
How stars make dust
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Mira Variables are Dust Factories for the galaxy

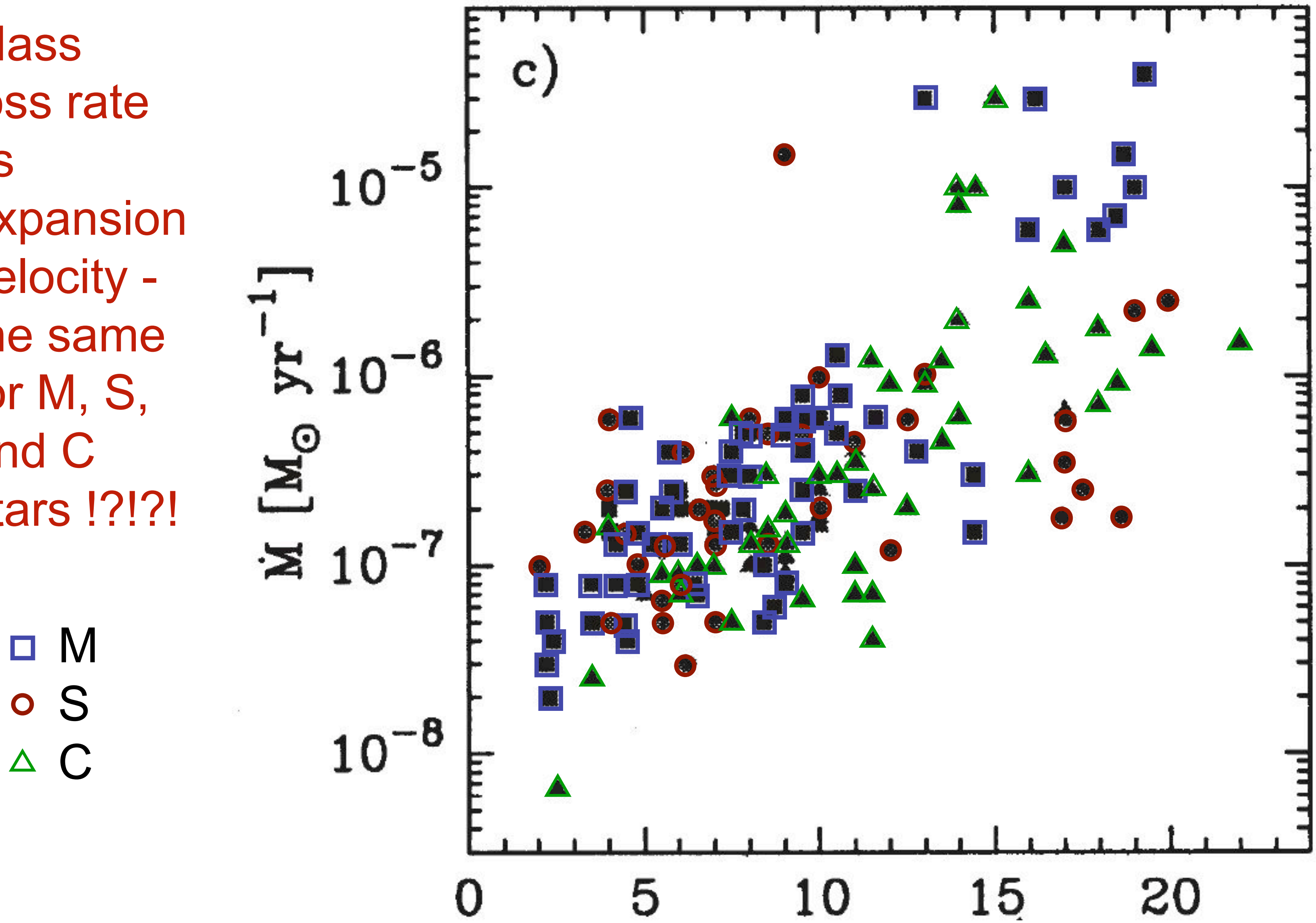
- They have IR excesses at 10-13 μ
- They have high-momentum winds possible only with dust

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 !?!?!



