

The image shows a detailed view of a star's surface, likely from a solar probe. The left side is dominated by a bright, golden-yellow, highly textured region with a complex, cellular or granular appearance. This transitions into a darker, more uniform greyish-blue region on the right. A prominent circular feature, possibly a sunspot or a solar flare, is visible in the center, showing a darker core and a lighter, filamentary structure. The overall texture is granular and uneven, characteristic of a stellar photosphere.

# How stars make dust

AAVSO Annual Meeting  
Nantucket MA  
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# Mira Variables are Dust Factories for the galaxy

- They have IR excesses at 10-13  $\mu$
- They have high-momentum winds possible only with dust

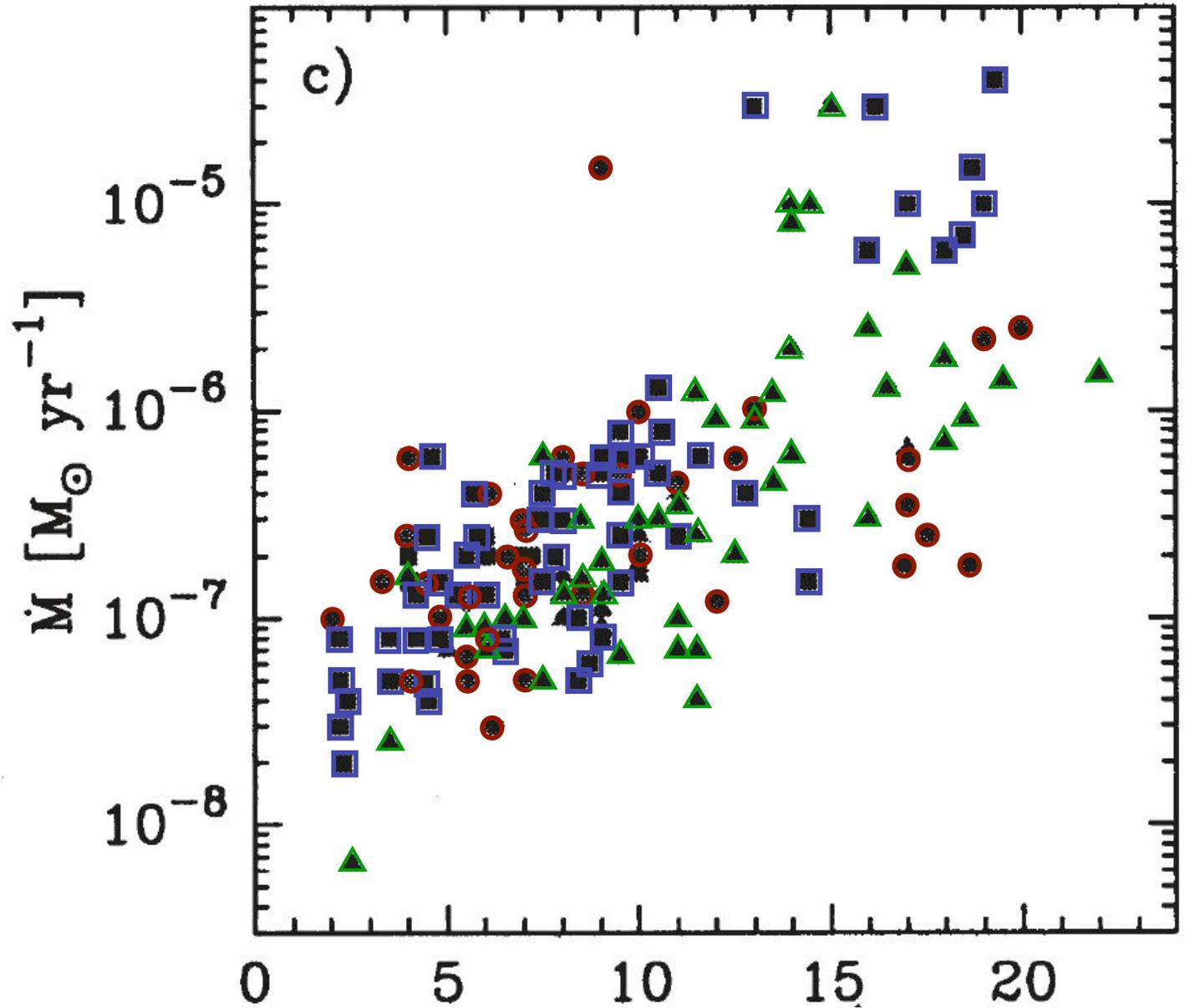
## 2006: A problem!

- Models for dusty winds from Carbon stars ( $C > O$ ) appeared OK (although they required high C/O and large luminosity) but
- Same codes applied to M and S stars predicted no winds could be driven.

*Discovered independently by S. Höfner and P. Woitke*

Mass  
loss rate  
vs  
expansion  
velocity -  
the same  
for M, S,  
and C  
stars !?!?!

