

Tracking ice growth pathways in mixed-phase Arctic clouds using stable water isotopes: Airborne in-situ measurements from CAESAR 2024.

Elise Rosky, Adriana Bailey, Mampi Sarkar, Aaron Bansemer, Sarah Woods, Harald Sodemann, Andrew Seidl, Bart Geerts, Greg McFarquhar, and Paquita Zuidema

NSF National Center for Atmospheric Research

University of Michigan
Rice University
University of Bergen
University of Wyoming
Oklahoma University
University of Miami



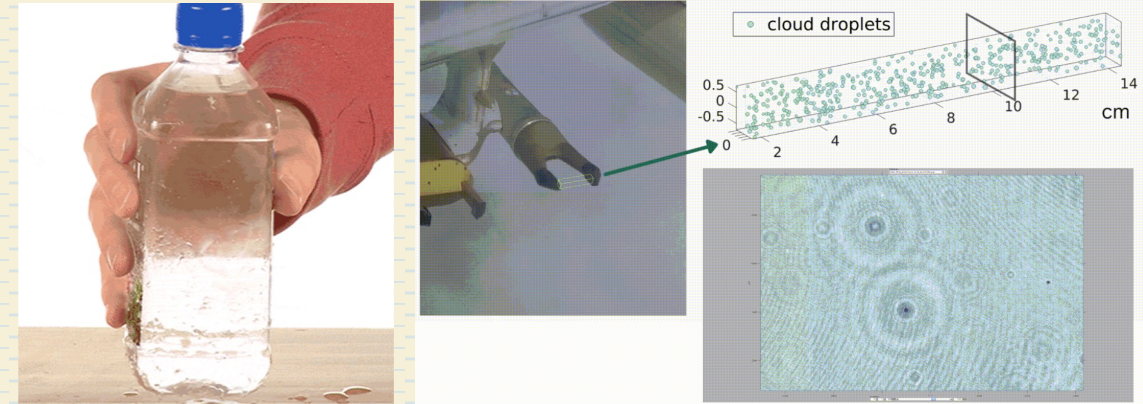
NCAR
OPERATED BY UCAR



Research Background

PhD: (Raymond Shaw, Will Cantrell)

- Process-level research on ice nucleation.
- Cloud microphysics with HOLODEC.



Brief Postdoc: (Adriana Bailey)

- Stable water isotope analysis during CAESAR! (Today's talk)

Current Postdoc: (NCAR Research Aviation Facility)

- All of the above!

**Science-policy interface
& Ethics in geosciences.**

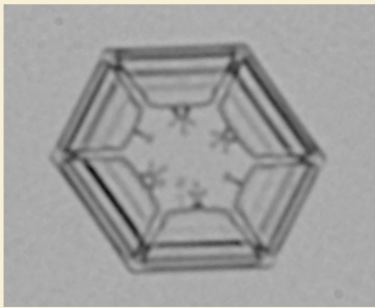


Ice growth in mixed-phase: depends on **supersaturation**
and **interaction with supercooled liquid**

Ice growth examples, in order of increasing supersaturation:

(Korolev JAS 2007)

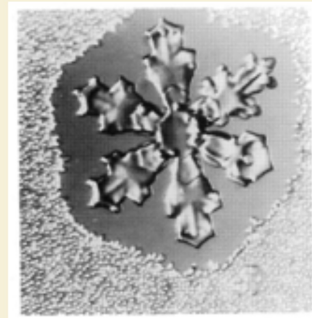
$$S = S_{ice}$$



Ice grows with no liquid
intermediate

DIRECT

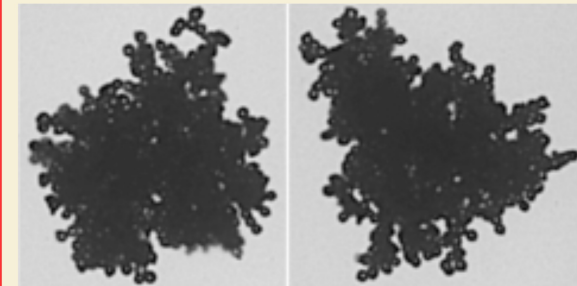
$$S_{ice} < S < S_{liq}$$



Ice grows from
evaporating droplets

WBF

$$S_{ice} < S_{liq} \leq S$$

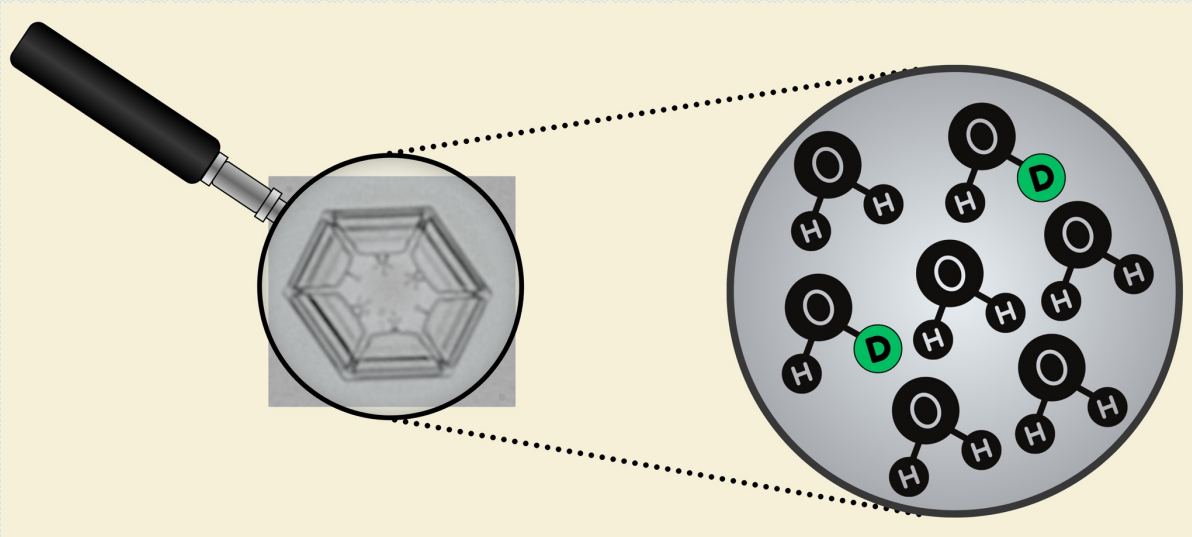


Liquid droplets grow
and freeze into ice

RIMING

In-situ measurement of the growth type is difficult.

Deeper than appearances:
Each ice particle stores a record of its thermodynamic history.



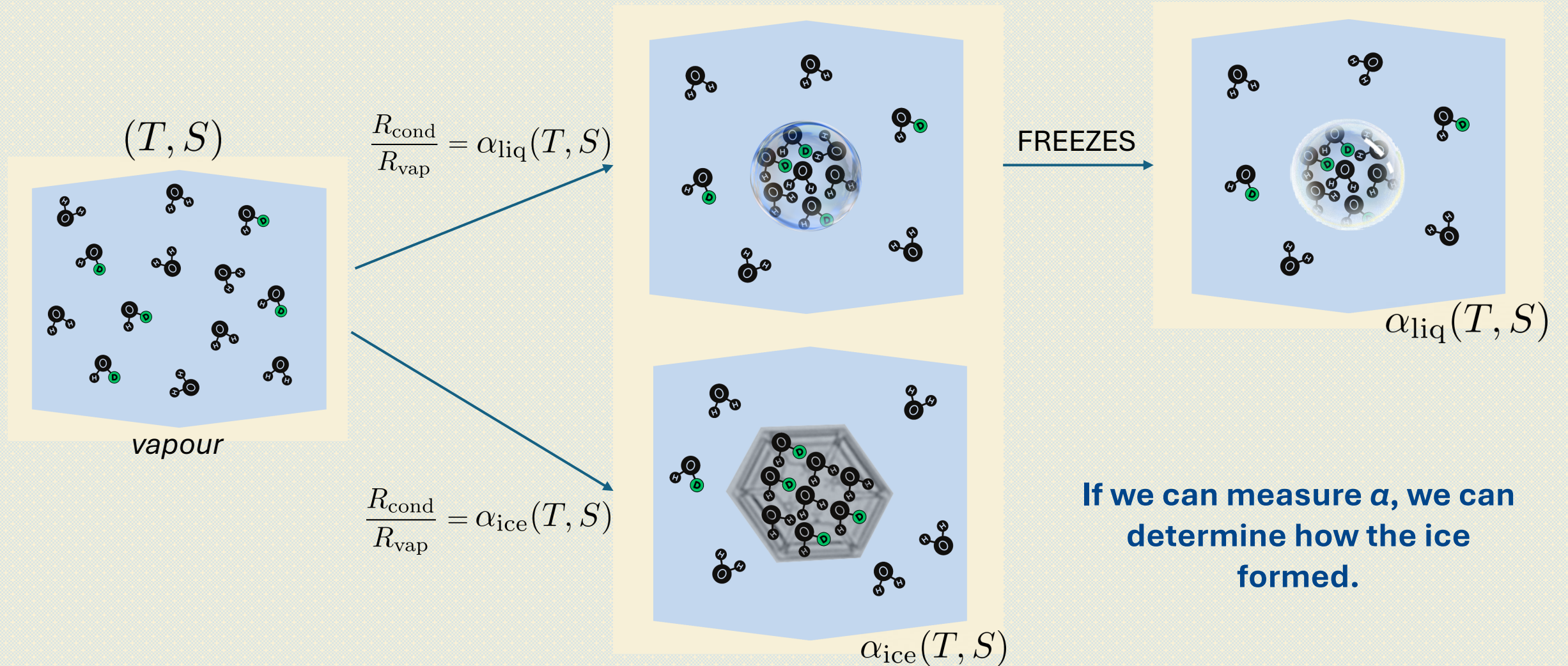
- Encoded into its heavy water ratio:

$$R = \frac{\text{heavy (HDO)}}{\text{normal (H}_2\text{O)}}$$

$$R_{\text{cond}} = \alpha \cdot R_{\text{vap}} \quad \alpha = \begin{cases} \alpha_{\text{liq}}(T, S) \\ \alpha_{\text{ice}}(T, S) \end{cases}$$

Jouzel and Merlivat (1984), Merlivat and Nief (1967), Majoube (1971) and Majoube (1970)

A frozen droplet looks isotopically distinct from ice growth through deposition.



