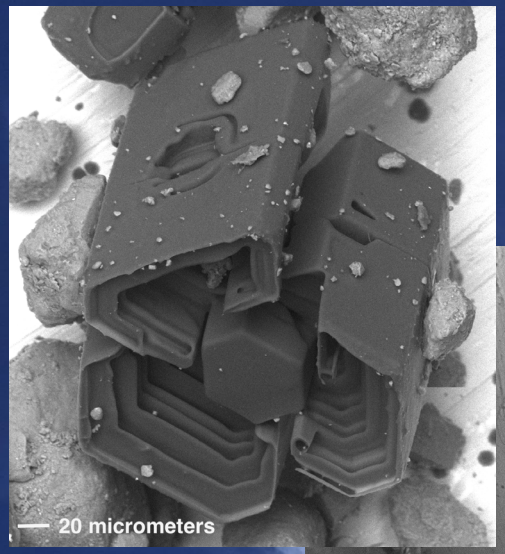
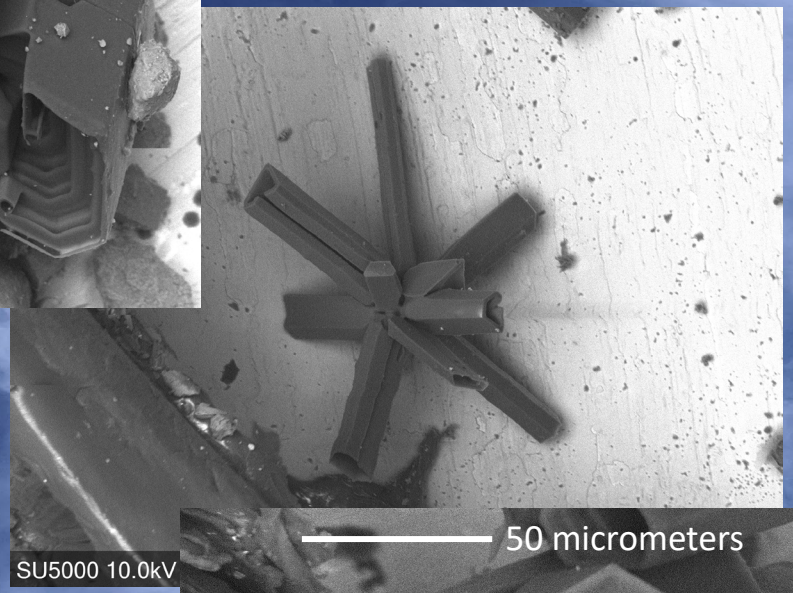
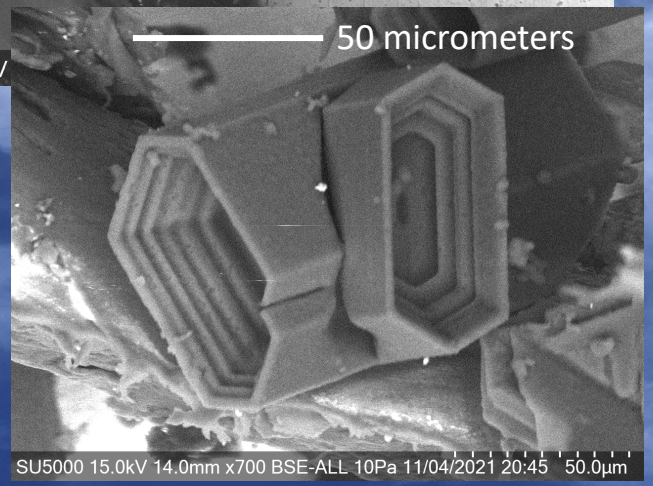
Effective Ice Crystal Densities in Cirrus: A General Criterion for The Morphological Instability that Causes Hollowing and Crystal Complexity







ICE-Ball Experiment 2021

Jerry Y. Harrington

with

Nathan Magee[2], Gwenore Pokrifka[1], Al Moyle[1], Israel Silber[3], Kamal Kant Chandrakar[4], and Hugh Morrison[4]

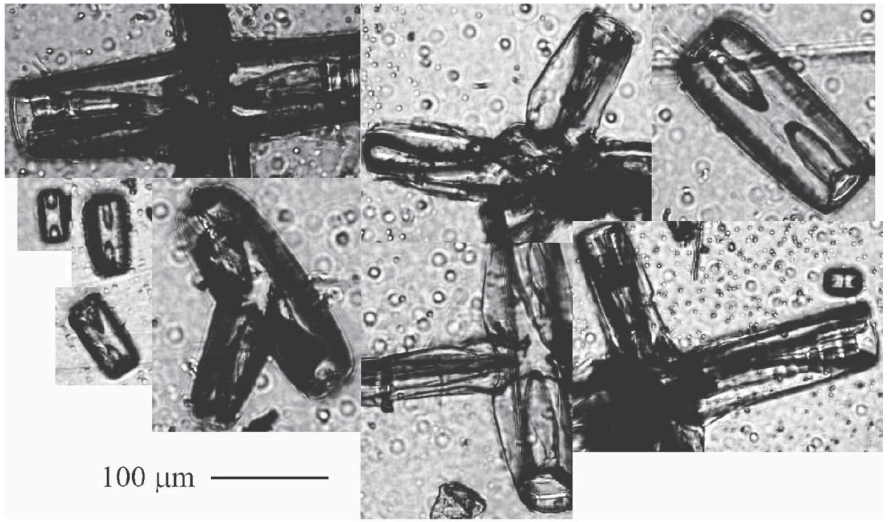
[1]The Pennsylvania State University

[2]The College of New Jersey

[3]Pacific Northwest National Lab

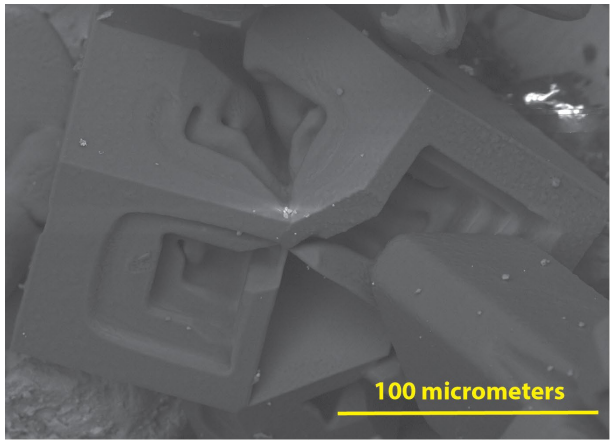
[4]National Center for Atmospheric Research

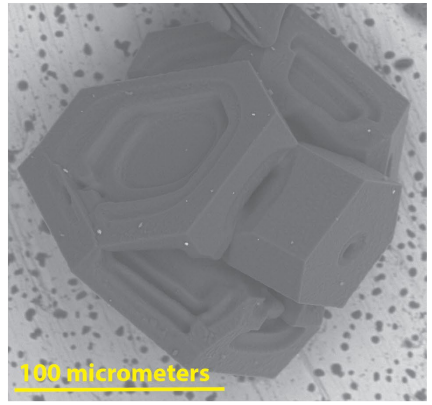
Morphology Transforms: hollowing is often the rule

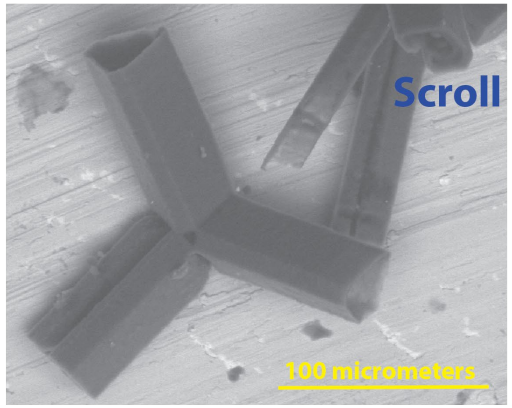


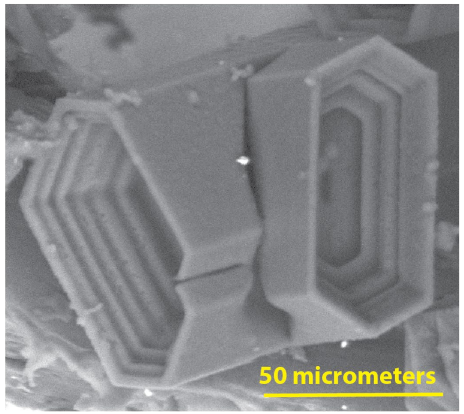
Schmitt and Heymsfield (2007)
~70% of Rosettes/Columns hollowed

ICE-Ball Experiment









Magee and Harrington (2023)