- M
- S
- △ C

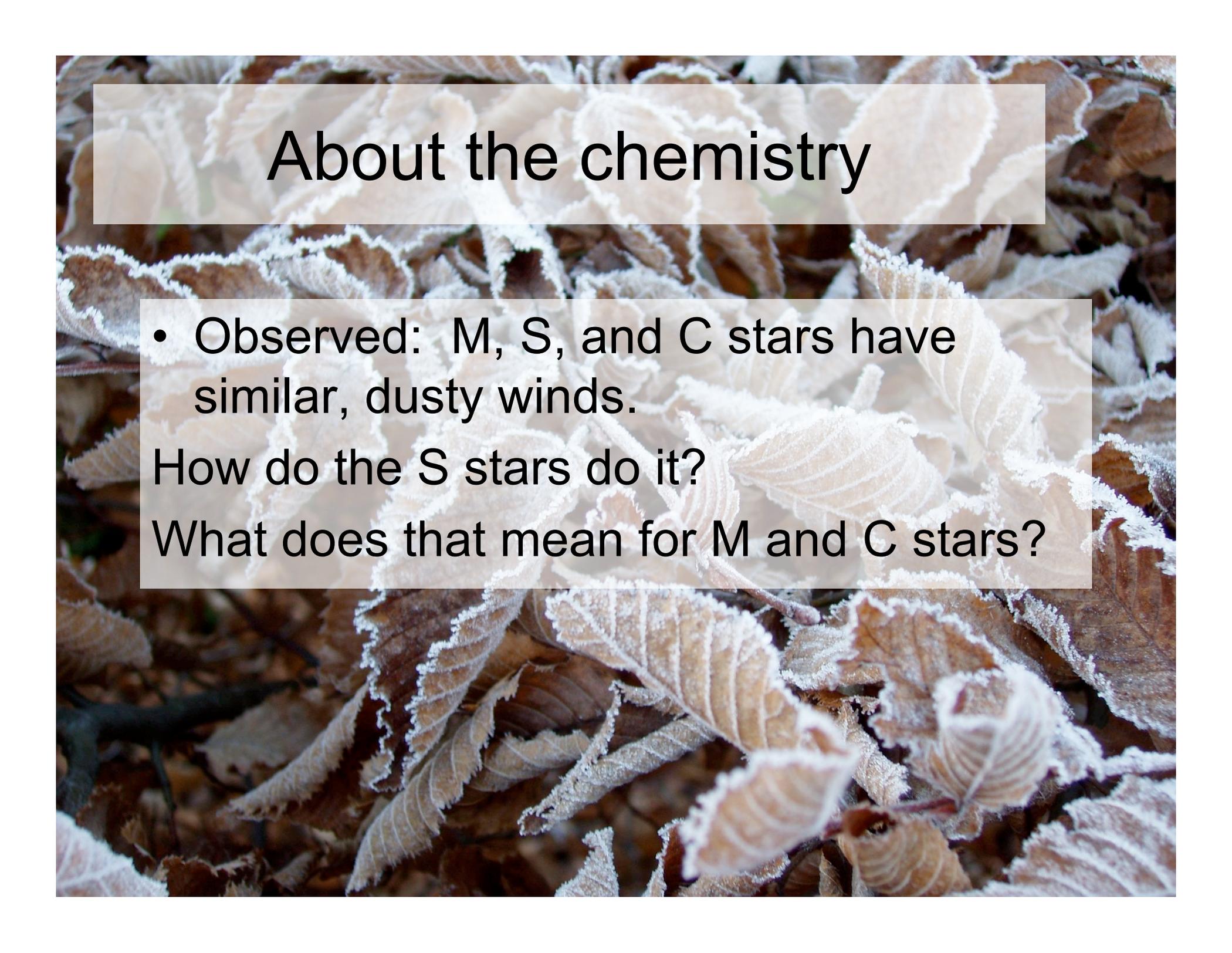


*From Ramstedt et al 2006*

# About the chemistry

- In equilibrium below about 4000K, C and O prefer to be CO
- For M stars,  $O > C$  and O is left over
- For C stars,  $C > O$  and C is left over
- For S stars,  $C = O$  and nothing is left over

Dust forms from what is left after CO forms

A close-up photograph of numerous leaves covered in a thick layer of white frost. The leaves are in various shades of brown and tan, and their intricate vein patterns are clearly visible through the frost. The background is a dense field of these frost-covered leaves, creating a textured and wintry scene.

# About the chemistry

- Observed: M, S, and C stars have similar, dusty winds.

How do the S stars do it?

