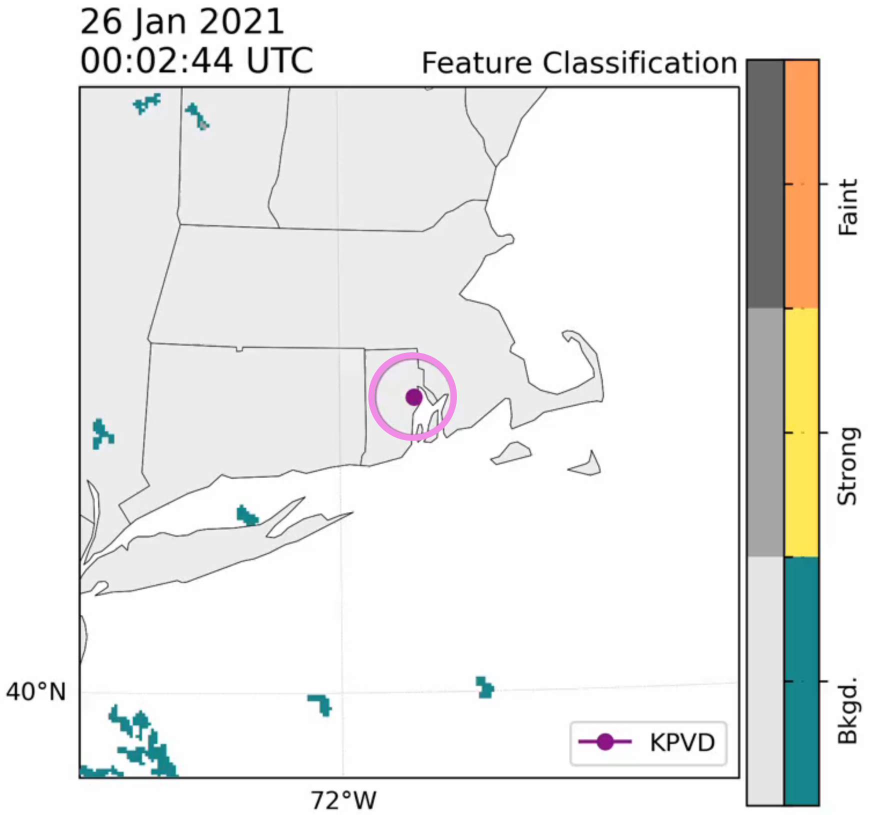


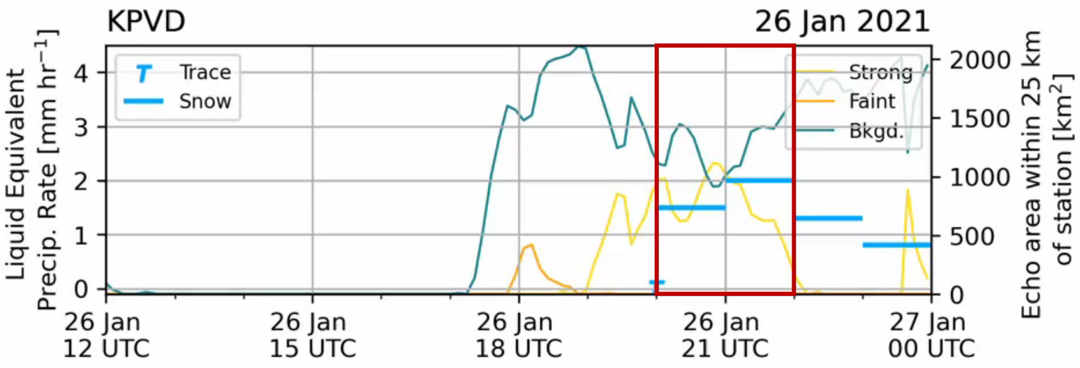



# Example:

High feature area, low/moderate snowfall

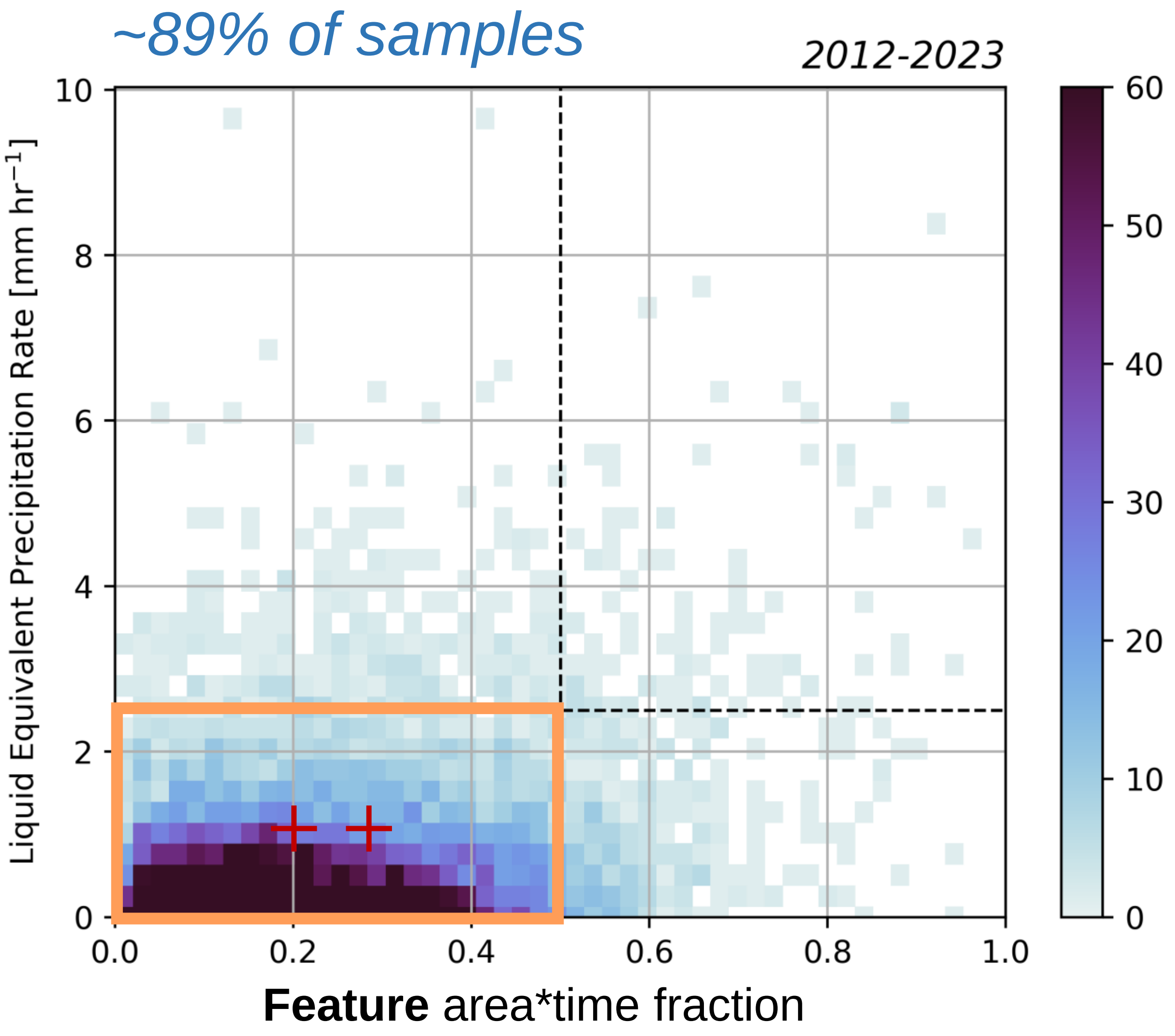


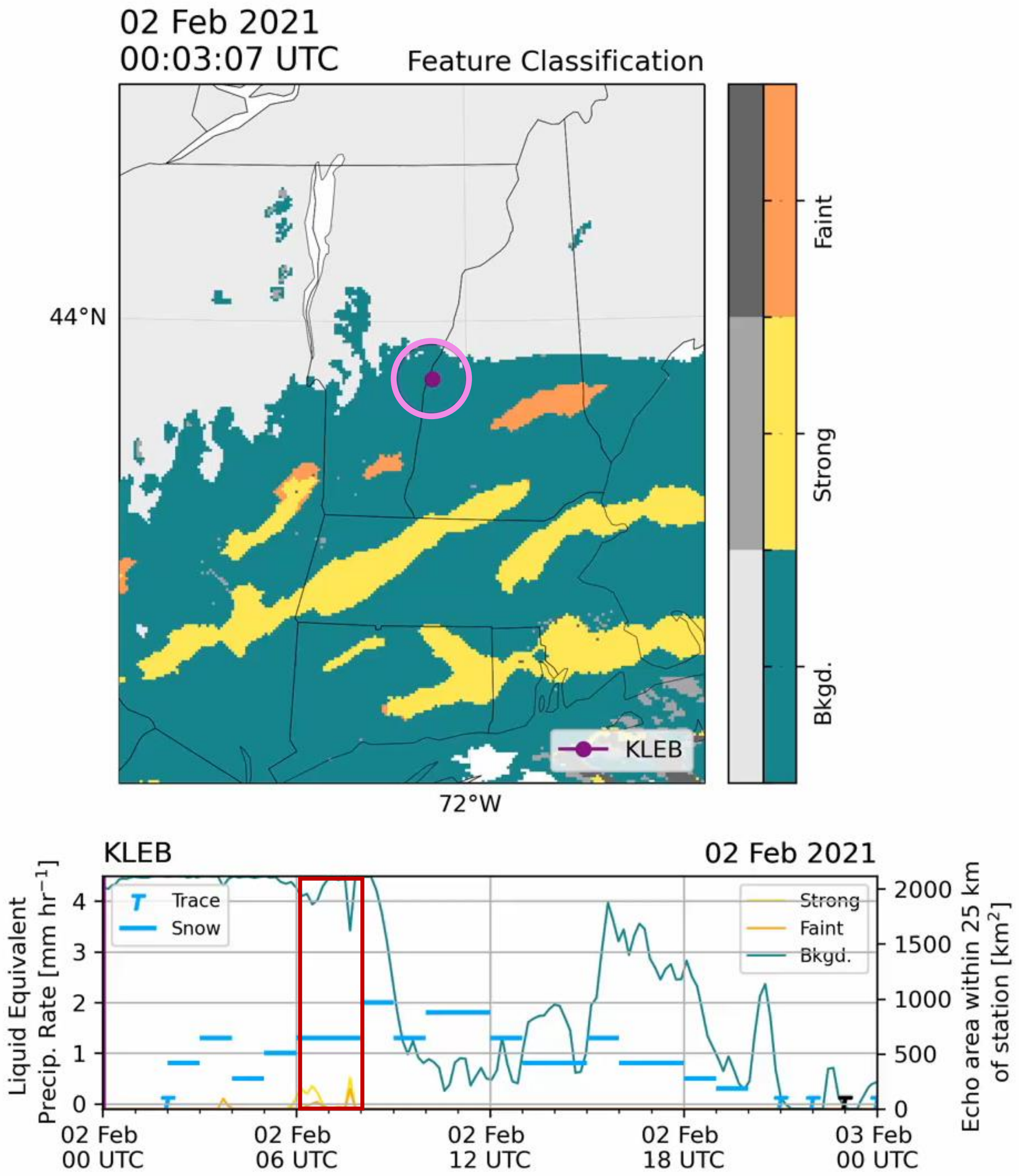



# Example:

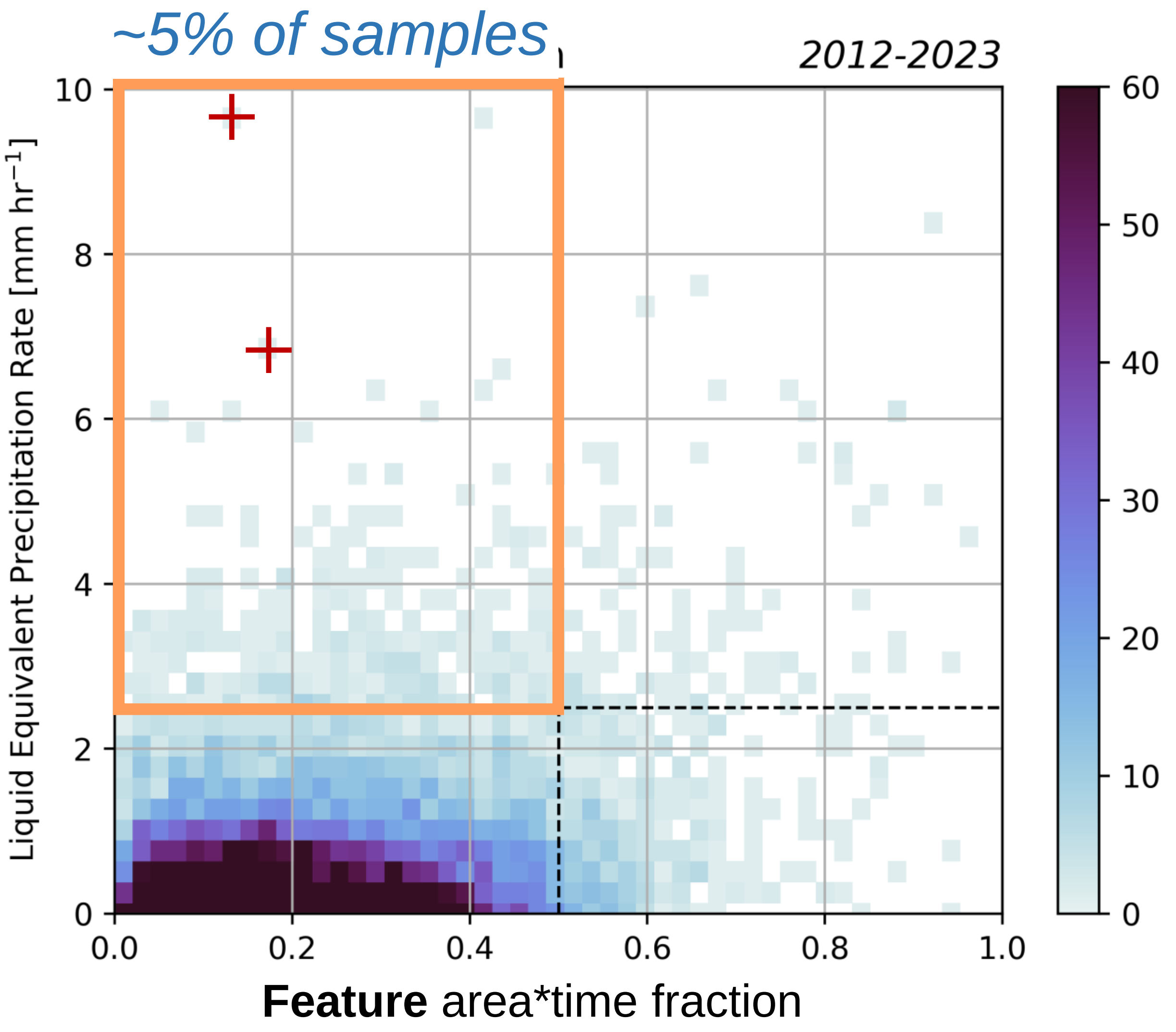
Low feature area, low/moderate snowfall

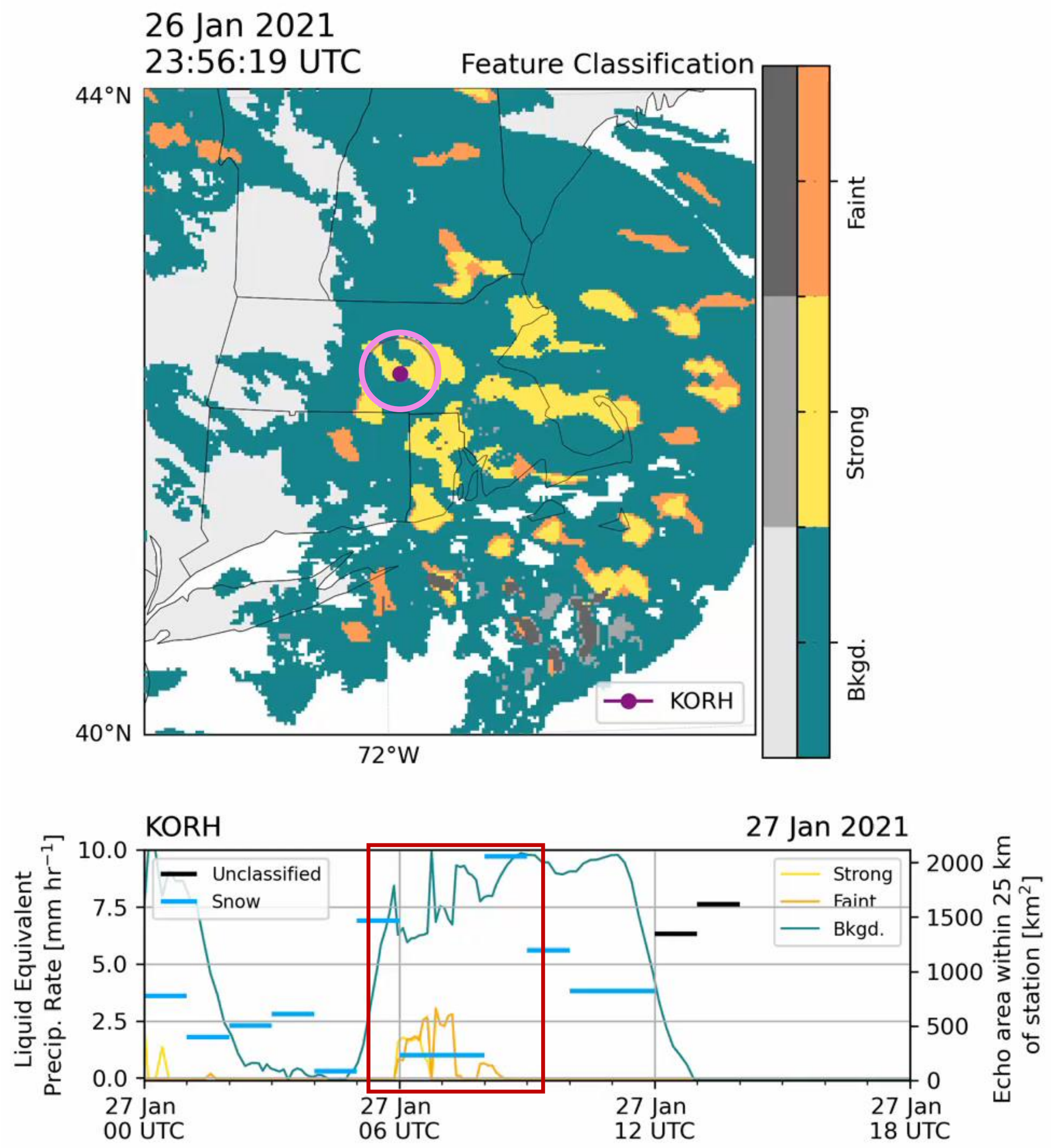