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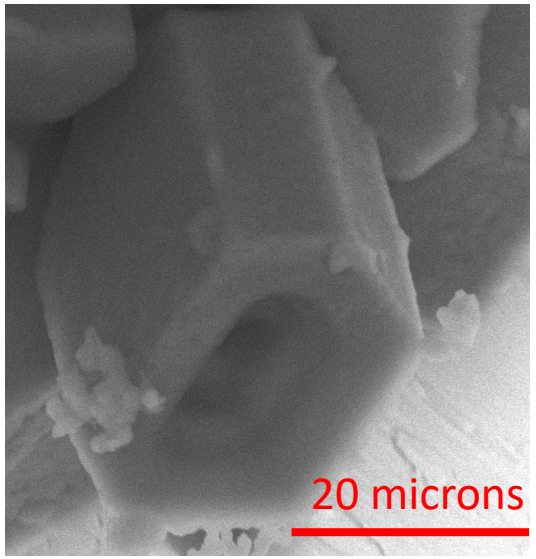
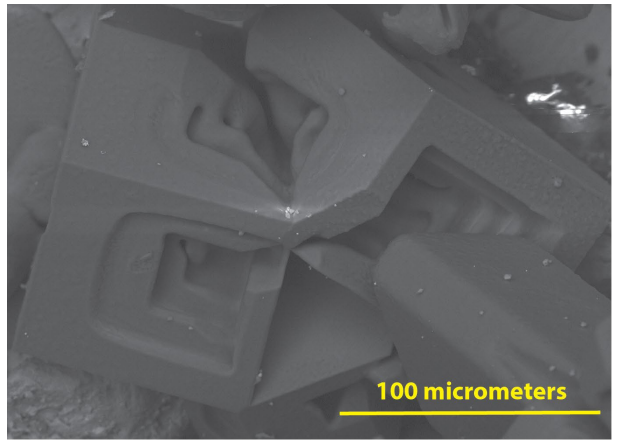
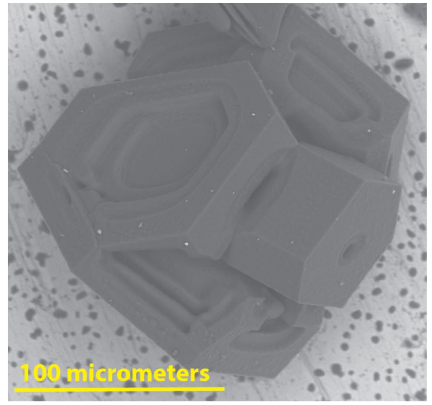
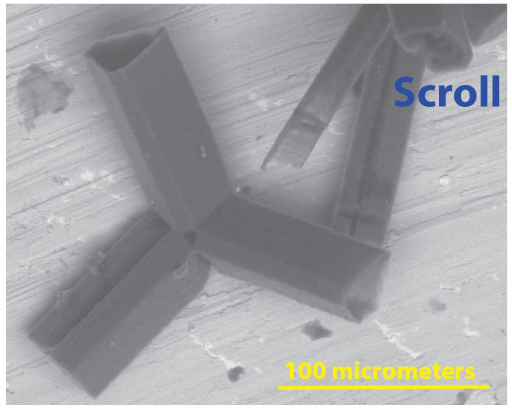


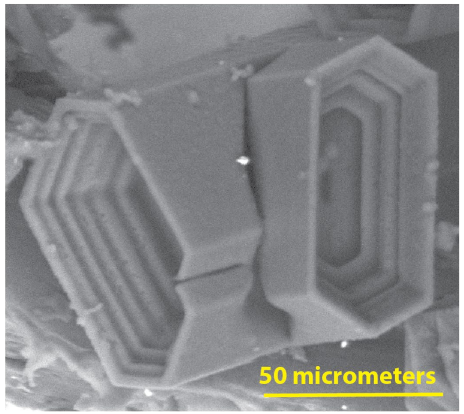
Even smallest crystals hollowed

ICE-Ball Experiment









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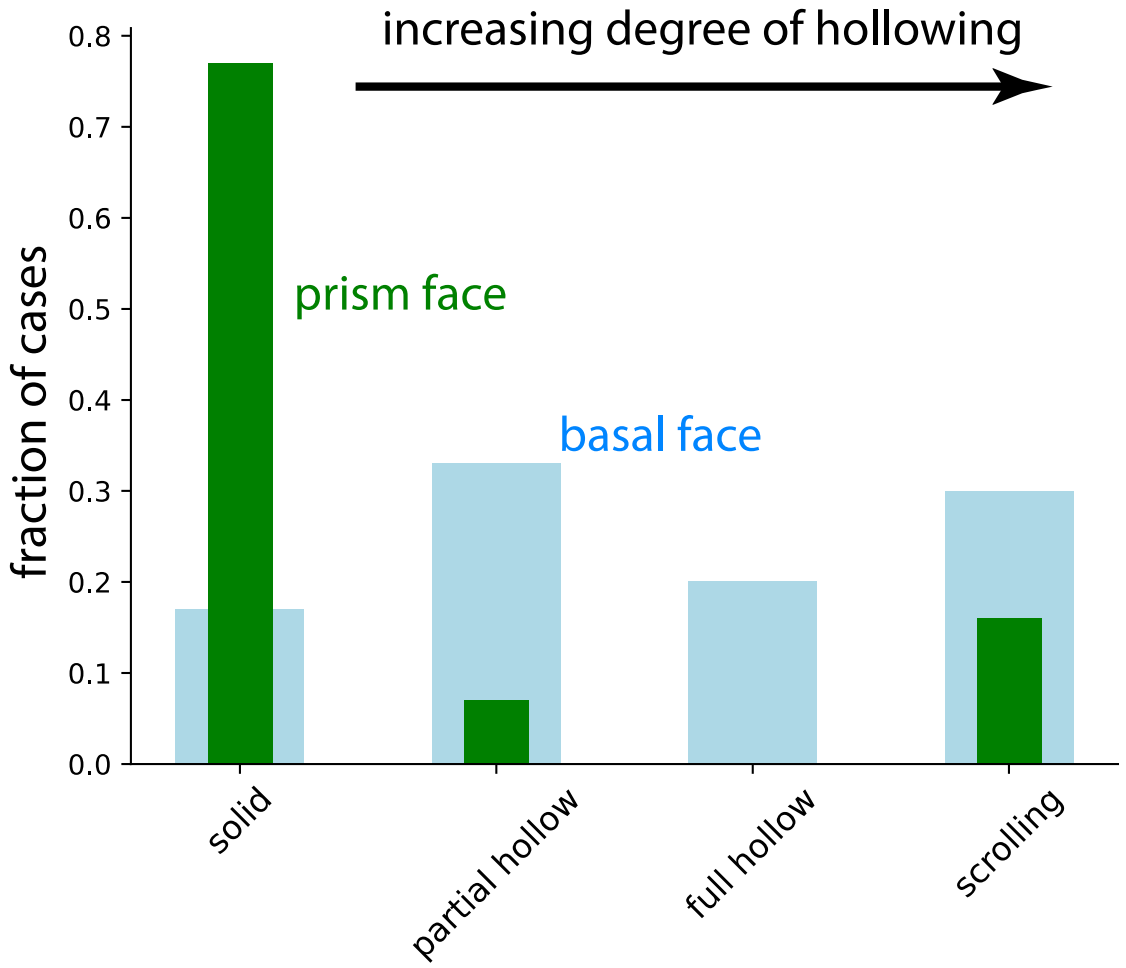
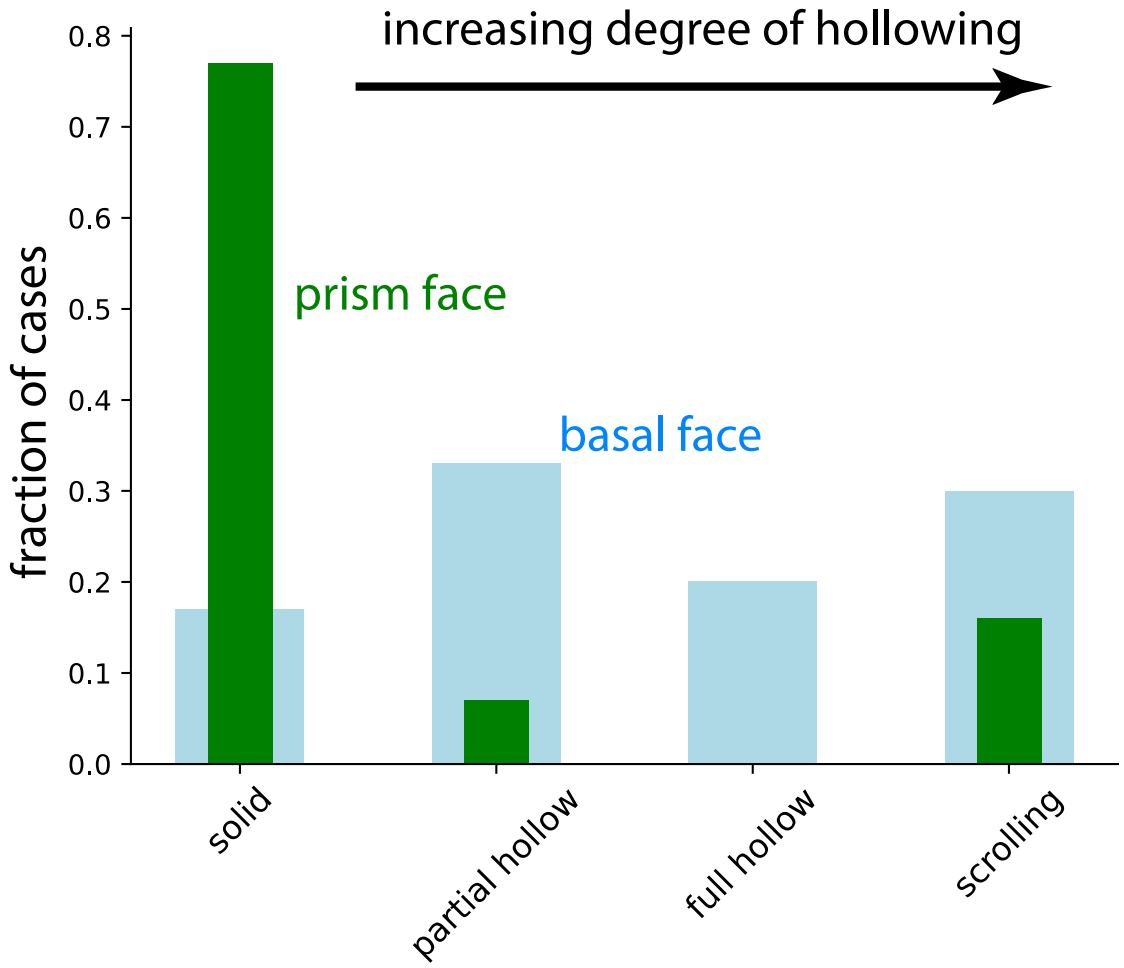