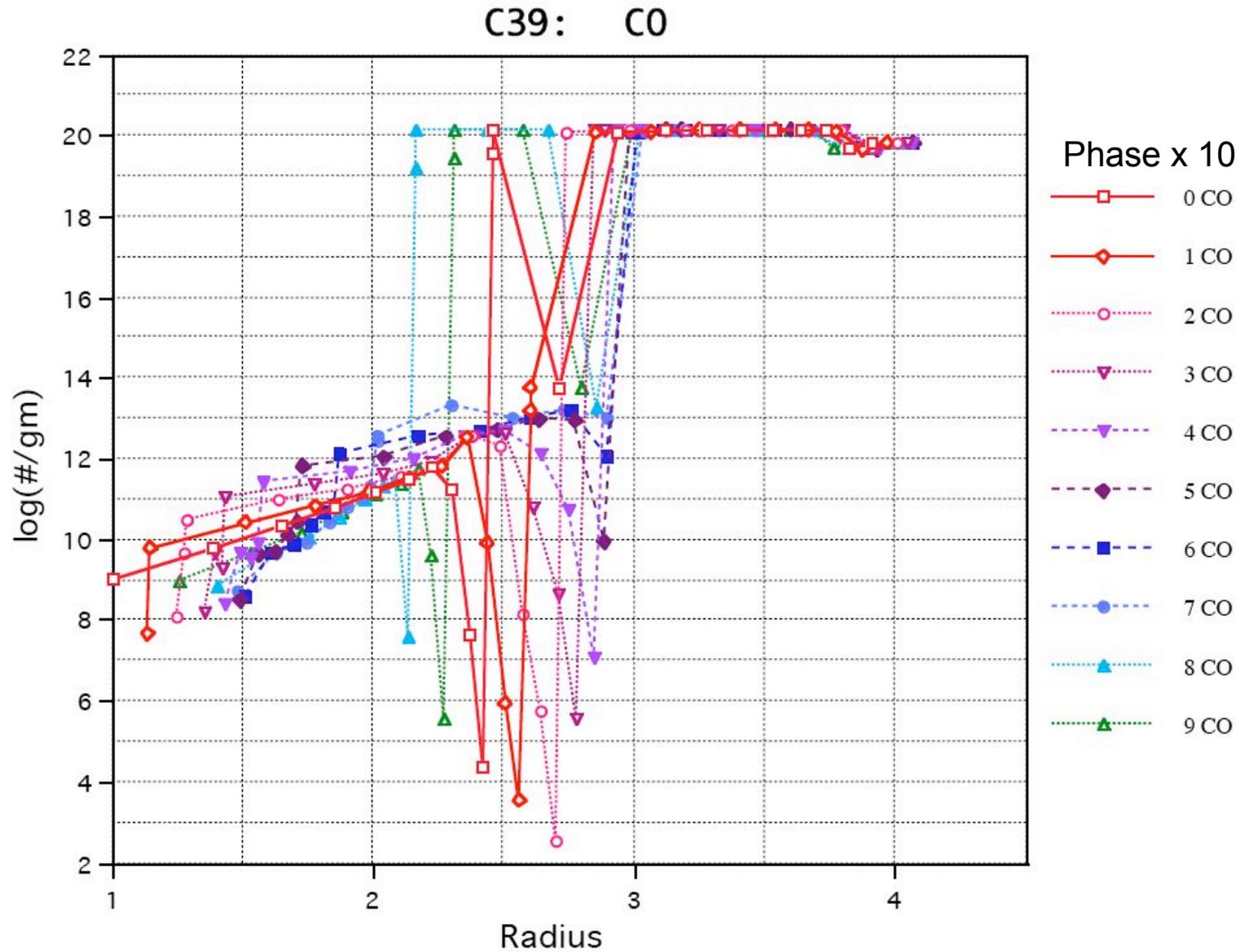
What does that mean for M and C stars?

# Shocks allow S stars to form dust

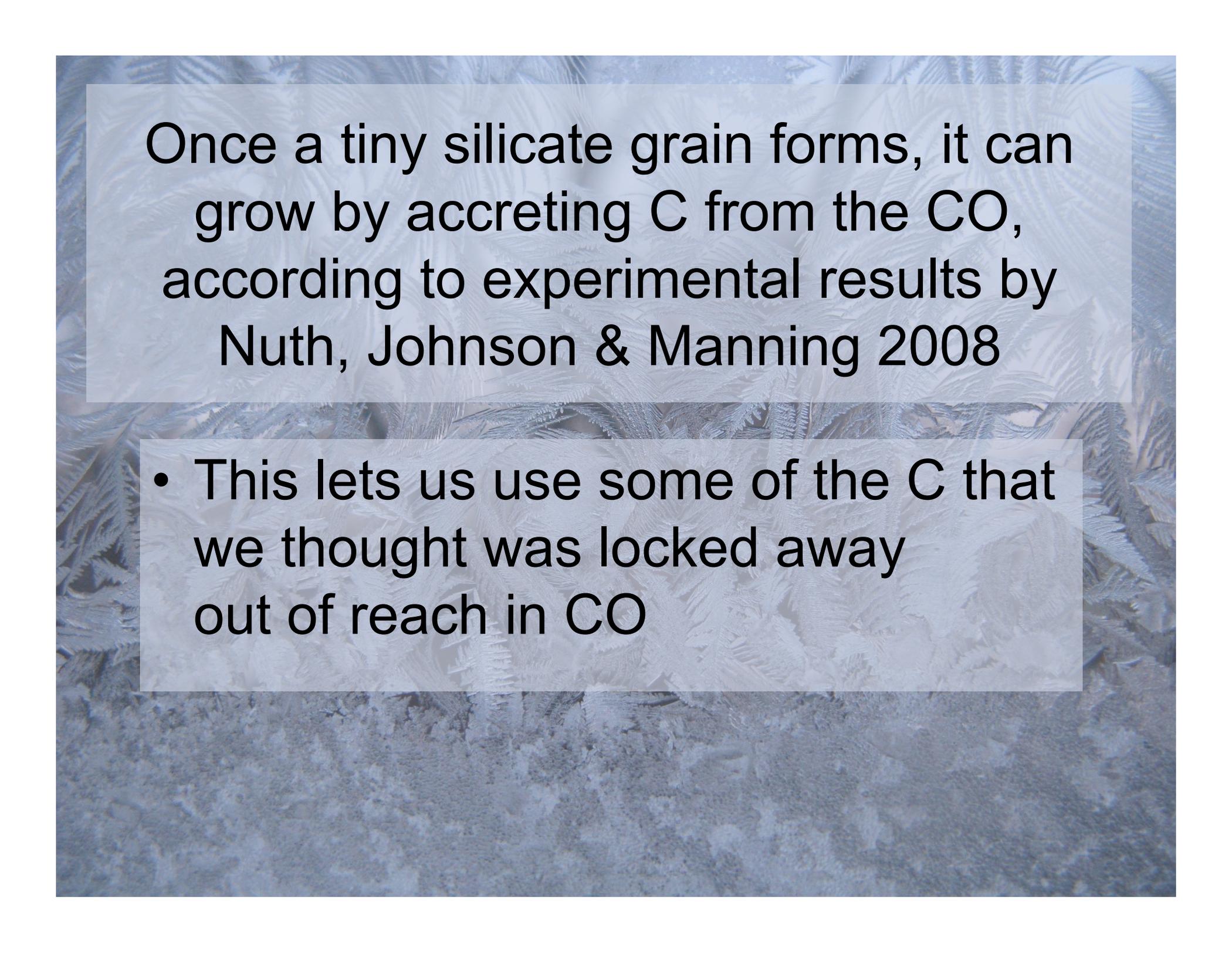
- In pulsating stars (the ones with dusty winds, the Miras), shocks break up  $\text{H}_2$  and  $\text{CO}$ .