The cloud condensate and vapour must be co-located to obtain a direct measurement of alpha (α).

Attempted this technique during CAESAR (*Cold Air outbreak Experiment in the Sub-Arctic Region*)



(inside the aircraft)

$$\alpha = \frac{R_c}{R_v}$$

- **Do the isotopic measurements yield physically realistic results?**
- **Do we observe different ice growth signatures in the cloud?**

In-cloud supersaturation from the condensate's perspective:
Do the isotopic measurements yield physically realistic results?

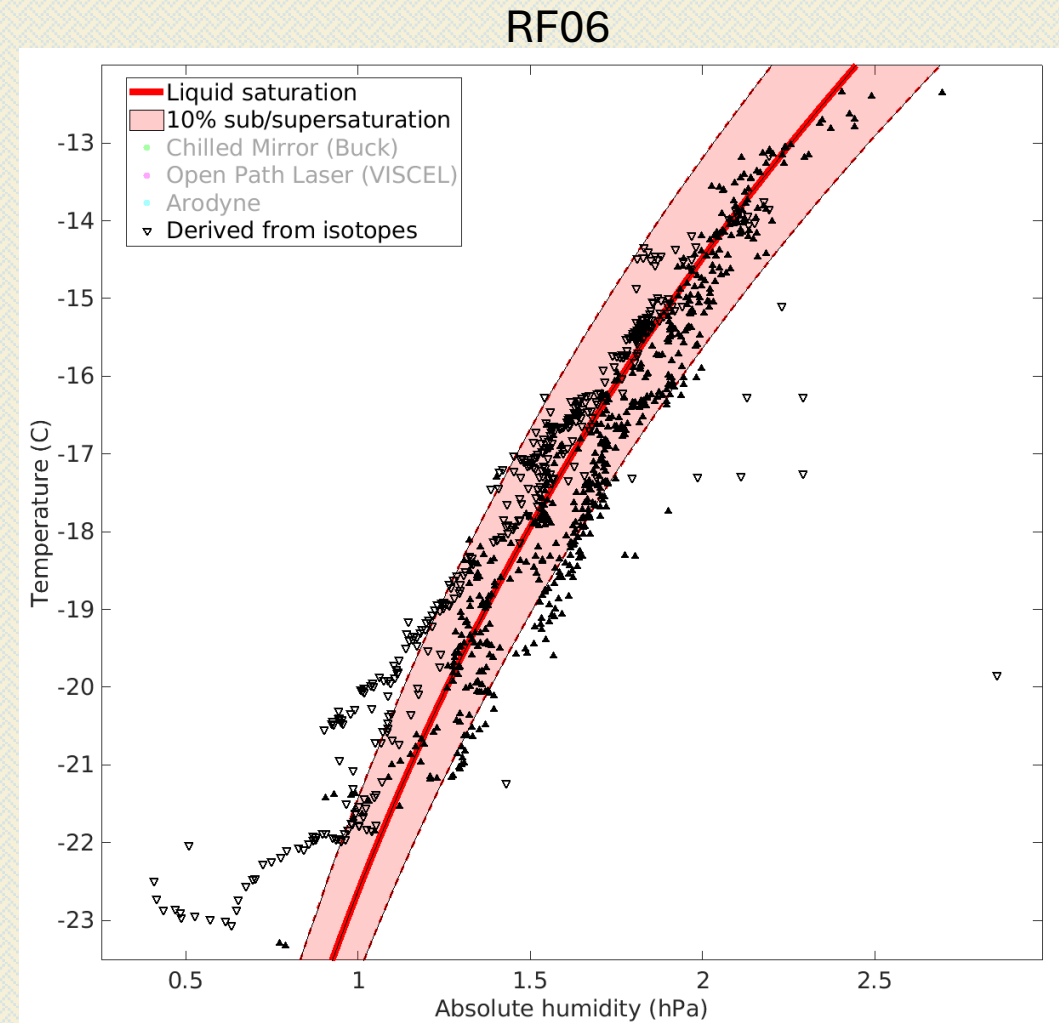
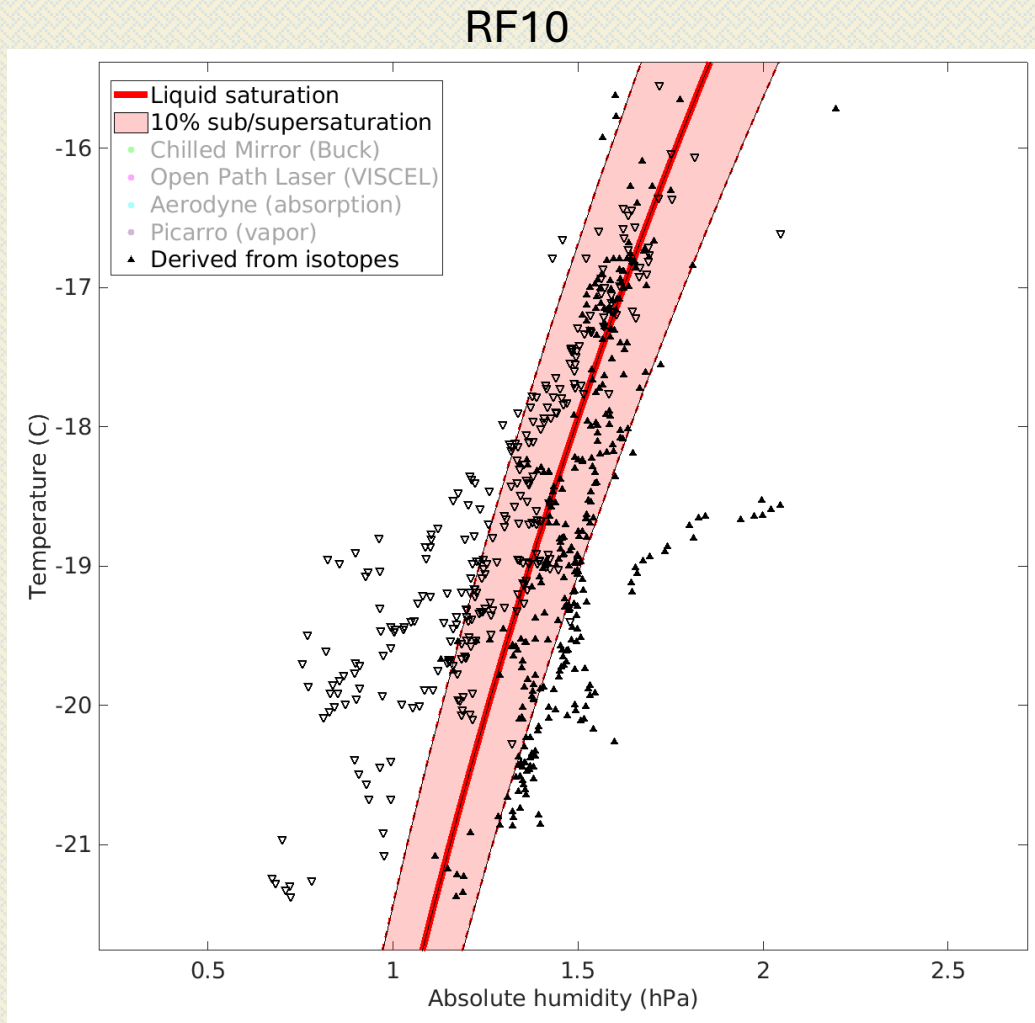
$$\alpha = \begin{cases} \alpha_{\text{liq}}(T, S) \\ \alpha_{\text{ice}}(T, S) \end{cases}$$

With direct measurement of α and temperature (T),
we only have two unknown variables:

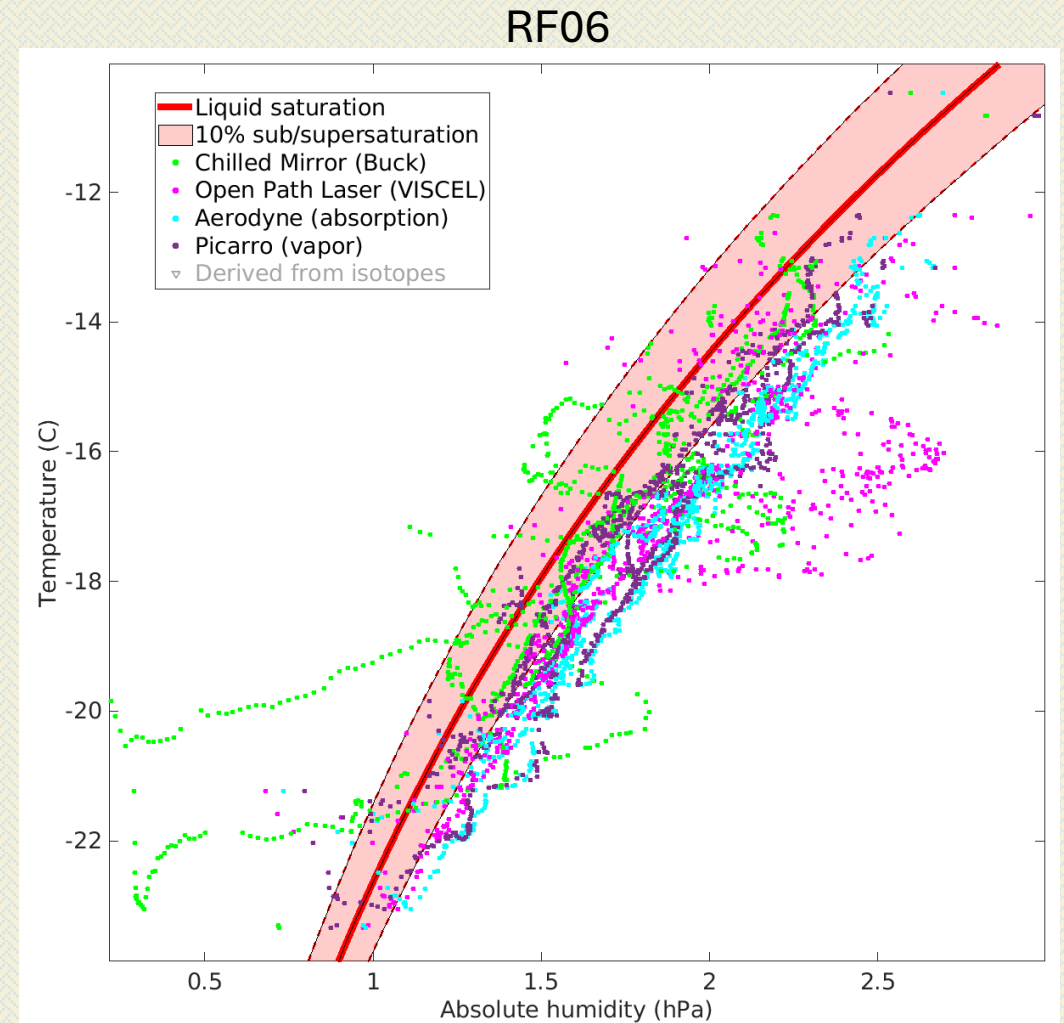
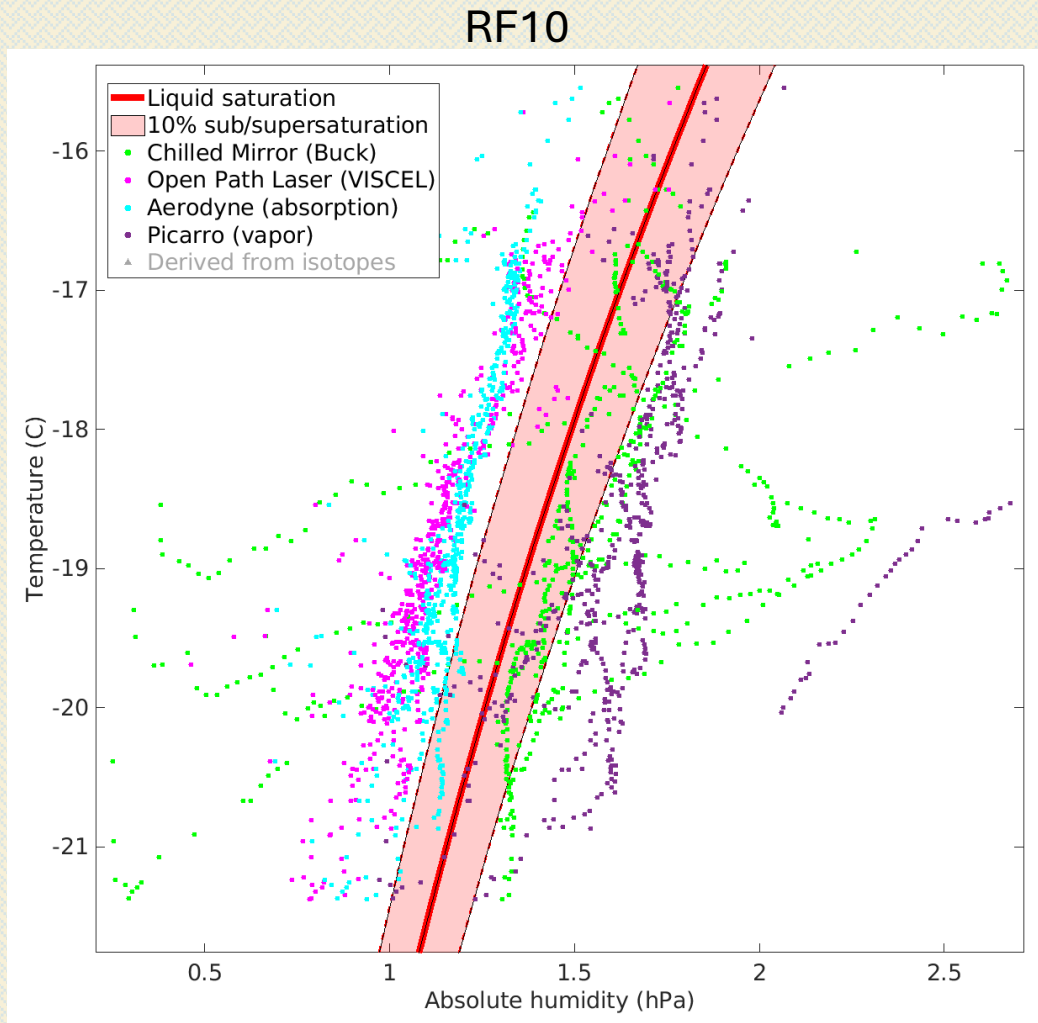
phase (*ice, liq*) and supersaturation (S)

LIQUID REGIONS: Solve for supersaturation (S)

In-cloud supersaturation from the condensate's perspective: Do the isotopic measurements yield physically realistic results?



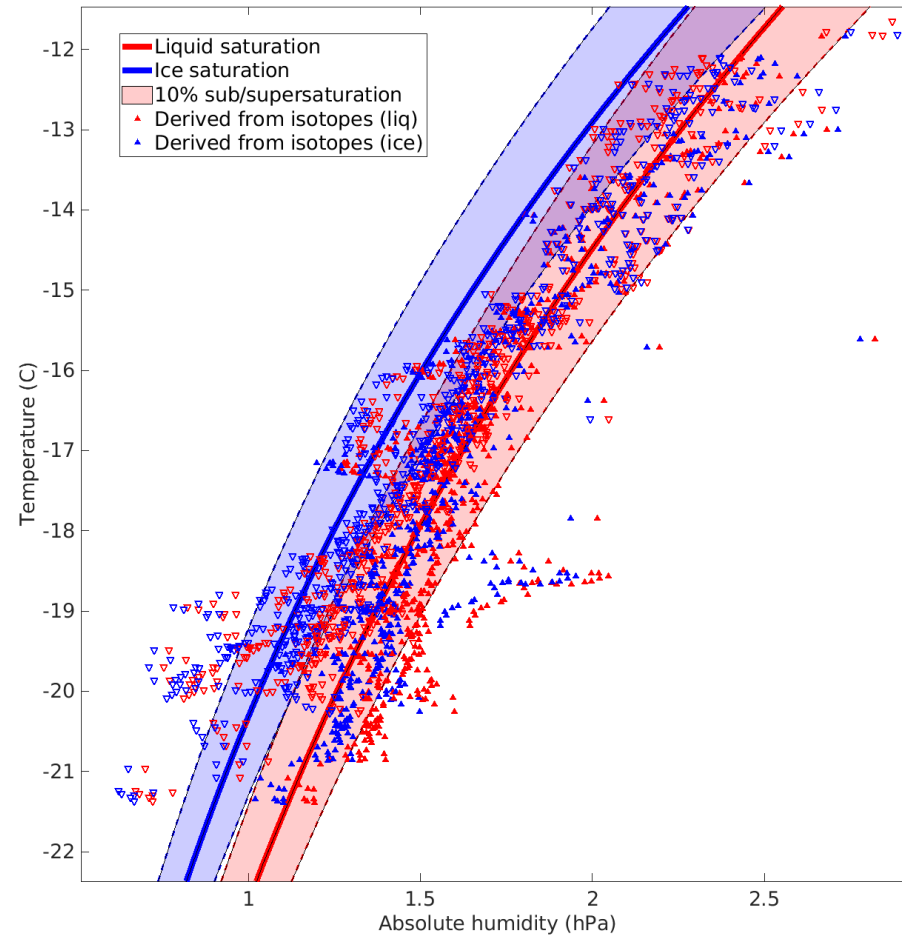
In-cloud supersaturation from the condensate's perspective: Do the isotopic measurements yield physically realistic results?



In-cloud supersaturation from the condensate's perspective: Does the isotopic measurement yield physically realistic results?

All cloud regions:

$$\alpha = \begin{cases} \alpha_{\text{liq}}(T, S) \\ \alpha_{\text{ice}}(T, S) \end{cases}$$



Looking for specific ice growth regimes:

Do we see distinct isotopic signatures in the cloud ice?