ICE-Ball October 23 Cirrus:

(1) Basal faces frequently hollowed (>80%)

(2) Prism faces infrequently hollowed

Morphology Transforms: hollowing is often the rule



ICE-Ball October 23 Cirrus:

(1) Basal faces frequently hollowed (>80%)

(2) Prism faces infrequently hollowed

(3) Effective Densities ~ 600 kg m^{-3} to solid ice

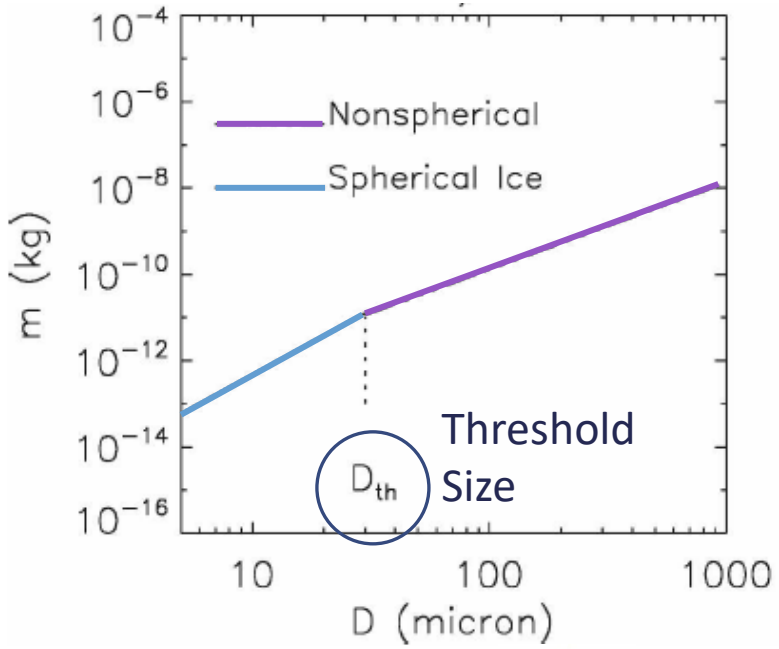
Morphology Transforms in numerical models

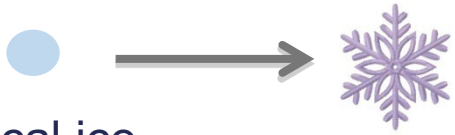
- **Size criterion** often used for morphological transformation:

$$m(D) = \alpha D^{\beta}$$

- But **supersaturation** appears to be the main driver**.**

Morrison and Milbrandt (2015)



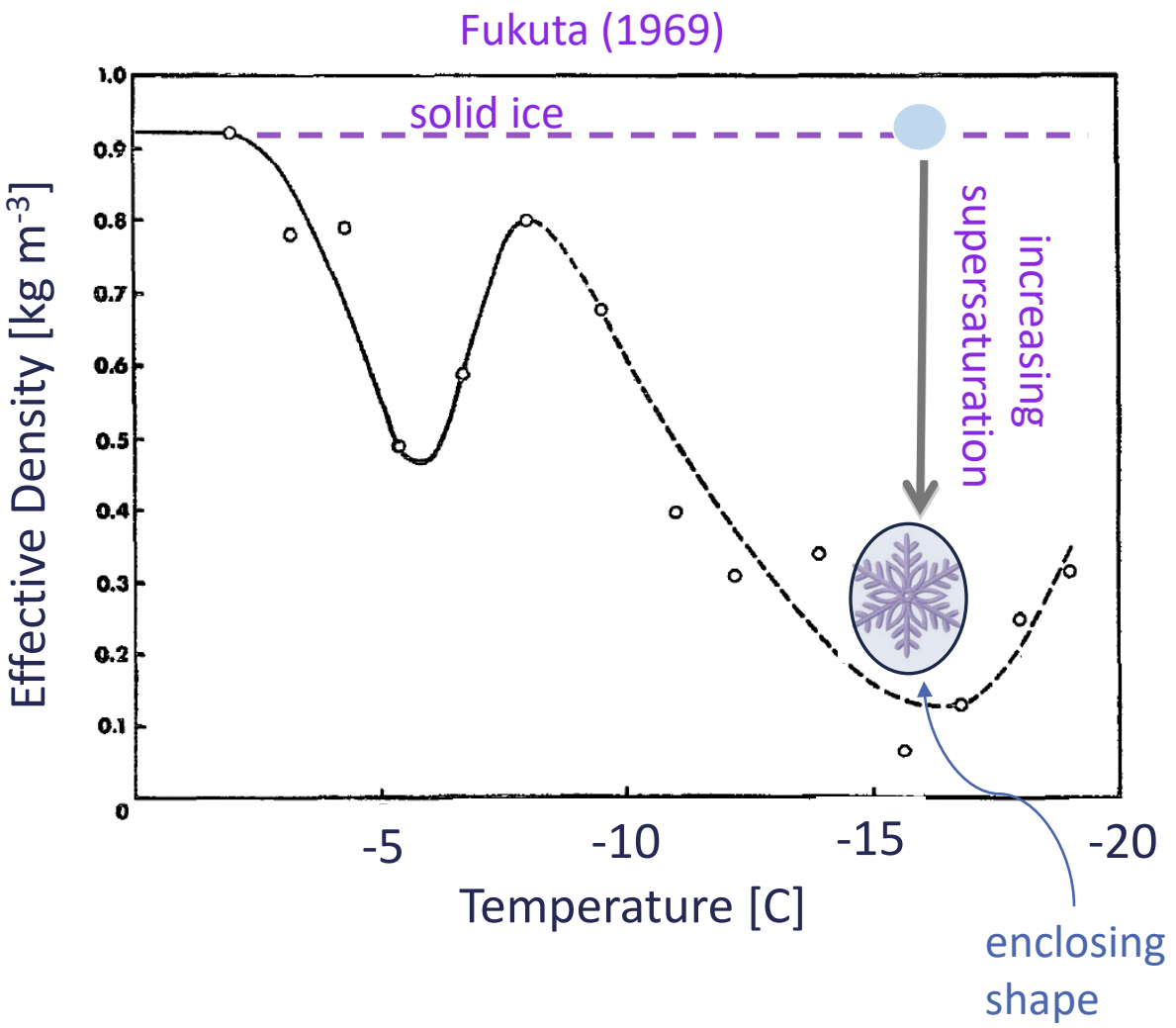


spherical ice
$\alpha_1 = \pi/6\ \rho_{bulk\_ice}$
$\beta_1 = 3$

non-spherical crystals
α_2 = const
$\beta_2 \sim 2$

Morphology Transforms in numerical models

- **Supersaturation Criterion:**
  - Some models use an **effective density**



Morphology Transforms in numerical models

- **Supersaturation Criterion:**
  - Some models use an **effective density**

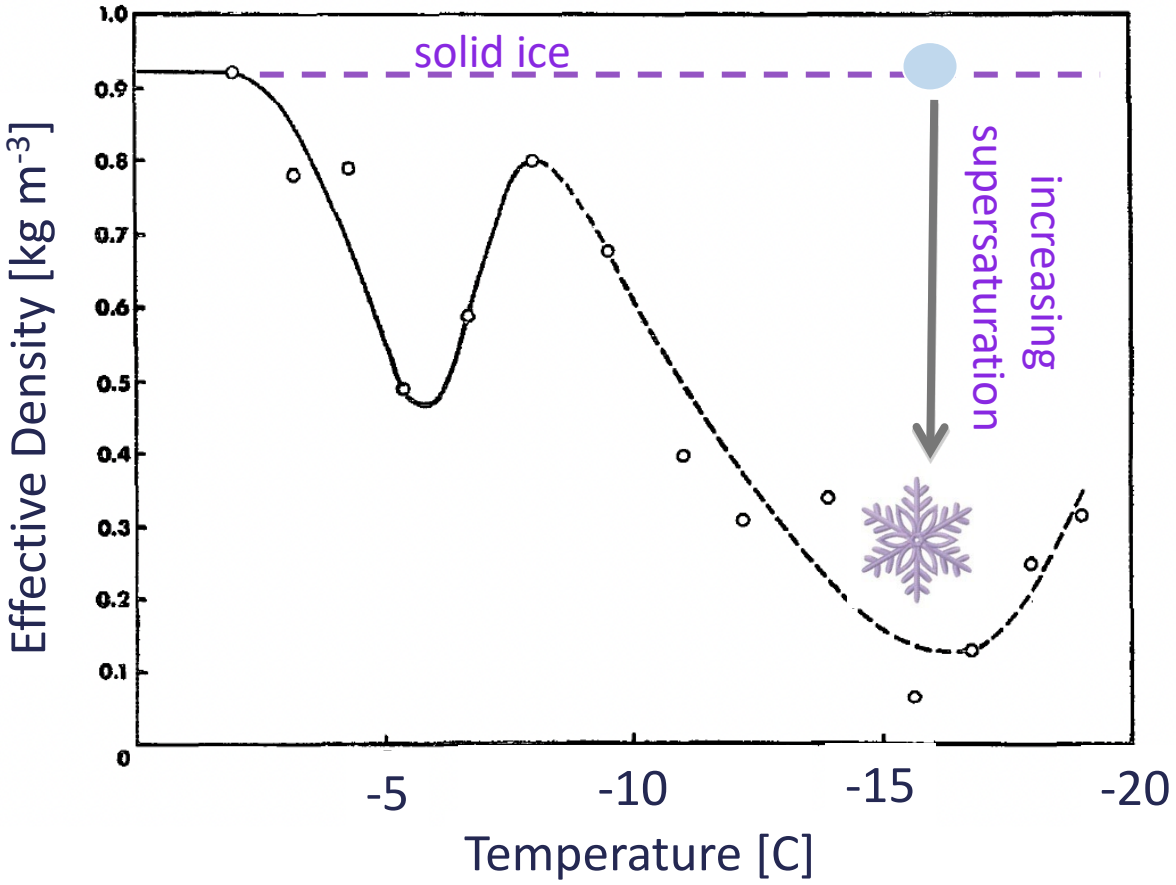
Chen & Lamb (1994)