Therefore:

We have extra O and some C in M stars, extra C and some O in C stars, and some C and some O in S stars, to make dust from  $\text{C}_2\text{H}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{SiO}$ .



*Calculation by James Pierce 2008; model does not include dust*



Once a tiny silicate grain forms, it can grow by accreting C from the CO, according to experimental results by Nuth, Johnson & Manning 2008

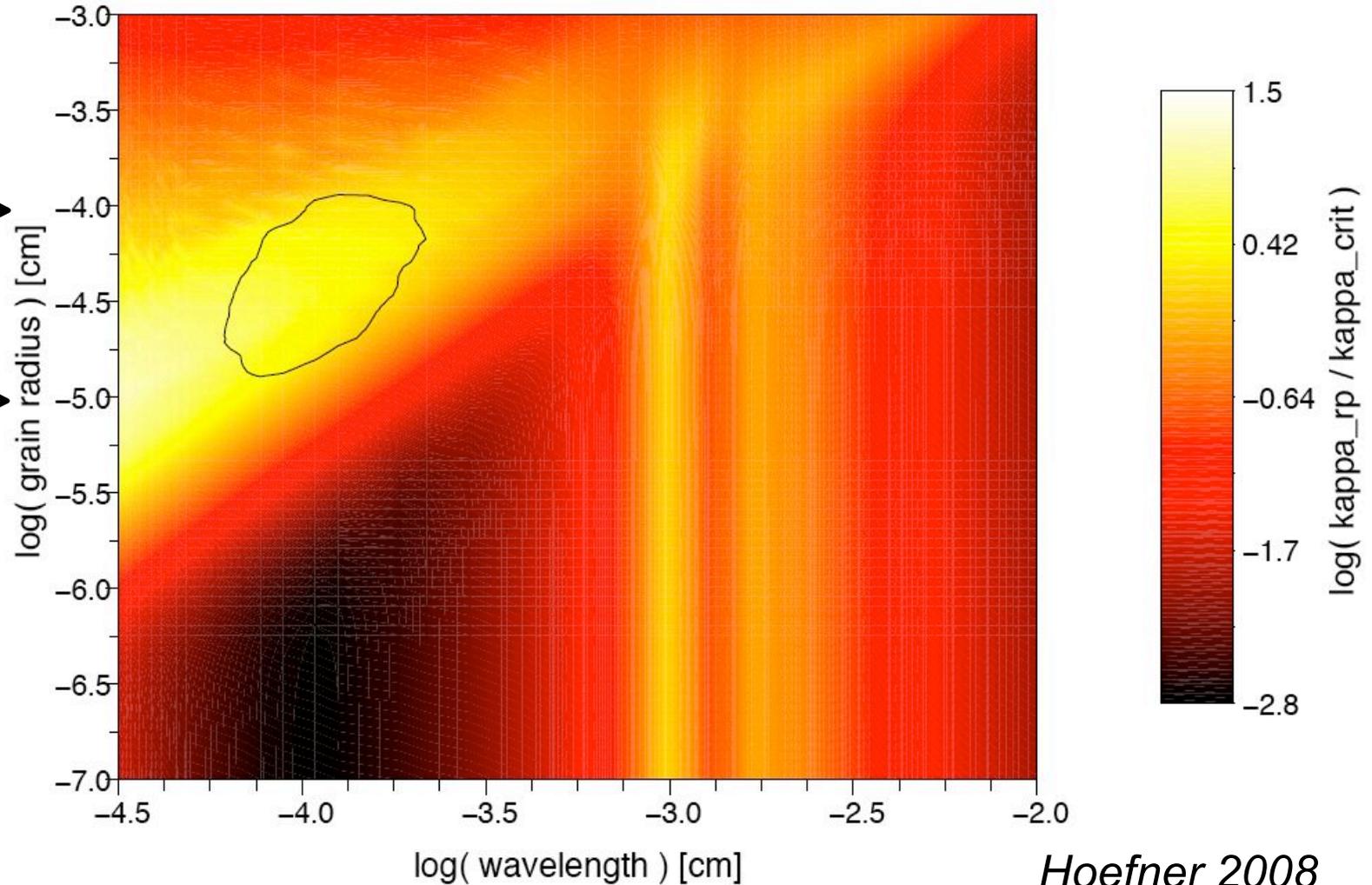
- This lets us use some of the C that we thought was locked away out of reach in CO