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

About the chemistry

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

How do the S stars do it?

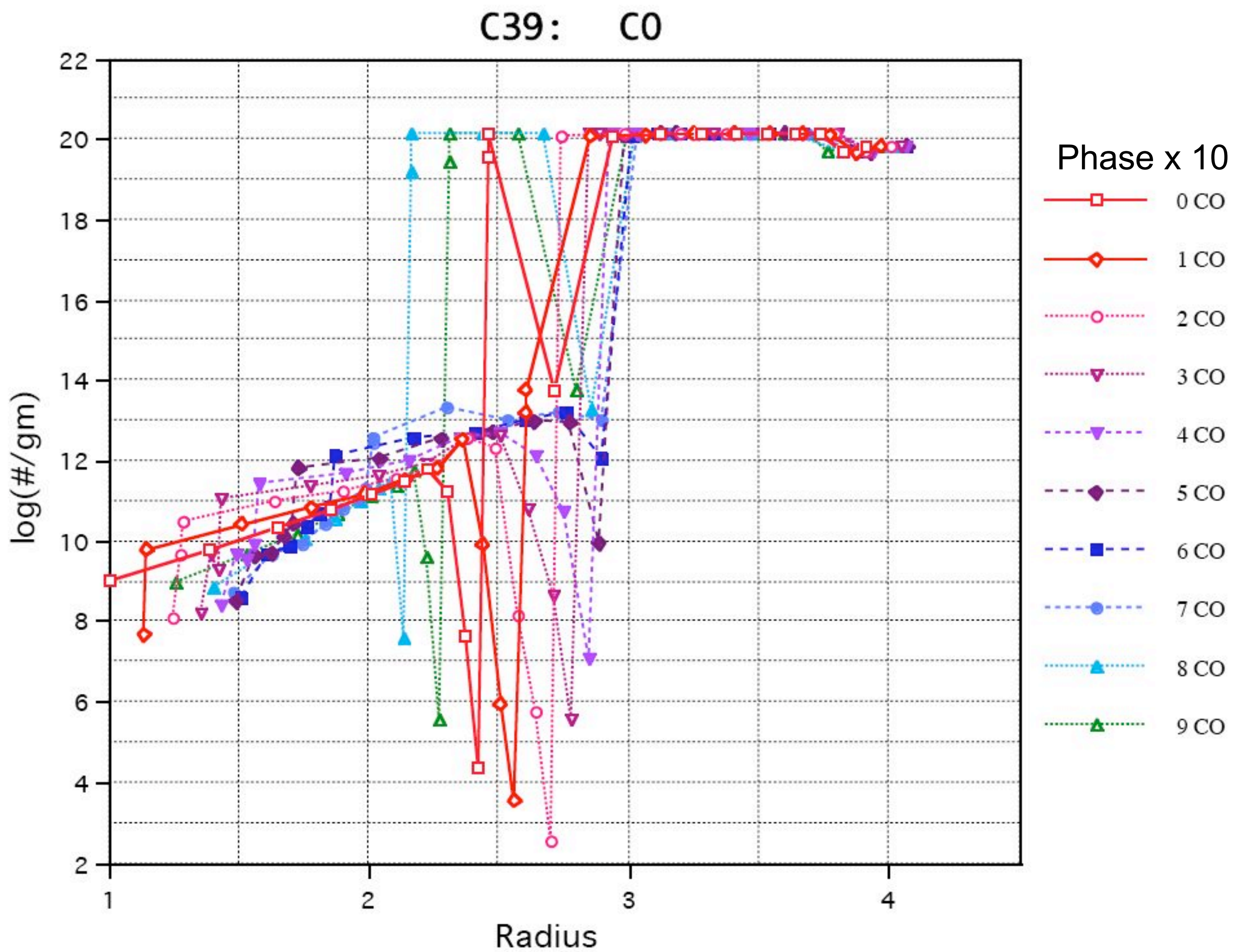
What does that mean for M and C stars?