$$\rho_{dep} = 0.91 \exp[-3 \cdot \max(\Delta\rho - 0.05, 0)/\Gamma(T)]$$

Miller & Young (1979)

$$\rho_s = 0.9 - \alpha(\Delta\rho - 0.05)$$

Fukuta (1969)



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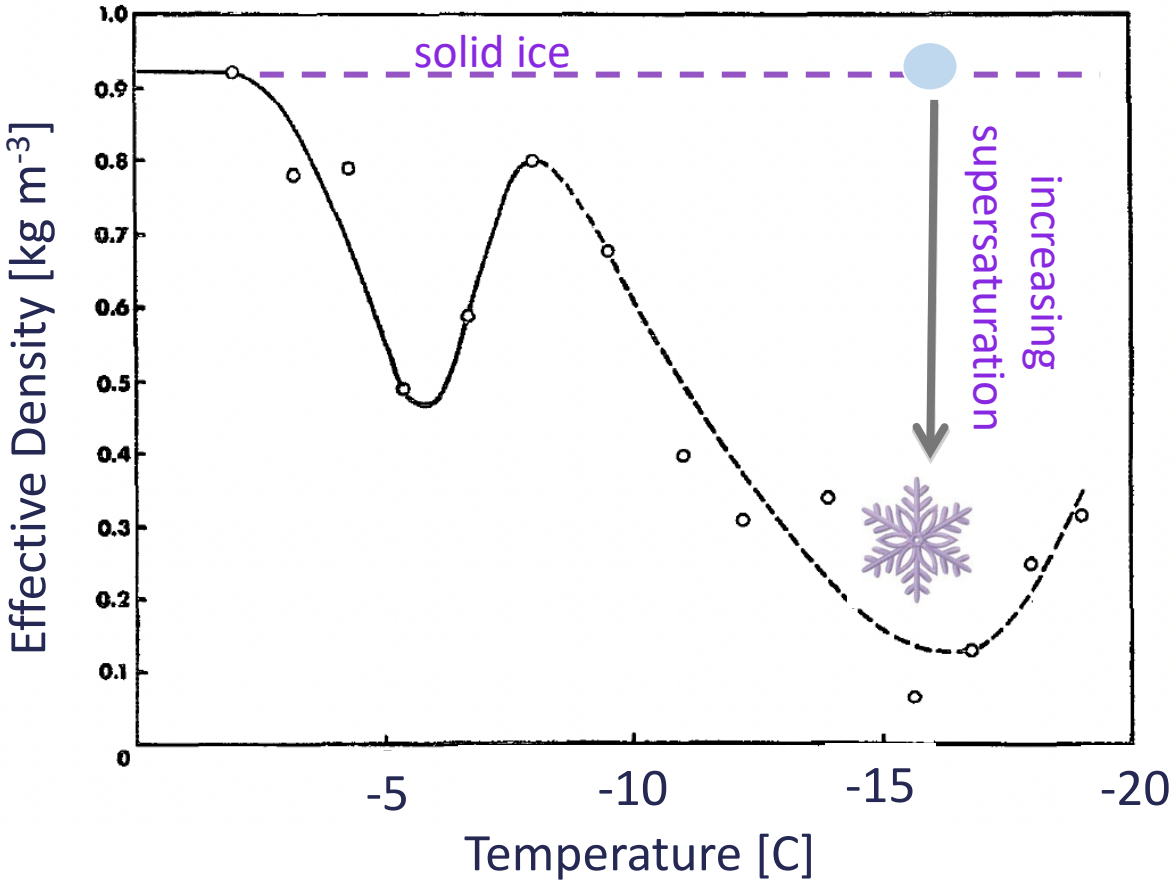
threshold value ($\Delta\rho_{thr}$)

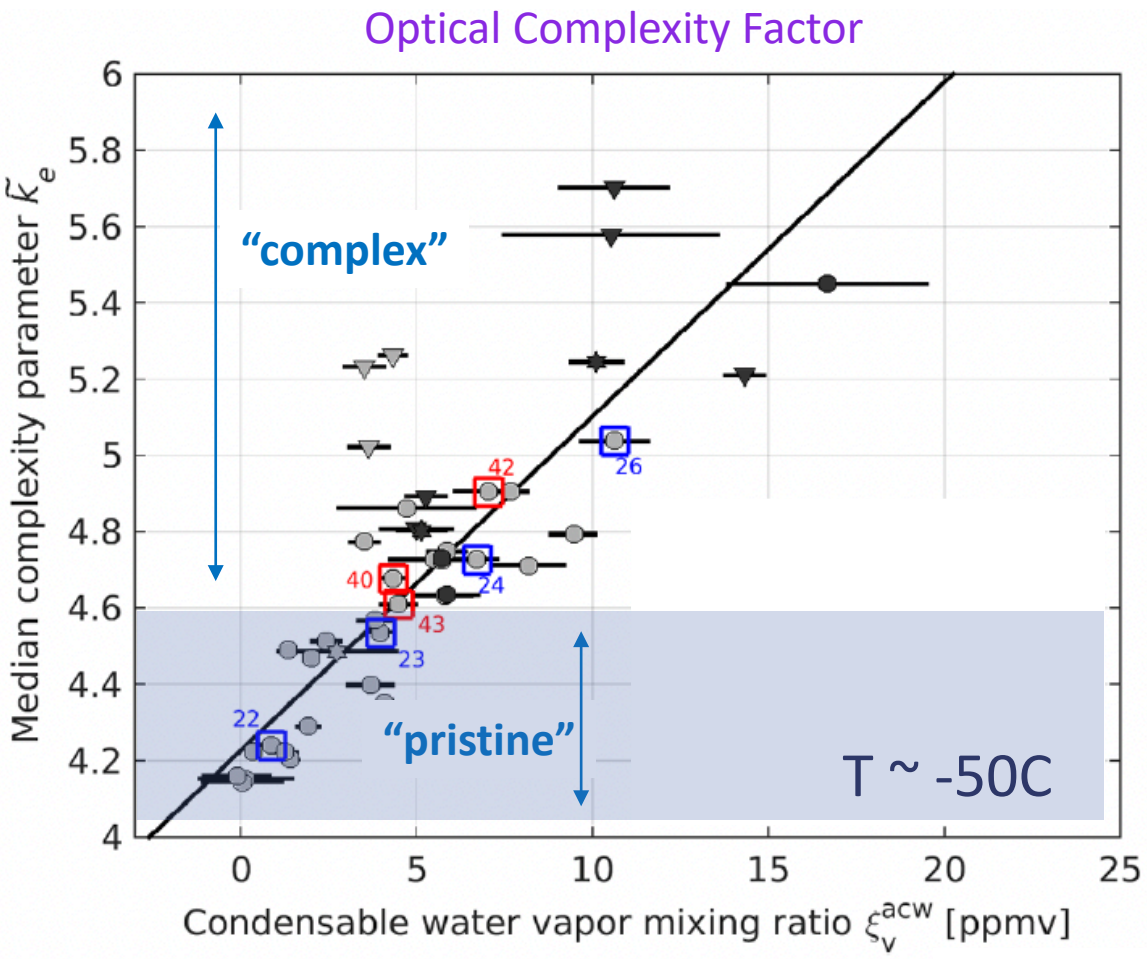
Fukuta (1969)



Morphology Transforms: low temperature threshold

- Low temperature (~ -50C)
- Transformation s_i ~ 20%

$\Delta\rho_{thr}$ ~ 0.006 g m^{-3}



Schnaiter et al. (2016)