This is important because small silicate grains are not opaque enough to drive material off these stars

1.0  $\mu$  →

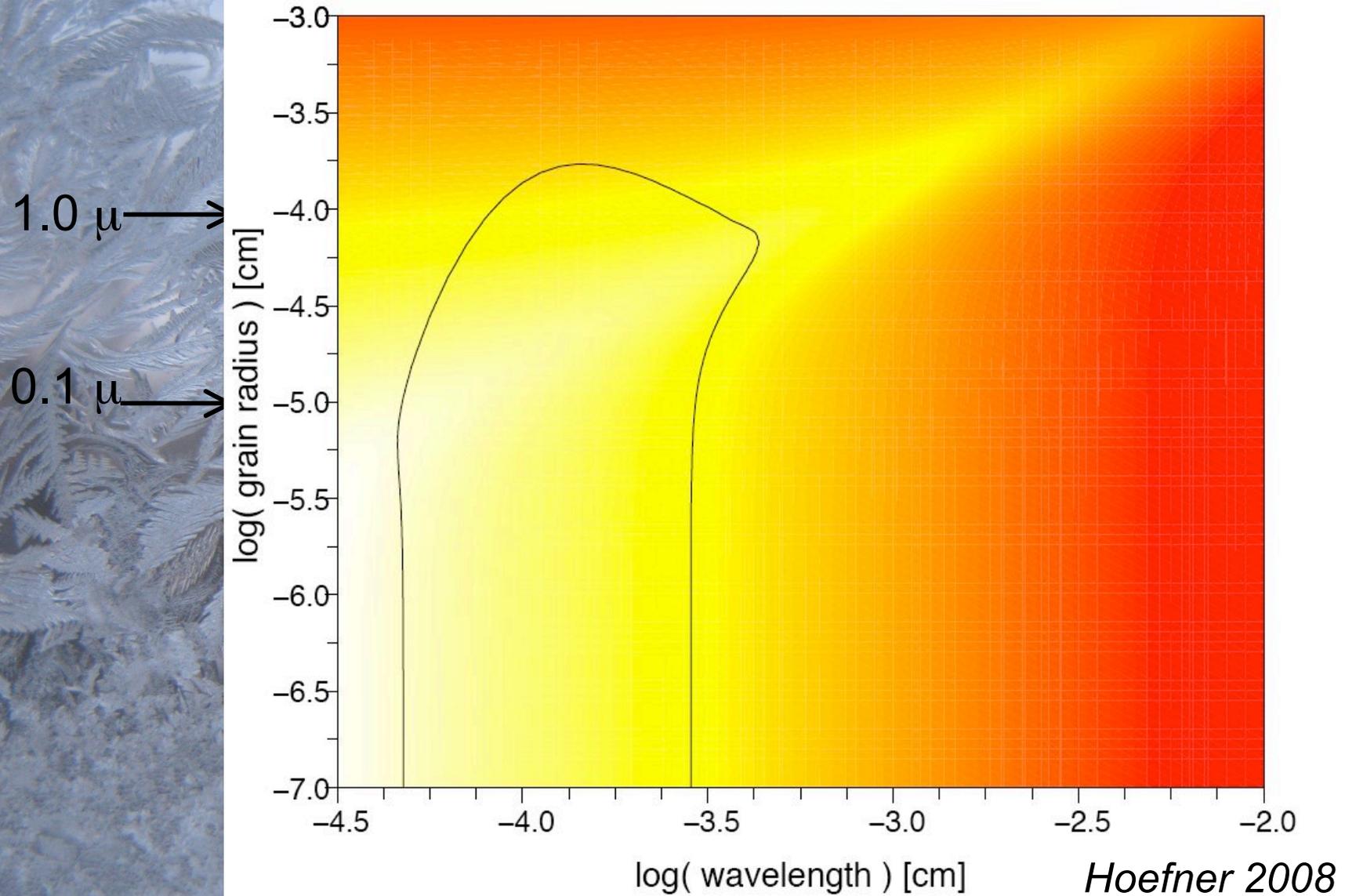
0.1  $\mu$  →

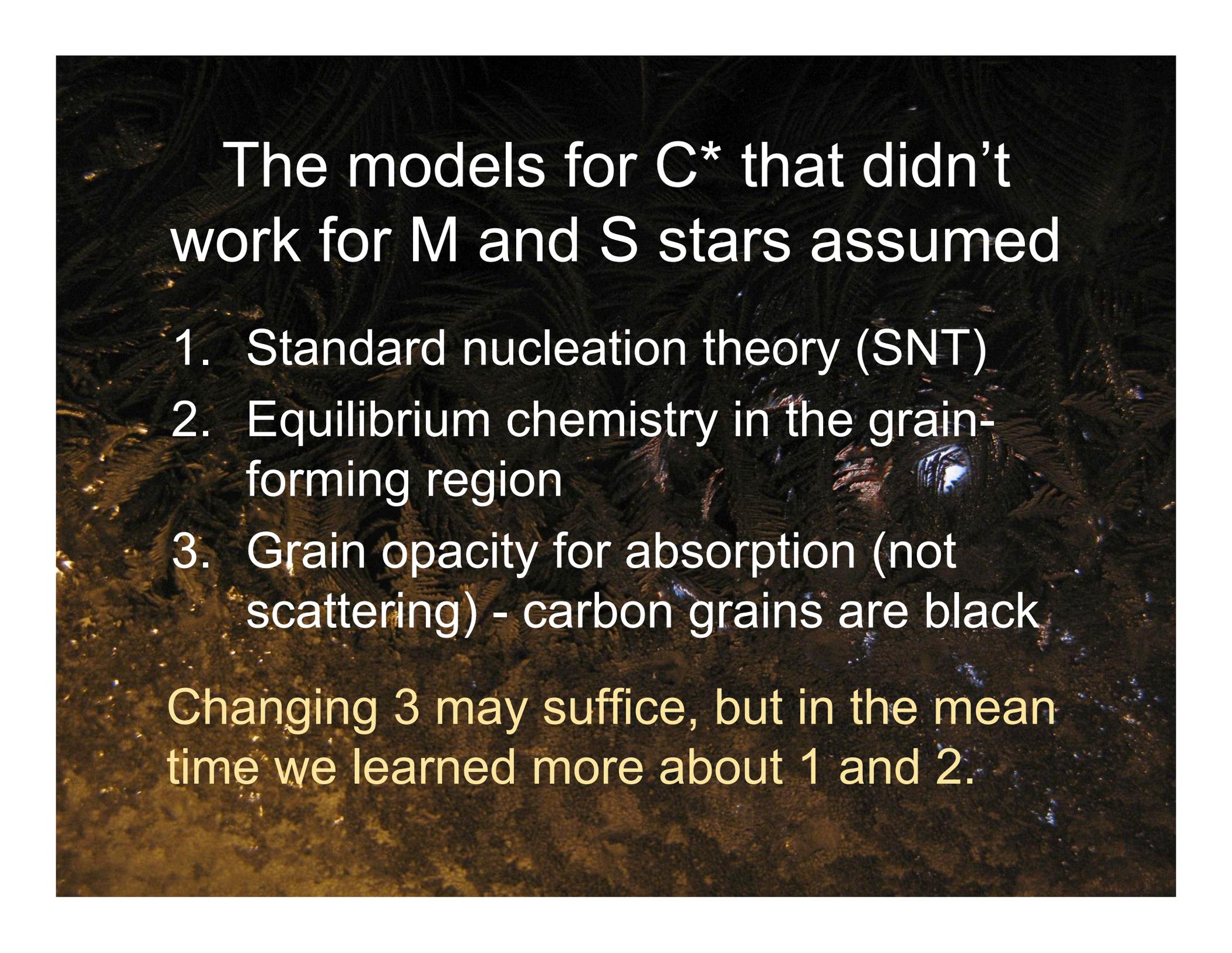
*0.1 m  
is  
about  
1000  
atoms*



*Hoefner 2008*

# Small carbon grains are able to drive mass loss

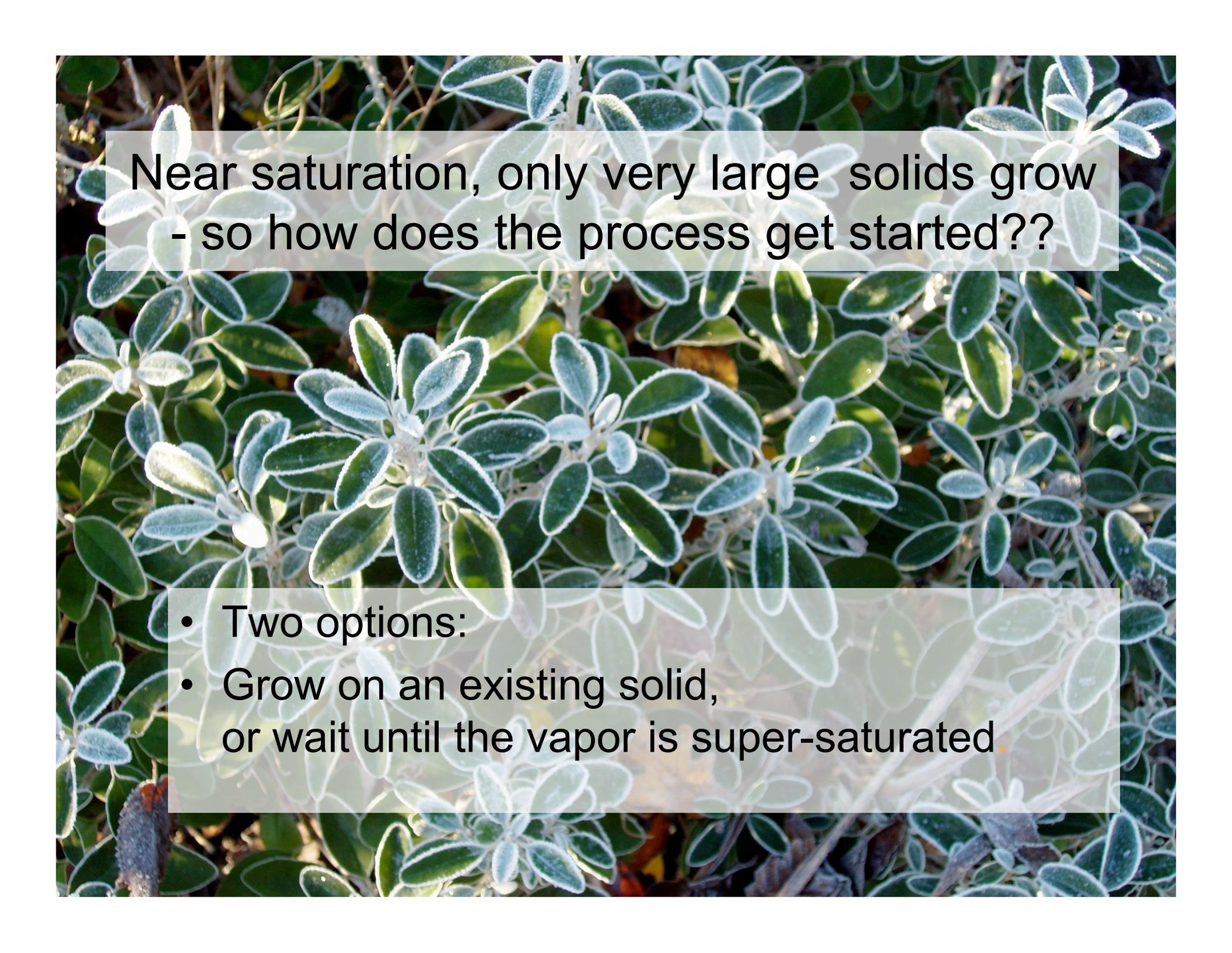




The models for C\* that didn't work for M and S stars assumed

1. Standard nucleation theory (SNT)
2. Equilibrium chemistry in the grain-forming region
3. Grain opacity for absorption (not scattering) - carbon grains are black

Changing 3 may suffice, but in the meantime we learned more about 1 and 2.

A close-up photograph of a dense cluster of small, green, fuzzy-leaved plants. The leaves are small, oval-shaped, and