# Example:

Low feature area, High snowfall



# Big picture takeaways from multi-year winter storm observations

## Low correlation between enhanced Z in "snow bands" detected on regional scanning radar and hourly surface snow rates

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- Mixtures yield varying distributions of shapes, sizes, and densities in the same volume which complicate interpretations and retrievals of snow rate

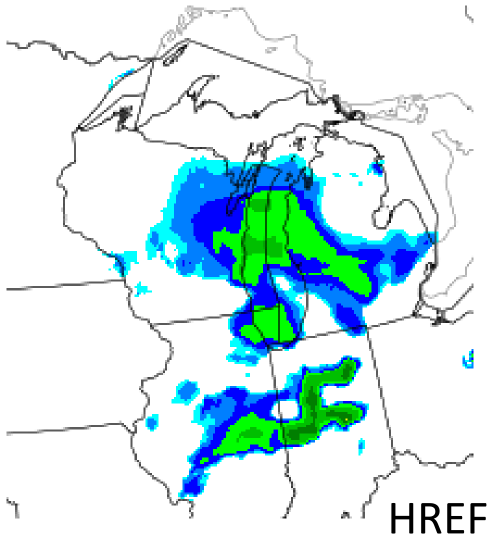
**In the 1-2 hours that it takes a precipitation-sized ice particle to fall from near cloud top to the surface, 3d ice streamers originating in generating cells are tilted and smeared**

- Lack of vertical column continuity in local enhancements in radar Z

# Further Thoughts

- In regions without distinct upward forcing (e.g. strong frontogenesis, orographic lifting), refrain from labeling as “snow bands” most *observed* mesoscale linear features of higher reflectivity in winter storms

- Beware of conflating *forecast model* predictions of locally enhanced snowfall based on ice water contents that are converted to radar reflectivity *for display* using simple Z-S relations (where there is a 1:1 between increasing snow rate and increasing Z) with *observed* radar reflectivities




- Suggest better bet for evaluating model predictions of snowfall are hourly surface snowfall liquid equivalent measurements (in non-blizzard conditions) rather than retrievals from observed radar data