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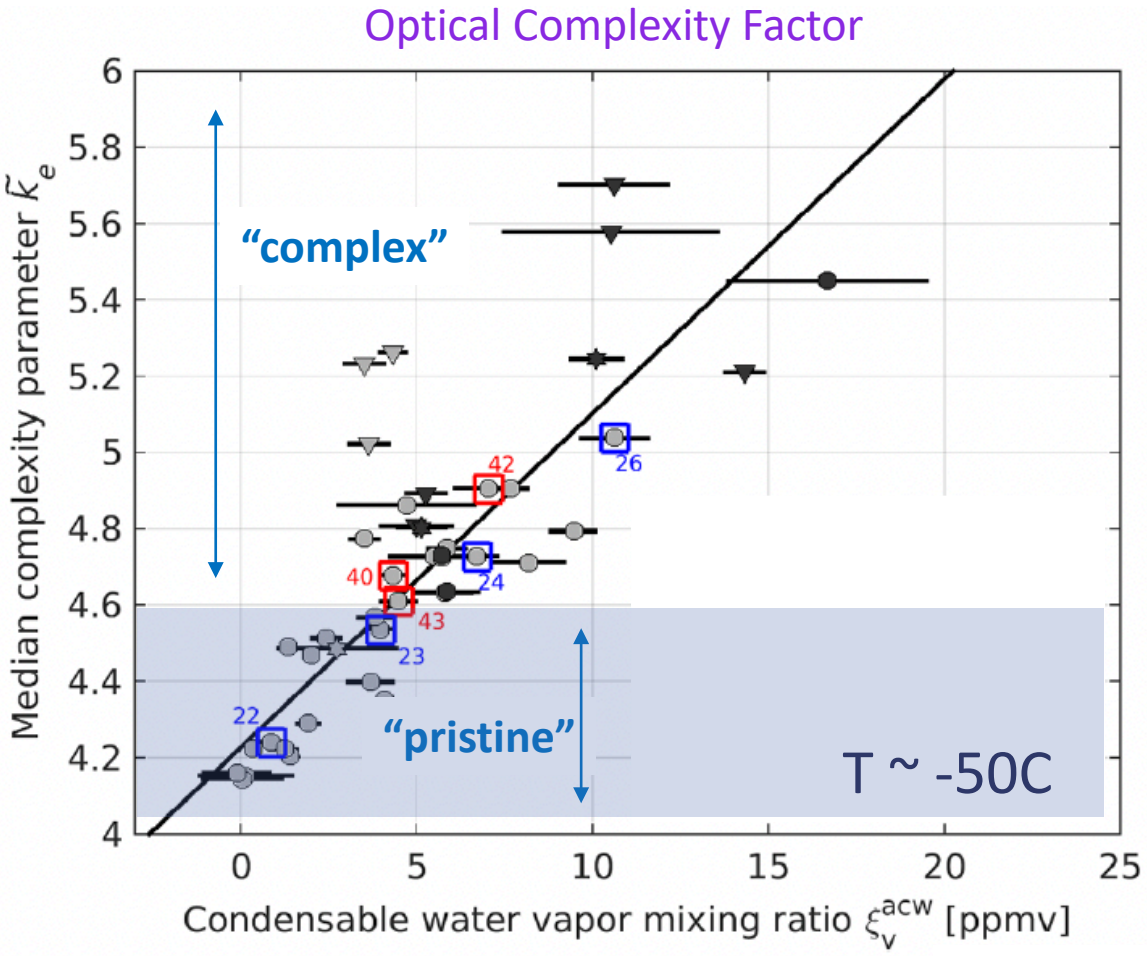

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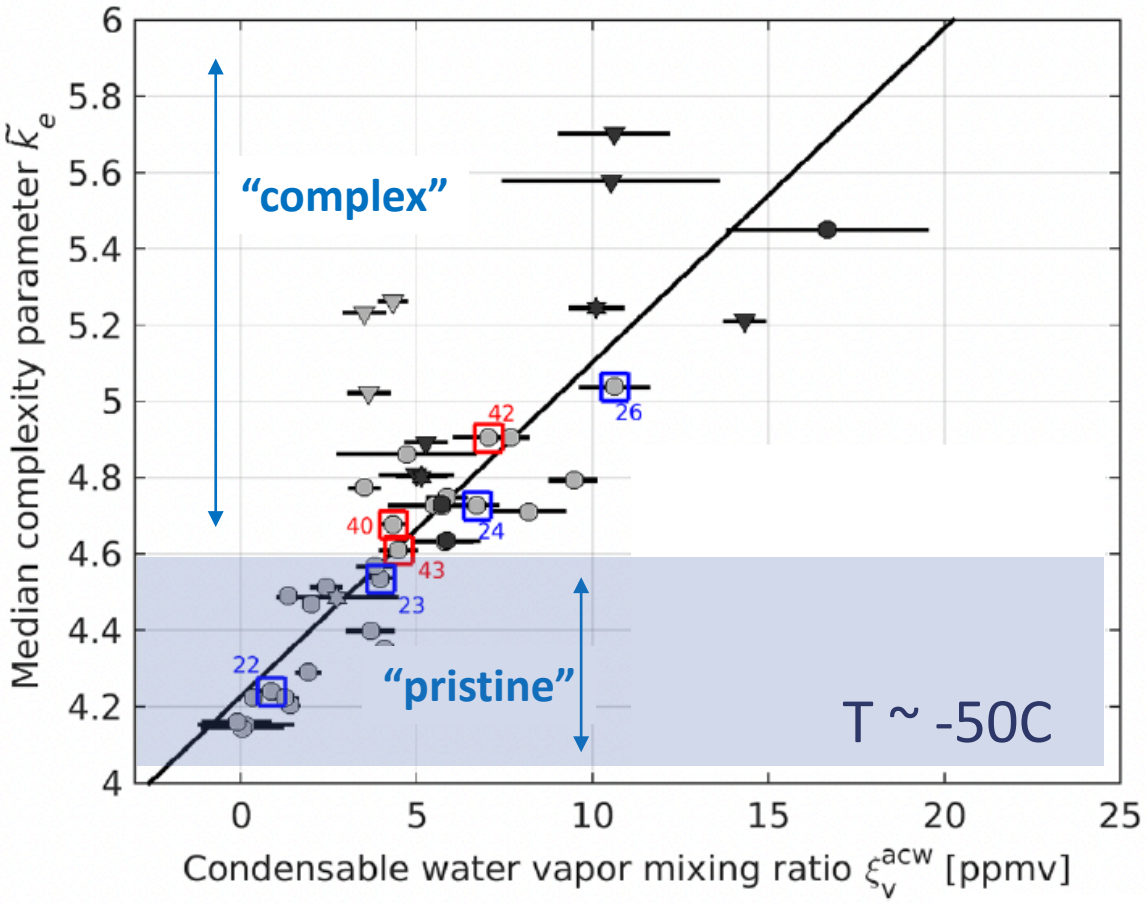
- **general criterion?**

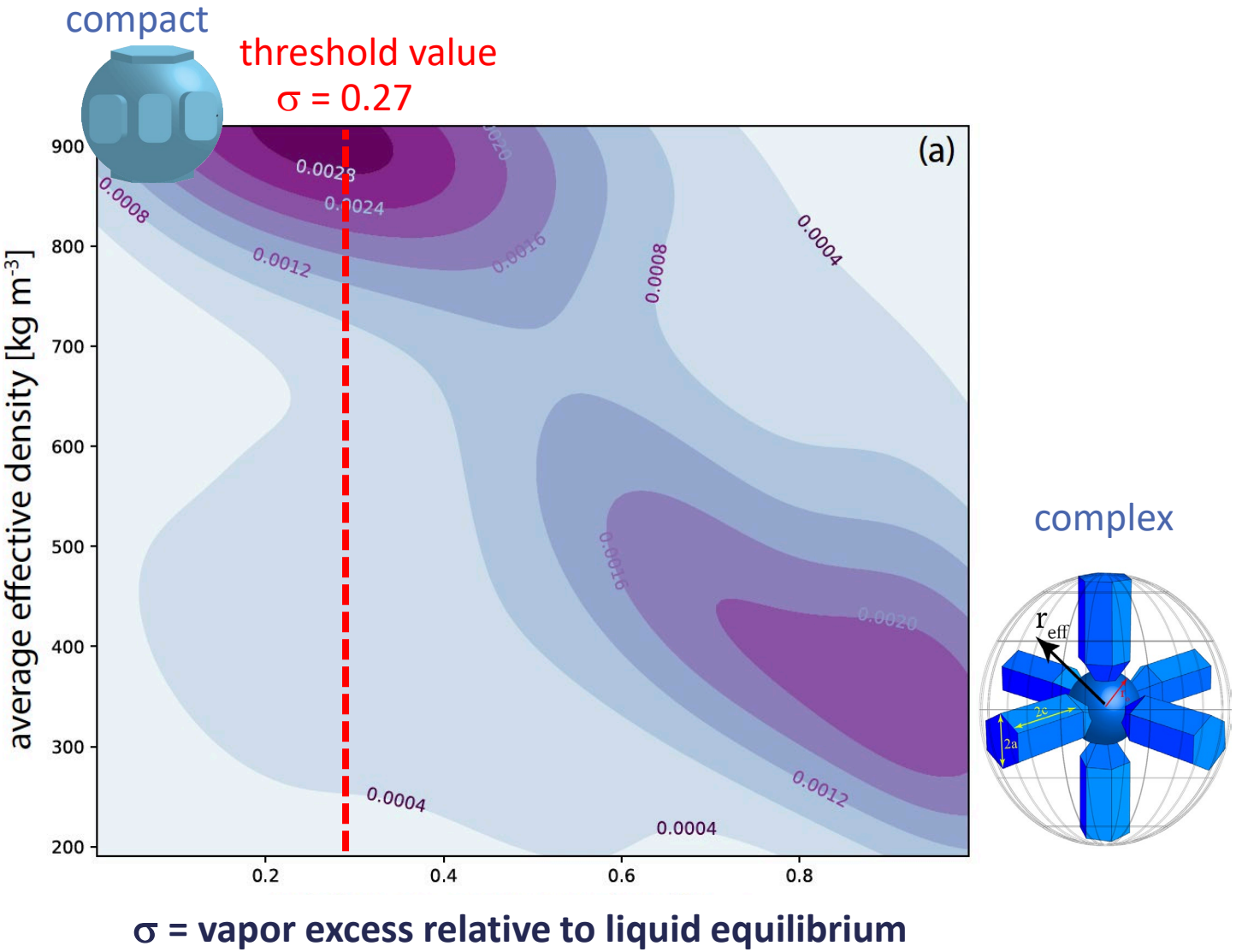
Optical Complexity Factor



Schnaiter et al. (2016)