Shocks allow S stars to form dust

- In pulsating stars (the ones with dusty winds, the Miras), shocks break up H_2 and 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 C_2H_2, Al_2O_3, and SiO.

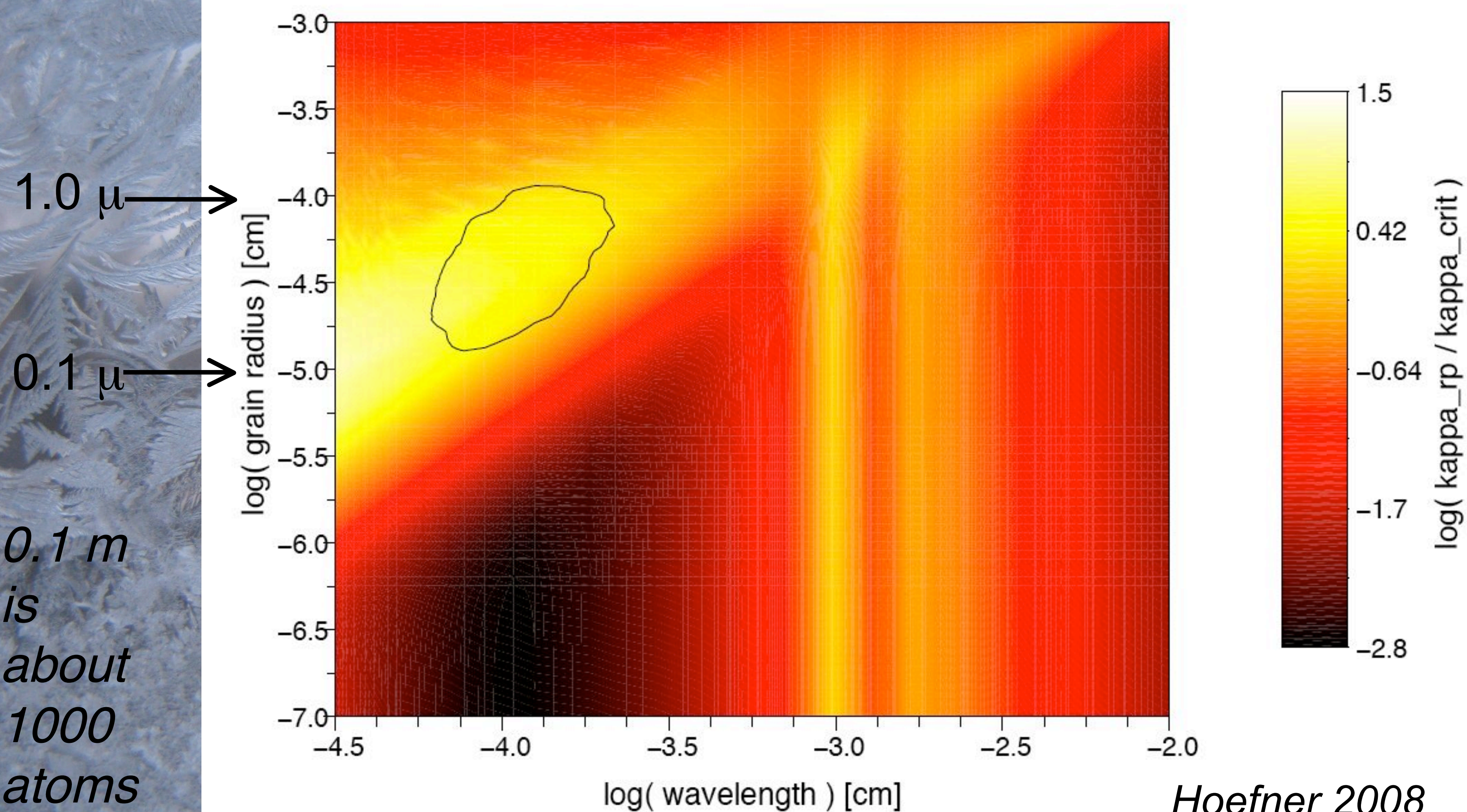


