Title: The Secret Life of a Snowflake: An Up-Close Look at the Science and the Splendor of Nature's Frozen Art

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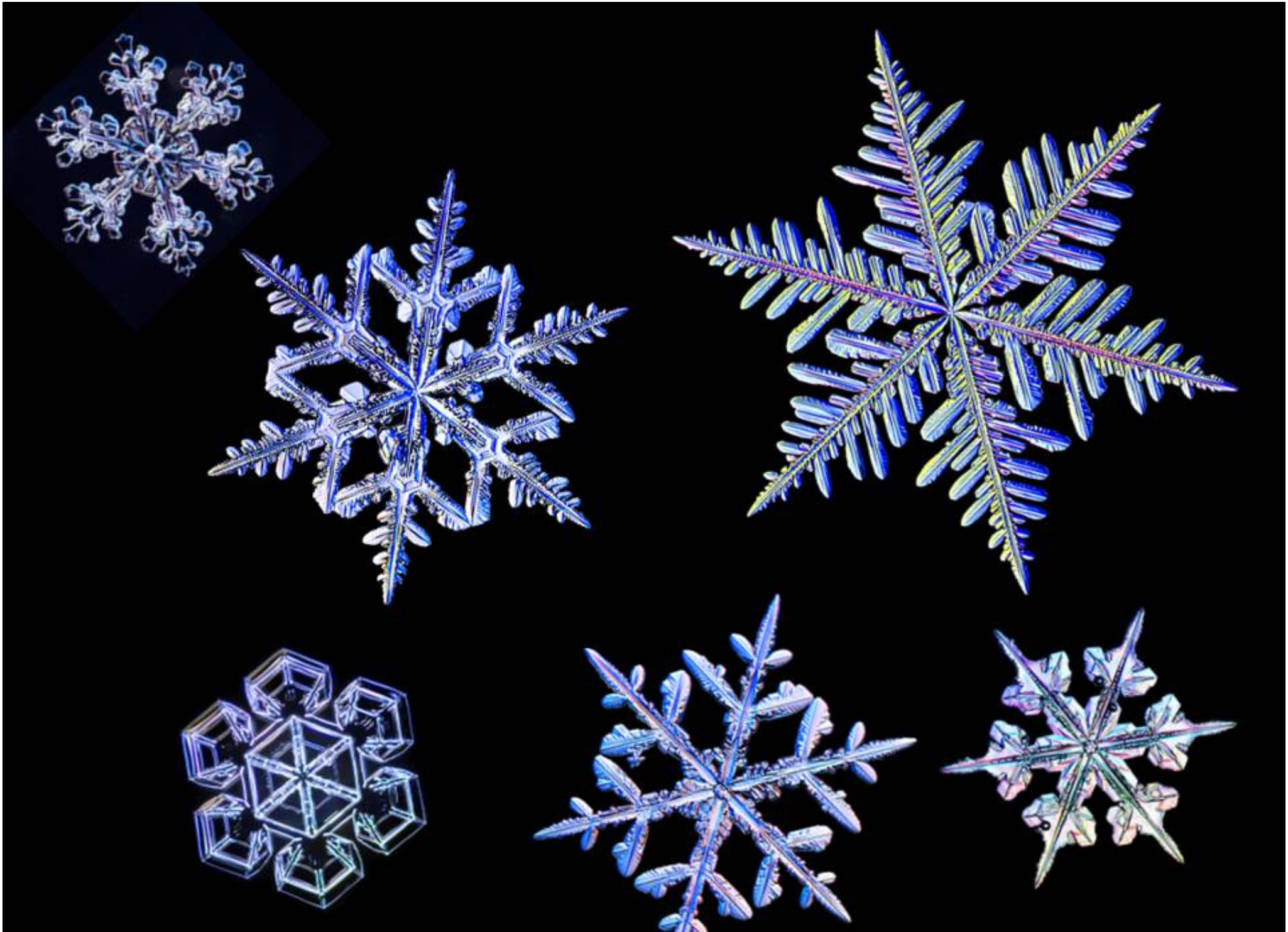
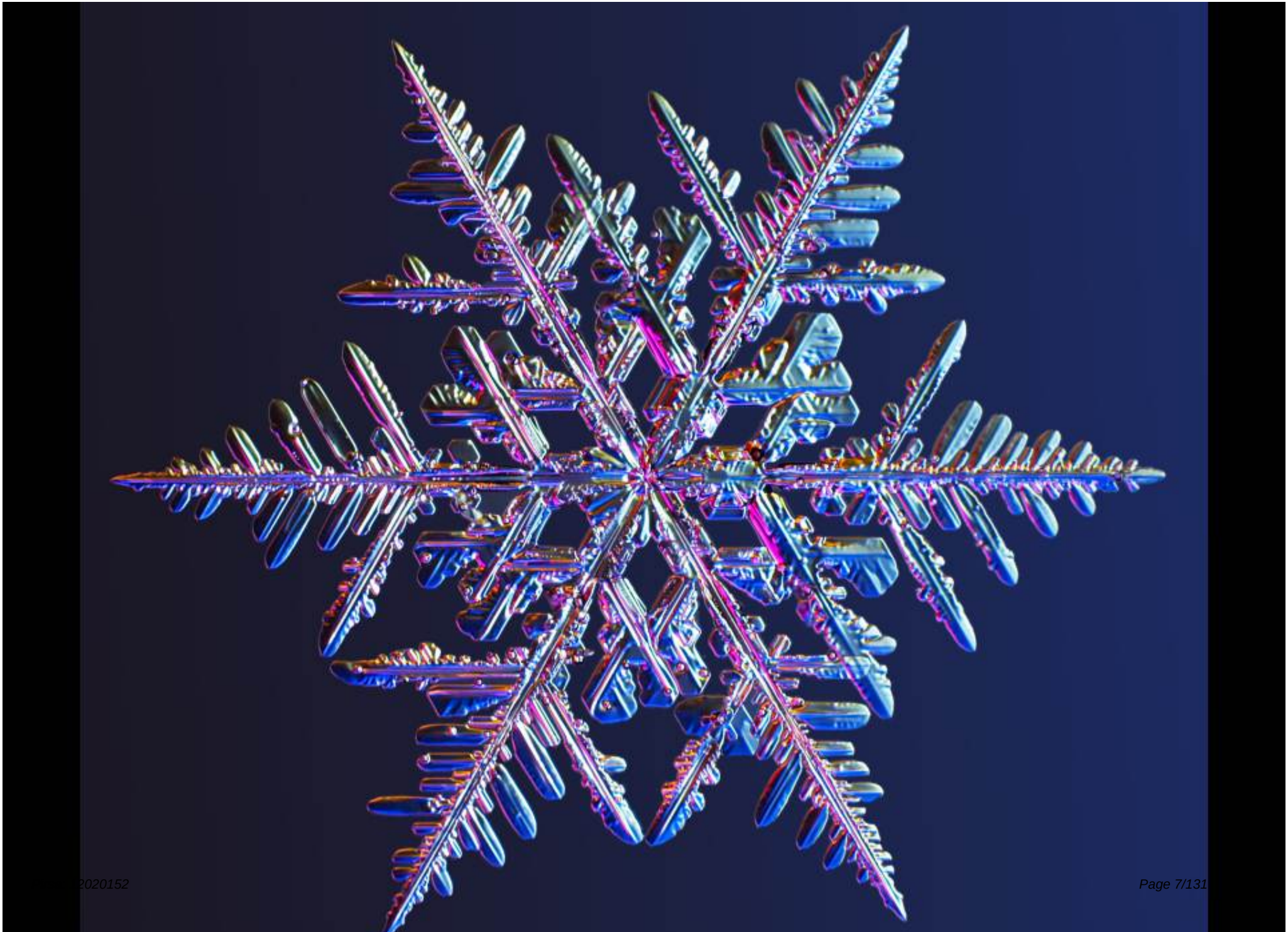
Abstract: How do snowflakes form? What creates their complex, symmetrical and strikingly beautiful shapes? Is it true that no two are exactly alike? Kenneth Libbrecht of Caltech, will reveal the secrets of snowflakes and the molecular dynamics of crystal growth through spectacular photographs of these miniature ice sculptures.

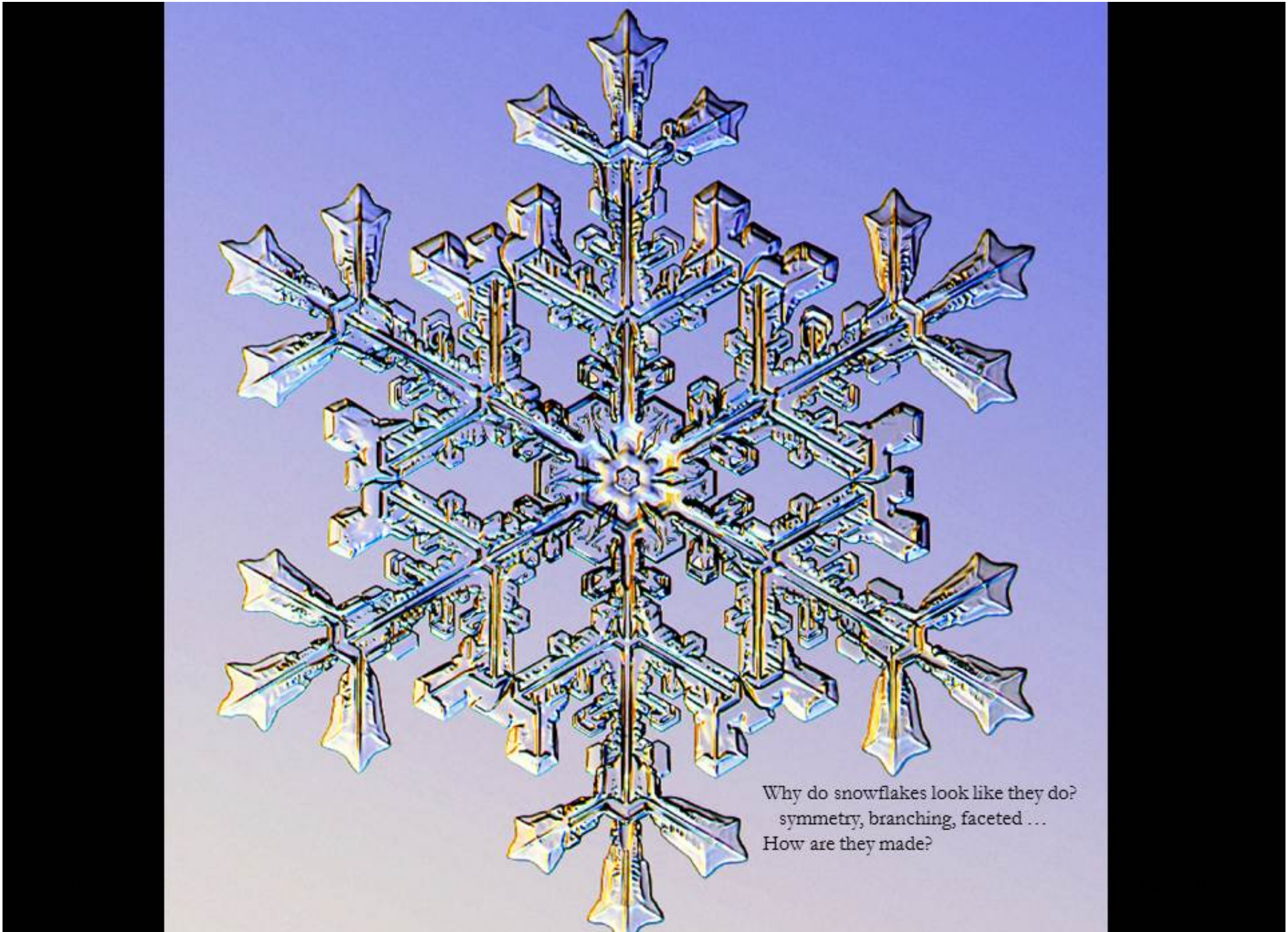
The Secret Life of a Snowflake

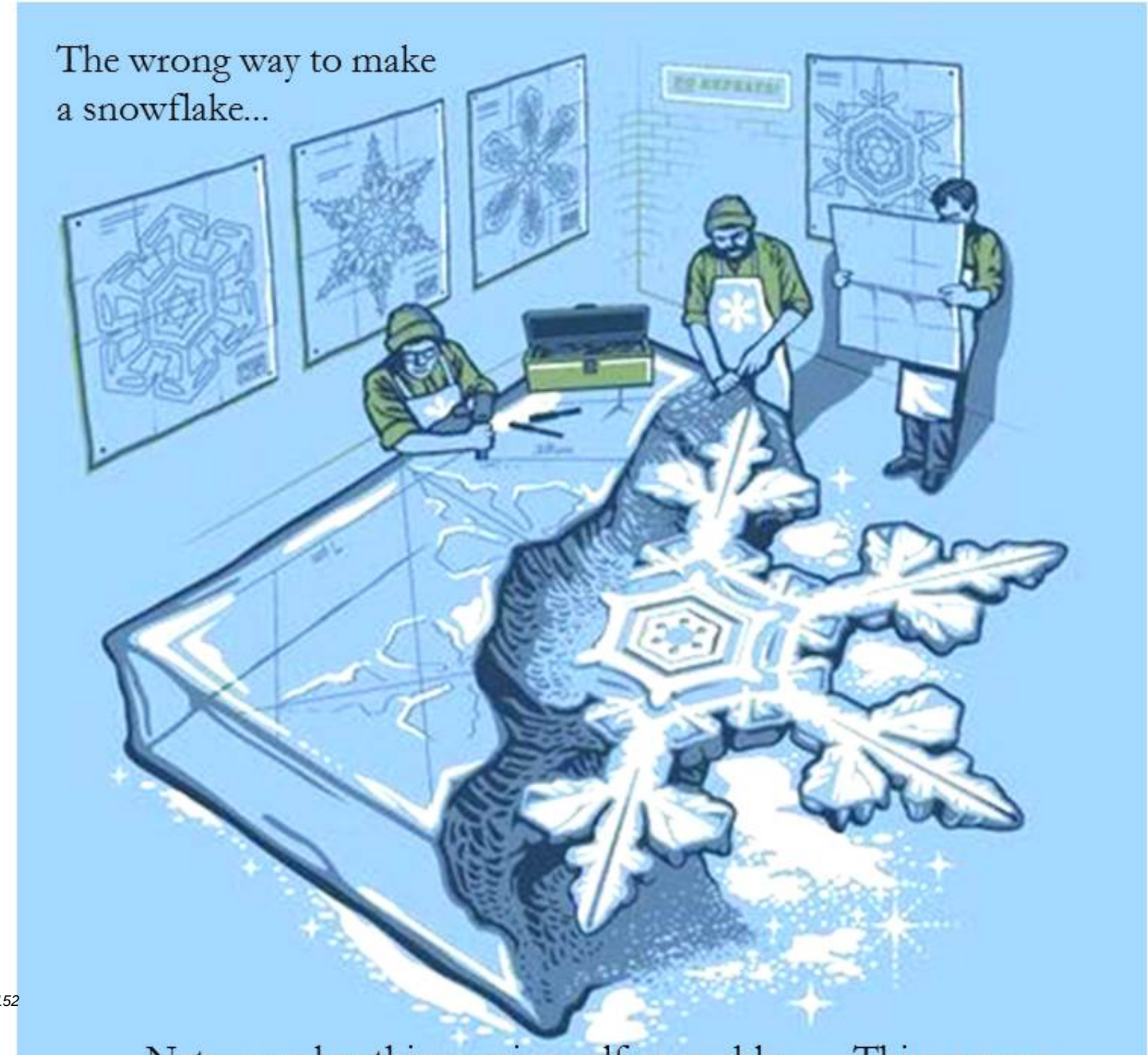
An Up-Close Look at the Science and the Splendor of Nature's Frozen Art

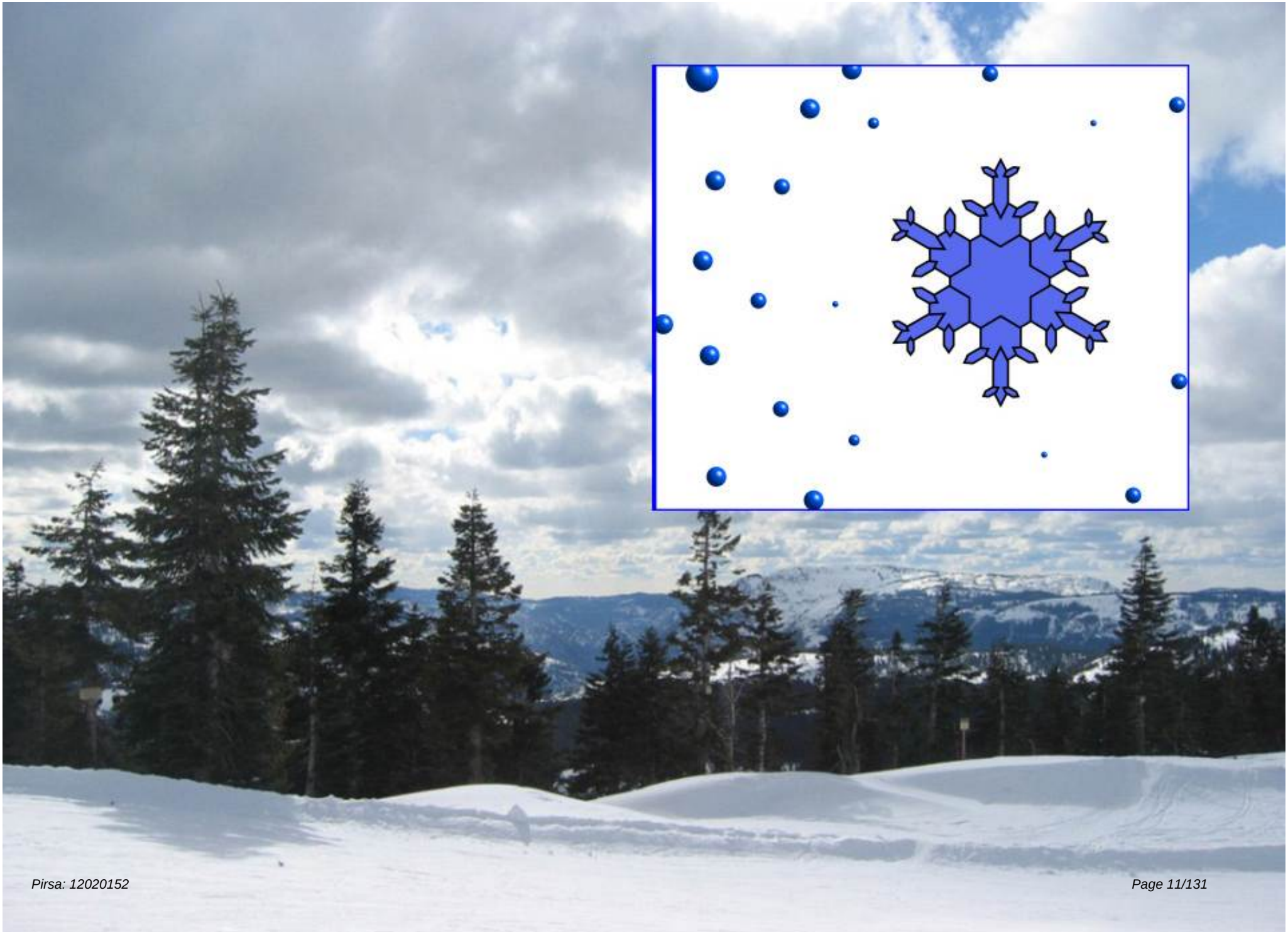
Kenneth G. Libbrecht
Caltech





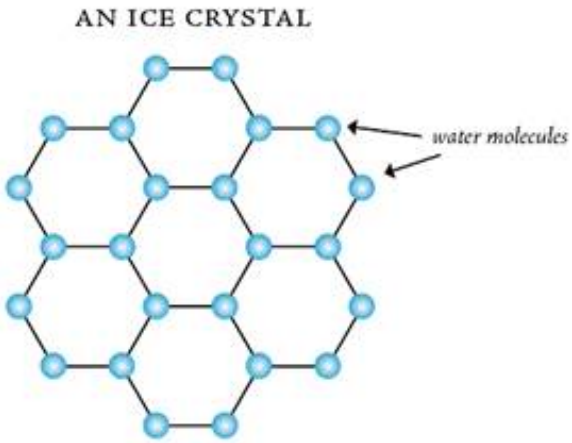

Why do snowflakes look like they do?
symmetry, branching, faceted …
How are they made?

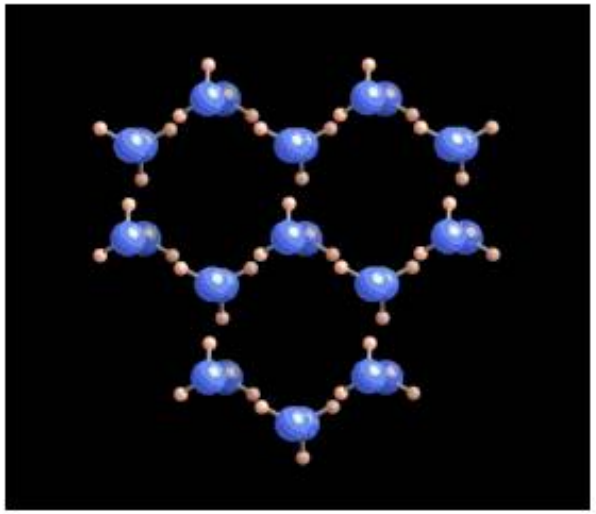

The wrong way to make
a snowflake...