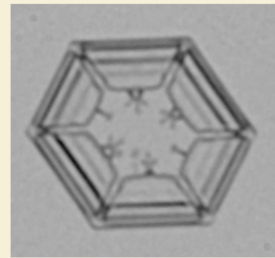
$$\alpha = \begin{cases} \alpha_{\text{liq}}(T, S) \\ \alpha_{\text{ice}}(T, S) \end{cases}$$

In the ice and mixed,
we still have two
unknowns:

liq/ice and
supersaturation

DIRECT

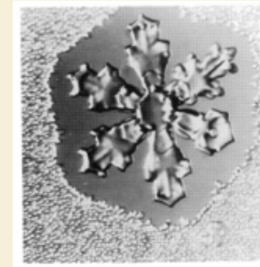
$$S = S_{\text{ice}}$$



Ice grows with no liquid
intermediate

WBF

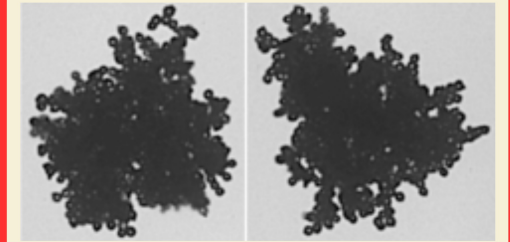
$$S_{\text{ice}} < S < S_{\text{liq}}$$



Ice grows from
evaporating droplets

RIMING

$$S_{\text{ice}} < S_{\text{liq}} \leq S$$



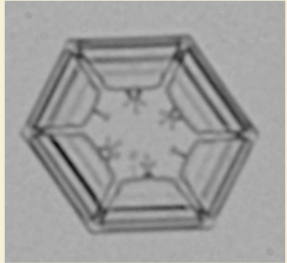
Liquid droplets grow
and freeze into ice

Looking for specific ice growth regimes: Do we see distinct isotopic signatures in the cloud ice?

$$\alpha = \begin{cases} \alpha_{\text{liq}}(T, S) \\ \alpha_{\text{ice}}(T, S) \end{cases}$$

DIRECT

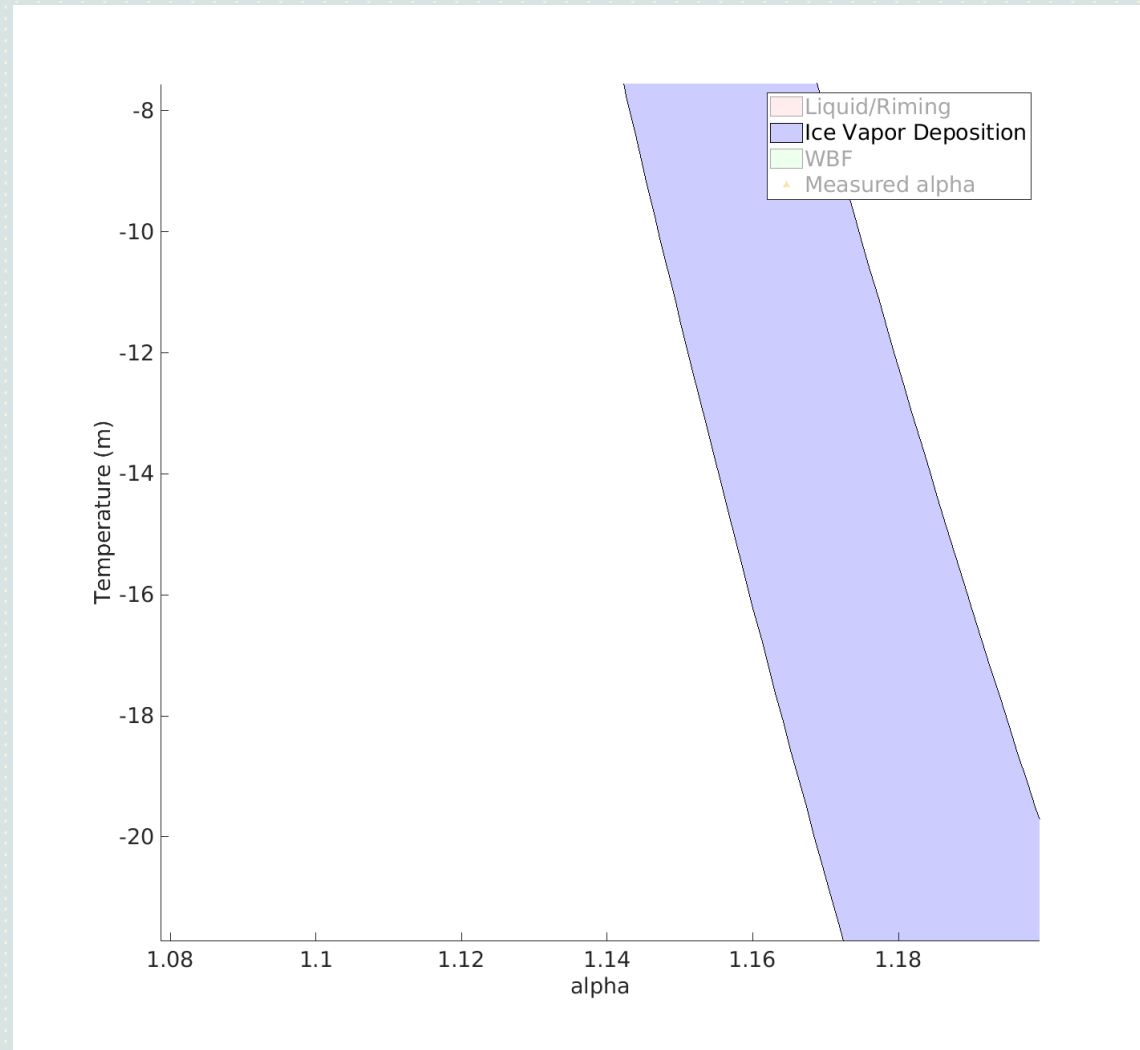
$$S = S_{\text{ice}}$$



Ice grows with no liquid intermediate

Isotopes resemble ice grown at saturation.

$$R_c = \alpha_i(e_i)R_v$$



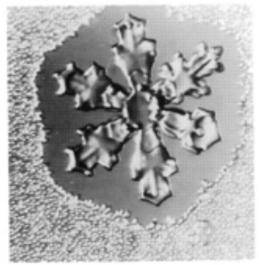
Looking for specific ice growth regimes:

Do we see distinct isotopic signatures in the cloud ice?

$$\alpha = \begin{cases} \alpha_{\text{liq}}(T, S) \\ \alpha_{\text{ice}}(T, S) \end{cases}$$

WBF

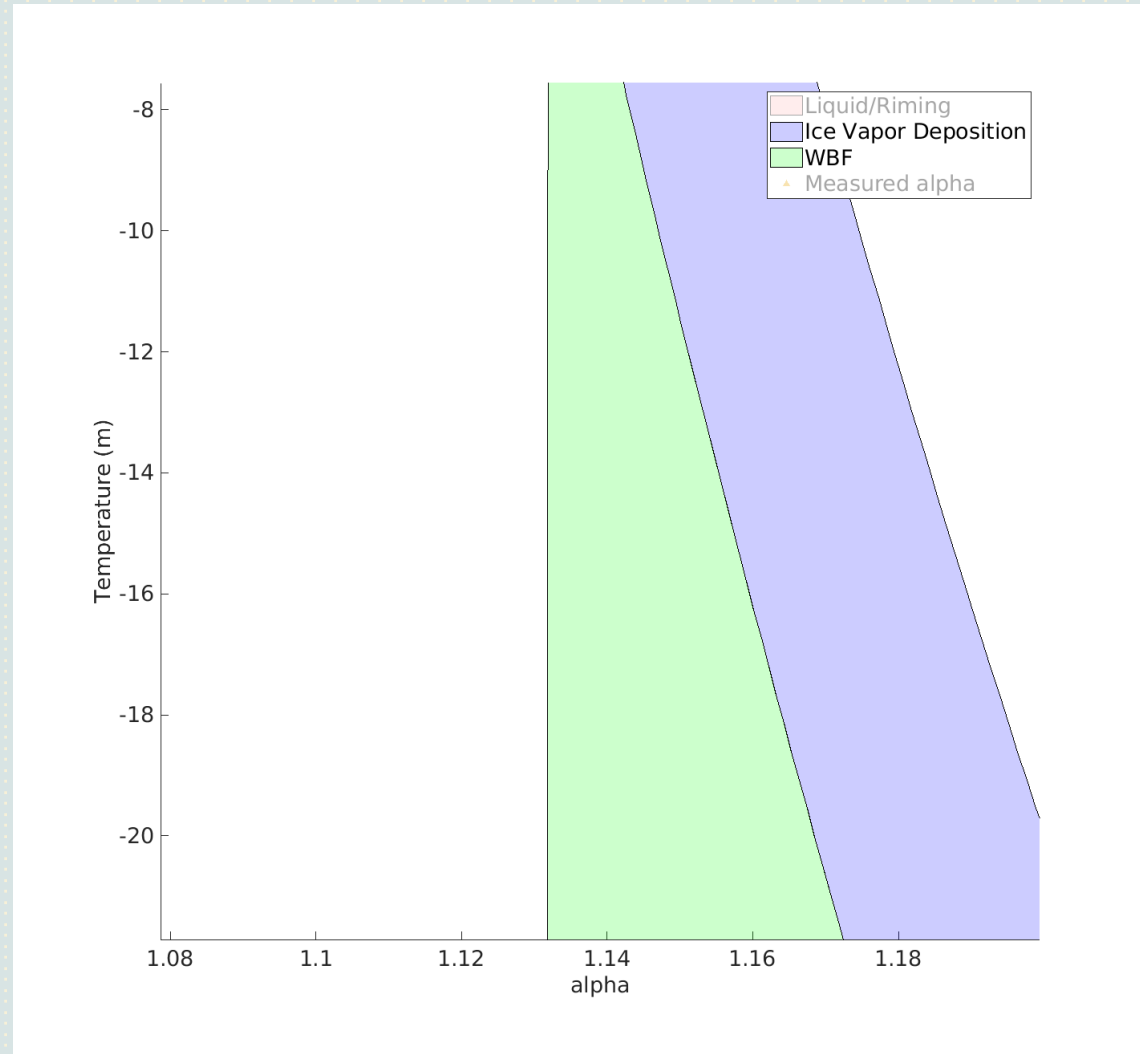
$$S_{\text{ice}} < \mathbf{S} < S_{\text{liq}}$$