Morphology Transforms: Lab Measurements

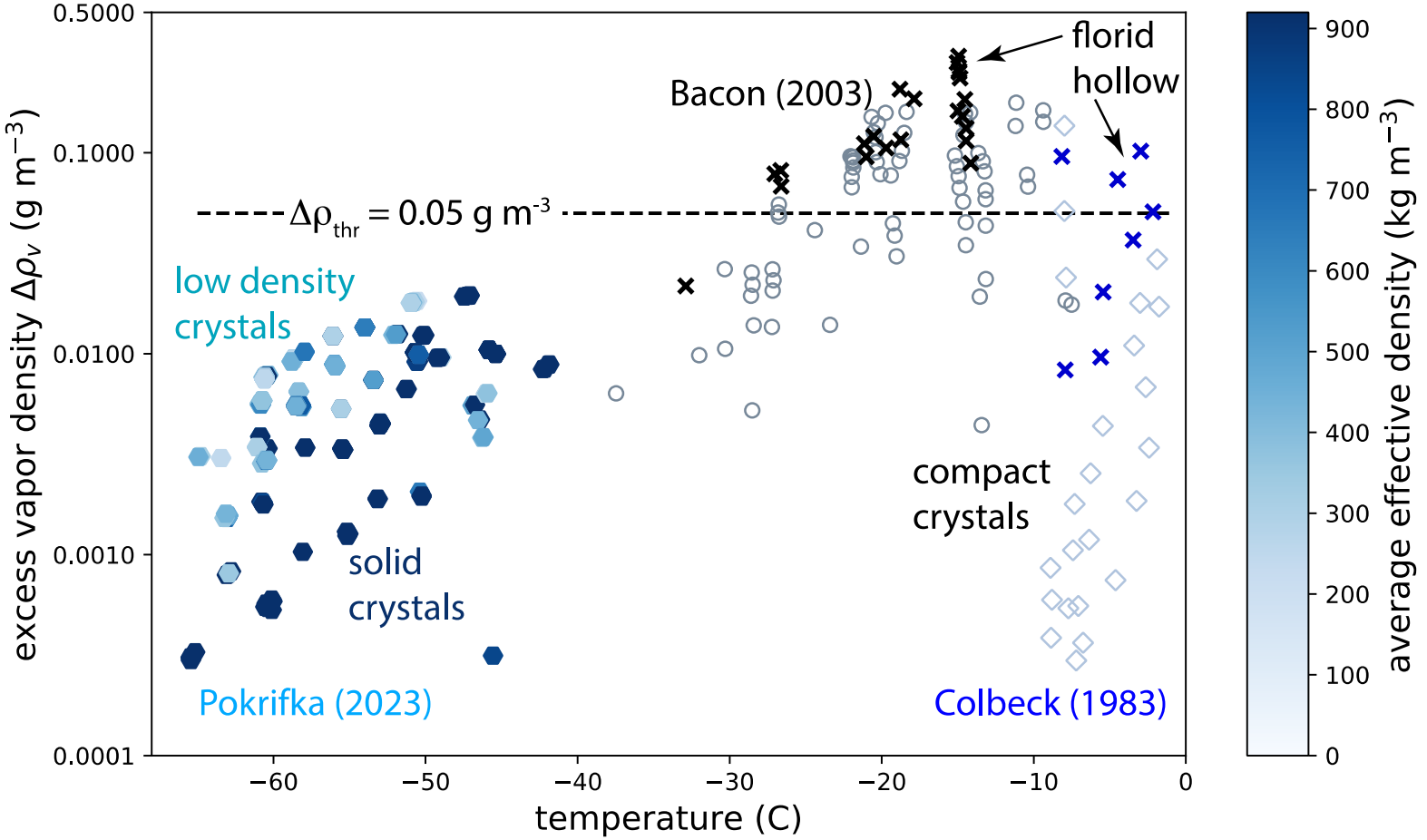
- Effective density from measured growth rates
- T = -65 to -40C
- Saturation => low to liquid equilibrium



Pokrifka et al. (2023)

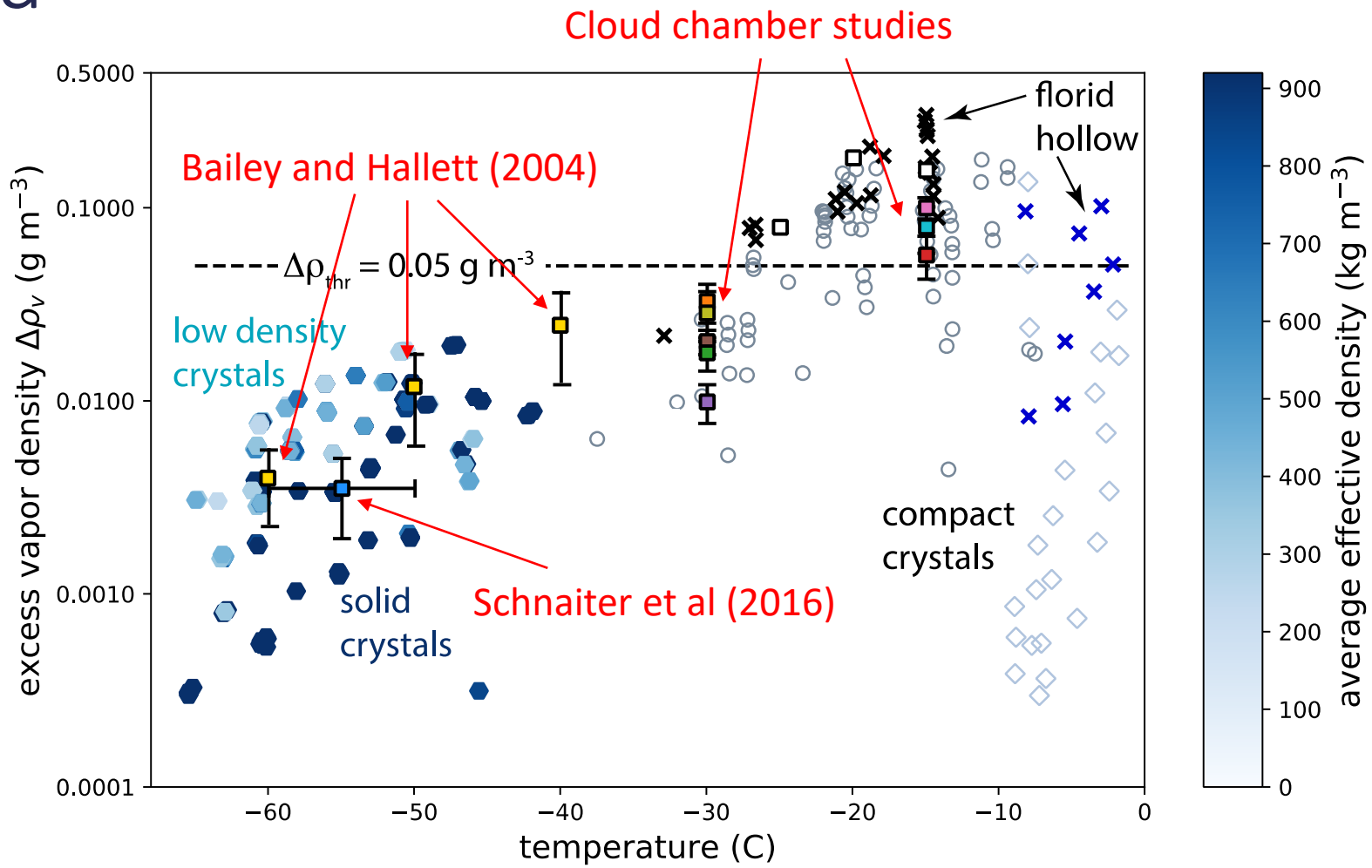
Morphology Transforms: Prior and our data