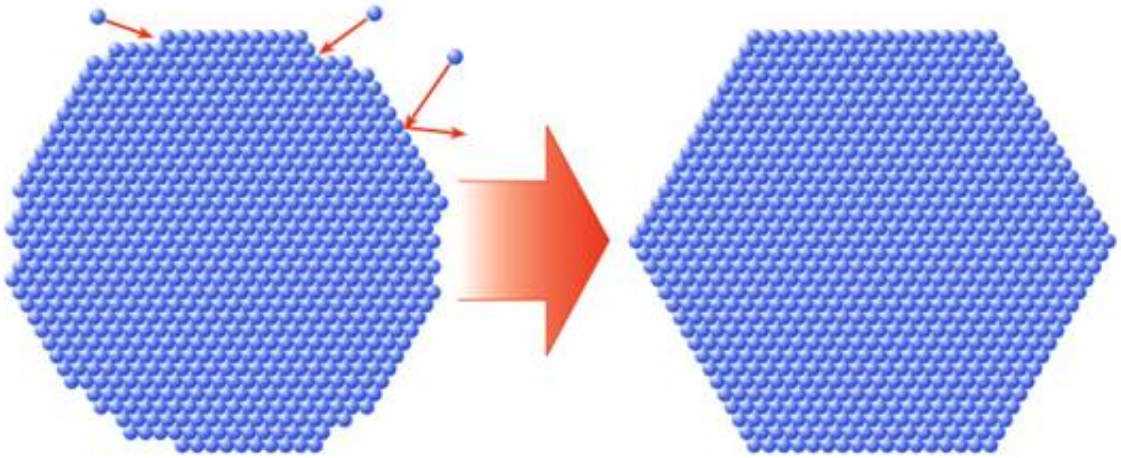


Snowflake Basics I - Faceting

Structure of the Ice Crystal → Facets

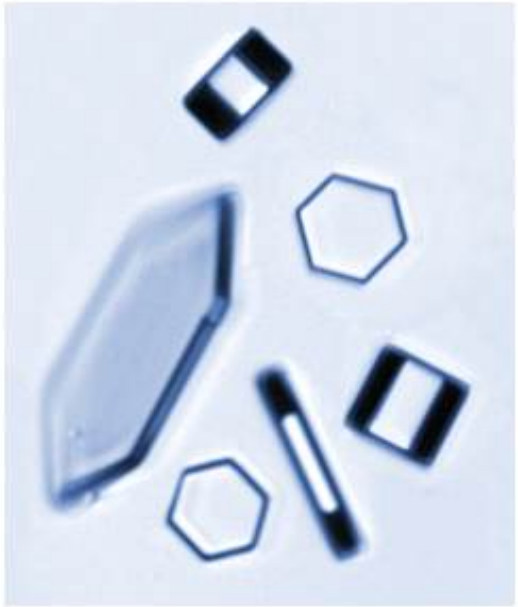






Molecules cannot readily attach to smooth surfaces
→ facets form as crystal grows

Faceting is how the geometry of the water molecule is transferred to the geometry of a crystal.



Tiny, laboratory grown snow crystals ~0.1 mm

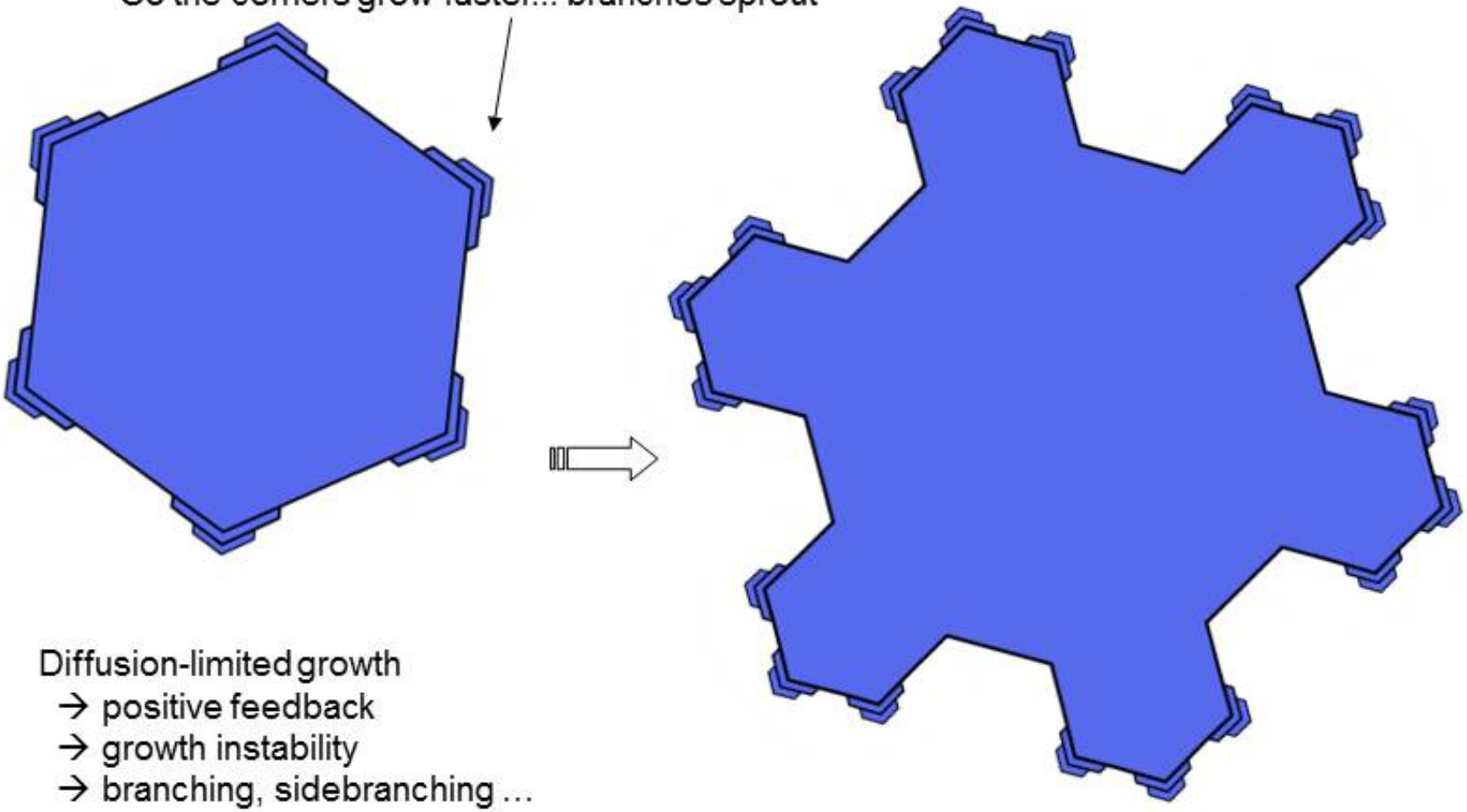
→ no 4-, 5-, 7-, 8-sided snow crystals!

Snowflake Basics II – The Branching Instability

Branches form as snowflakes grow larger

A *Growth Instability* – responsible for most complex structure in snow crystals

The six corners stick out farther into the humid air
So the corners grow faster... branches sprout



Diffusion-limited growth
→ positive feedback
→ growth instability
→ branching, sidebranching …
→ complex structures

Snowflake Basics III - Complexity and Symmetry

(an explanation of the "No-Two-Alike" conjecture)

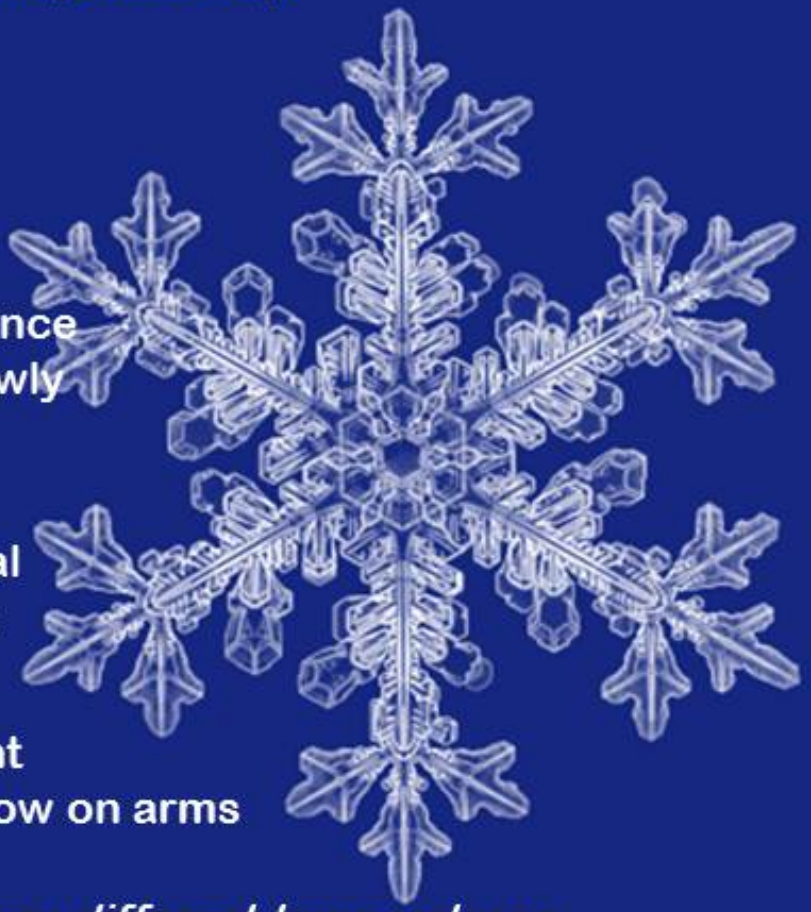
- Nucleation of ice particle

Grows to hexagonal prism, since smooth facets grow most slowly

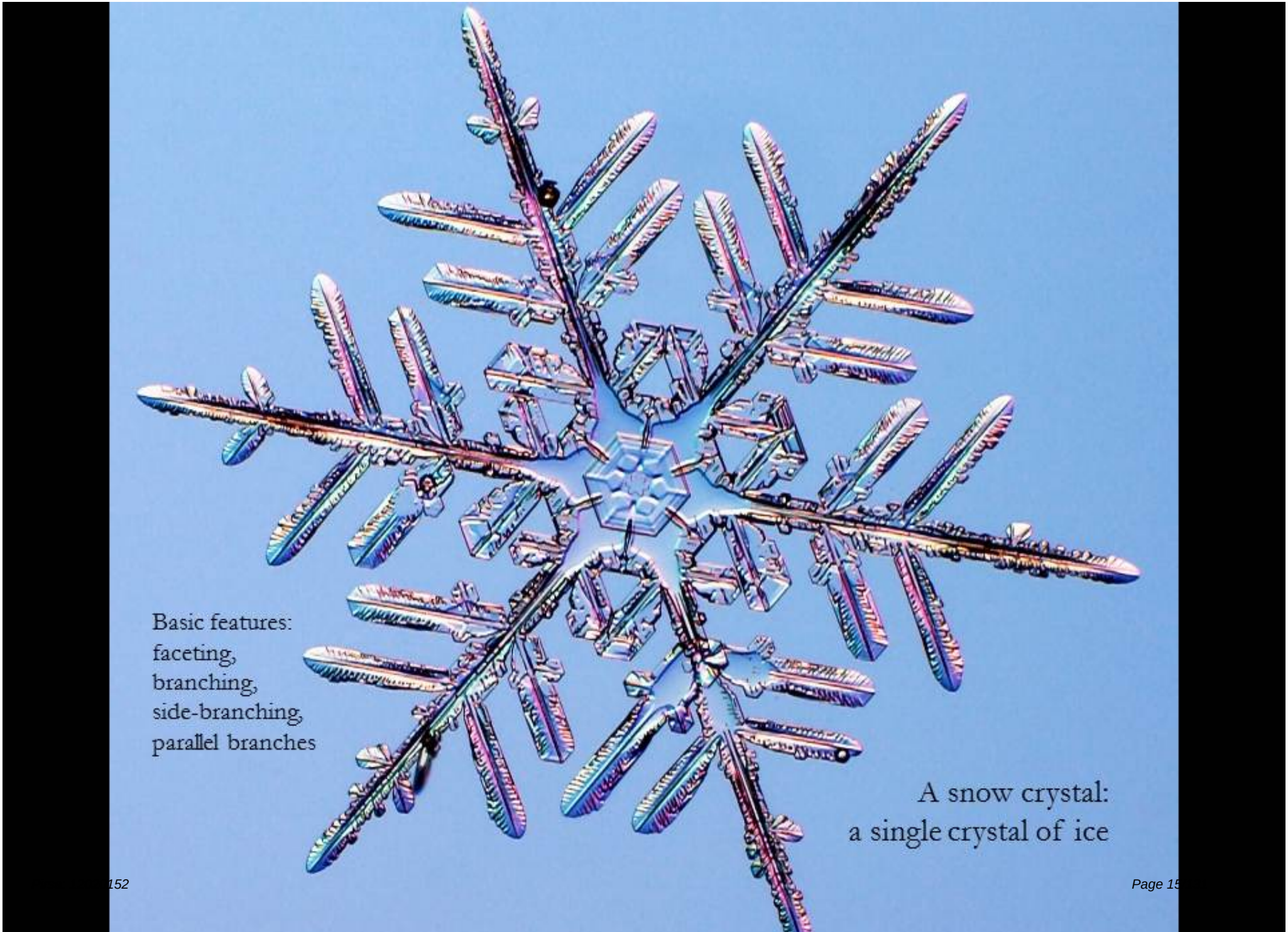
Simple plate unstable as crystal grows larger … corners sprout arms

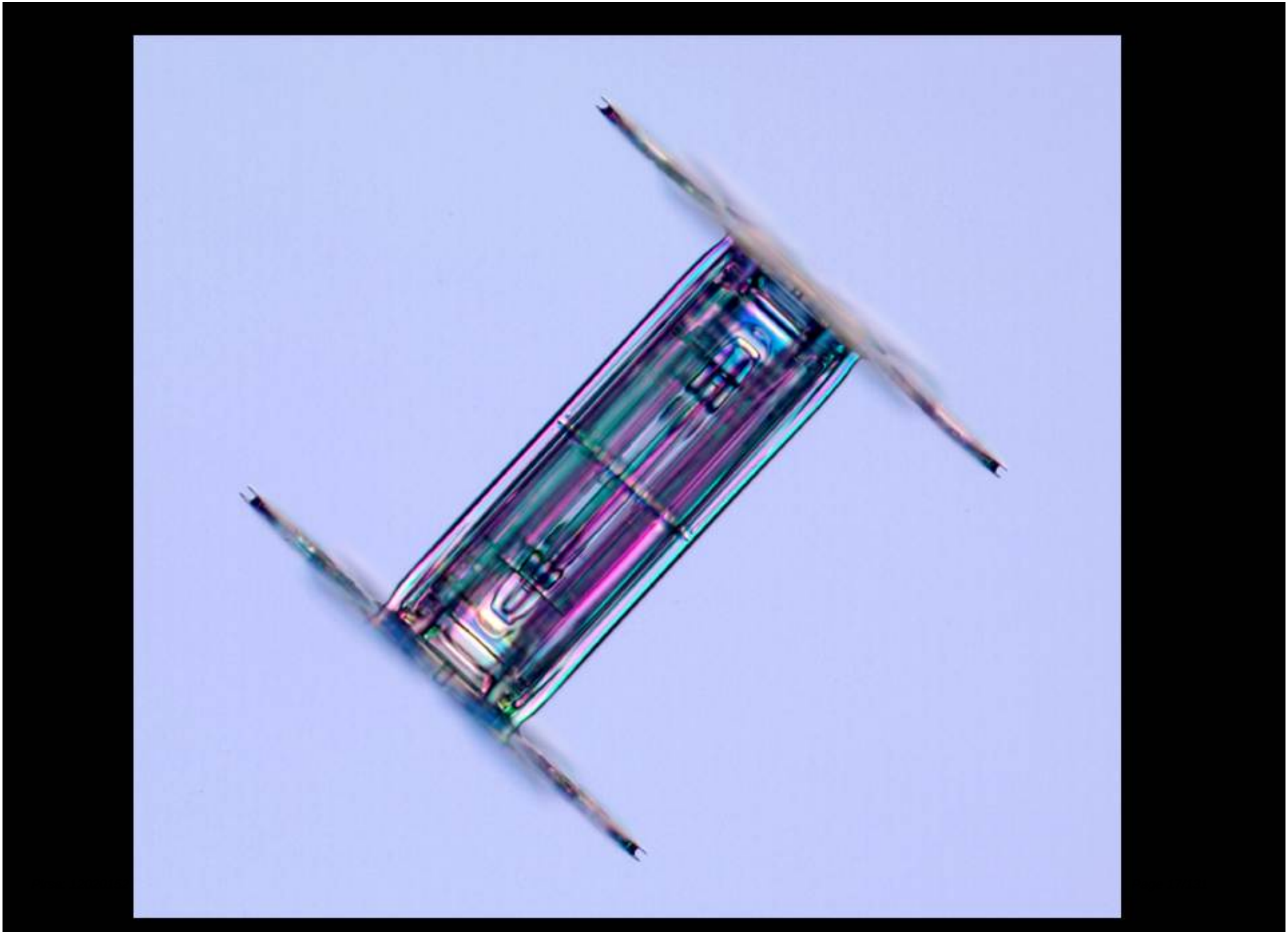
Crystal moves to different temperature … plates grow on arms

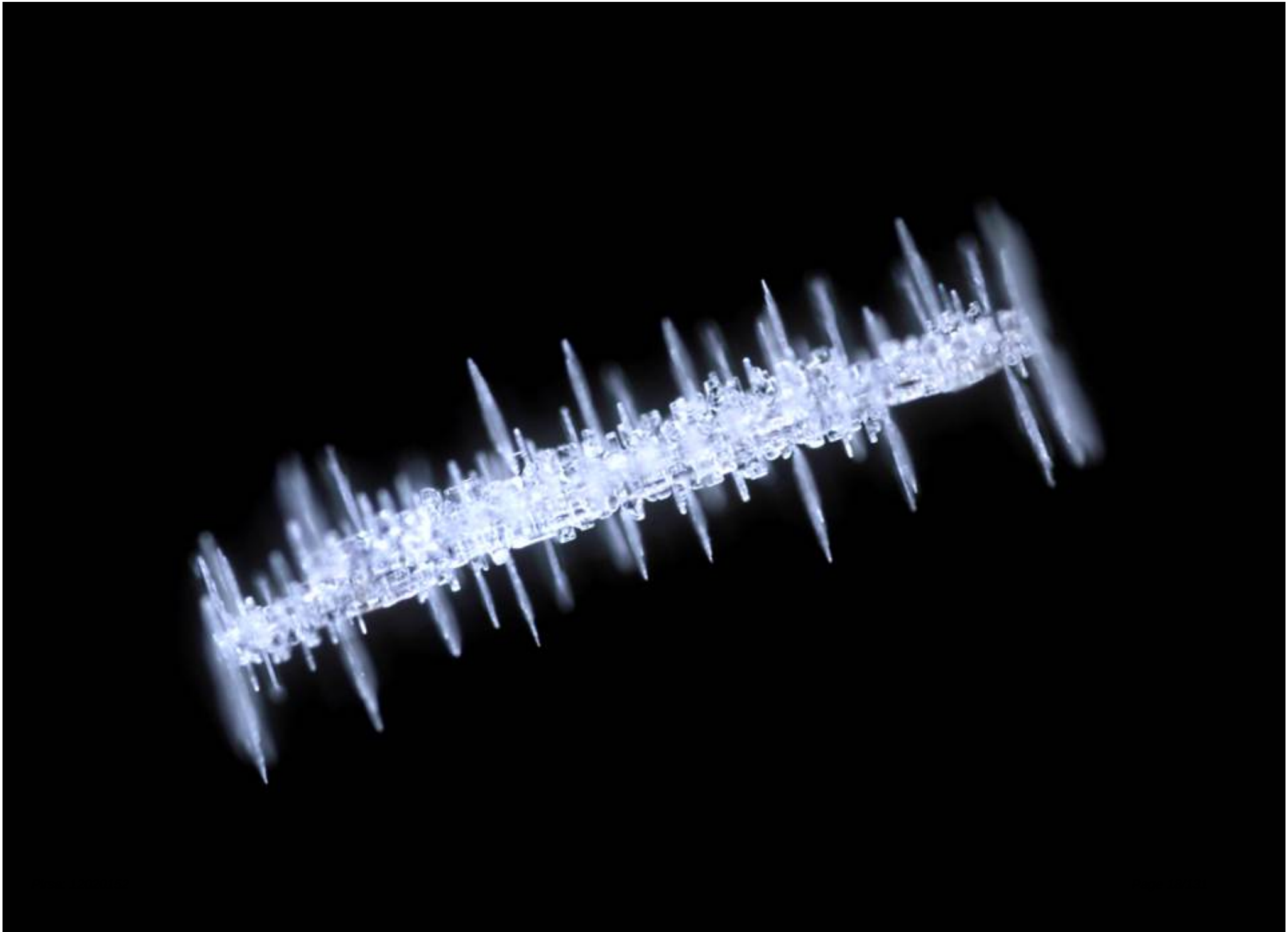
Crystal moves through *many different temperatures* … each change causes new growth behavior on arms



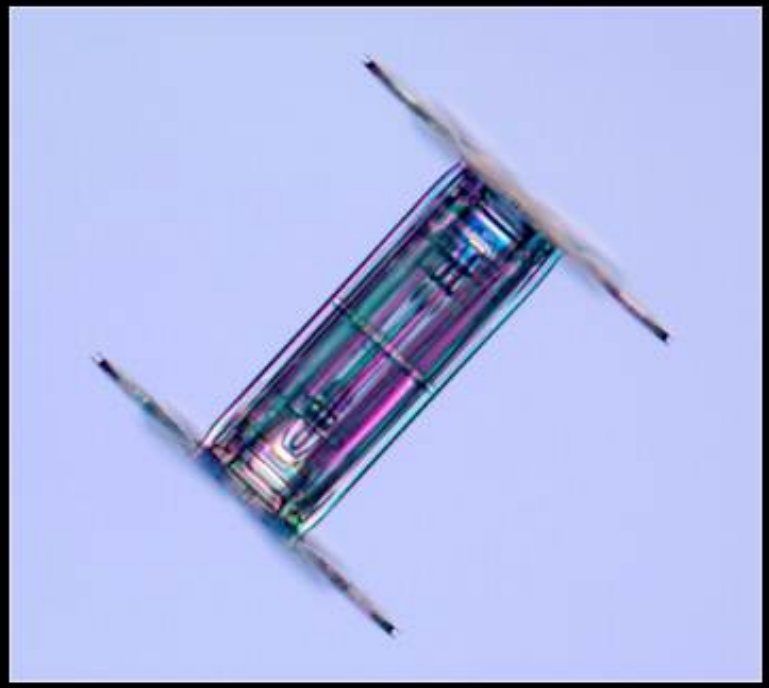
Complex history → Complex crystal shape
Each arm experiences same history → Symmetry
No two paths are the same → No two alike
All because growth sensitive to temperature, humidity