Ice grows from evaporating droplets

Isotopes resemble ice grown in supersaturation.

$$R_c = \alpha_i(e_l > e > e_i)R_v$$

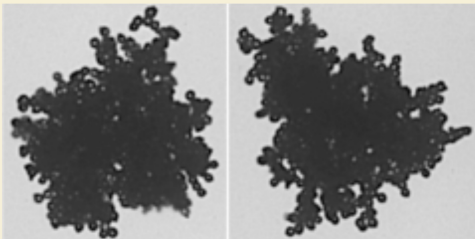


Looking for specific ice growth regimes: Do we see distinct isotopic signatures in the cloud ice?

$$\alpha = \begin{cases} \alpha_{\text{liq}}(T, S) \\ \alpha_{\text{ice}}(T, S) \end{cases}$$

RIMING

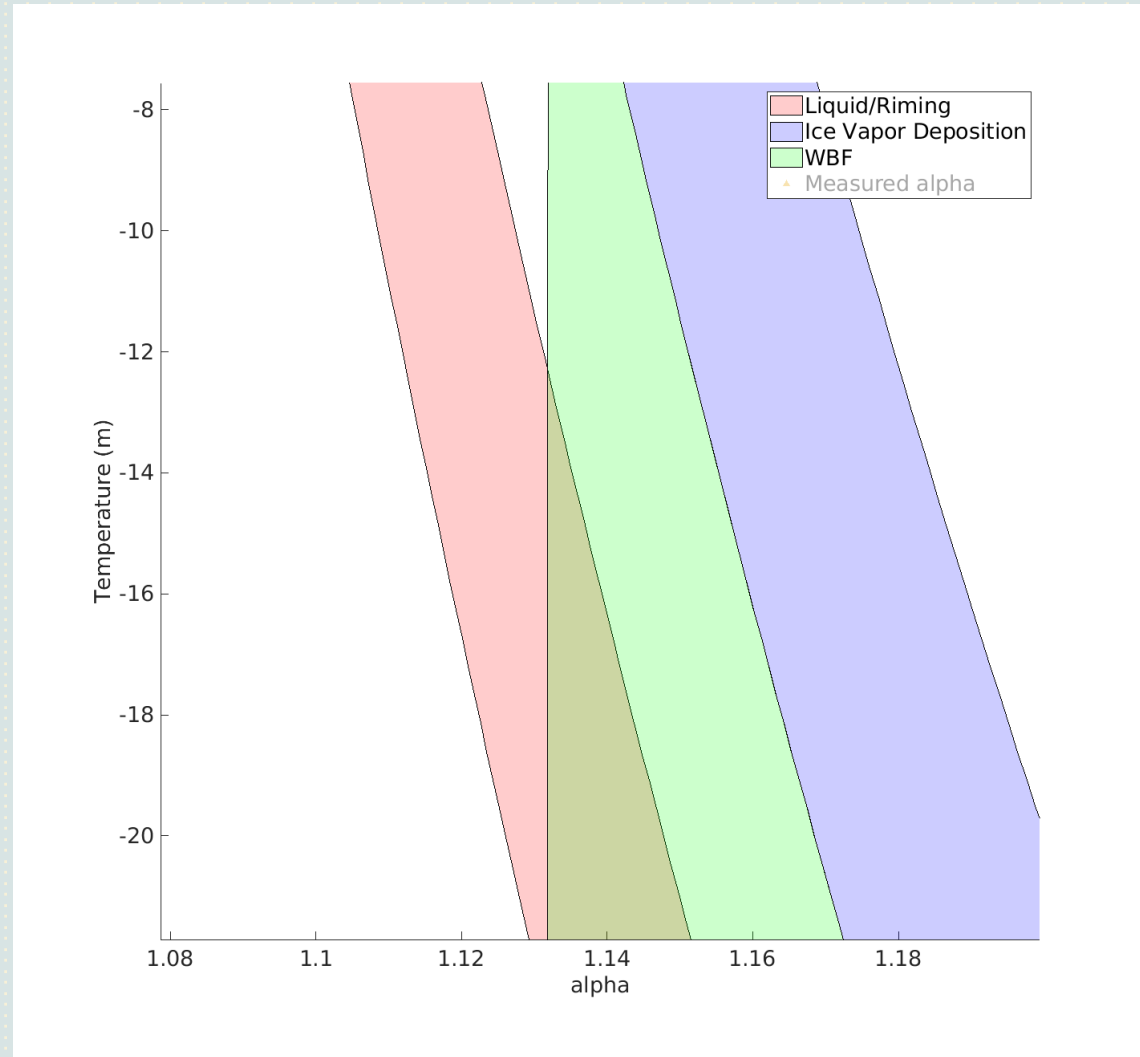
$$S_{\text{ice}} < S_{\text{liq}} \leq S$$



Liquid droplets grow
and freeze into ice

Isotopes resemble liquid
grown at saturation.

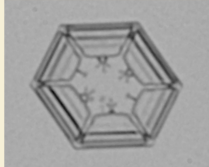
$$R_c = \alpha_l(e_l)R_v$$



Looking for specific ice growth regimes:

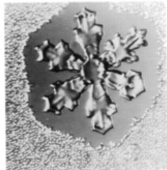
Do we see distinct isotopic signatures in the cloud ice?

$$S = S_{ice}$$



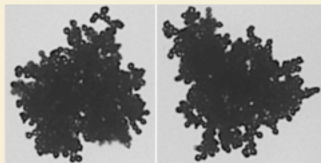
Ice grows with no liquid intermediate

$$S_{ice} < S < S_{liq}$$

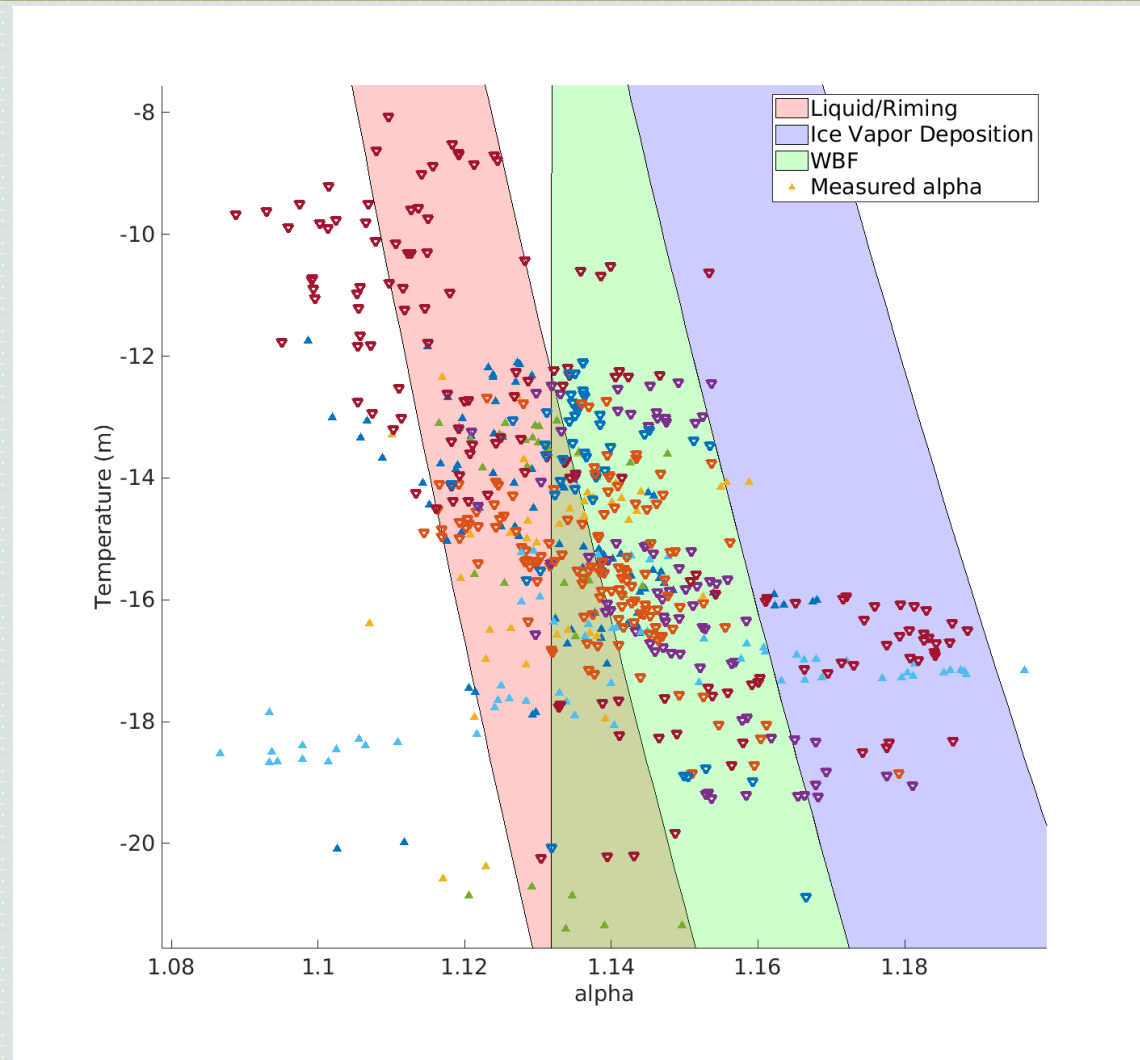


Ice grows from evaporating droplets

$$S_{ice} < S_{liq} \leq S$$

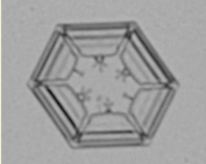


Liquid droplets grow and freeze into ice



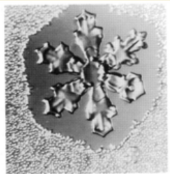
Looking for specific ice growth regimes: Do we see distinct isotopic signatures in the cloud ice?