downward trend in $\Delta\rho_{thr}$



Morphology Transforms: Prior and our data

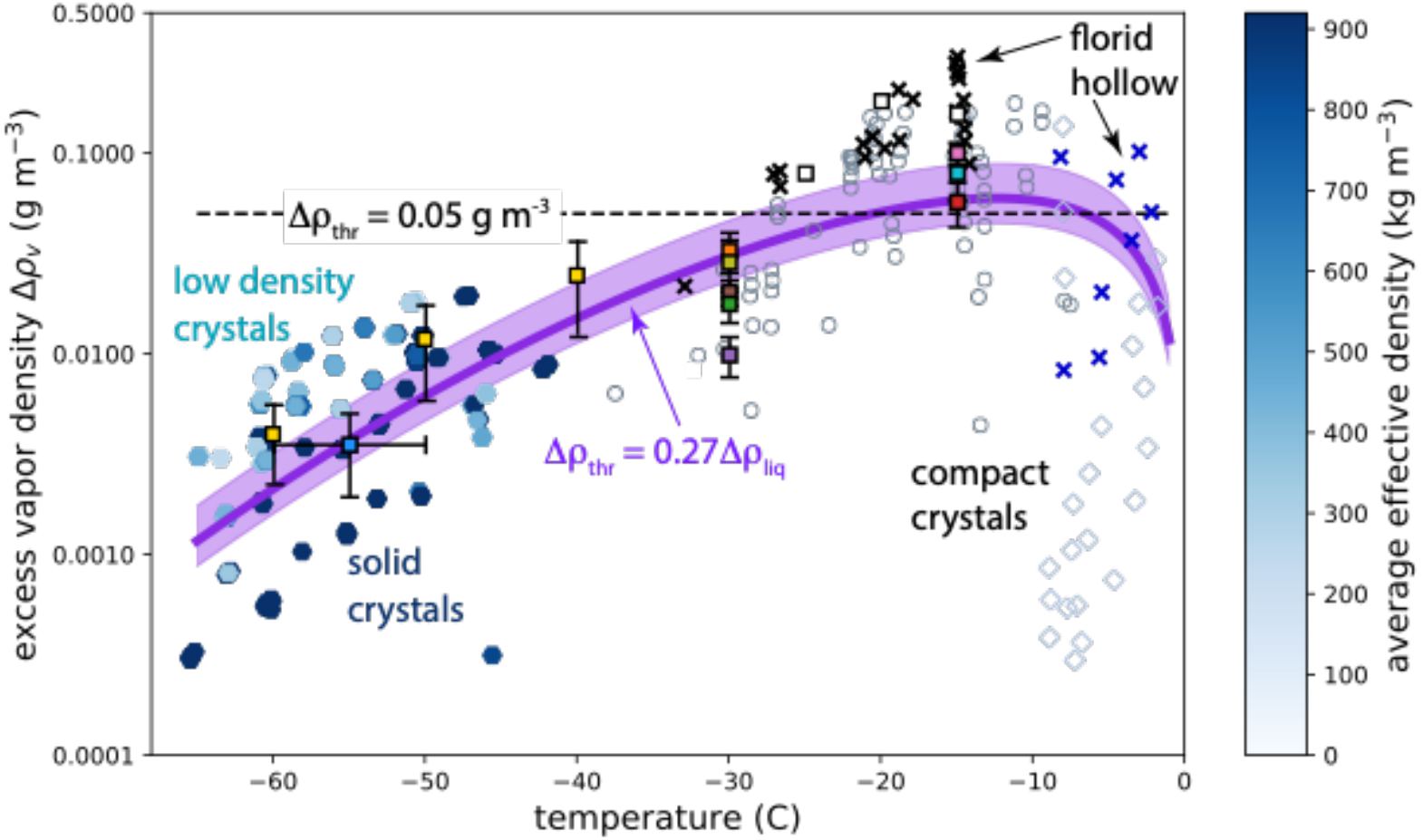
Experimental estimates of $\Delta\rho_{thr}$



Morphology Transforms: Prior and our data

Our empirical result:

- ⇒ $\sigma \sim 0.27$
- ⇒ $\Delta\rho_{thr} \sim 0.27 * \Delta\rho_{liq}$



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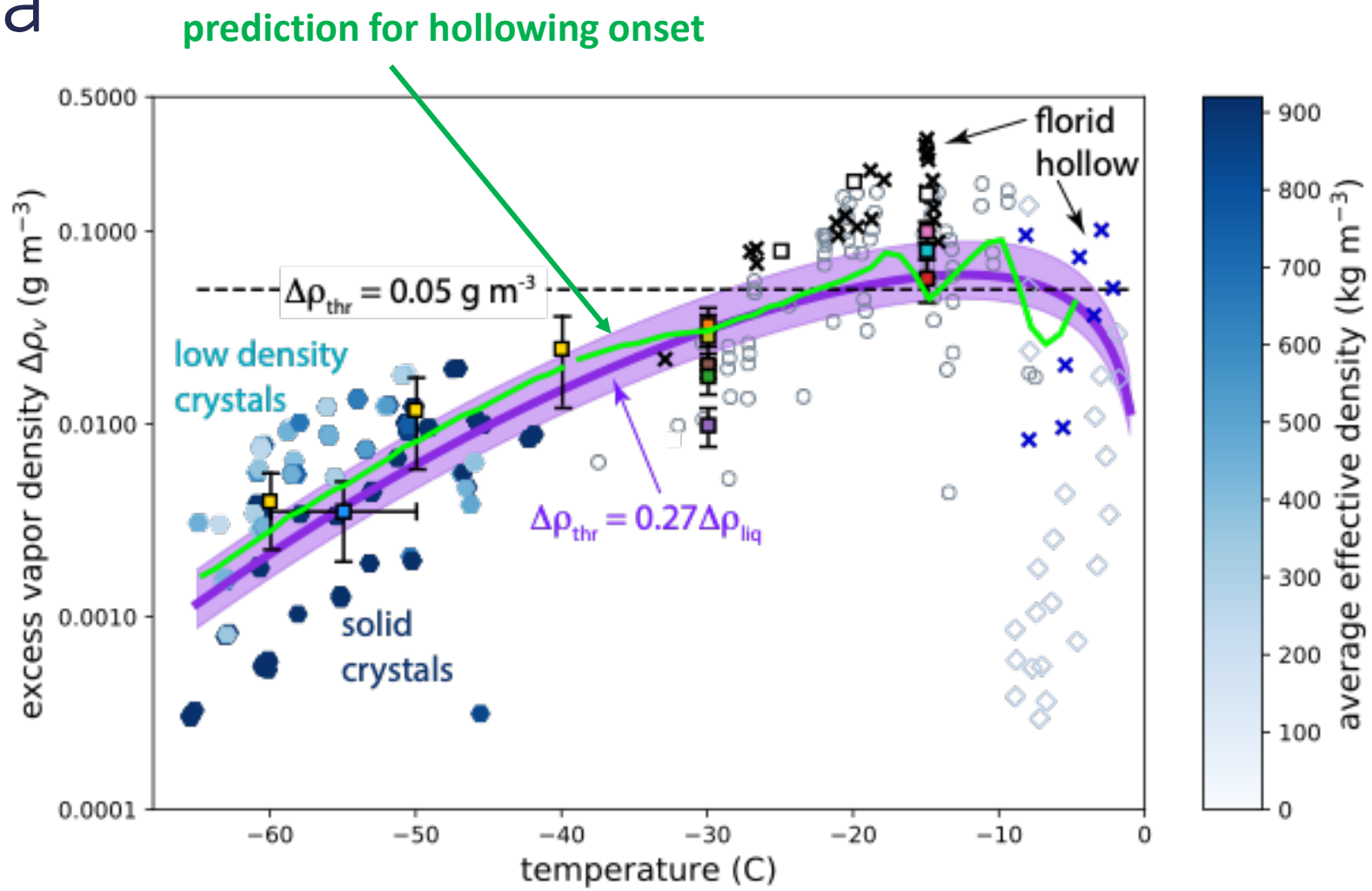

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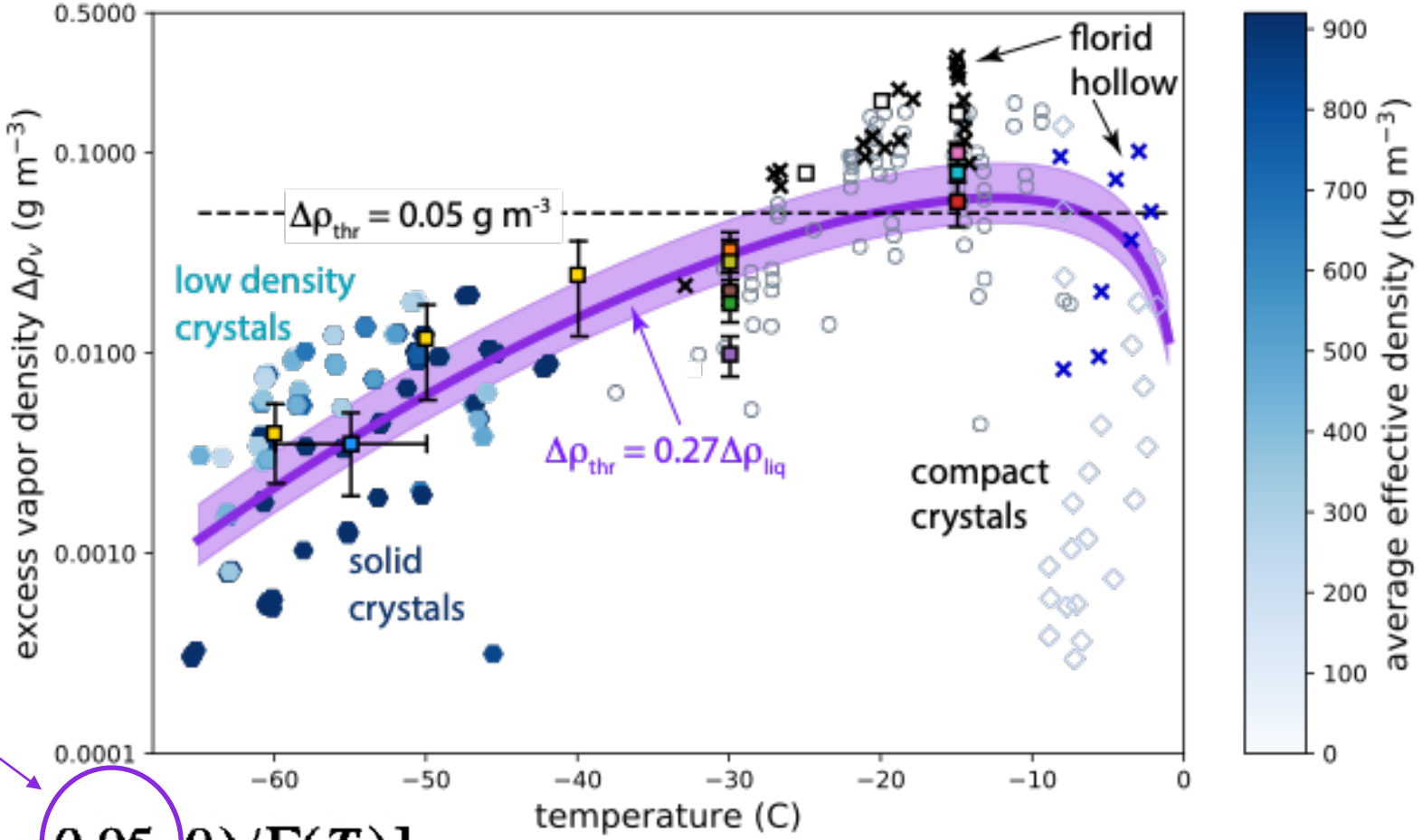
replace