Calculation by James Pierce 2008; model does not include dust

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

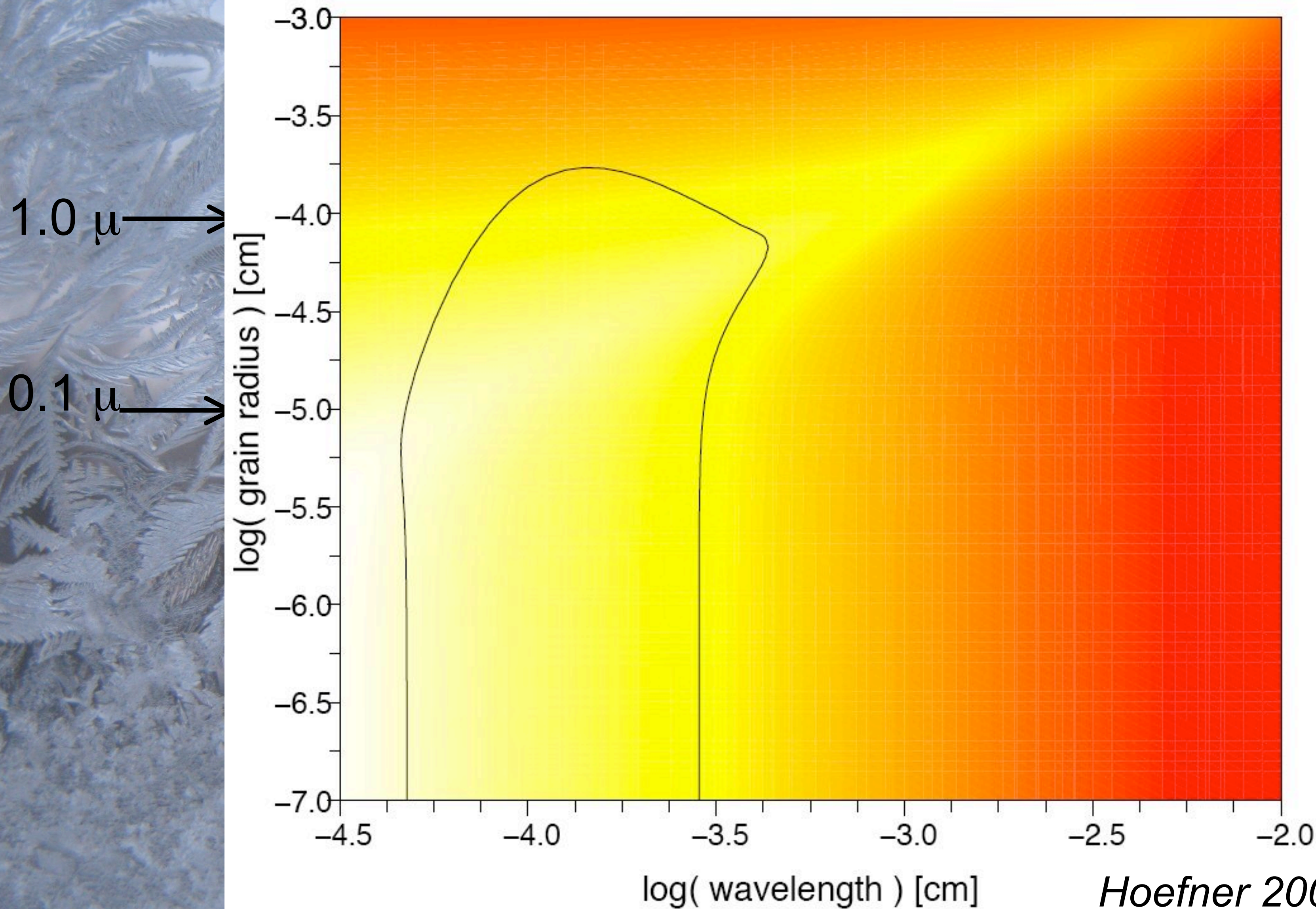
This is important because small silicate grains are not opaque enough to drive material off these stars