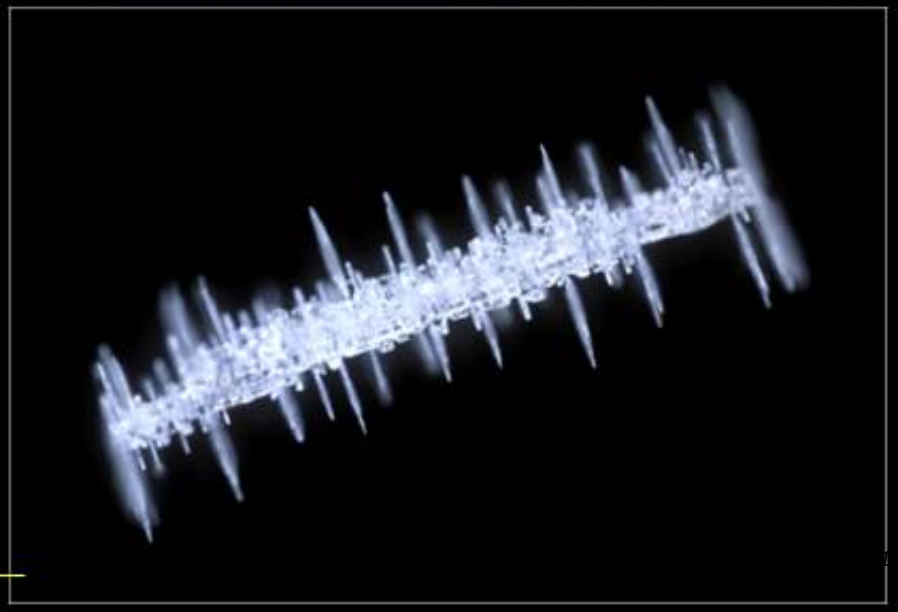

Basic features:
faceting,
branching,
side-branching,
parallel branches
A snow crystal:
a single crystal of ice



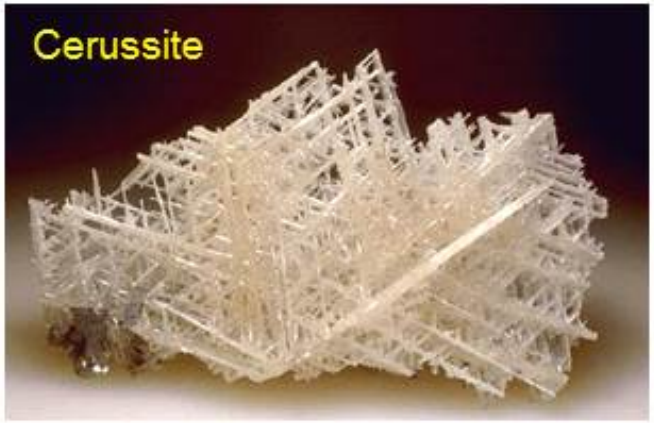


Each is a snow crystal – a single crystal of ice…





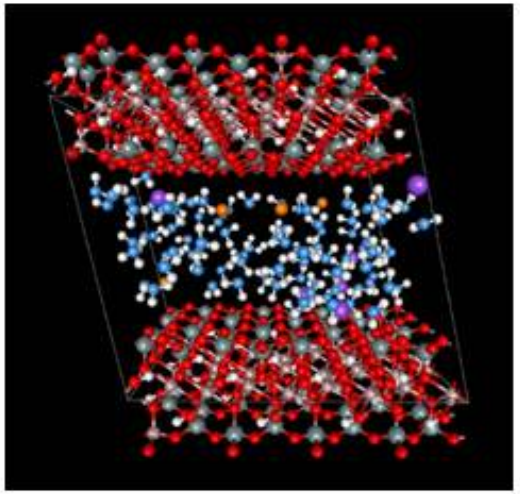
Mineral crystals also show diverse morphologies



~5000 different minerals known (including ice)
molecular structures determined by X-ray crystallography
growth morphologies cataloged for some
growth often complex (as with ice)

Crystallography = statics problem
Crystal growth = dynamics problem

Model growth from molecular dynamics simulations?
No, simulations cannot deal with range of lengths, times



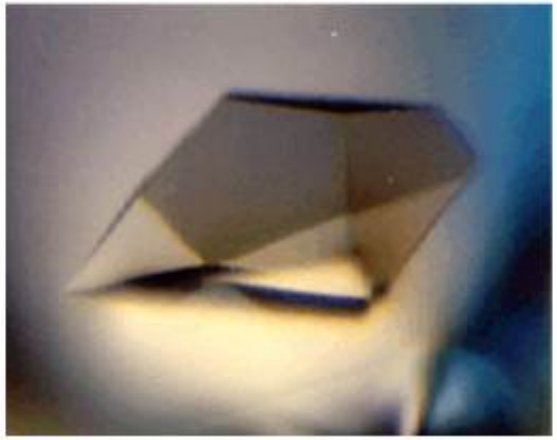
→ morphologies, growth rates cannot yet be explained (for essentially all crystals)

Growth dynamics is important for industrial crystals

(but trial-and-error is still the most successful engineering strategy)

Synthetic gemstones

Protein crystals



Semiconductor crystals

Optical crystals

Biomineralization

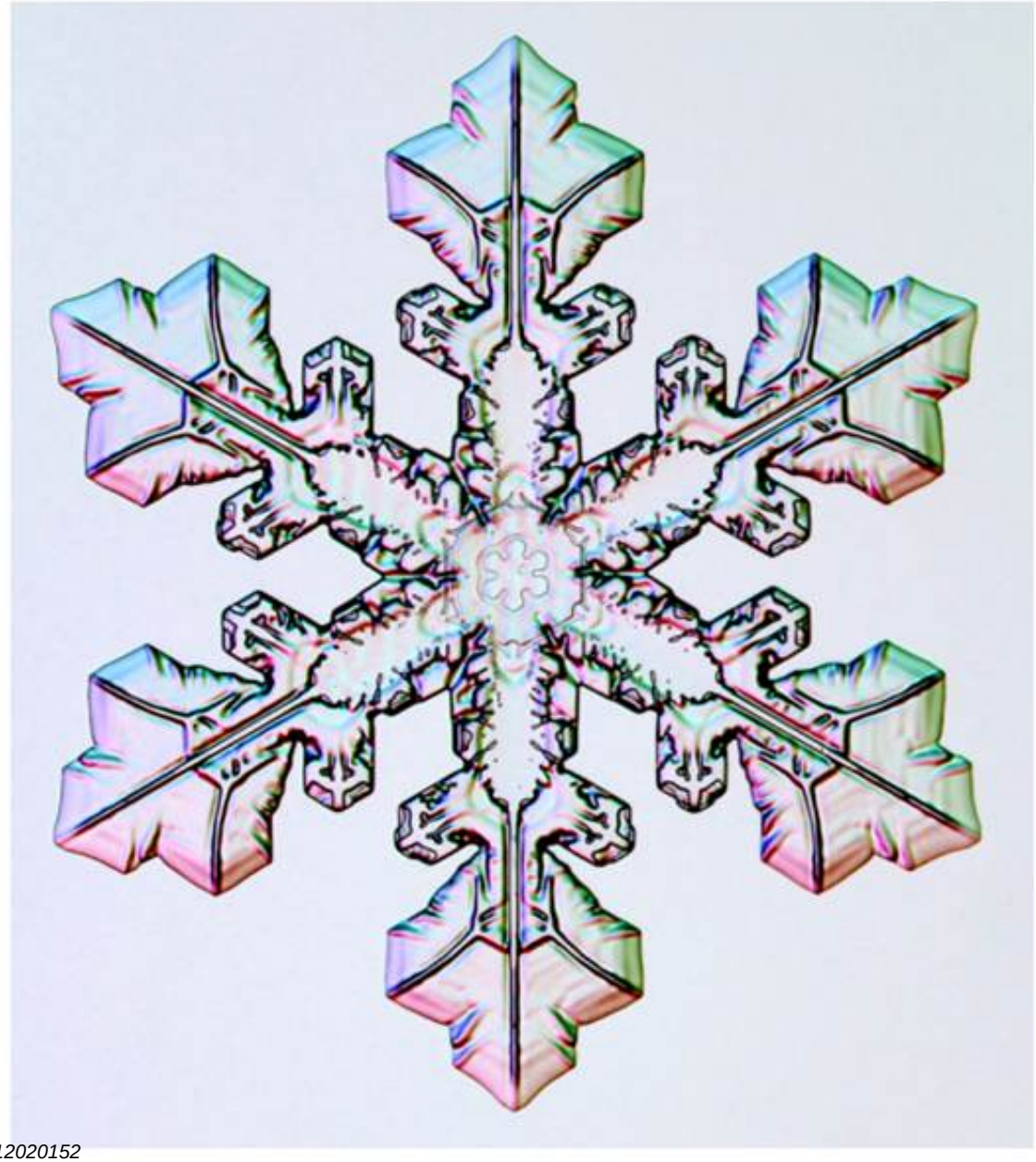
The fundamental physics of crystal growth is not well understood... even in silicon and other industrial crystals.

Engineering → recipes → desired final products

→ *morphologies, growth rates not well understood*

...technology advances if understand basic science better

A case study in crystal growth...



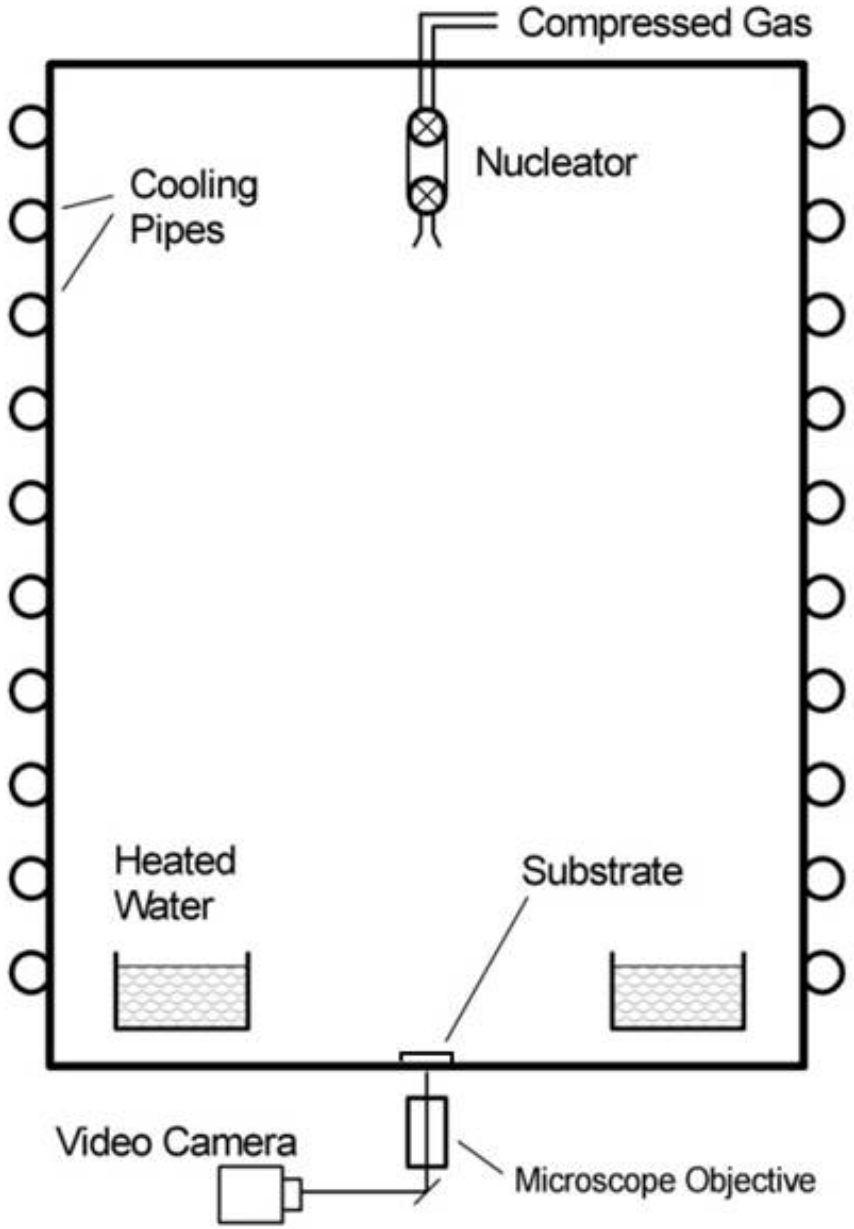
Why Ice?

- Monomolecular System
- Well Characterized Material
- Growth from Vapor
- Rich Phenomenology
- Inexpensive
- No Safety Issues
- Many Unsolved Puzzles

→ Molecular Dynamics of Crystal Growth

Ice growth from water vapor is a fascinating physical system

Growing Snow Crystals in the Lab

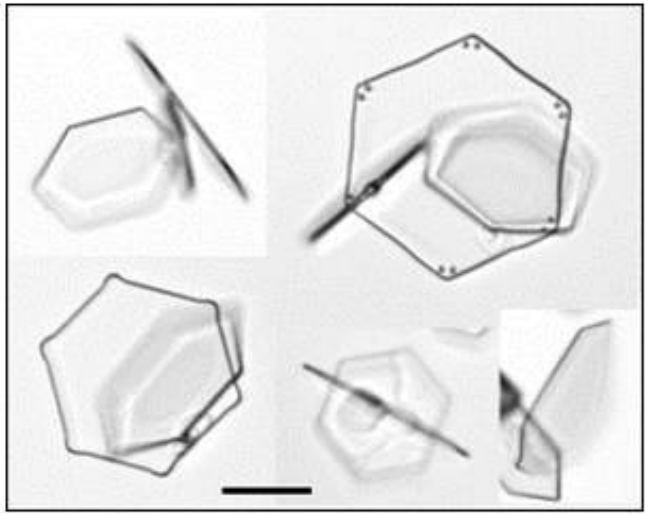


Tank chilled to desired temperature

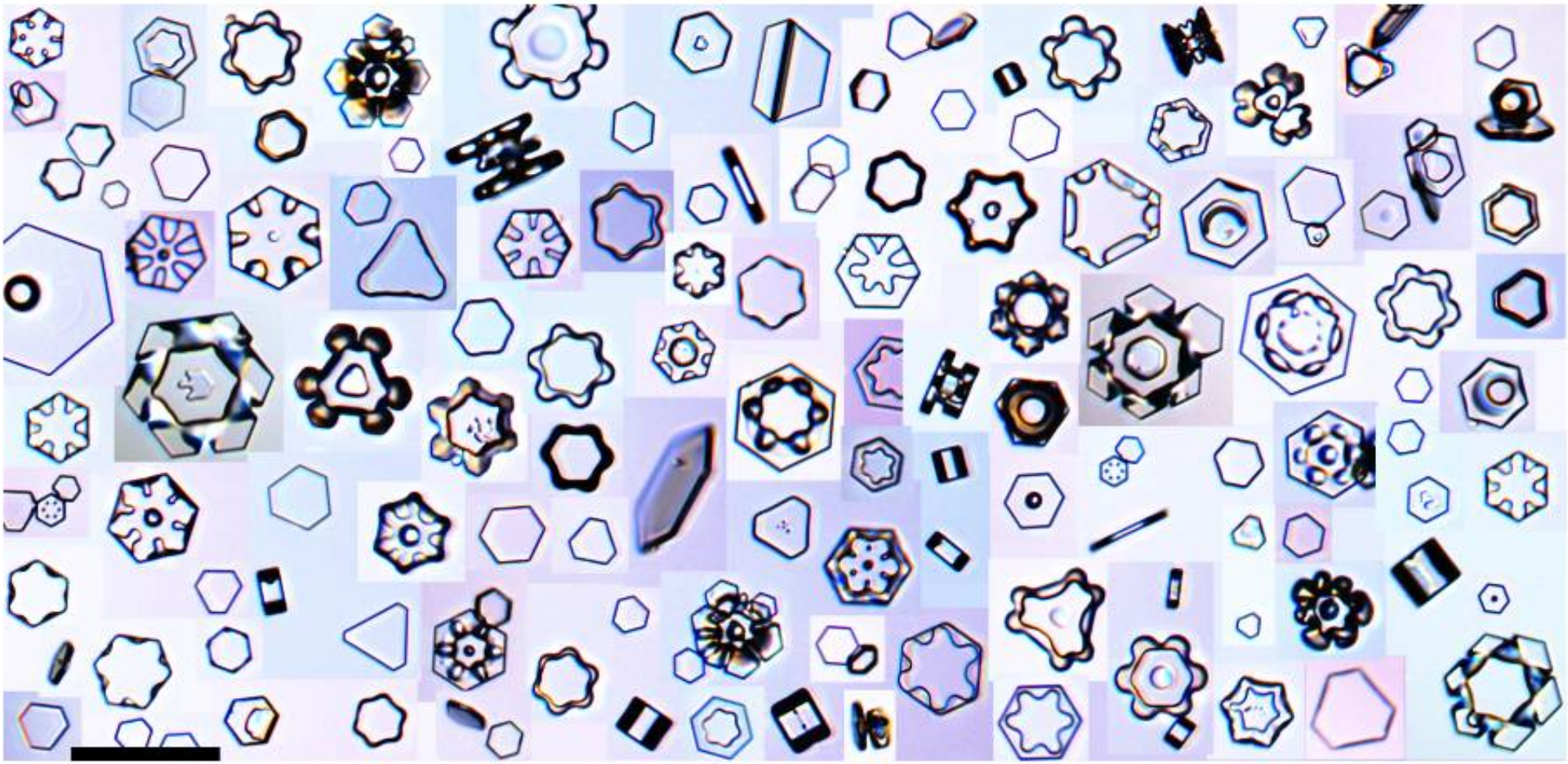
Heated water provides water vapor; mixed by convection

Nucleator creates pulses of cold gas to produce crystals

Crystals fall and are viewed on substrate



Laboratory Grown Snow Crystals: At -2 C



50 micron
scale bar

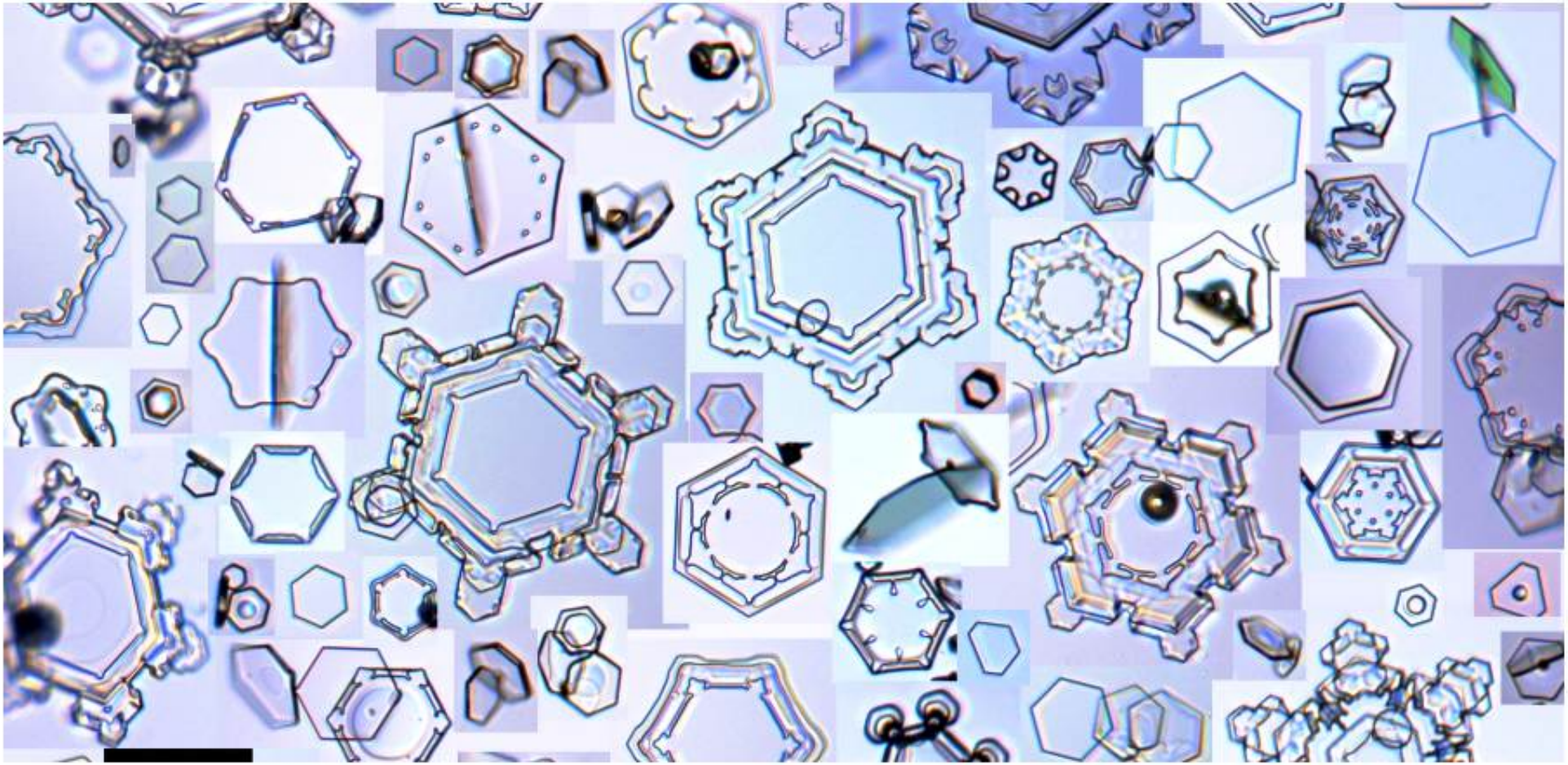
Mostly small, thin plates (some seen edge-on)
Some columns, odd-looking crystals, etc.