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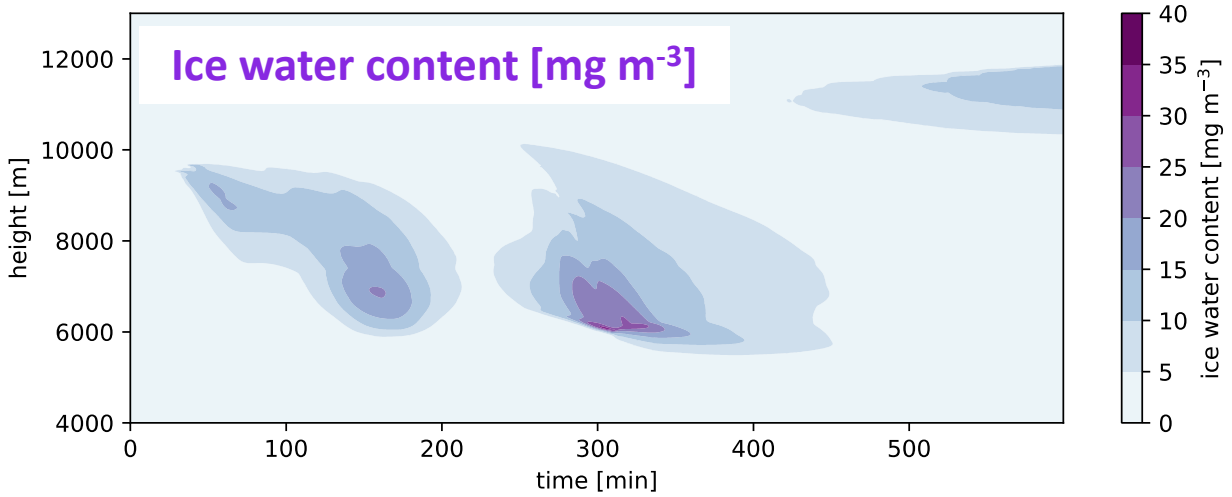
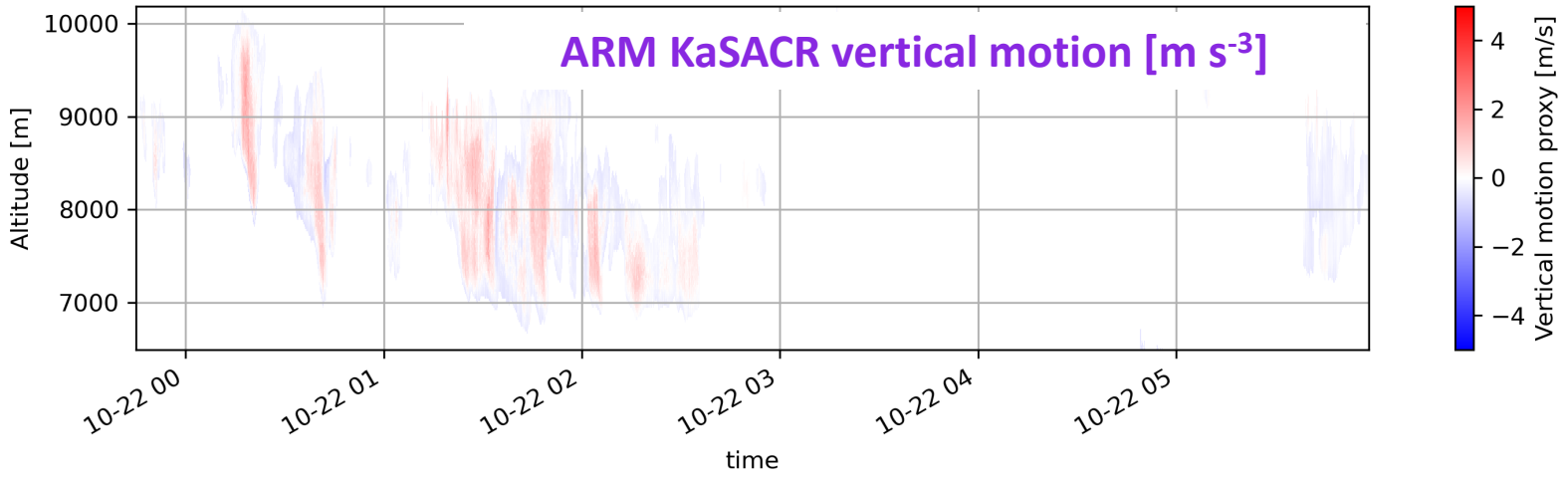
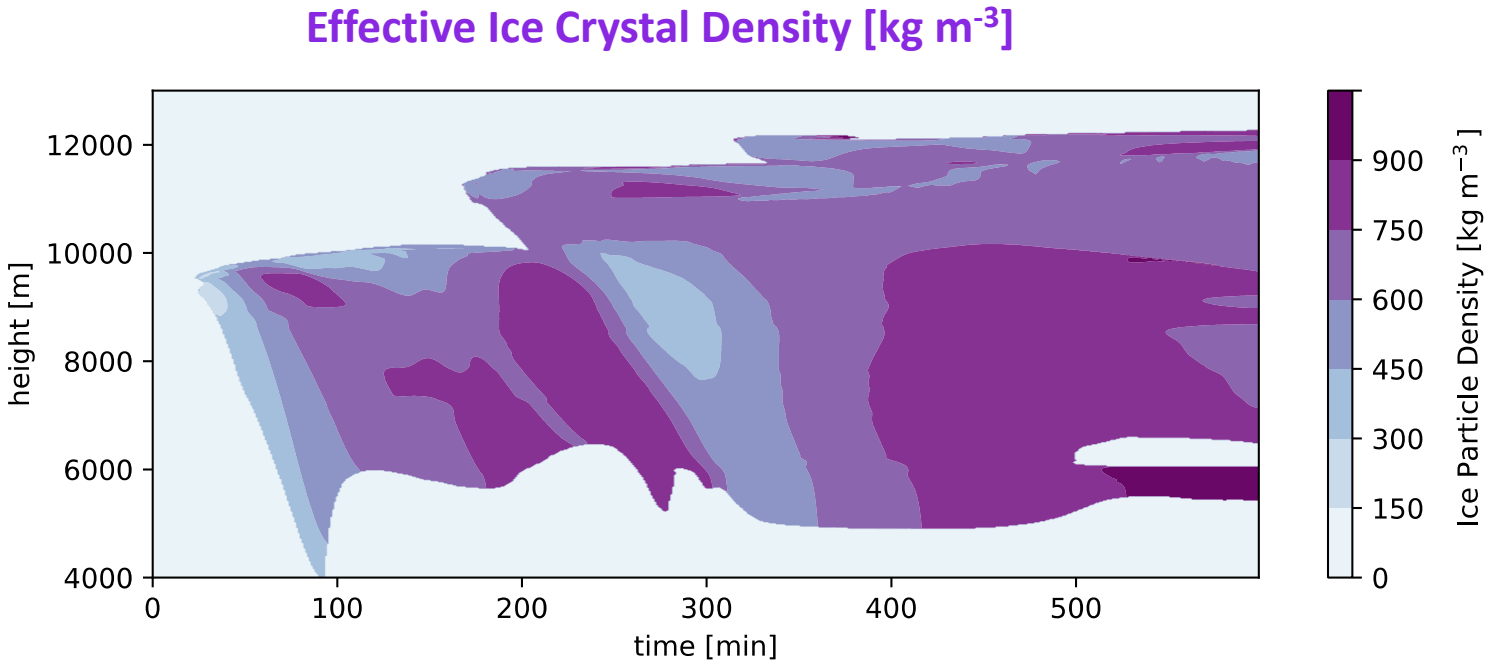
October 21 simulated cirrus: Lab-based criterion & density





- Simulations produce cirrus generating heads
- Similar to observed reflectivity fields and vertical motions
- Simulated TKE similar to the radar-derived vertical motions

October 21 simulated cirrus: Lab-based criterion & density



Lab-based criterion ($\Delta\rho_{thr}$) produces:

Densities ~ 500 to 900 kg m^{-3}

within the range of the observed crystals

- Conclusions -

- Developed a general, lab-based criterion for the relative excess vapor density at which crystals transform from compact to complex forms
- The criterion can be predicted from theoretical growth models using measured critical supersaturations for faceted growth.
- The criterion is relatively broad in range but matches most prior measurements.
- Observations show frequent hollowing even on facets as small as 20 microns and densities like those derived from lab growth measurements
- Use of the laboratory-based criterion and in simulations of an observed cirrus produces effective densities, and cloud structure, similar to observations.