0.1 m is about 1000 atoms

Hoefner 2008

Small carbon grains are able to drive mass loss

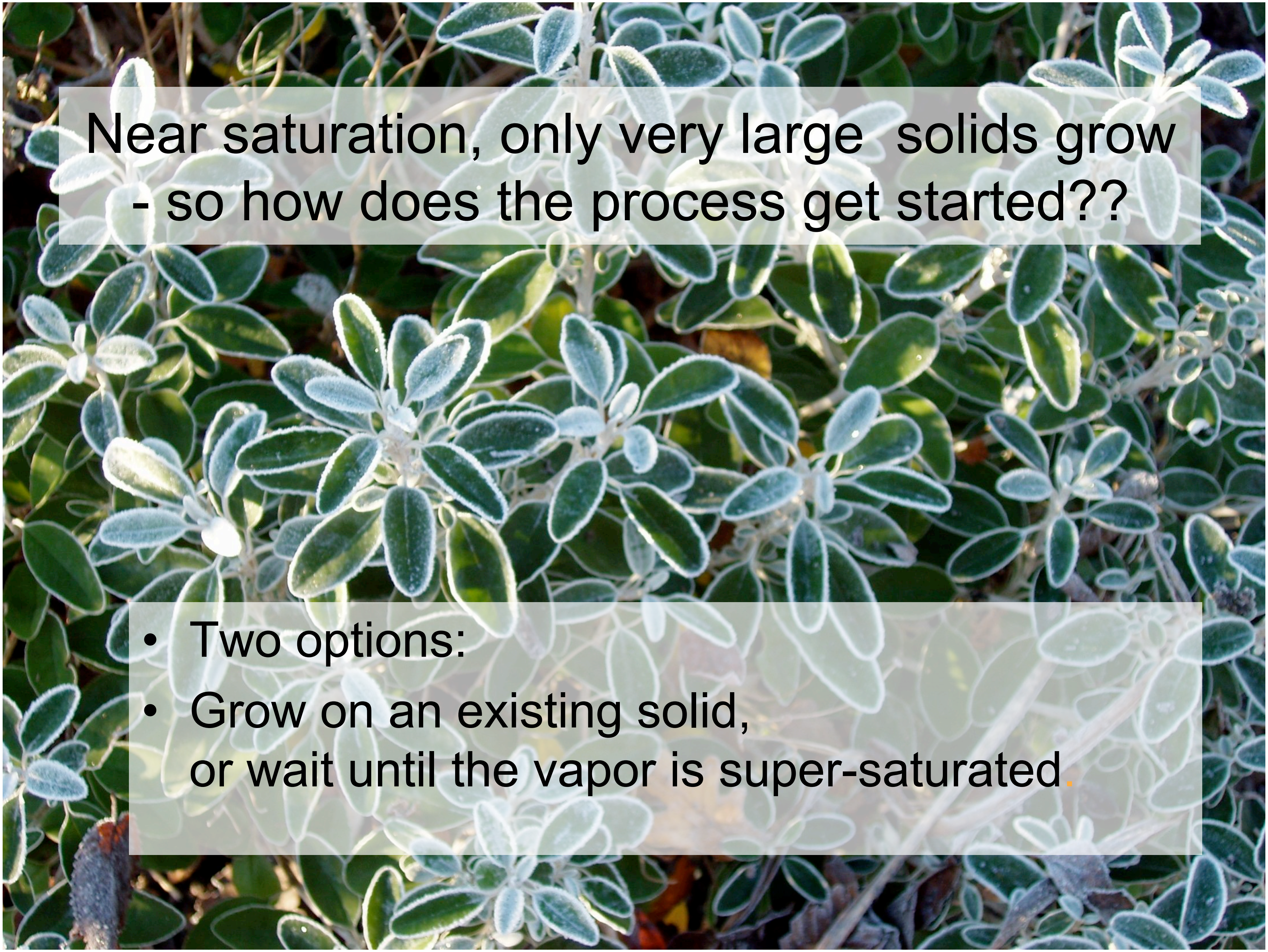


Hoefner 2008

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 mean time we learned more about 1 and 2.