Laboratory Grown Snow Crystals: At -5 C

50 micron
scale bar

Mostly hexagonal columns (some with hollows)

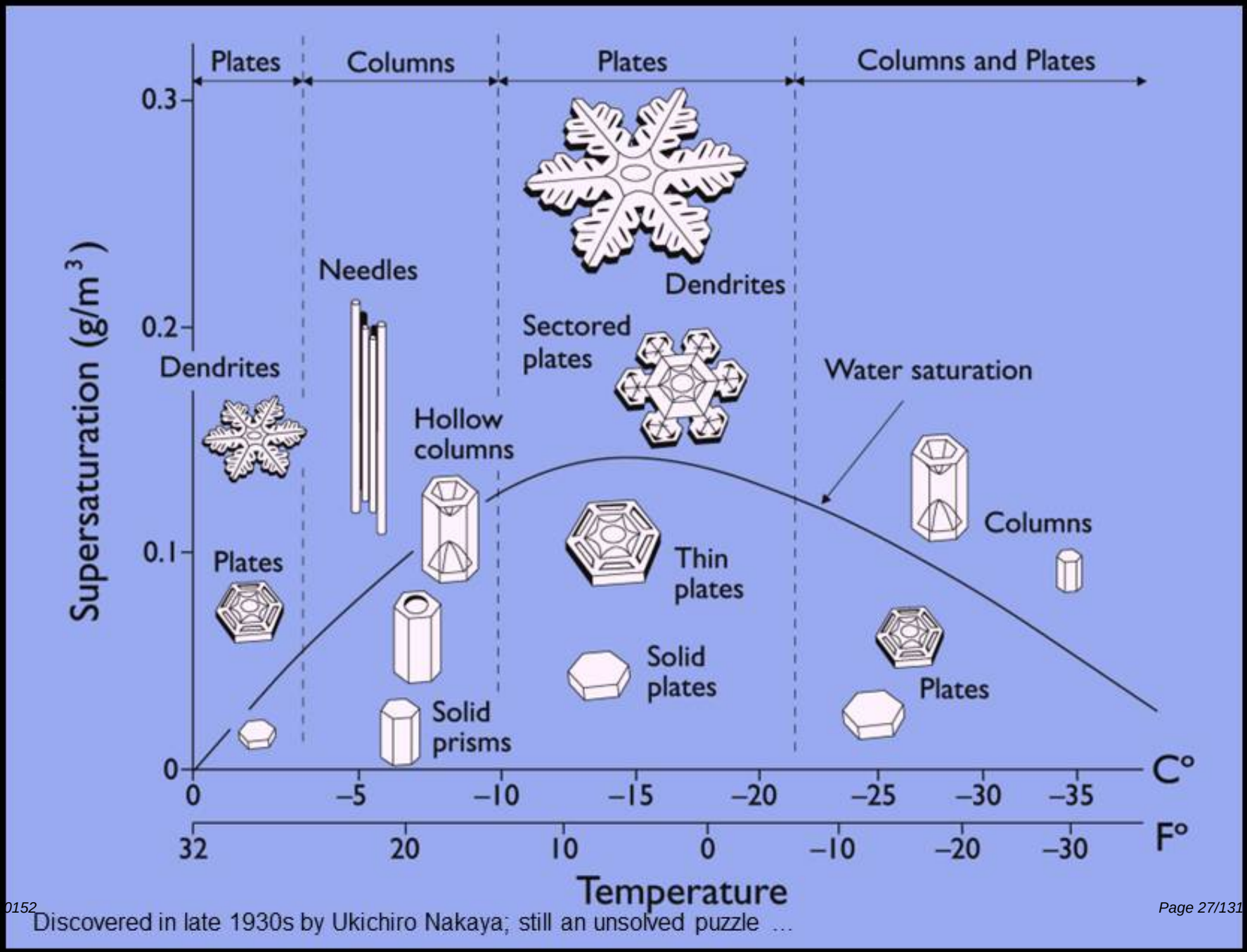
Laboratory Grown Snow Crystals: At -15 C



50 micron
scale bar

Mostly large, very thin plates
Some hexagonal, some branched

The Snow Crystal Morphology Diagram



Discovered in late 1930s by Ukichiro Nakaya; still an unsolved puzzle …

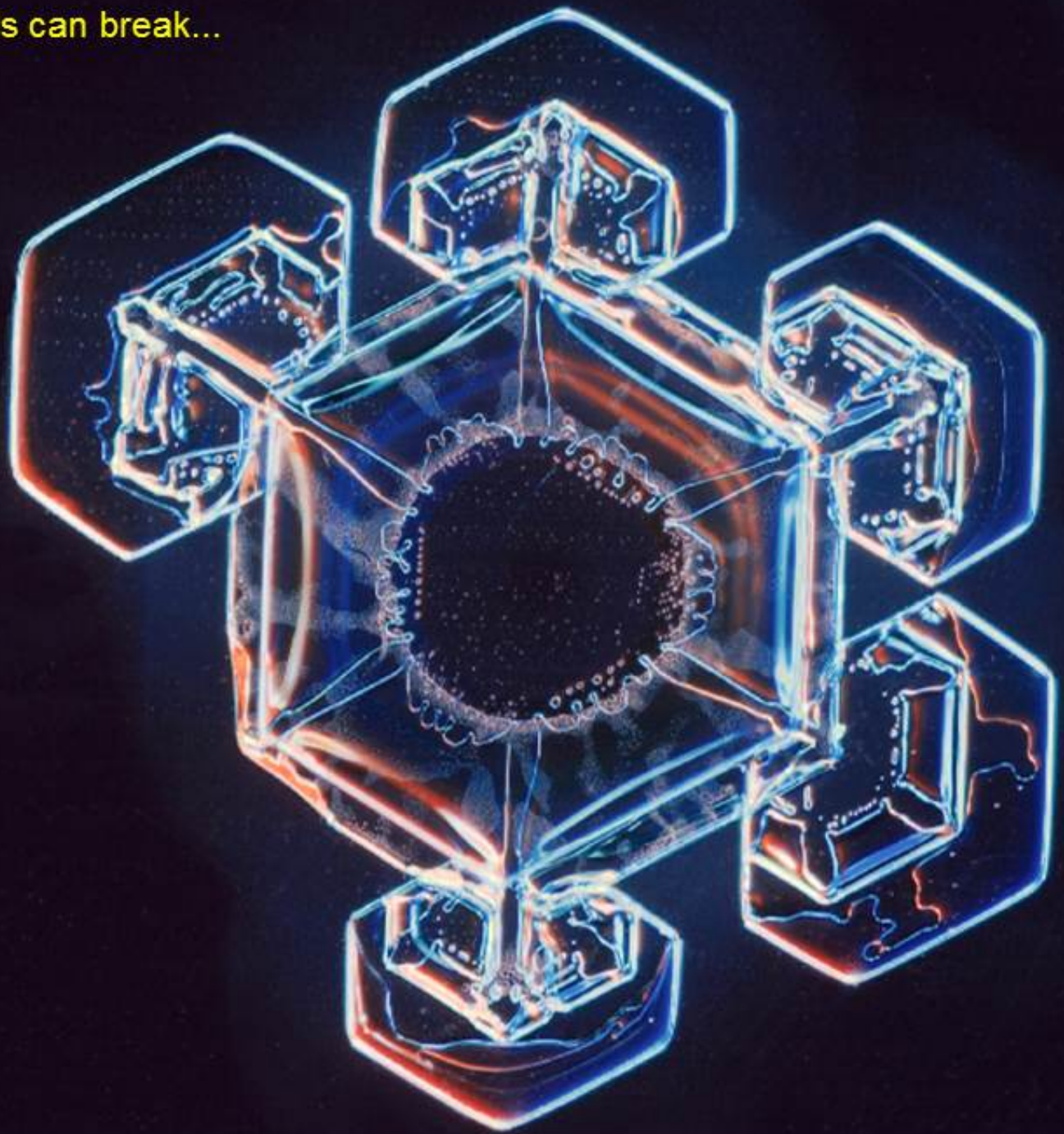
Photographing Snowflakes

Pictures taken with a snowflake photo-microscope

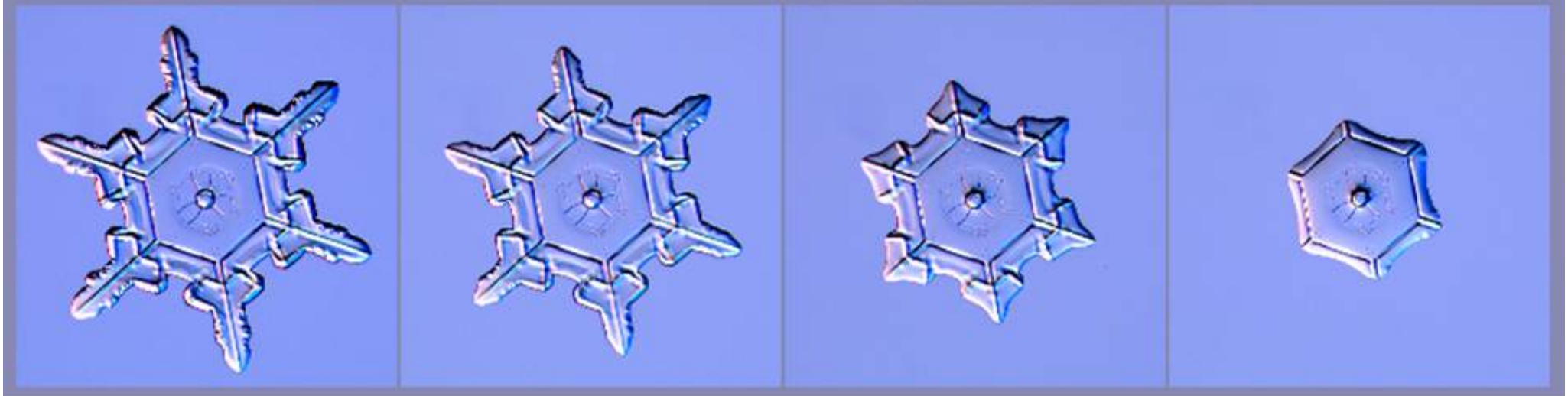
But you can also see a lot with a simple magnifier …

In the Field...

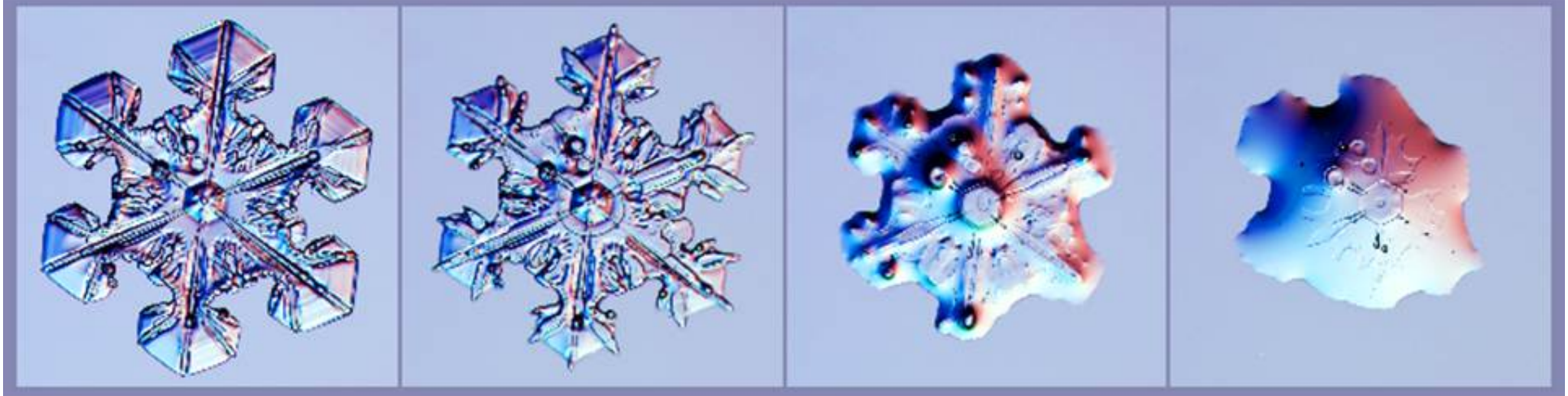
Snow crystals can break...



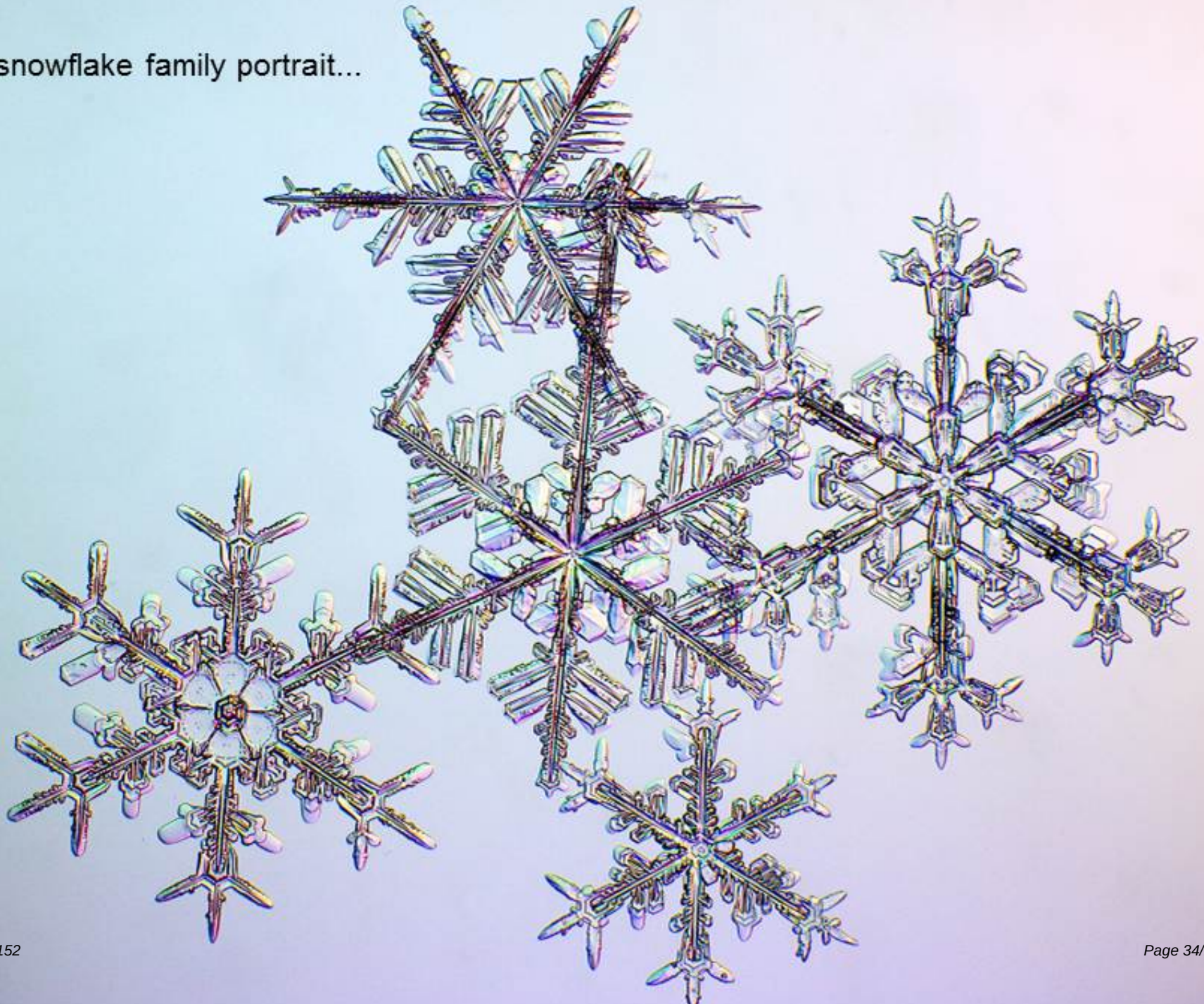
Snow crystals evaporate (elapsed time, 2 minutes) ...

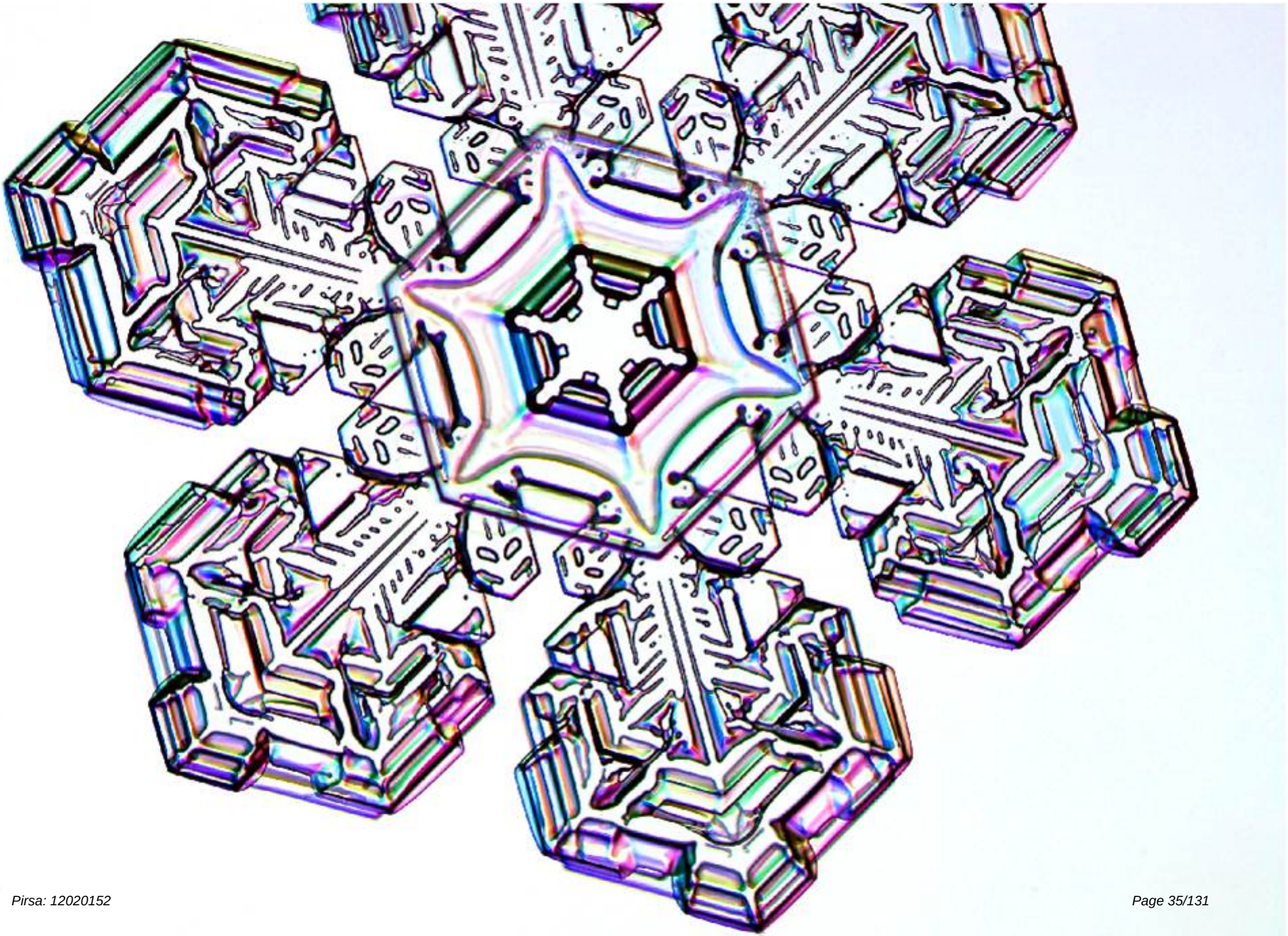


... and they melt (elapsed time 27 seconds)

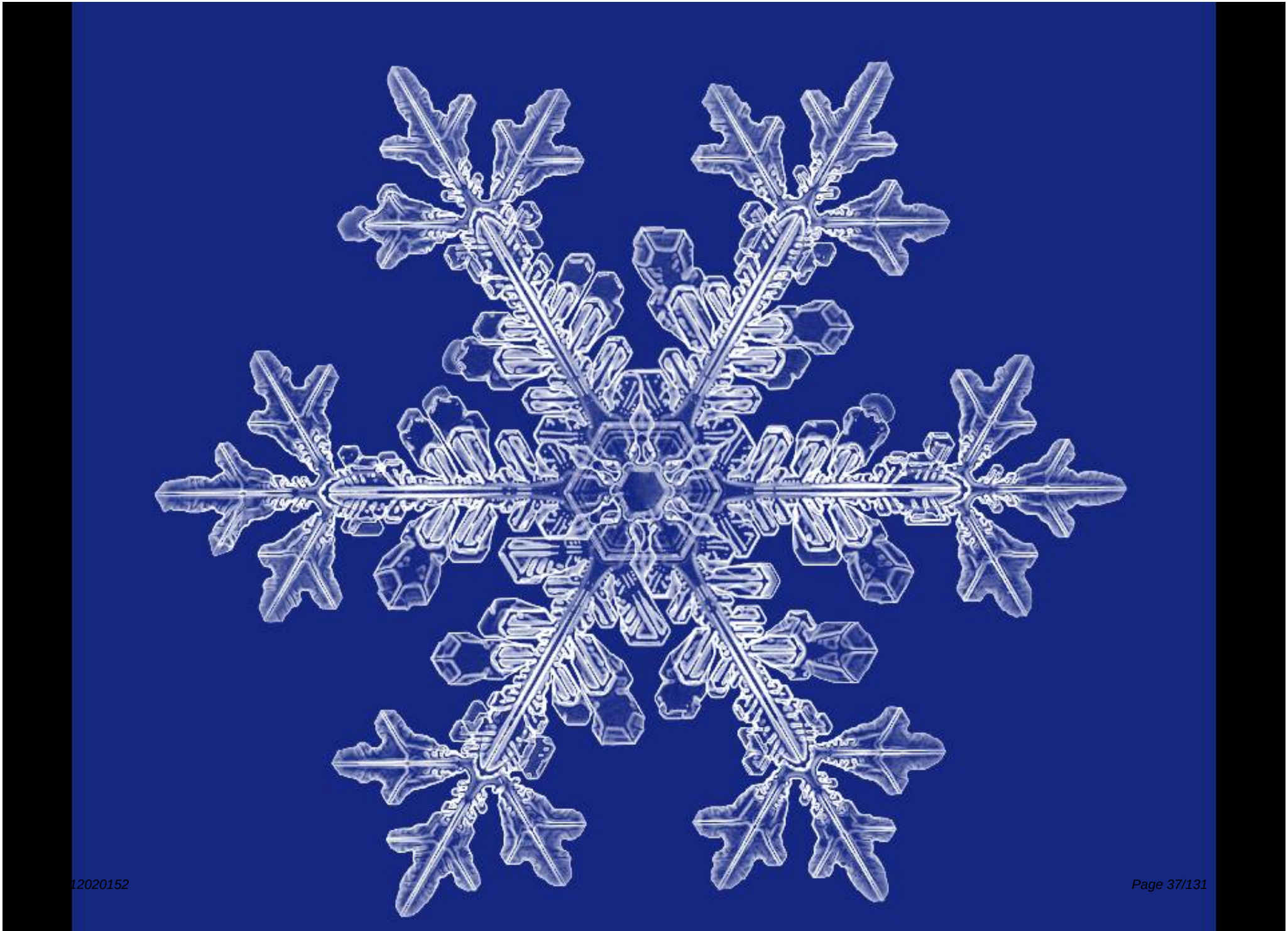


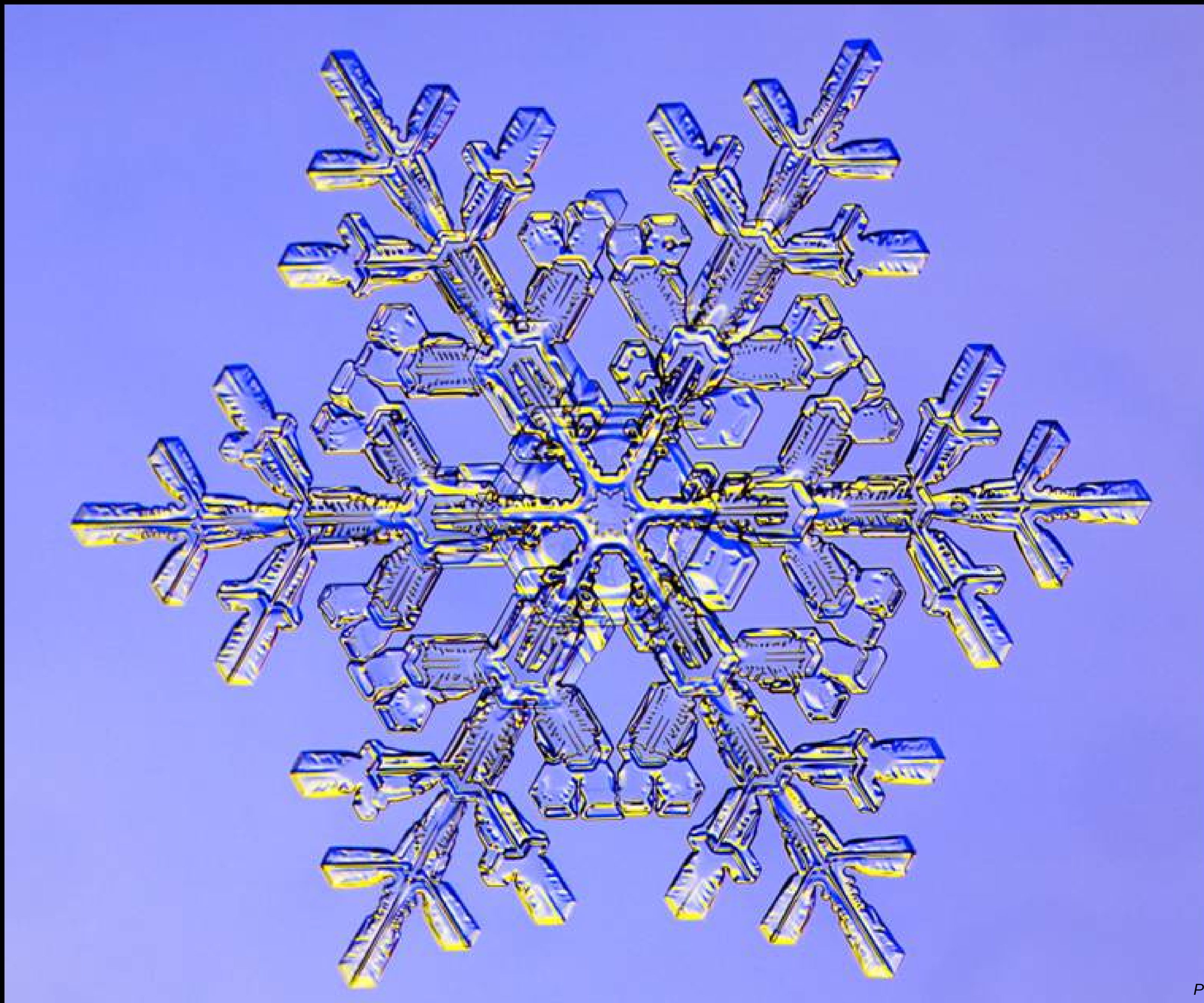
A snowflake family portrait...