have a silvery-green, fuzzy texture. The plants are growing in a cluster, with some stems visible. A semi-transparent white text box is overlaid on the upper portion of the image, containing text. Another semi-transparent white text box is overlaid on the lower portion of the image, containing a bulleted list.

Near saturation, only very large solids grow  
- so how does the process get started??

- Two options:
- Grow on an existing solid, or wait until the vapor is super-saturated.

# IN STARS ... SUPERSATURATION

- The higher the supersaturation, the smaller the particles that can grow.
- There is a critical cluster size, with  $N=N^*$  atoms, that is stable.
- Clusters with  $N>N^*$  grow. Clusters with  $N<N^*$  are more likely to shrink than grow.
- An equilibrium for  $N<N^*$  is possible, with more clusters of size  $N$  than of size  $N+1$ .

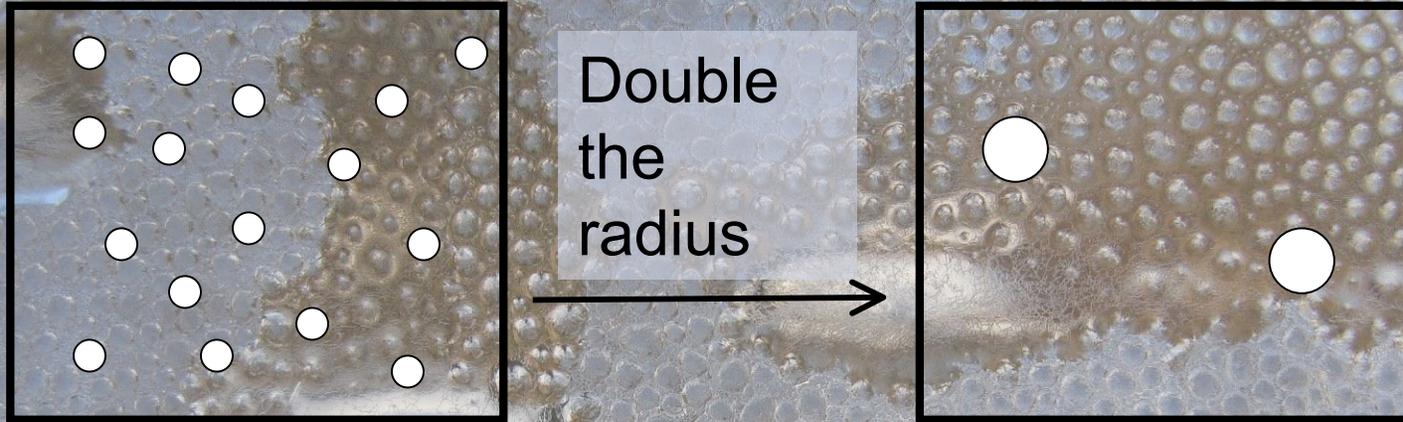
# Standard nucleation theory

- Compute  $N^*$  from surface tension
- Assume  $N < N^*$  are in equilibrium
- Higher supersaturation (usually, faster cooling)  $\Rightarrow N^*$  is smaller
- Smaller  $N^*$   $\Rightarrow$  more grains get to  $N^*$
- $N \geq N^*$  grow until the material is all in grains.
- Higher supersaturation  $\rightarrow$  more, smaller grains

A micrograph showing a complex, dendritic structure of metal grains, likely formed during slow cooling. The grains are light blue and have a feathery, branching appearance. A semi-transparent grey box in the upper right corner contains text explaining the relationship between cooling rate and grain size.