$S = S_{ice}$



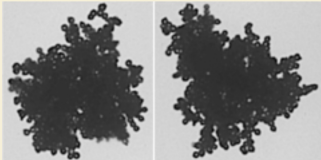
Ice grows with no liquid intermediate

$S_{ice} < S < S_{liq}$



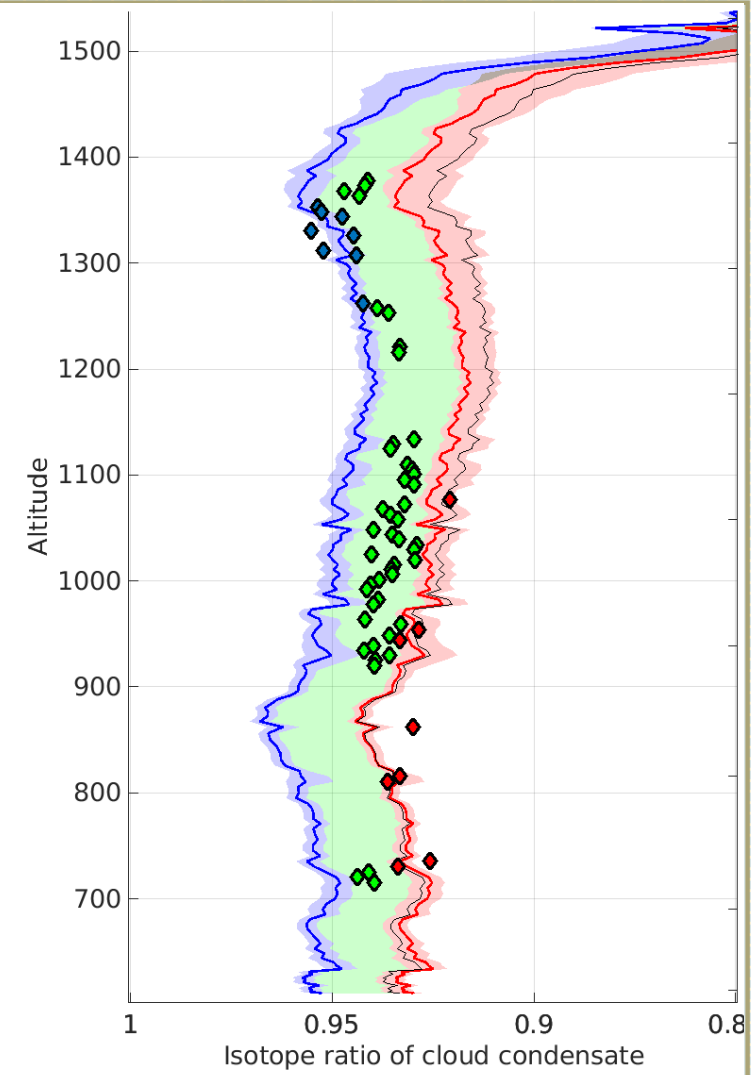
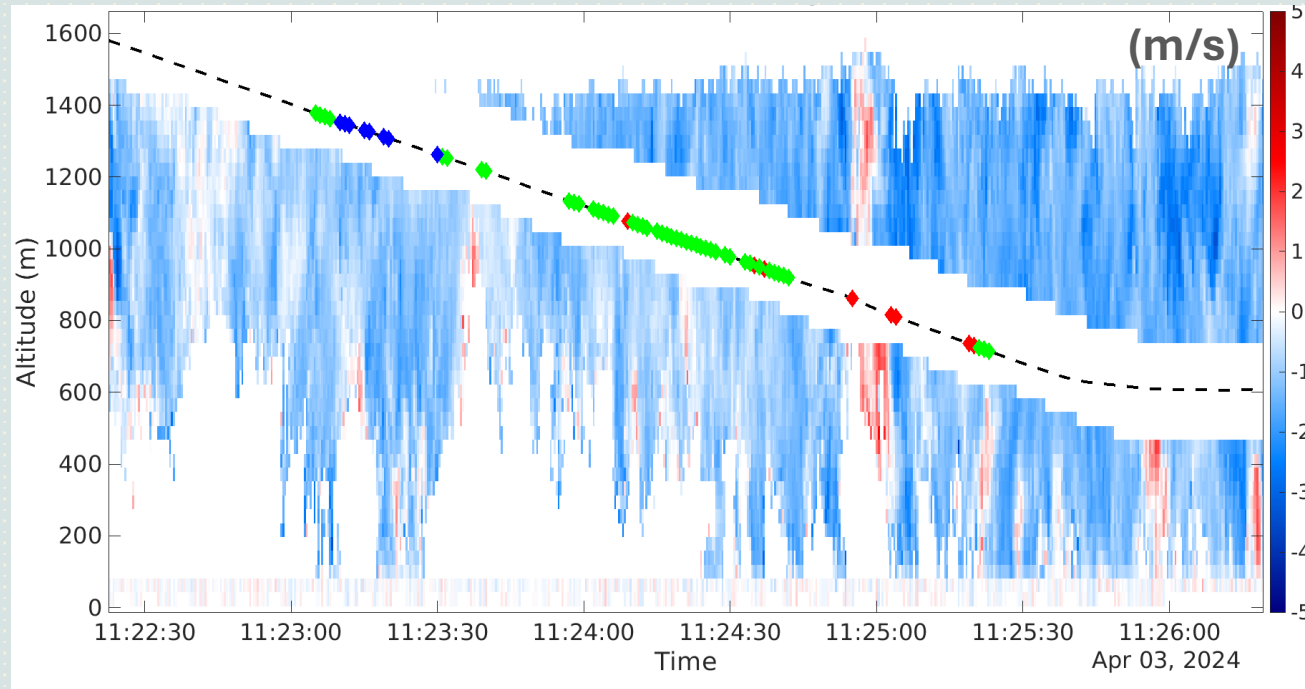
Ice grows from evaporating droplets

$S_{ice} < S_{liq} \leq S$

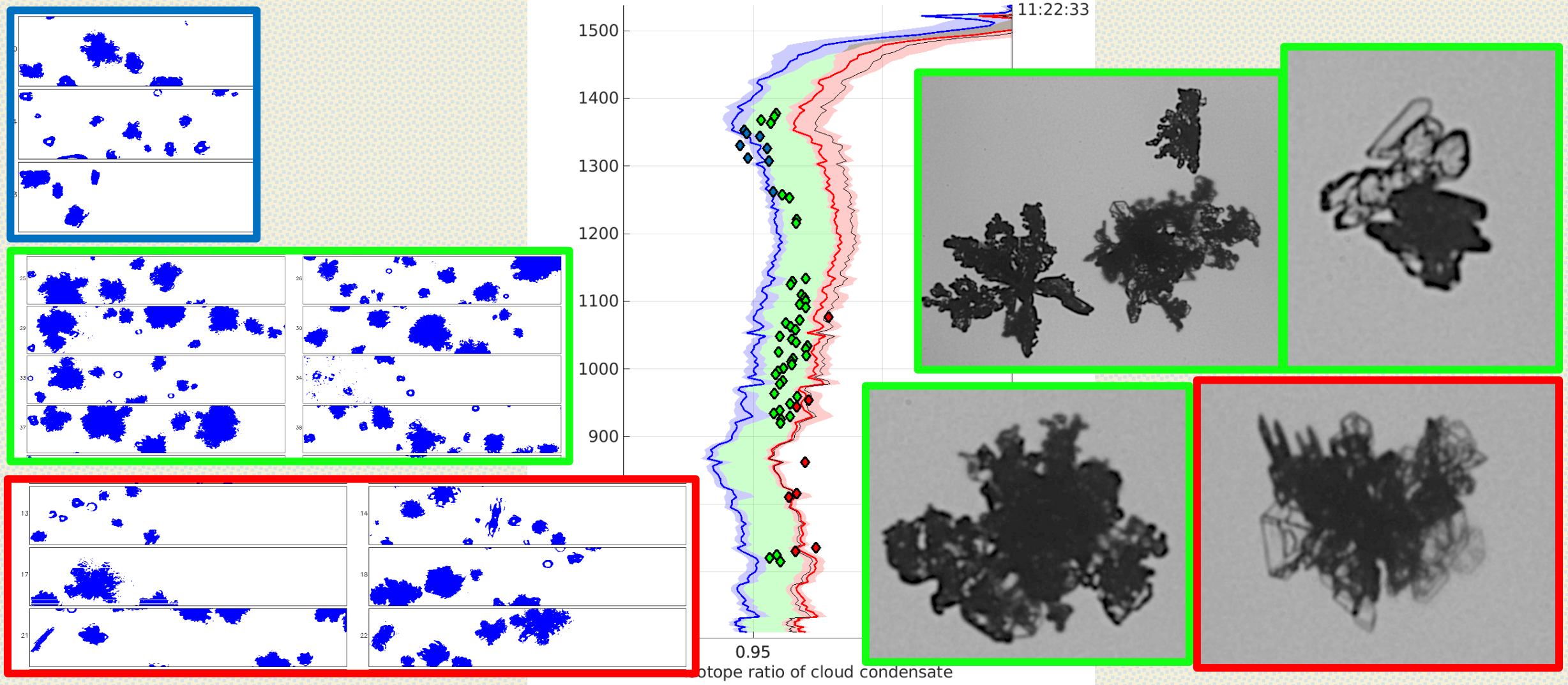


Liquid droplets grow and freeze into ice

Analyzing ice-dominated cloud regions only
(liquid cloud not included)