Not all snow crystals
are beautifully formed






Southern California: Not a good spot for snowflakes...


Michigan Upper Peninsula: A better snowflake location...

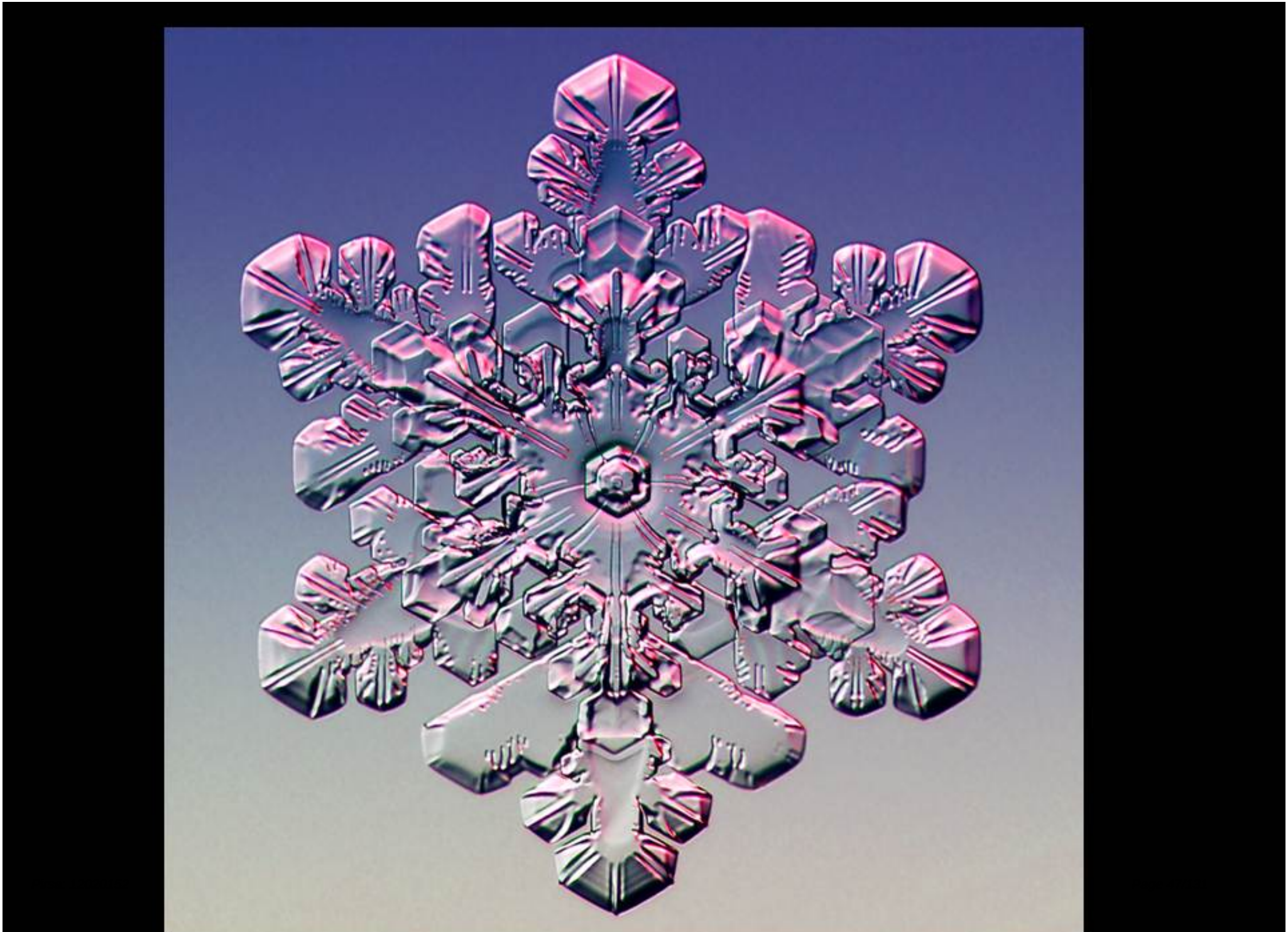

Fairbanks, Alaska

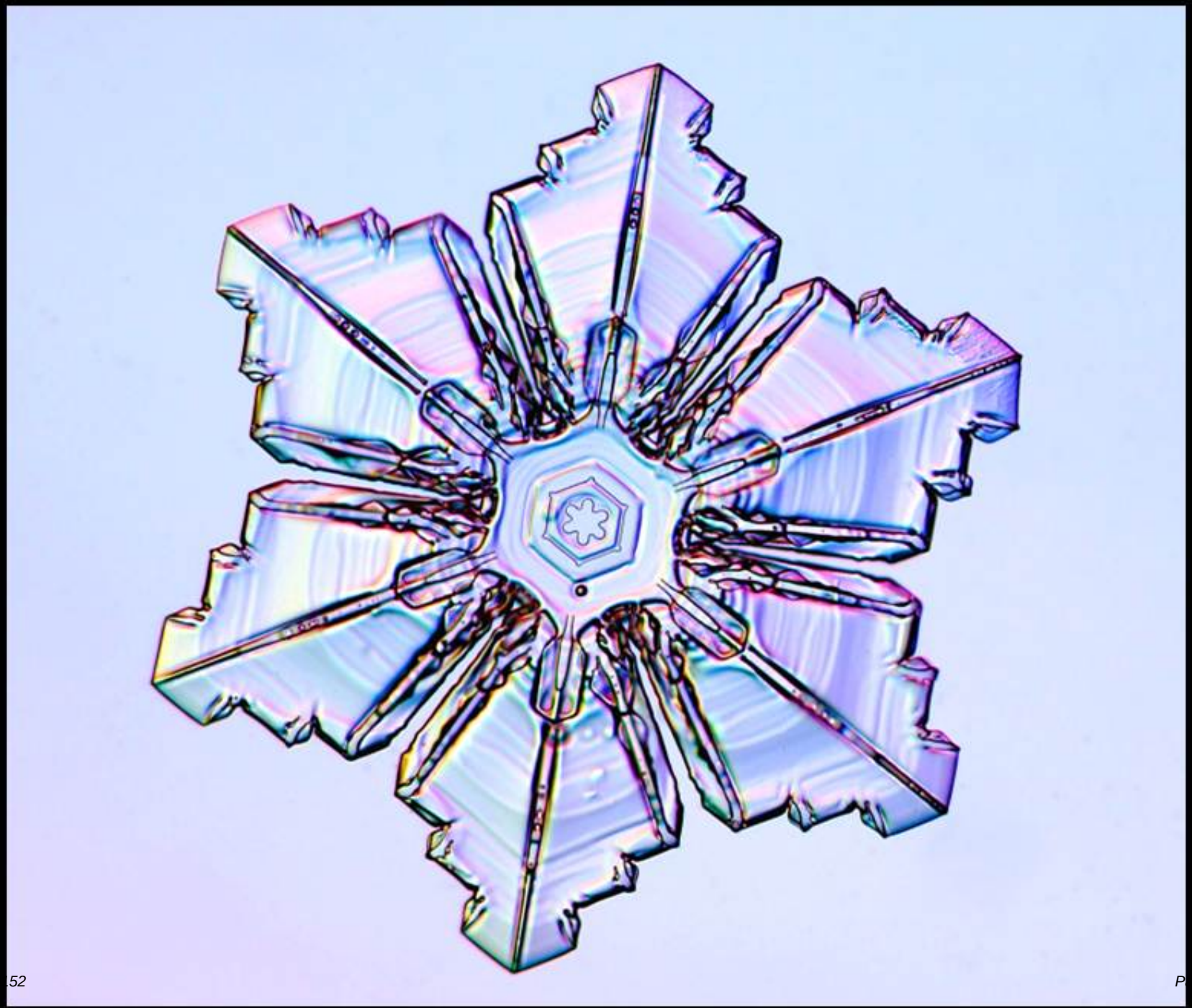

Kiruna, Sweden
50

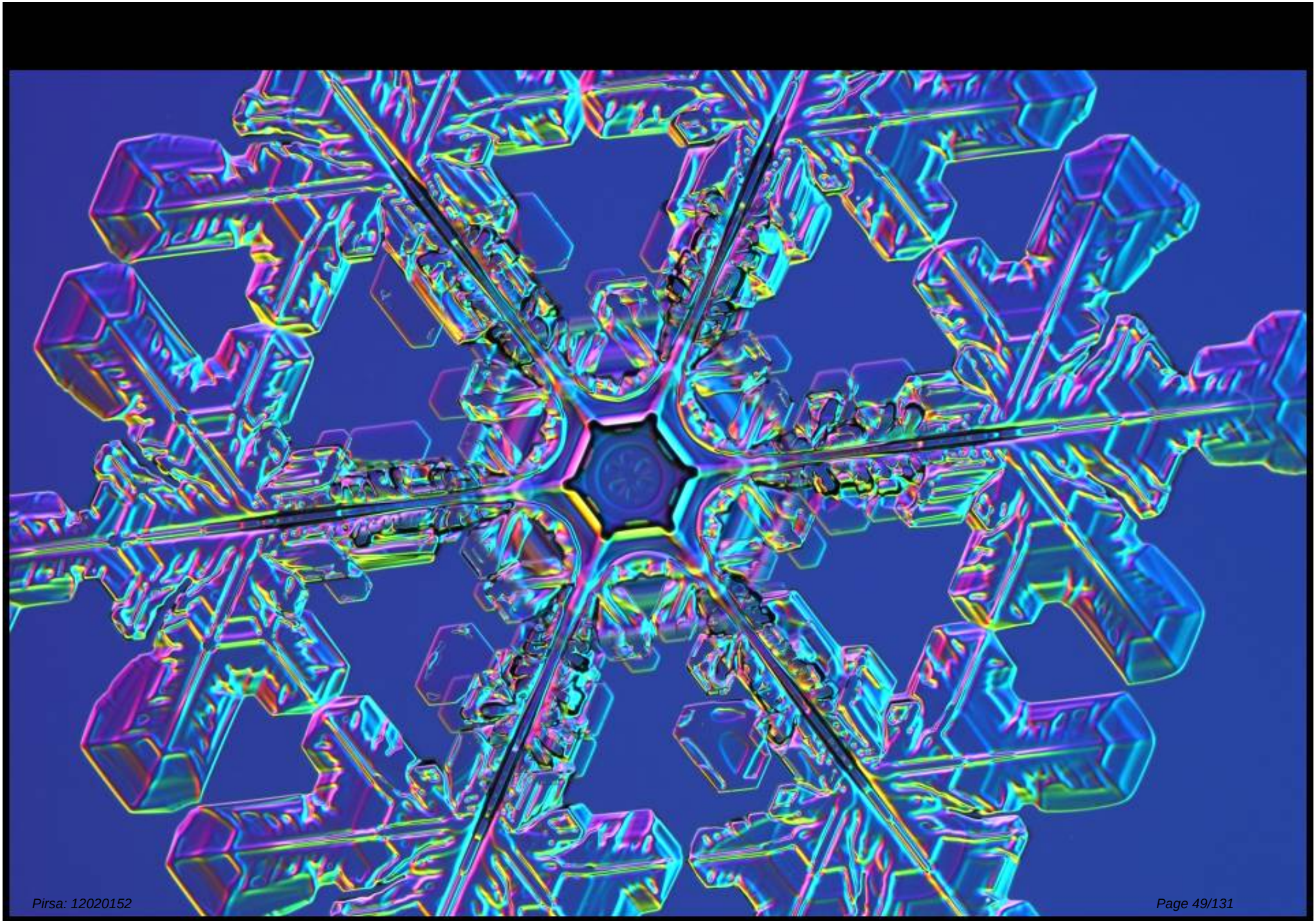

Hokkaido, Japan


Cochrane, Ontario

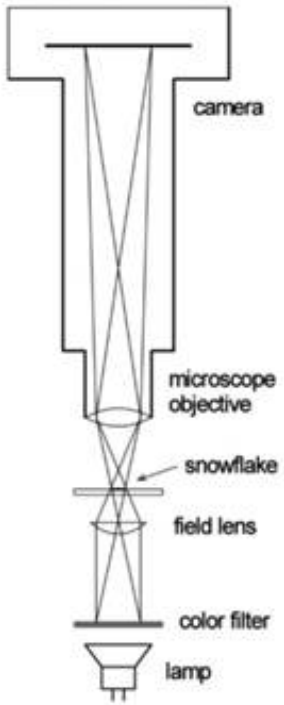
Cochrane, Ontario

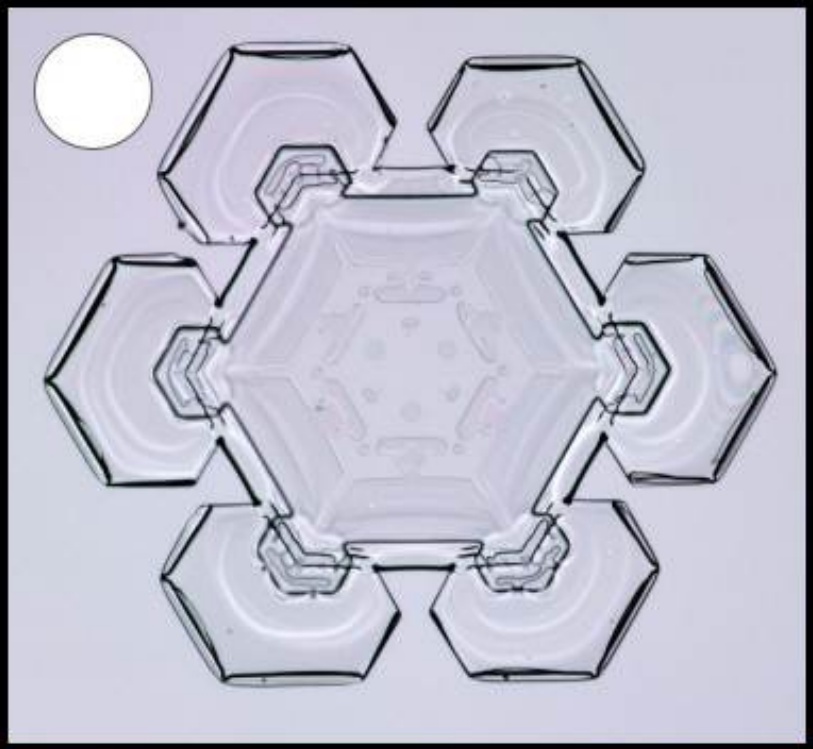


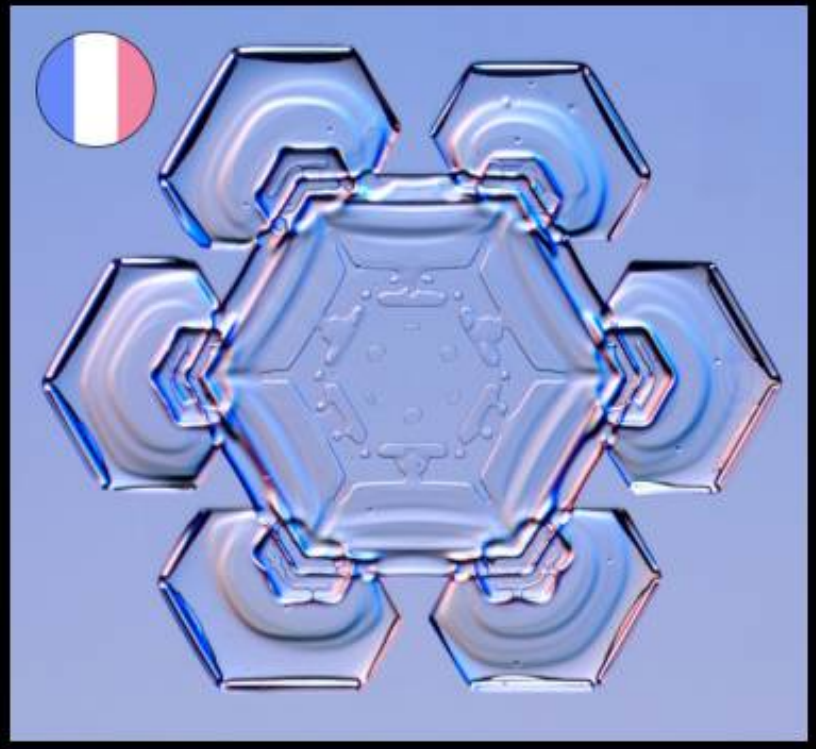


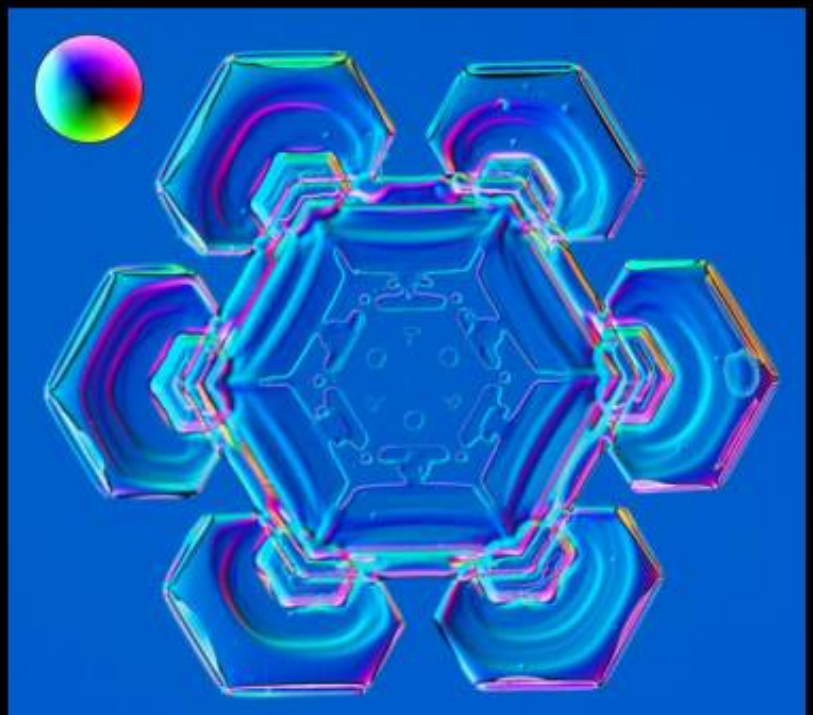


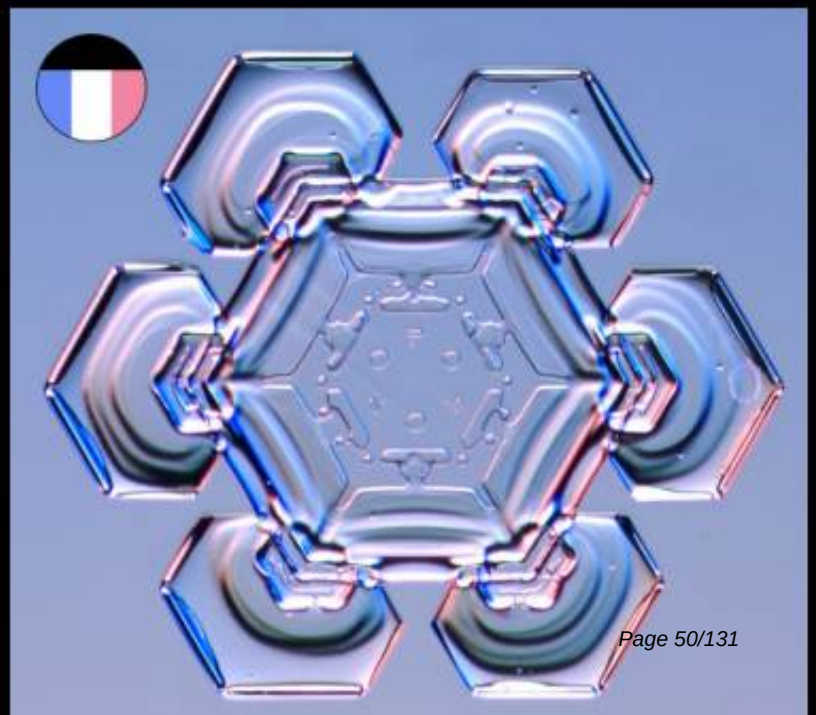
Changing color filters...