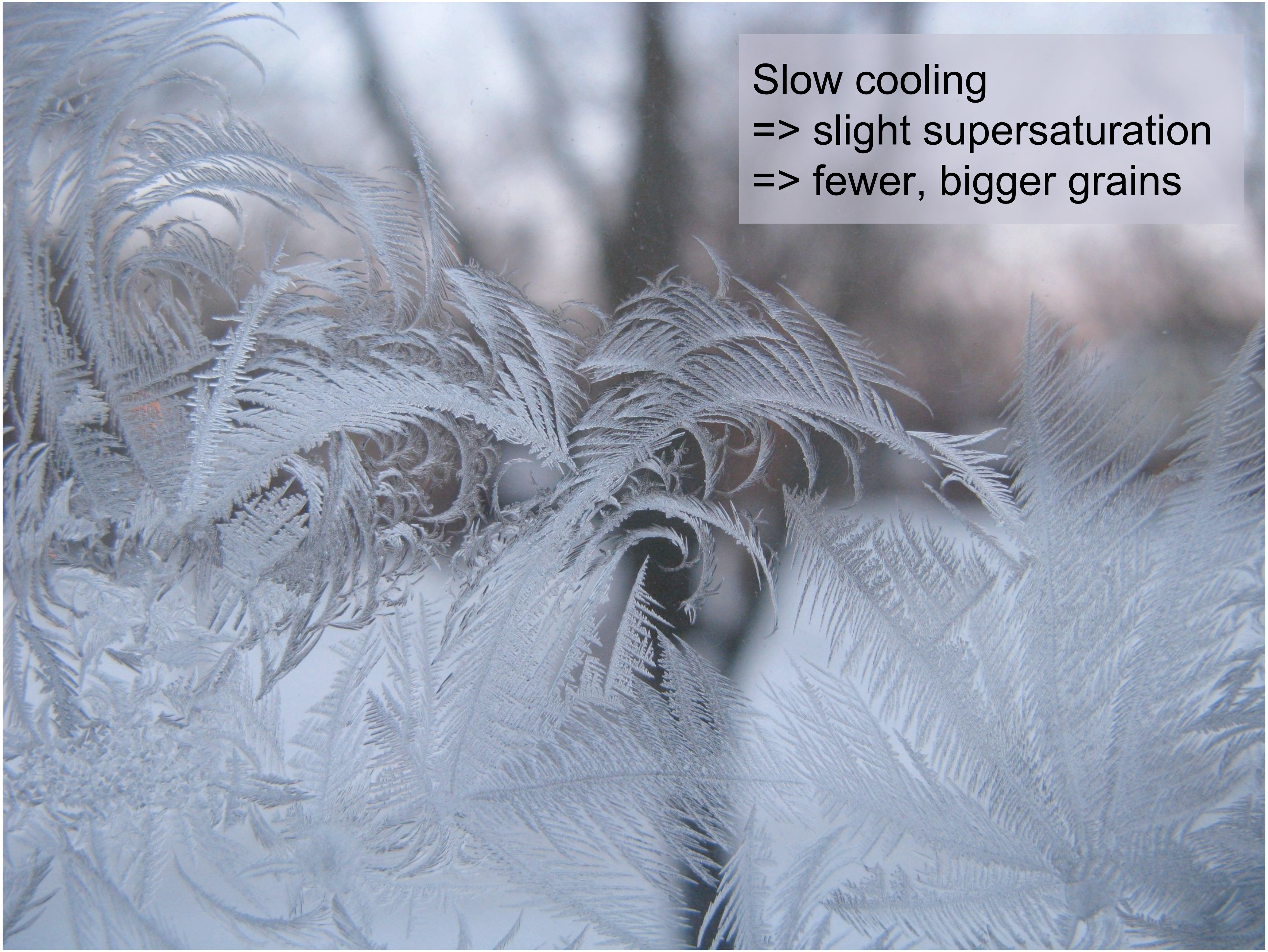

Near saturation, only very large solids grow - so how does the process get started??
• Two options:
• Grow on an existing solid, or wait until the vapor is super-saturated.

IN STARS … SUPERSATURATION

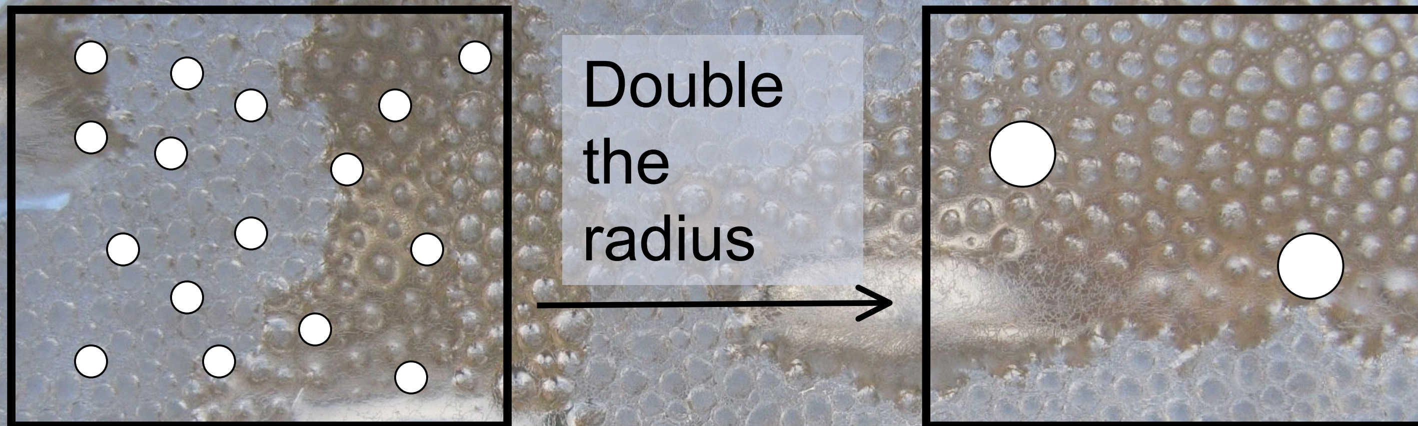
- The higher the supersaturation, the smaller the particles that can grow.
- There is a critical cluster size, with $N=N^*$ atoms, that is stable.
- Clusters with $N>N^*$ grow. Clusters with $N<N^*$ are more likely to shrink than grow.
- An equilibrium for $N<N^*$ is possible, with more clusters of size 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) => N* is smaller
- Smaller N* => more grains get to N*
- N ≥ N* grow until the material is all in grains.
- Higher supersaturation -> more, smaller grains

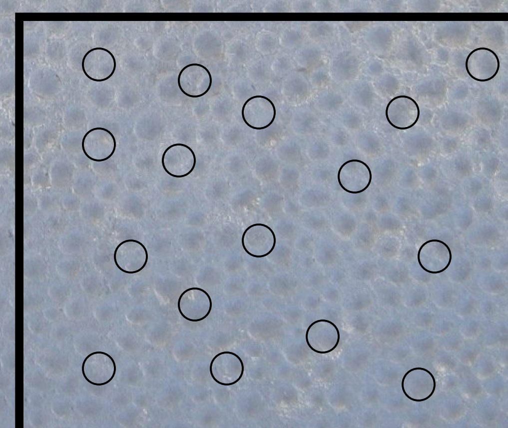

Slow cooling
=> slight supersaturation
=> fewer, bigger grains

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



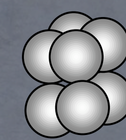
If they are opaque, many small grains intercept more light than a few large ones with the same total mass.