Particle Images: F2DS, PHIPS



Conclusions: Proof of Concept

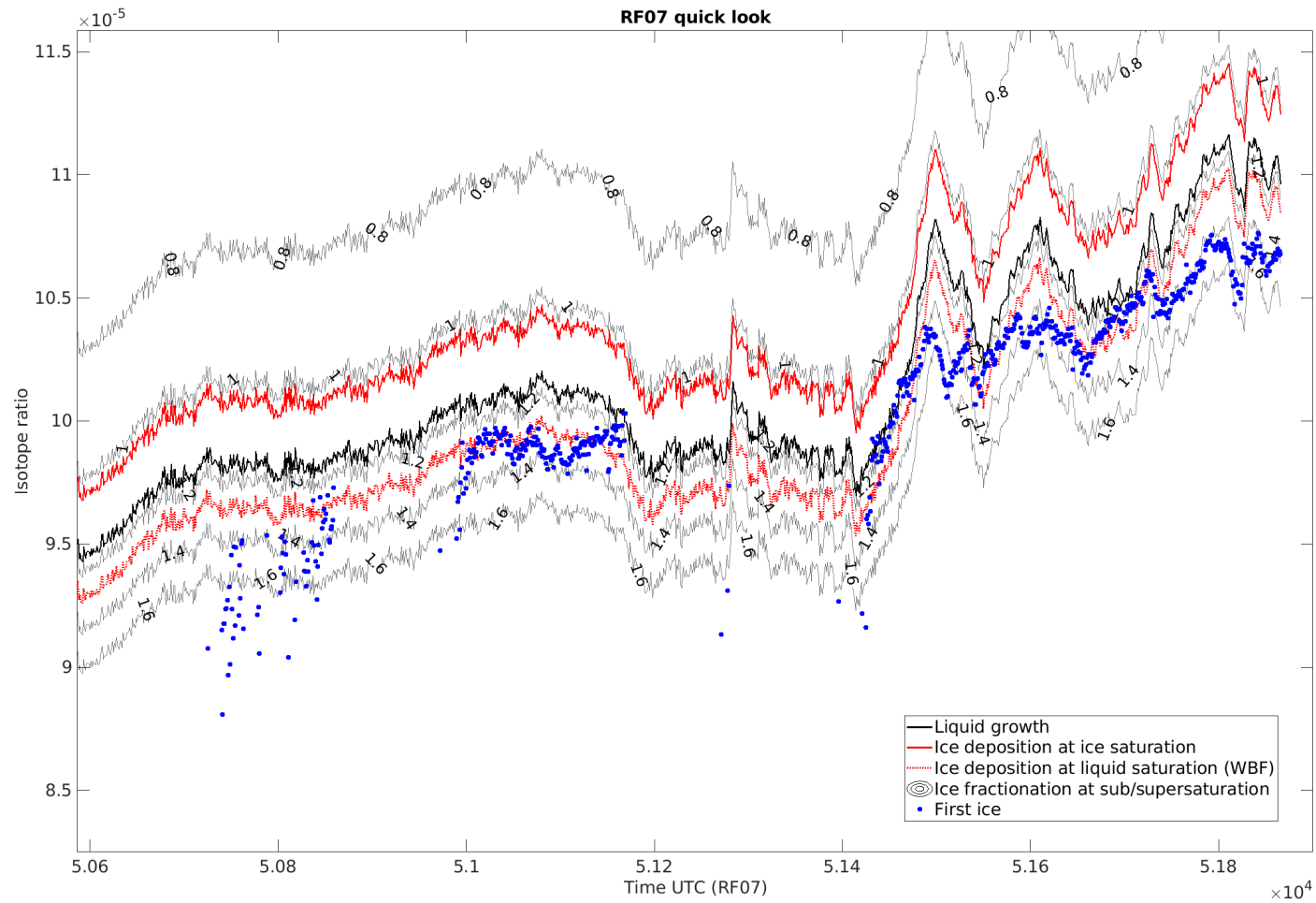
In-situ isotopic analysis holds potential for observational constraints on mixed-phase thermodynamics and microphysics.

(Rosky et al. 2026, In preparation.)

- Hasn't been used for science yet.
- Stickers at dinner
- Unofficial CAESAR snowflake music video:



RF07

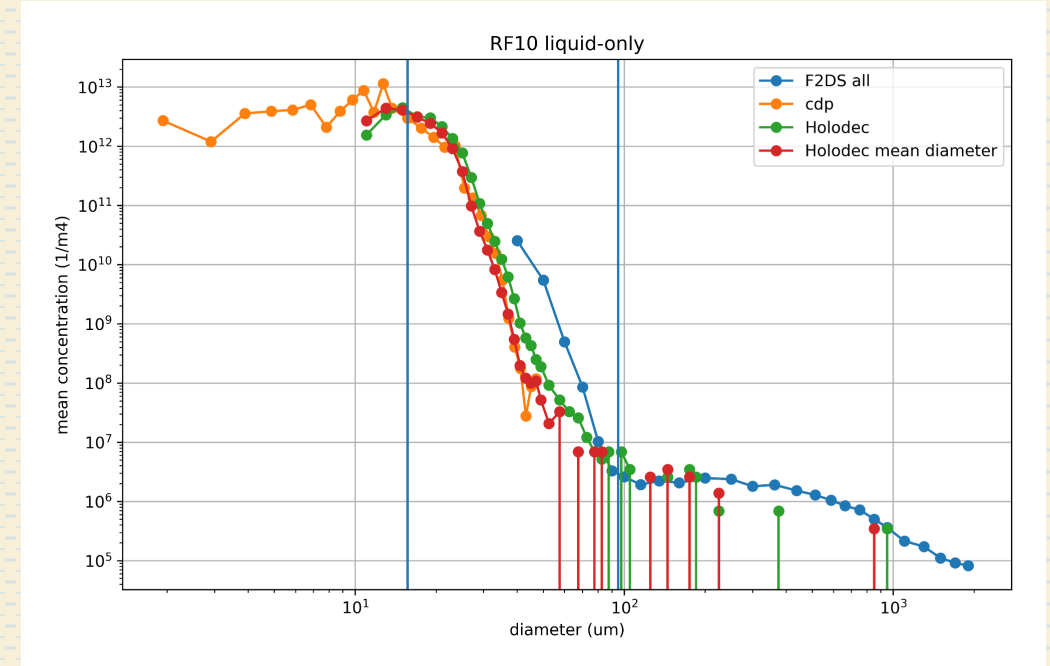
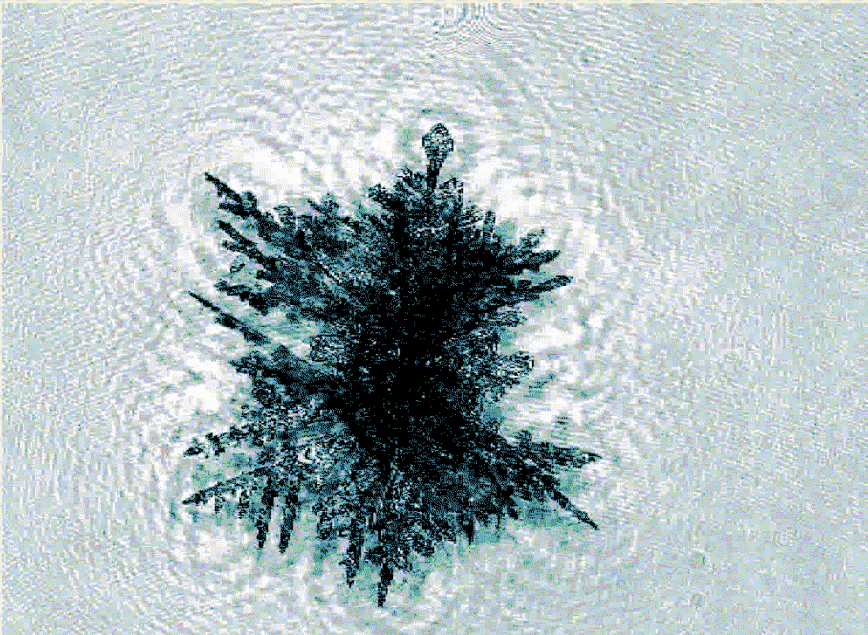


HOLODEC

NCAR EOL Field Data Archive

➤ CAESAR: Cloud Microphysics Value Added Product

- Indispensable in helping improve the 2DS data (Aaron Bansemer, NCAR).