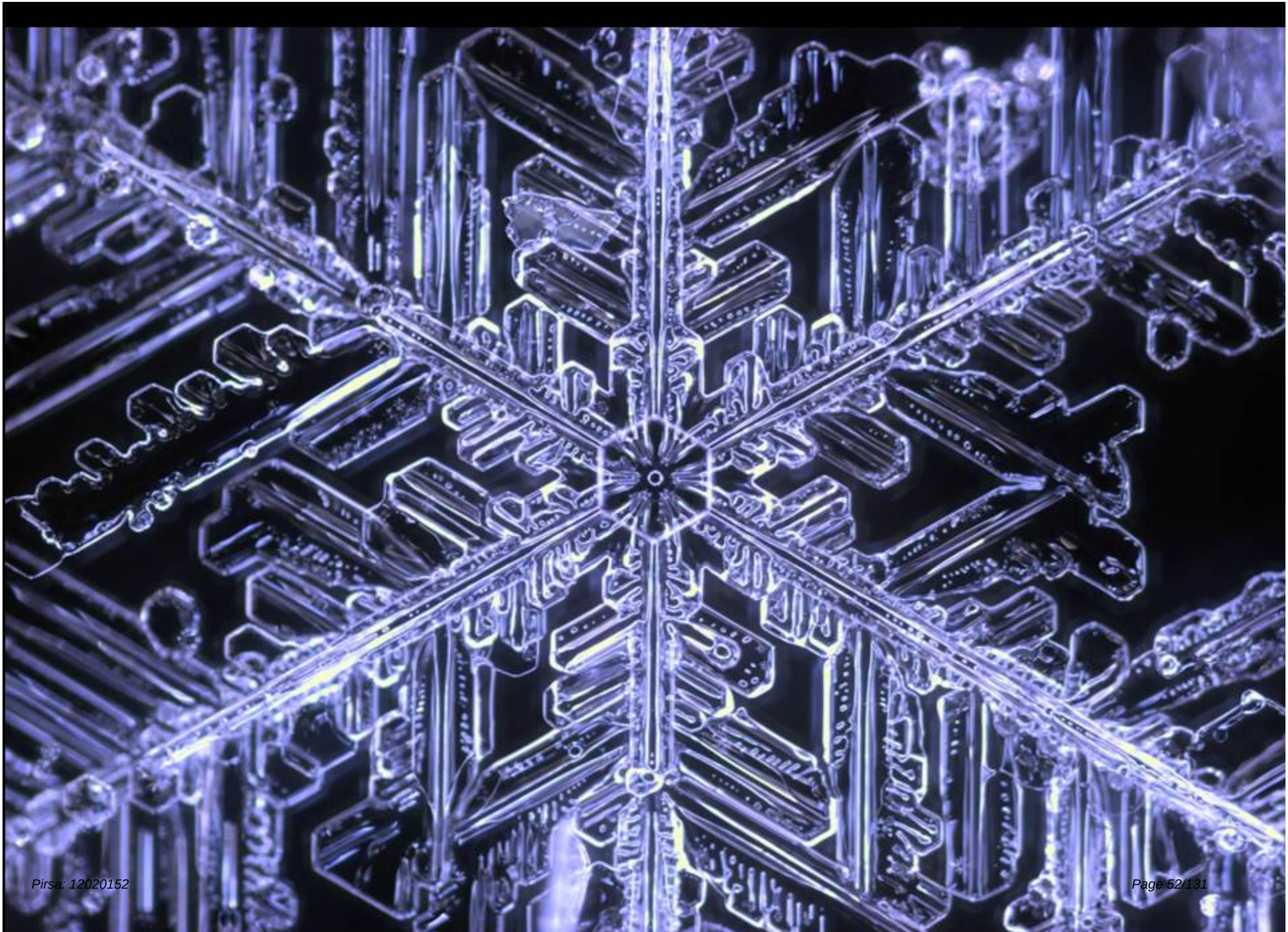


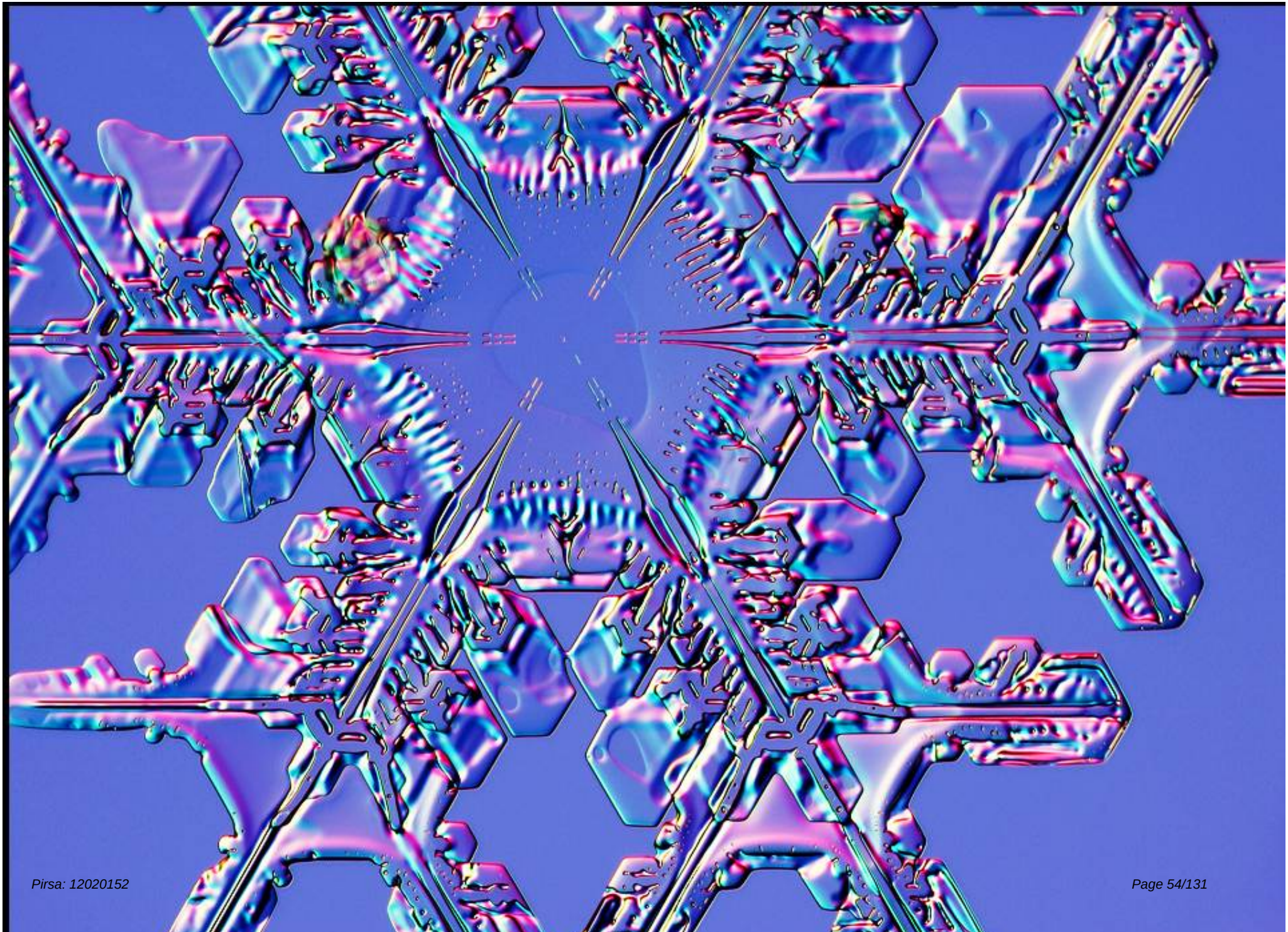




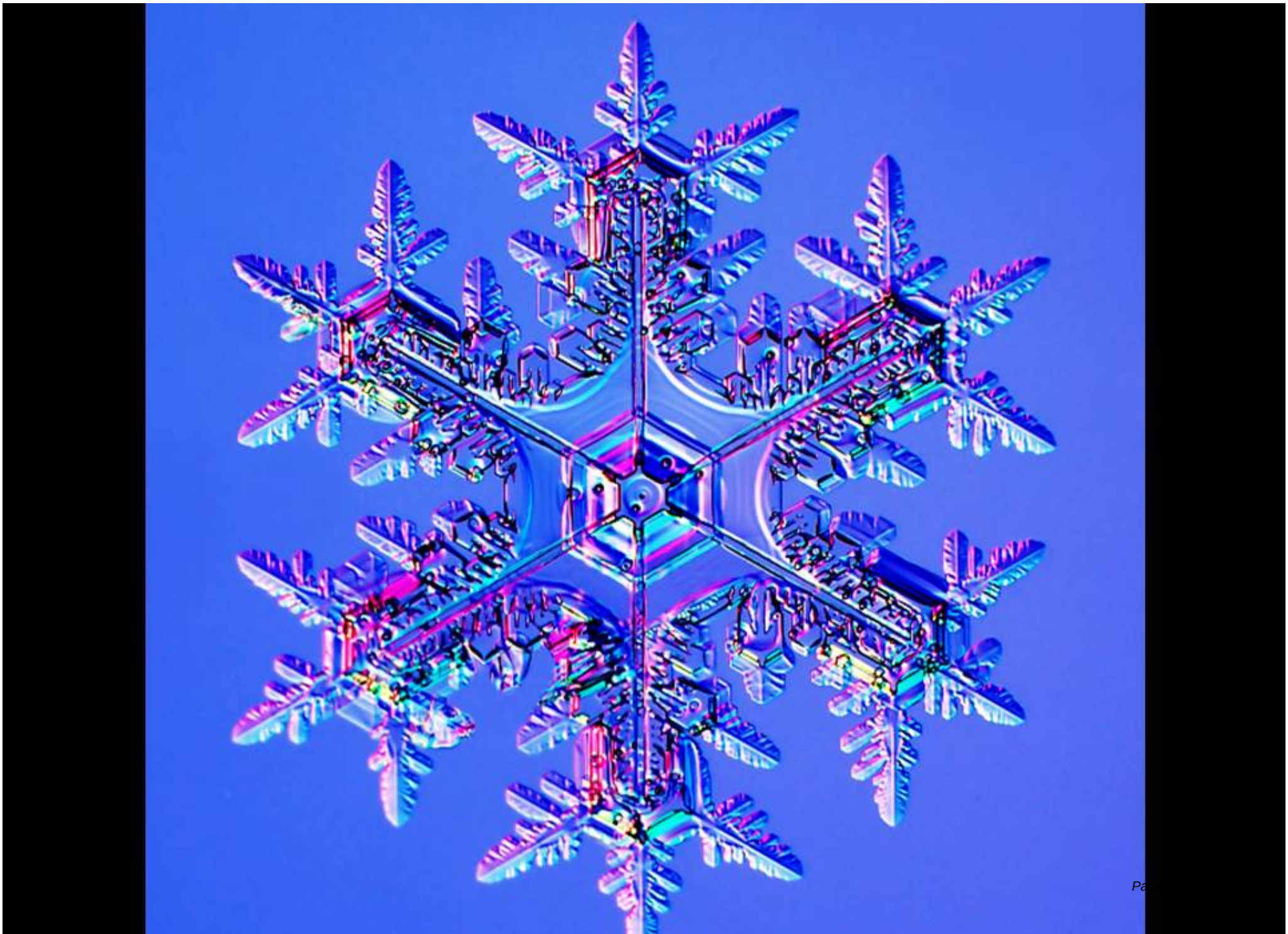
Lighting from the back

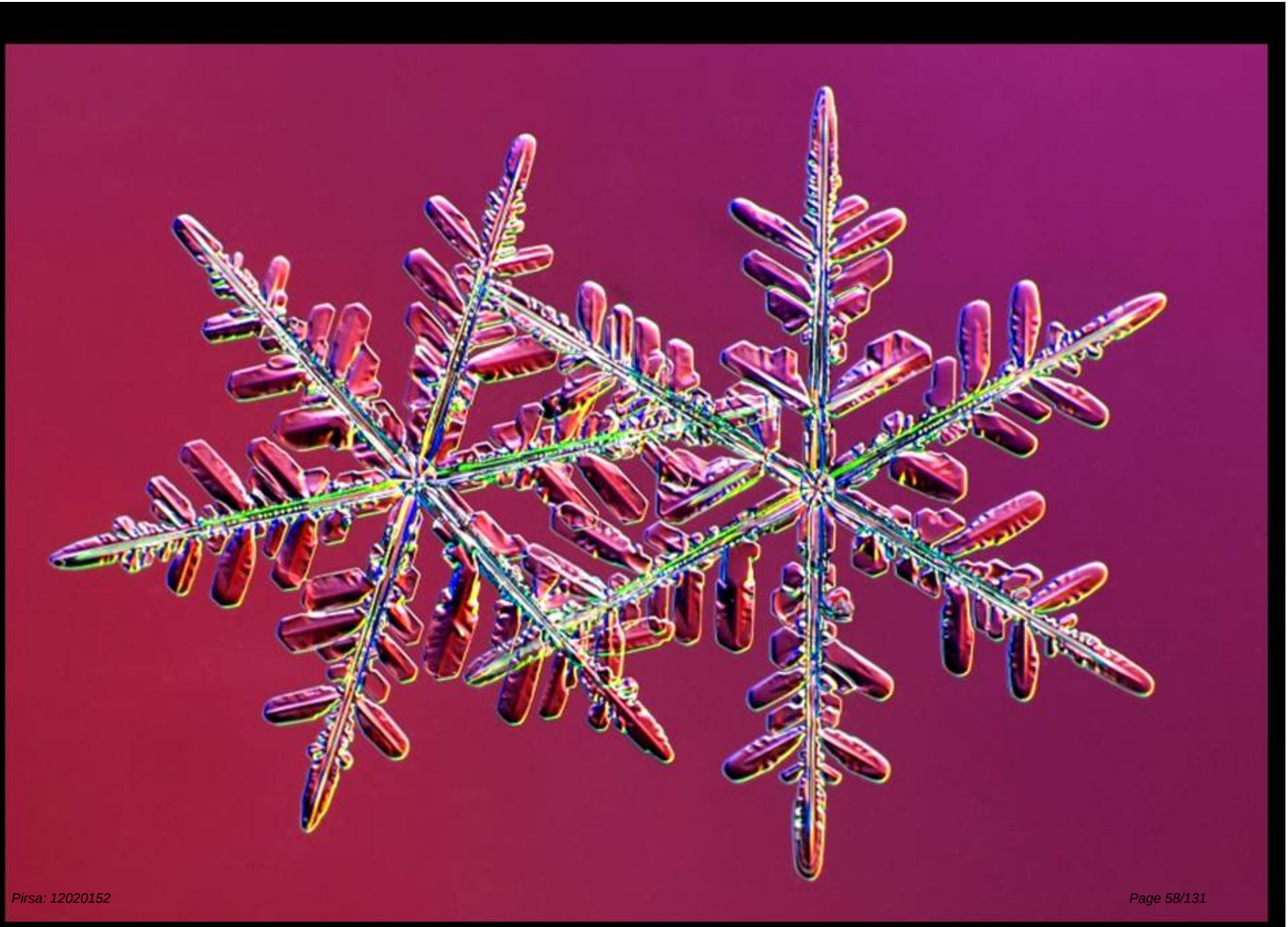
Lighting from the front





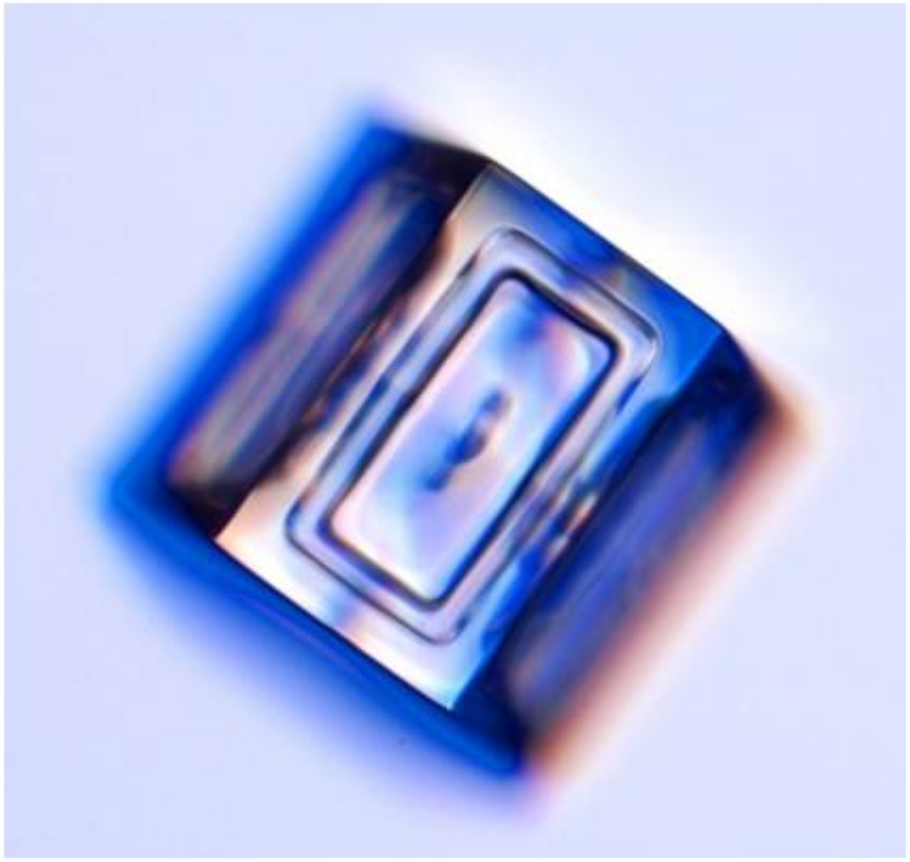

colors from illumination
(not polarized light)
(not colorized)





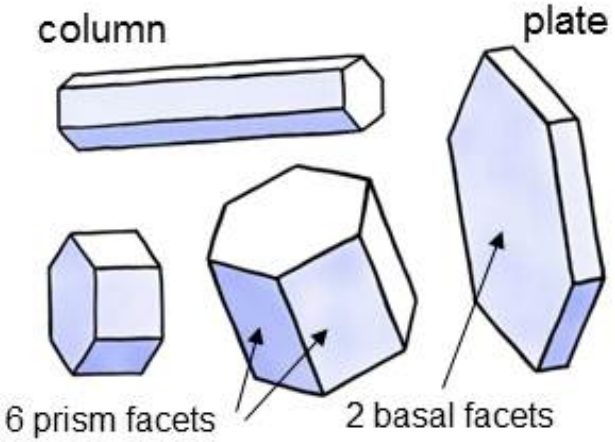
What Falls from the Sky...