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



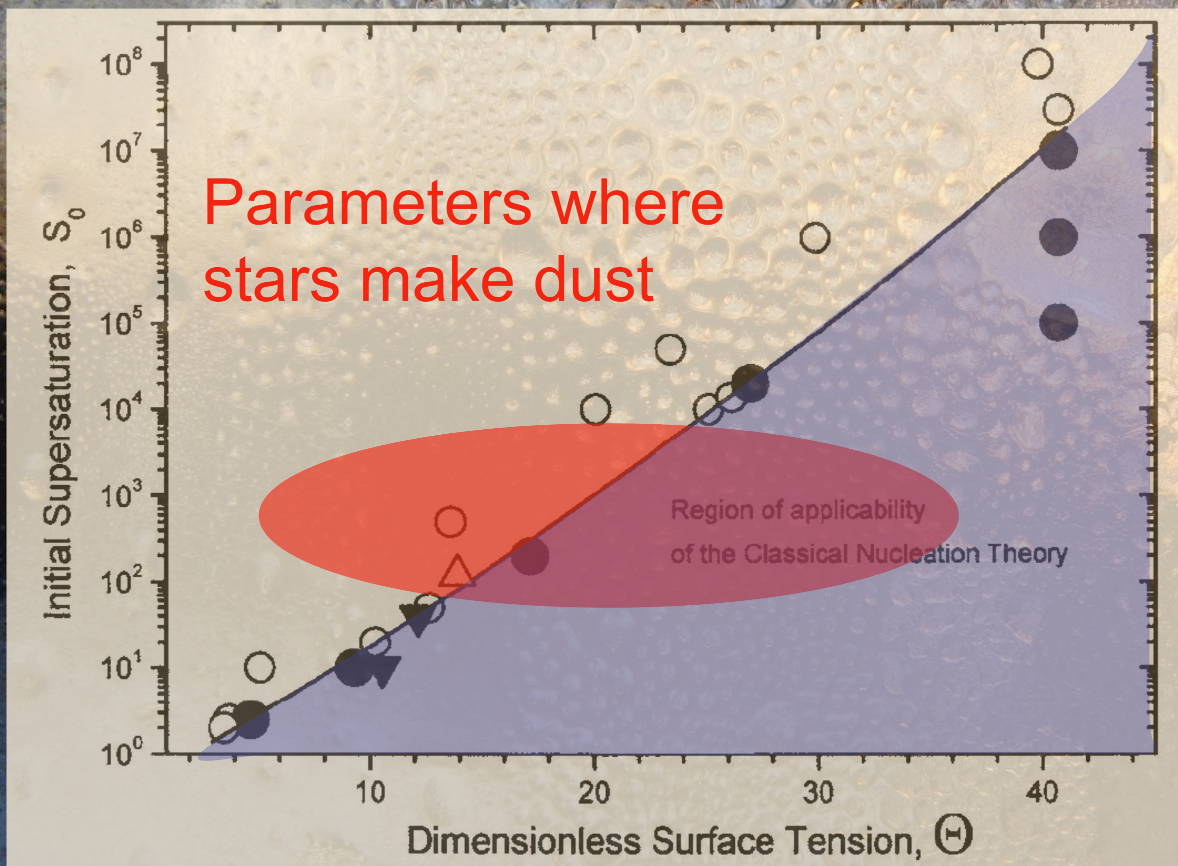
Problems with SNT for stars

- Calculations make use of macroscopic properties - surface tension etc.



- In stars, N* turns out to be ≤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.

$\Theta = \Delta G/kT$ where G = 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
LAW in 2007 & 2008