- Habit ID capability (similar to PHIPS).
- Also similar to PHIPS in that ice statistics are small.

$$R_{\text{condensate}} = \alpha \cdot R_{\text{vapor}}$$

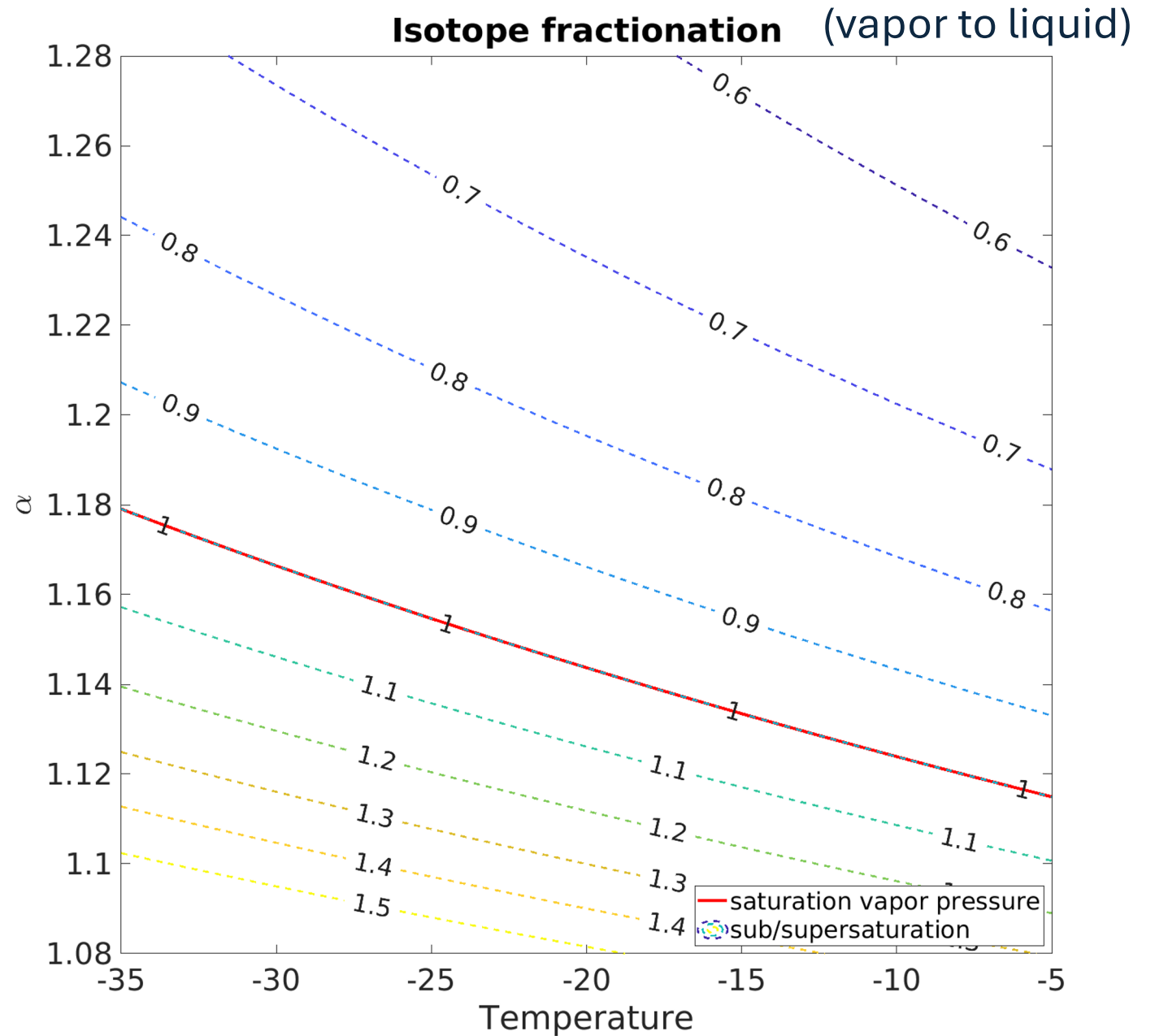
α is a function of temperature

α also a function of supersaturation (dashed lines)

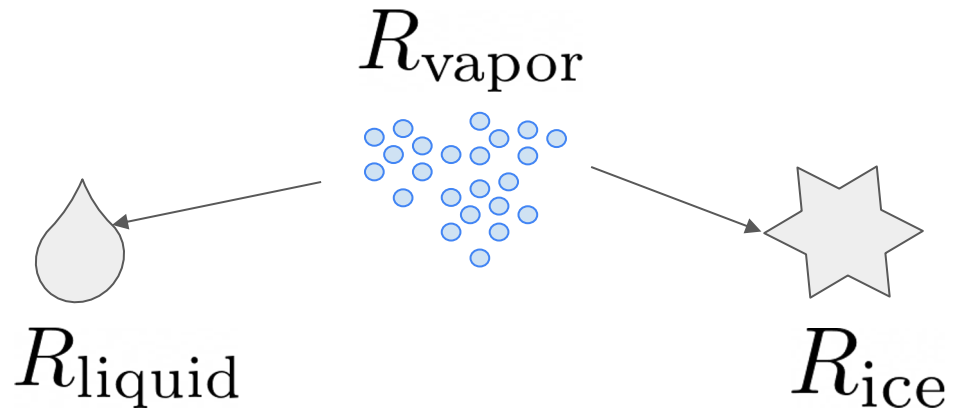
Jouzel and Merlivat (1984)

Merlivat and Nief (1967)

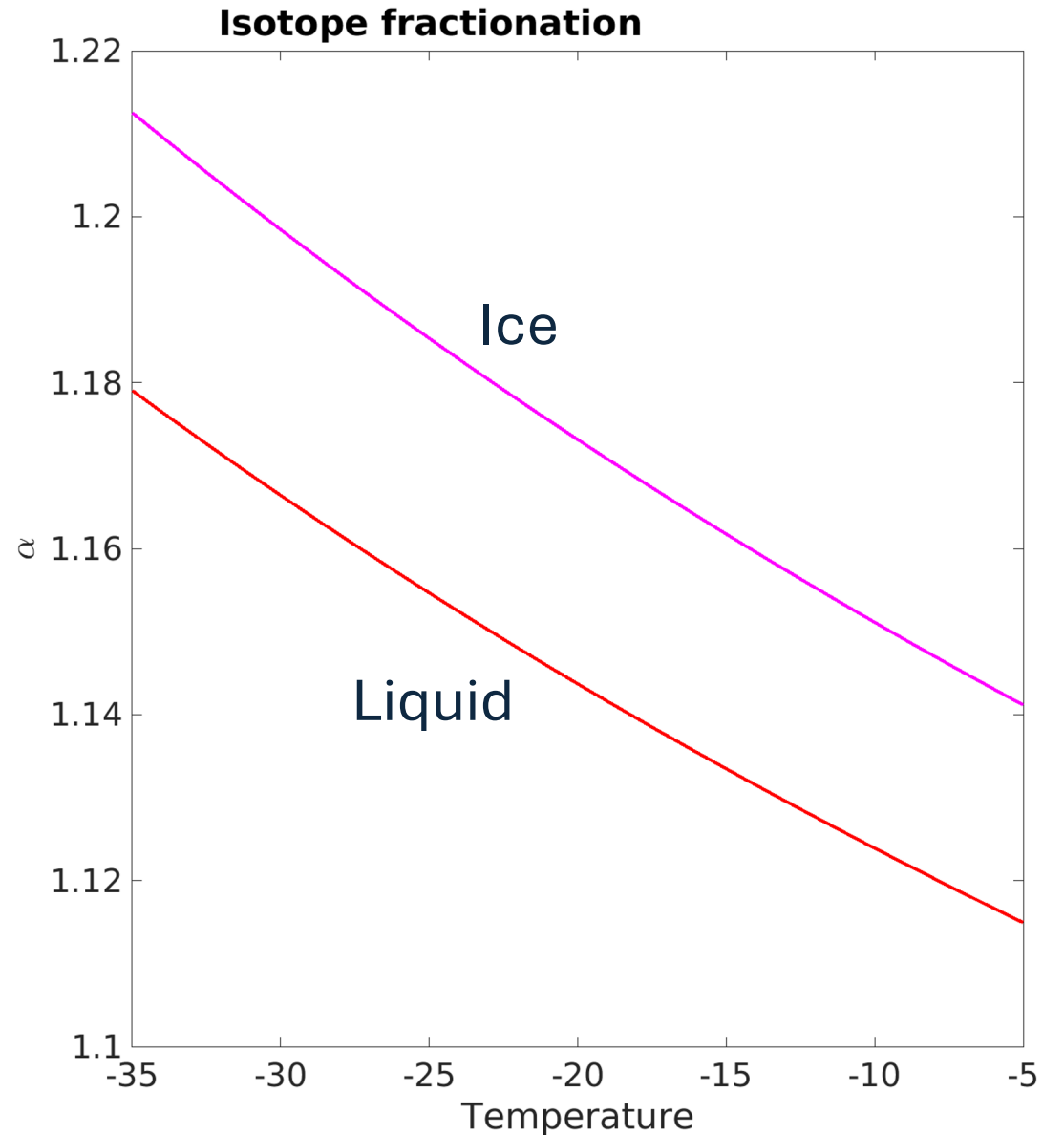
Majoube (1971) and Majoube (1970)



α differs for liquid and ice growth



$$R_{\text{ice}} = \alpha_{\text{ice}} \cdot R_{\text{vapor}}$$
$$R_{\text{liq}} = \alpha_{\text{liq}} \cdot R_{\text{vapor}}$$



The original formulation of α_k from Jouzel and Merlivat (1984):

$$\alpha_{k|v \rightarrow i} = \frac{\alpha_{e|v \rightarrow i} S_i}{\alpha_{e|v \rightarrow i} (K_v / K'_v) (S_i - 1) + 1}$$

$$\alpha_{e|v \rightarrow l}^D = \exp(15013/T^2 - 0.1)$$

$$\alpha_{e|v \rightarrow i}^D = \exp(16289/T^2 - 0.0945)$$

$$\alpha_{e|v \rightarrow l}^{18} = \exp\left(\frac{1137}{T^2} - \frac{0.4156}{T} - 0.0020667\right)$$

$$\alpha_{e|v \rightarrow i}^{18} = \exp\left(\frac{11.839}{T} - 0.028224\right)$$

Merlivat and Nief (1967)

Majoube (1971) and Majoube (1970)

$$\frac{K_v^H}{K_v^D} = 1.0251$$

$$\frac{K_v^O}{K_v^{18}} = 1.0289$$