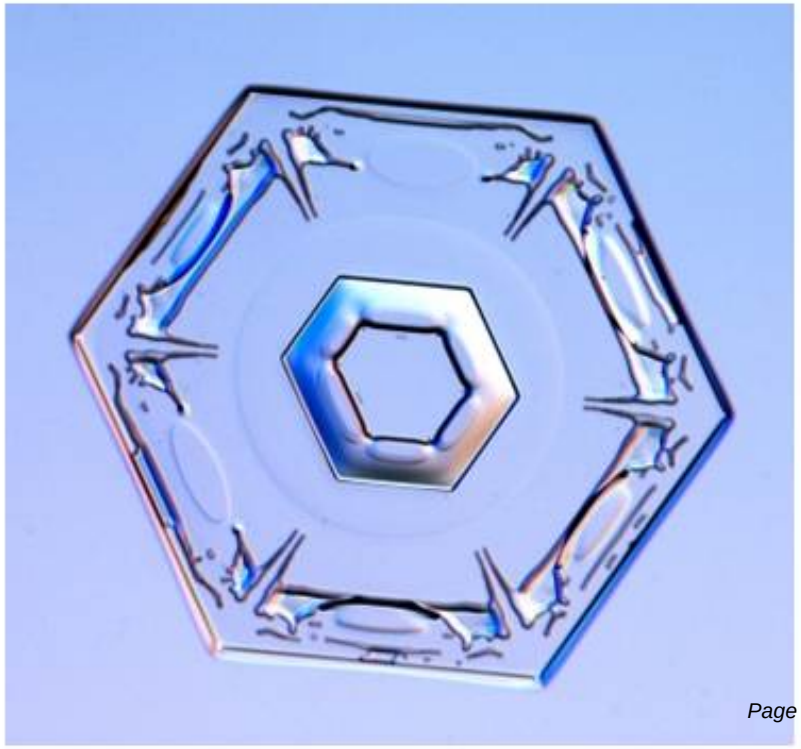
Simple Plates and Columns

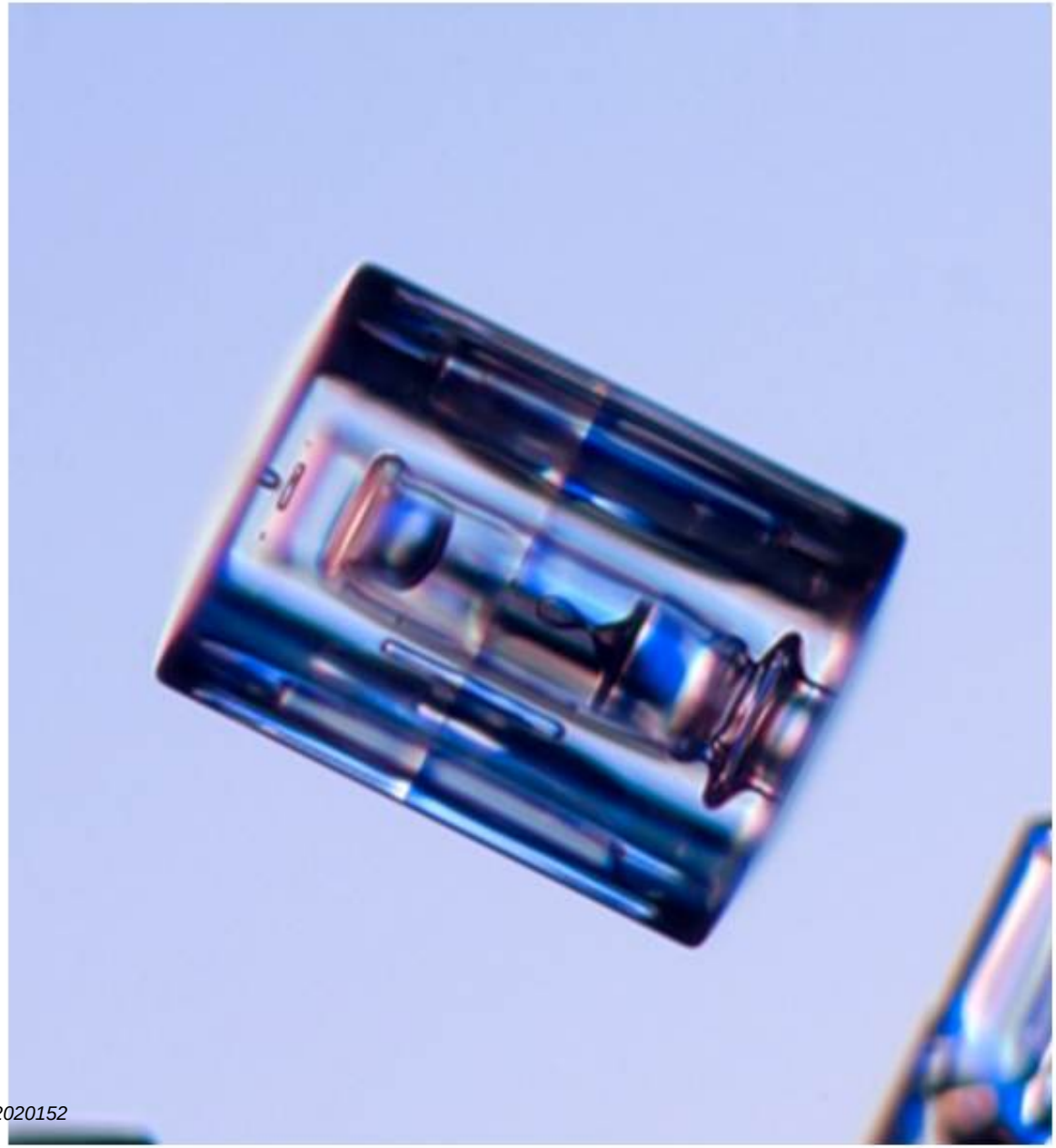


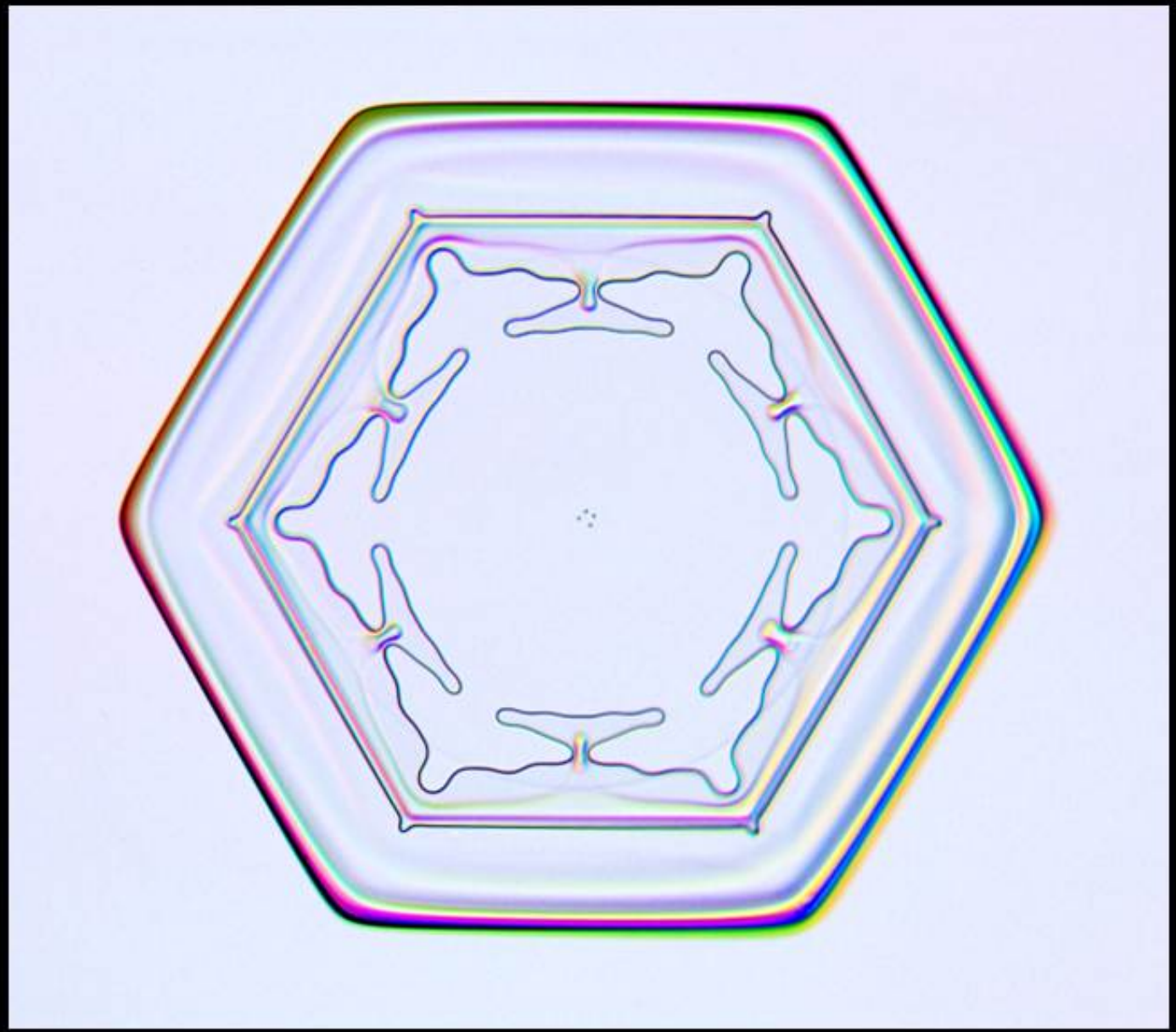
Small, about 0.3 mm
Faceted
Often hollow faces
Usually patterned
"diamond dust"

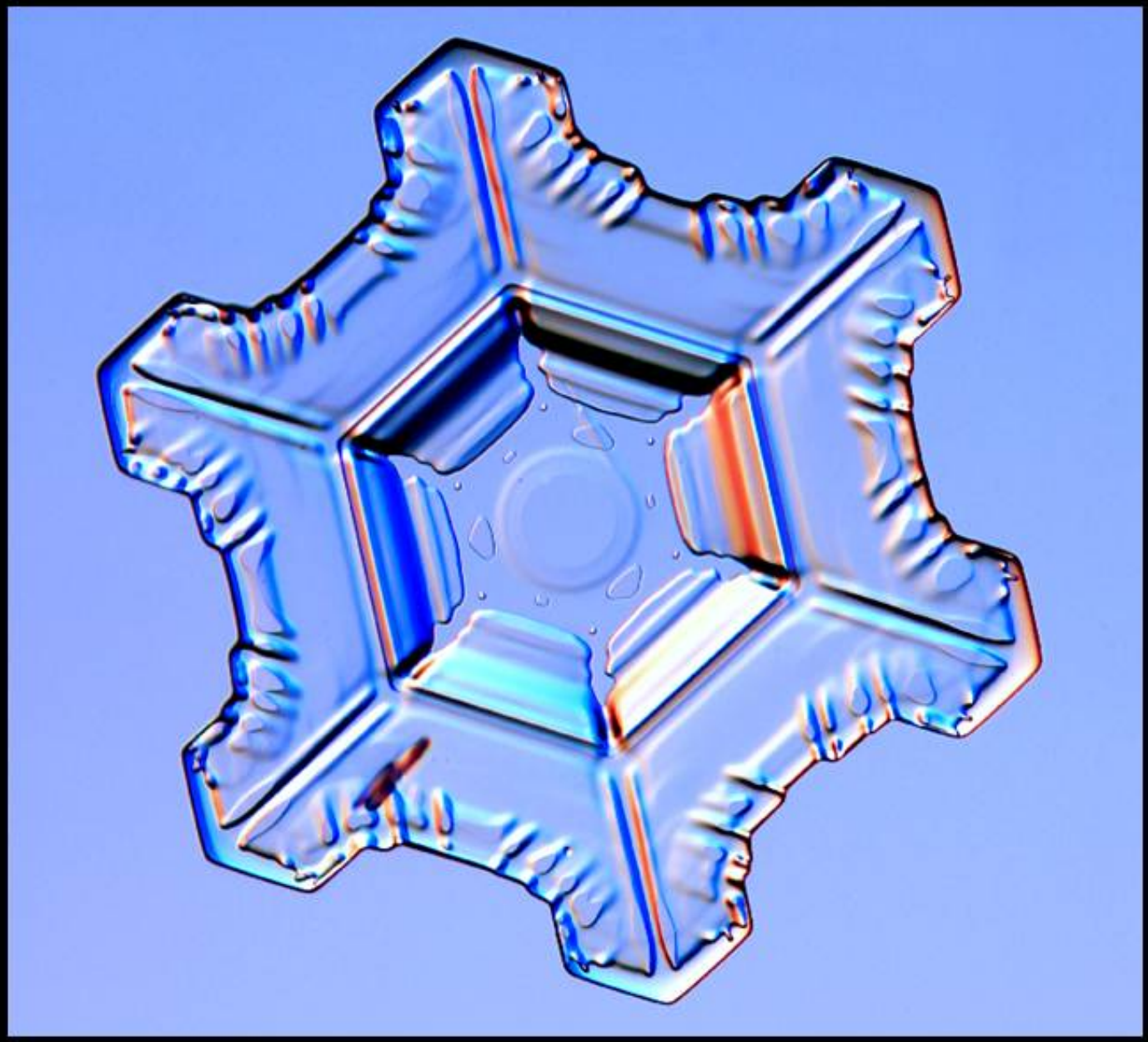
Hexagonal Prisms





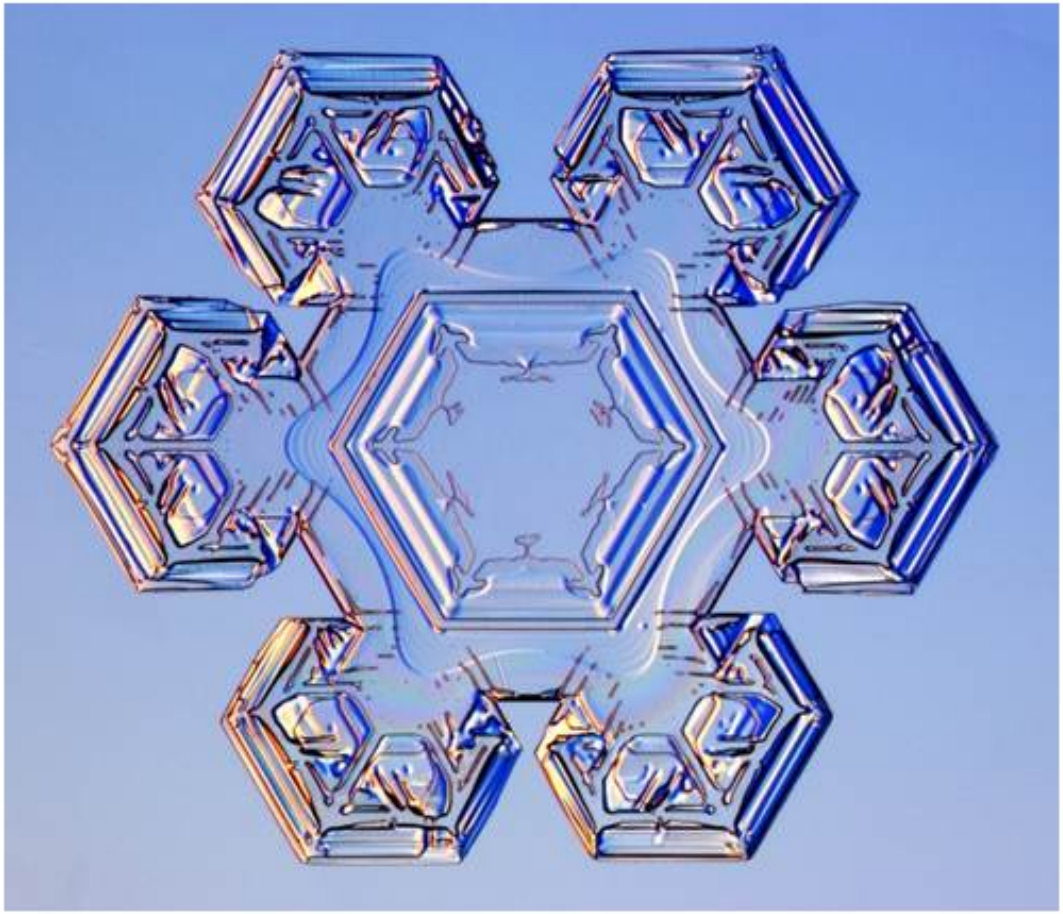


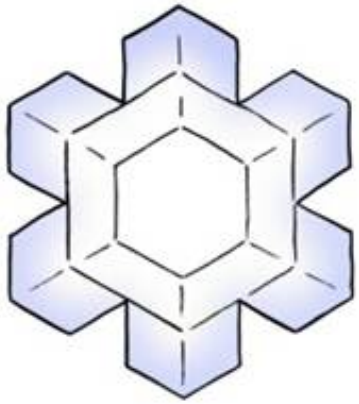




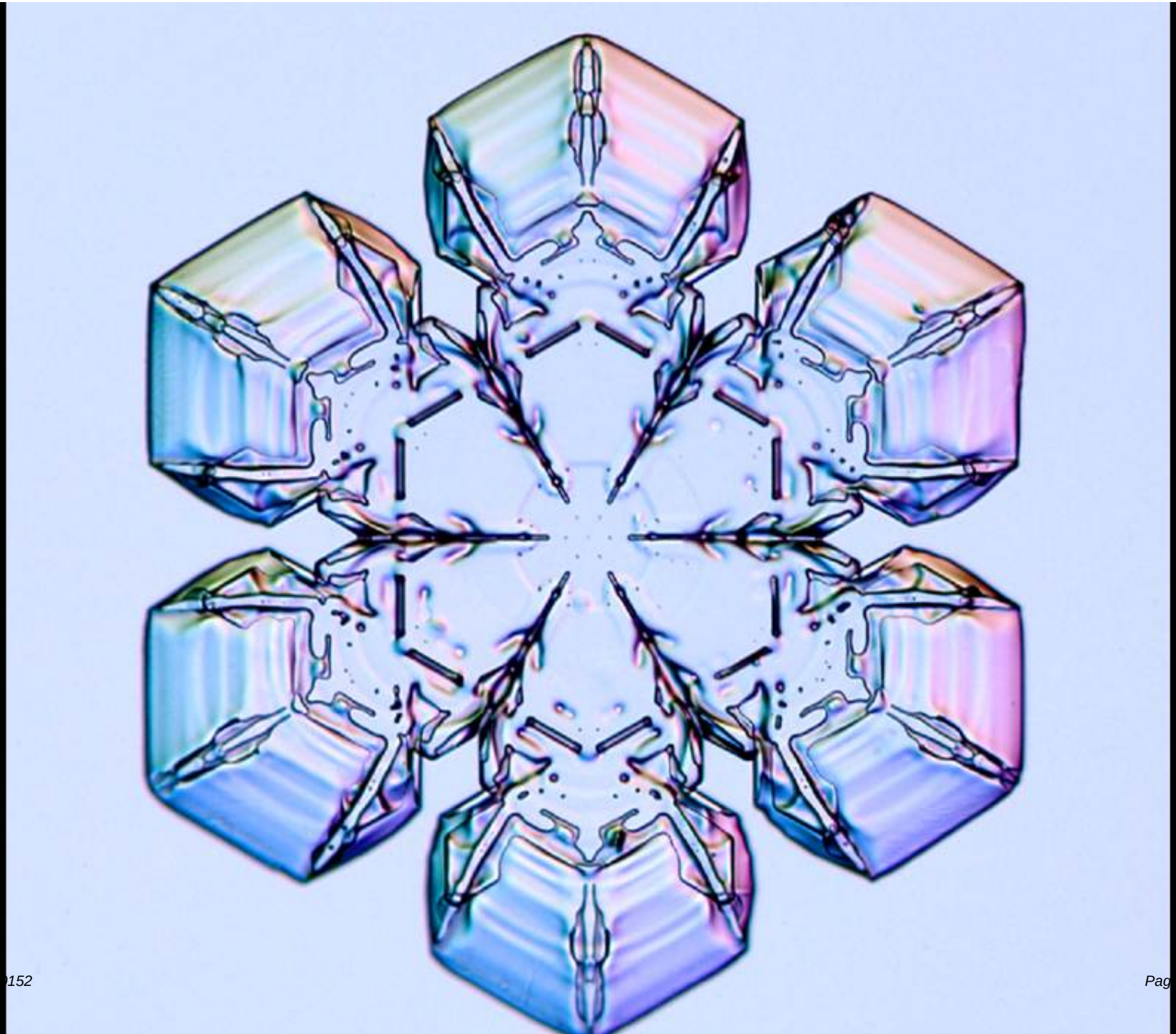
What Falls from the Sky...