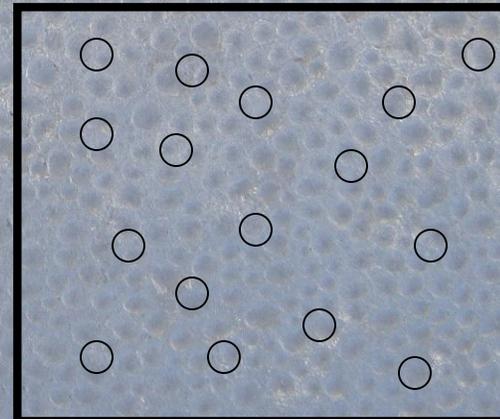
Slow cooling  
=> slight supersaturation  
=> fewer, bigger grains

# How to get high opacity from the grains: there is an optimal size

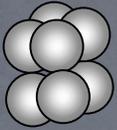


If they are opaque, many small grains intercept more light than a few large ones with the same total mass.

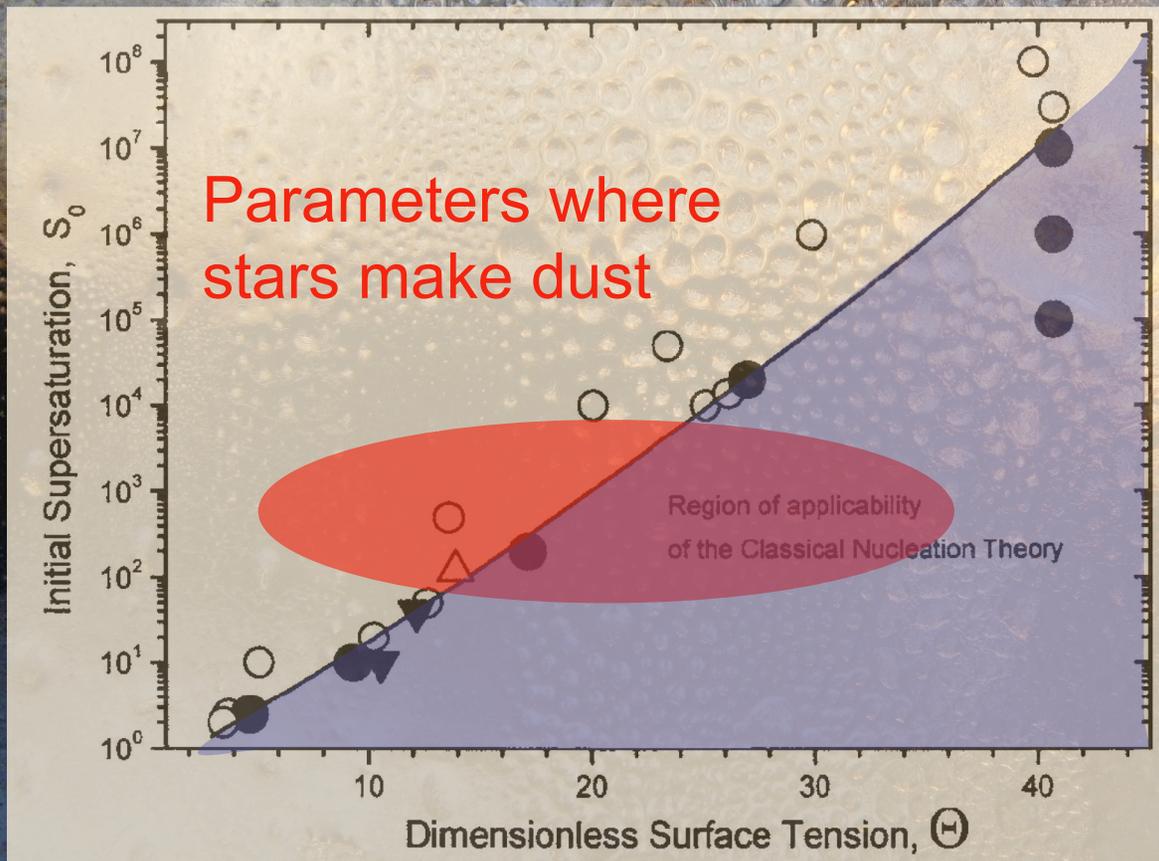
However, if the grains are too small, they will be transparent and intercept less light.



# Problems with SNT for stars

- Calculations make use of macroscopic properties - surface tension etc. 
- In stars,  $N^*$  turns out to be  $\leq 10$  or so - lumpy & all atoms on the surface
- Also, at high supersaturation,  $N < N^*$  don't achieve equilibrium concentrations

# Chesnokov et al 2007 model for nucleation and growth at high supersaturation



Region where current theory is OK.

$$\Theta = \Delta G/kT \text{ where } G = \text{Gibbs Free Energy}$$



The problem was:

Not enough dust opacity in M stars and no dust expected in S stars, but M, S, and C stars have similar winds

We found 3 solutions to the problem:

1. Big silicate grains work via scattering in M stars.
2. Non-equilibrium chemistry => more C and O available to make grains.
3. Silicate and carbon grains can steal C from CO.

And also learned that the underlying Standard Nucleation Theory has some inconsistencies when applied to stars.



*Background photos taken by  
L.A.W in 2007 © 2008*