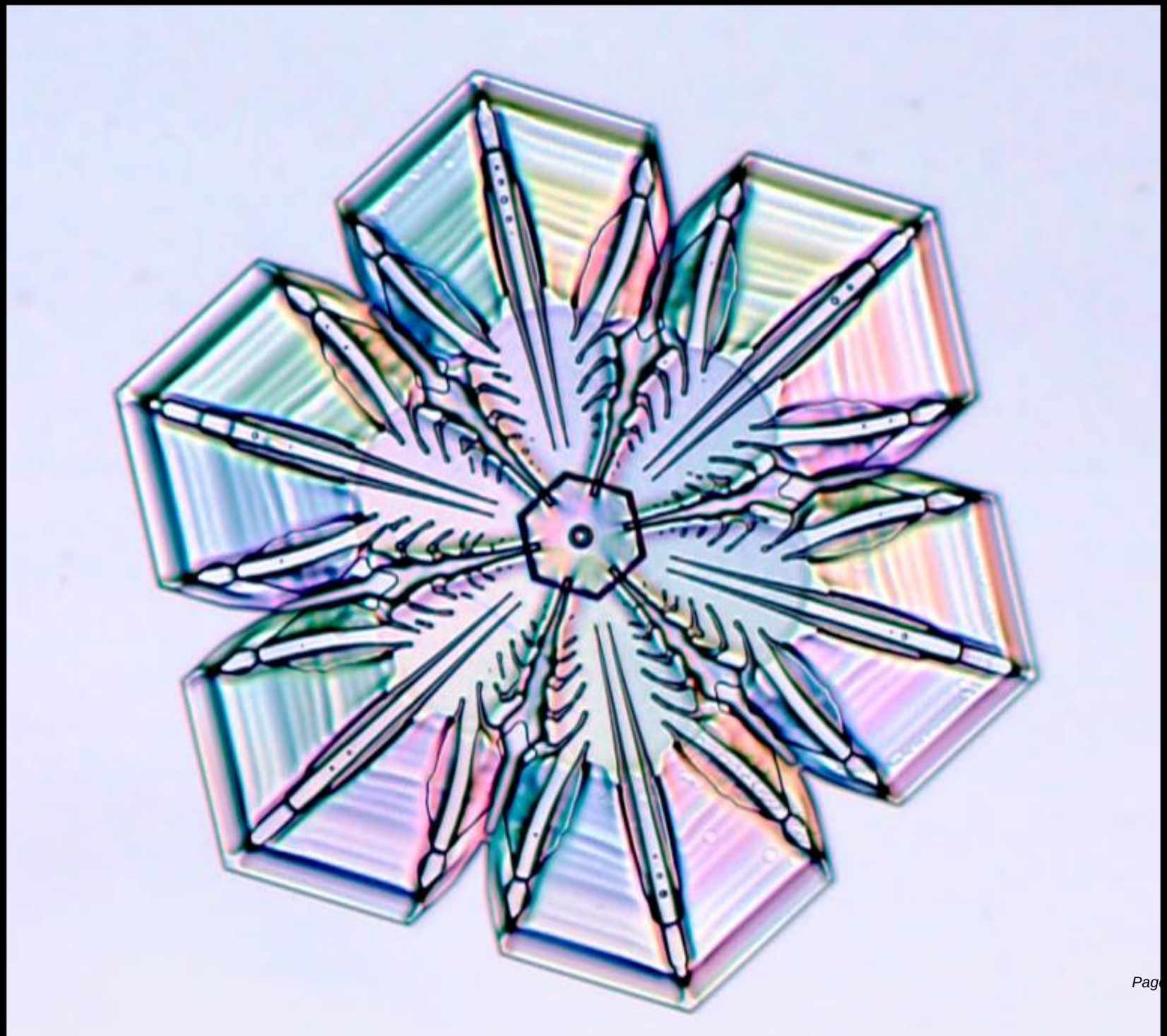
Broad-branched Stellar Plates

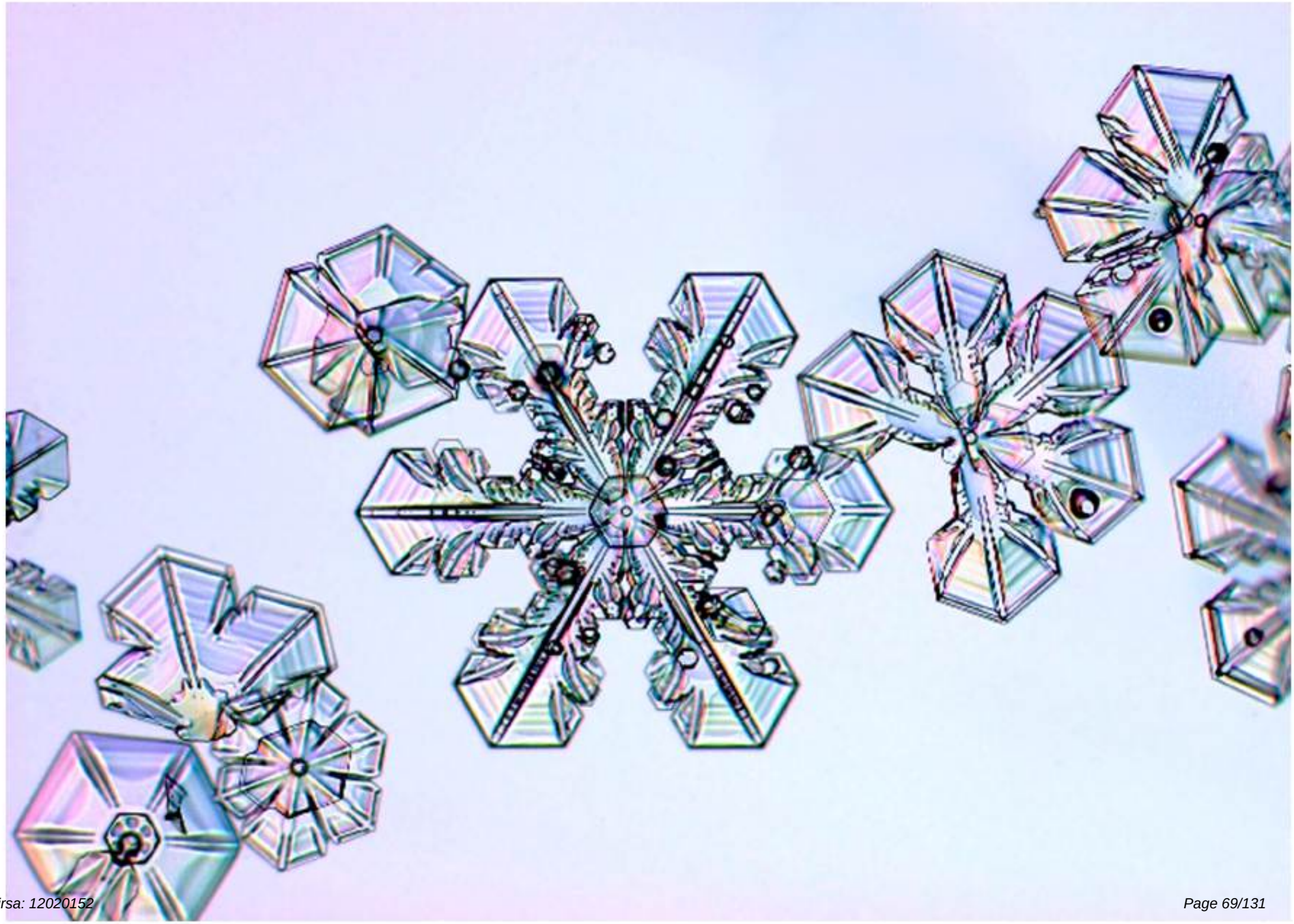


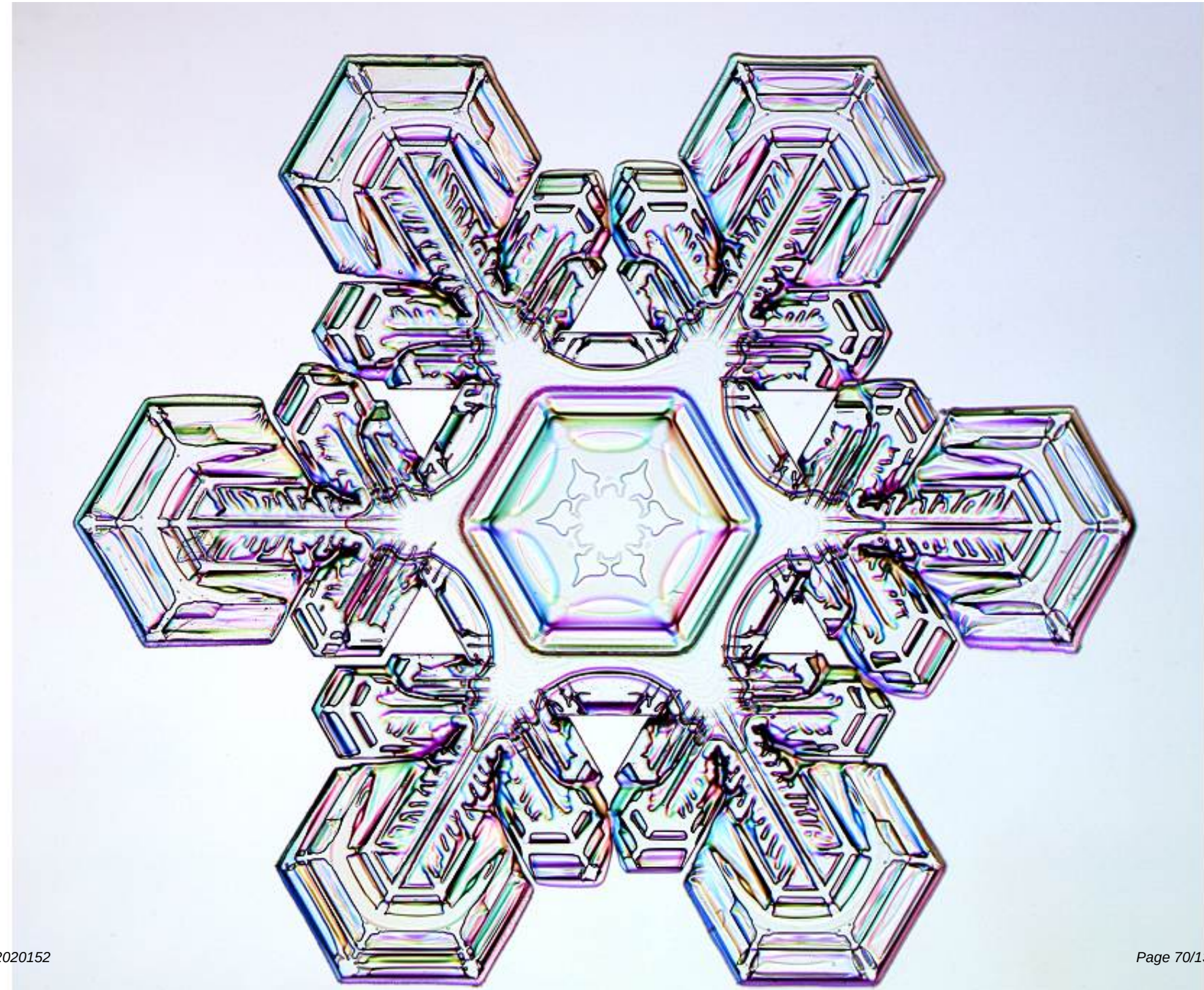


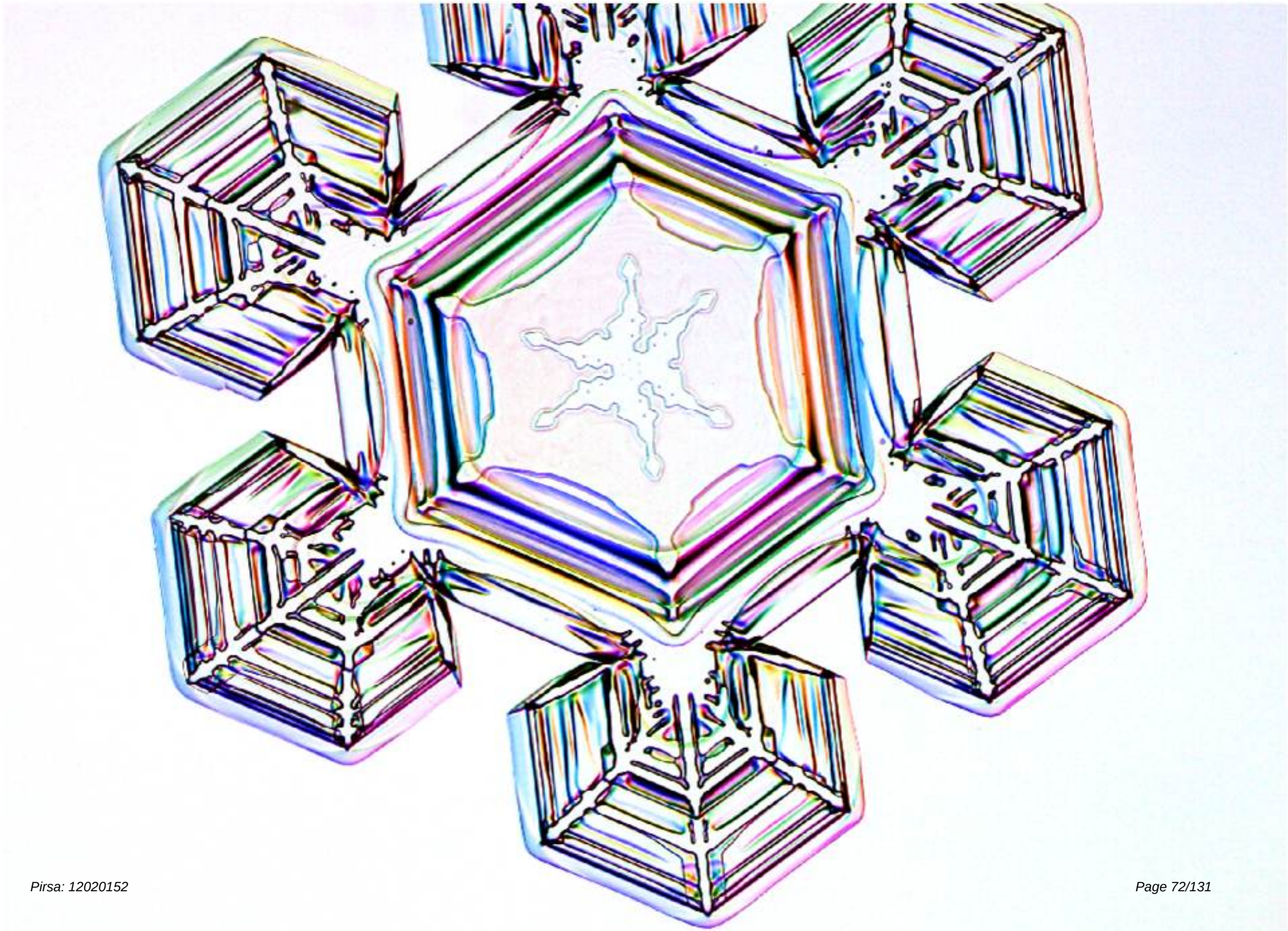
Sizes 1-3 mm
Thin plates, broad branches
Six-fold symmetry (hence stellar)
Intricate surface markings





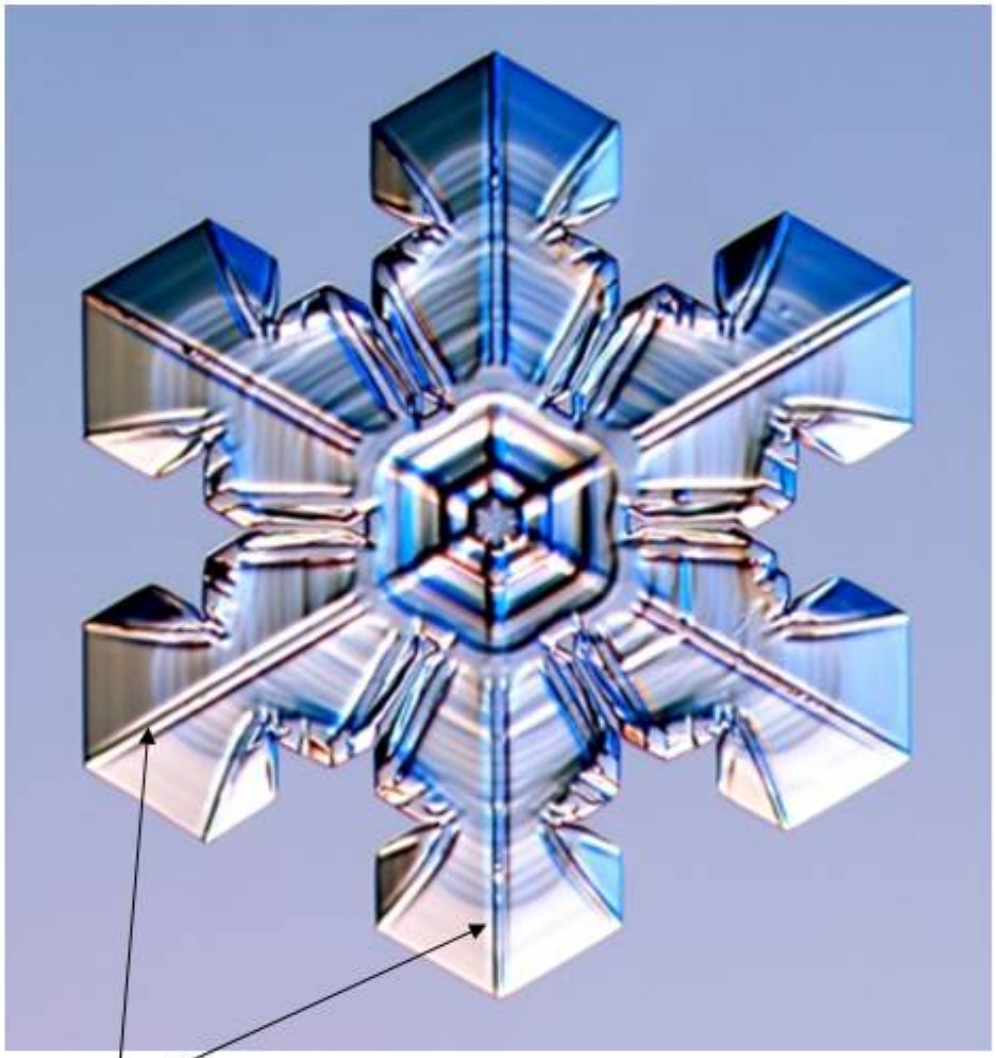




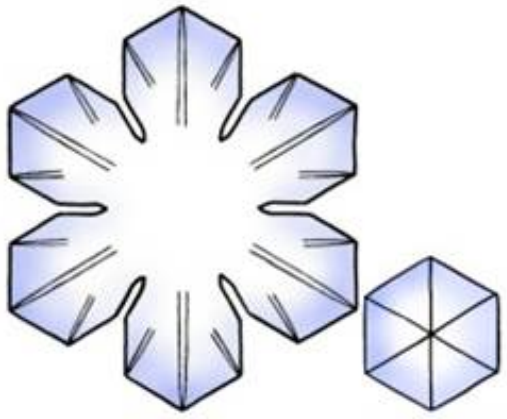


What Falls from the Sky...

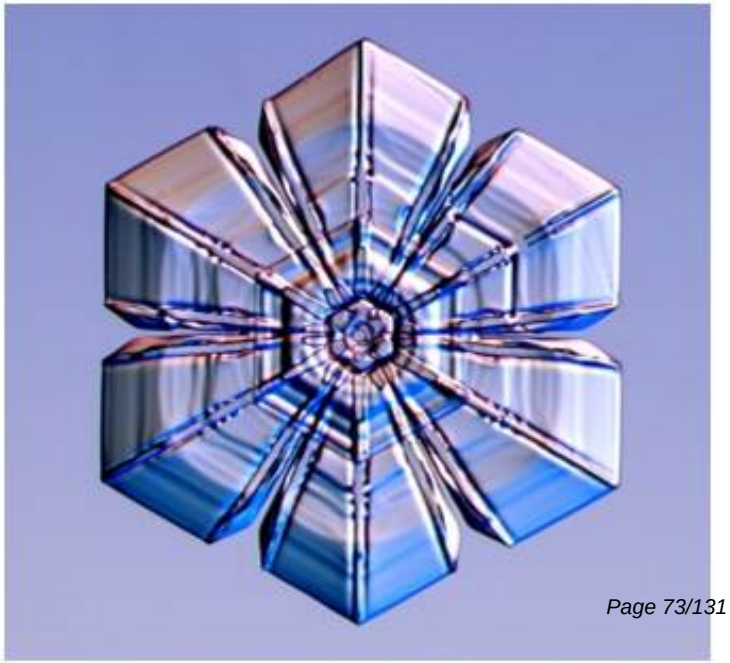
Sectored Plates

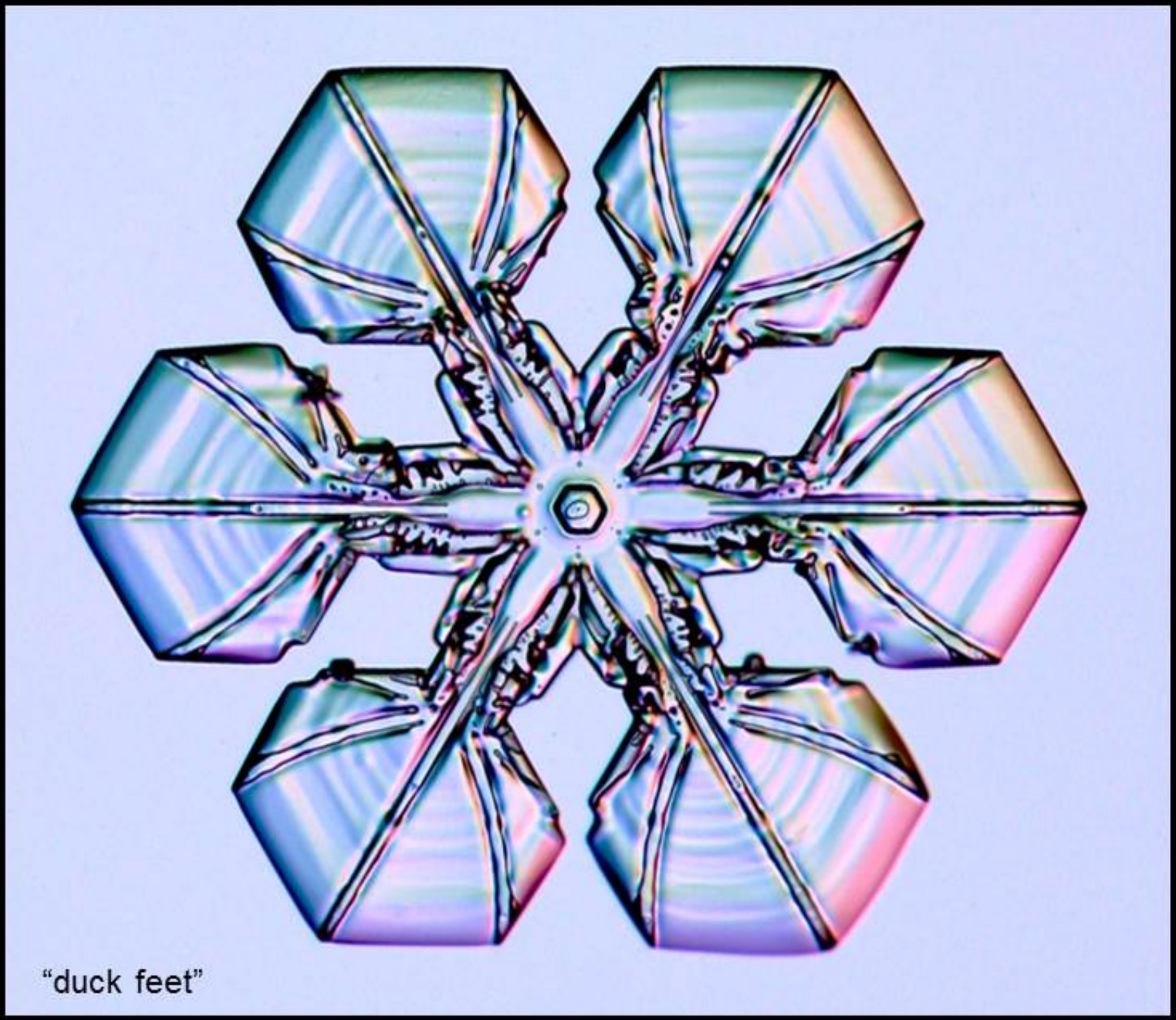


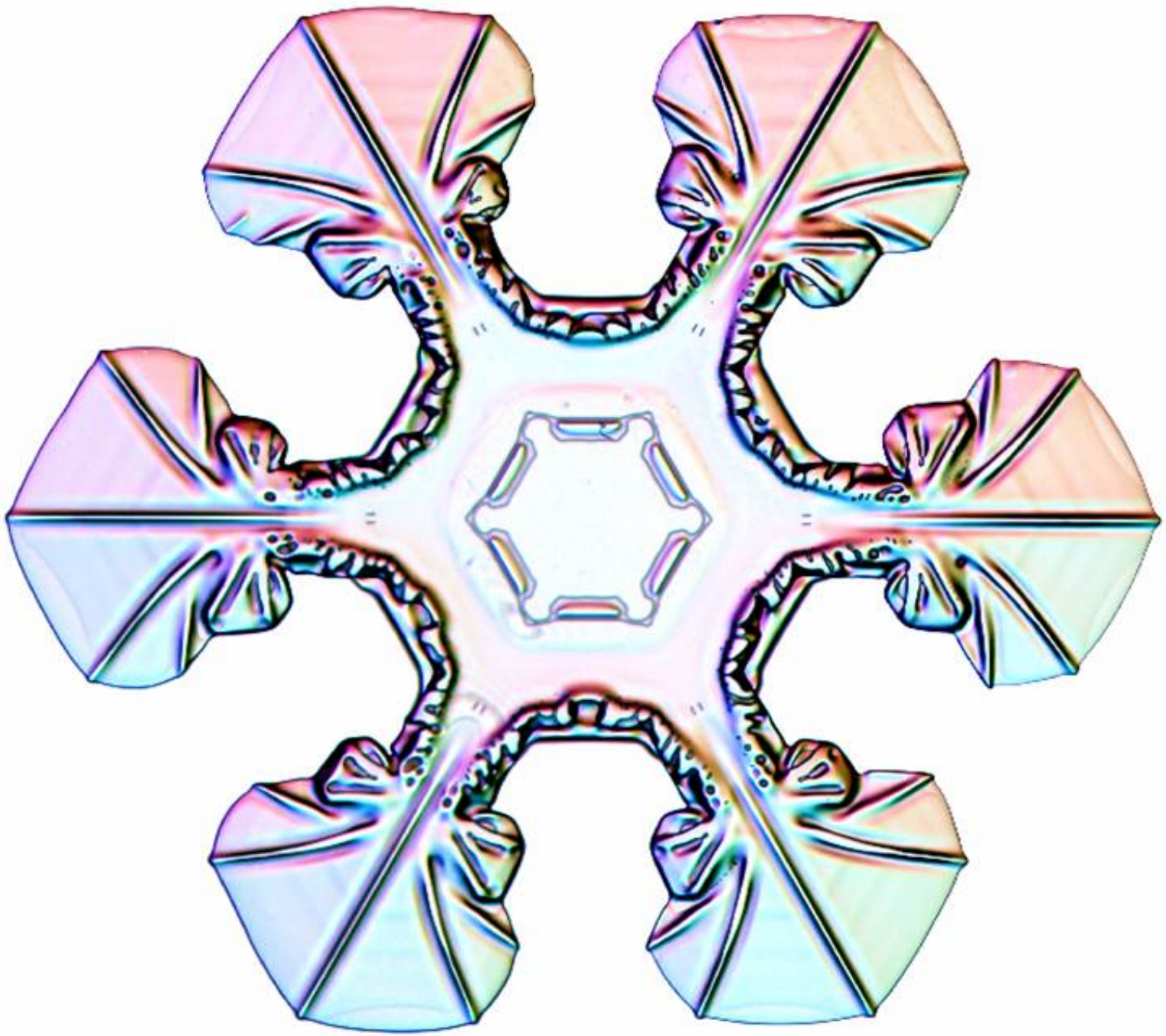
ridges – a common snowflake feature

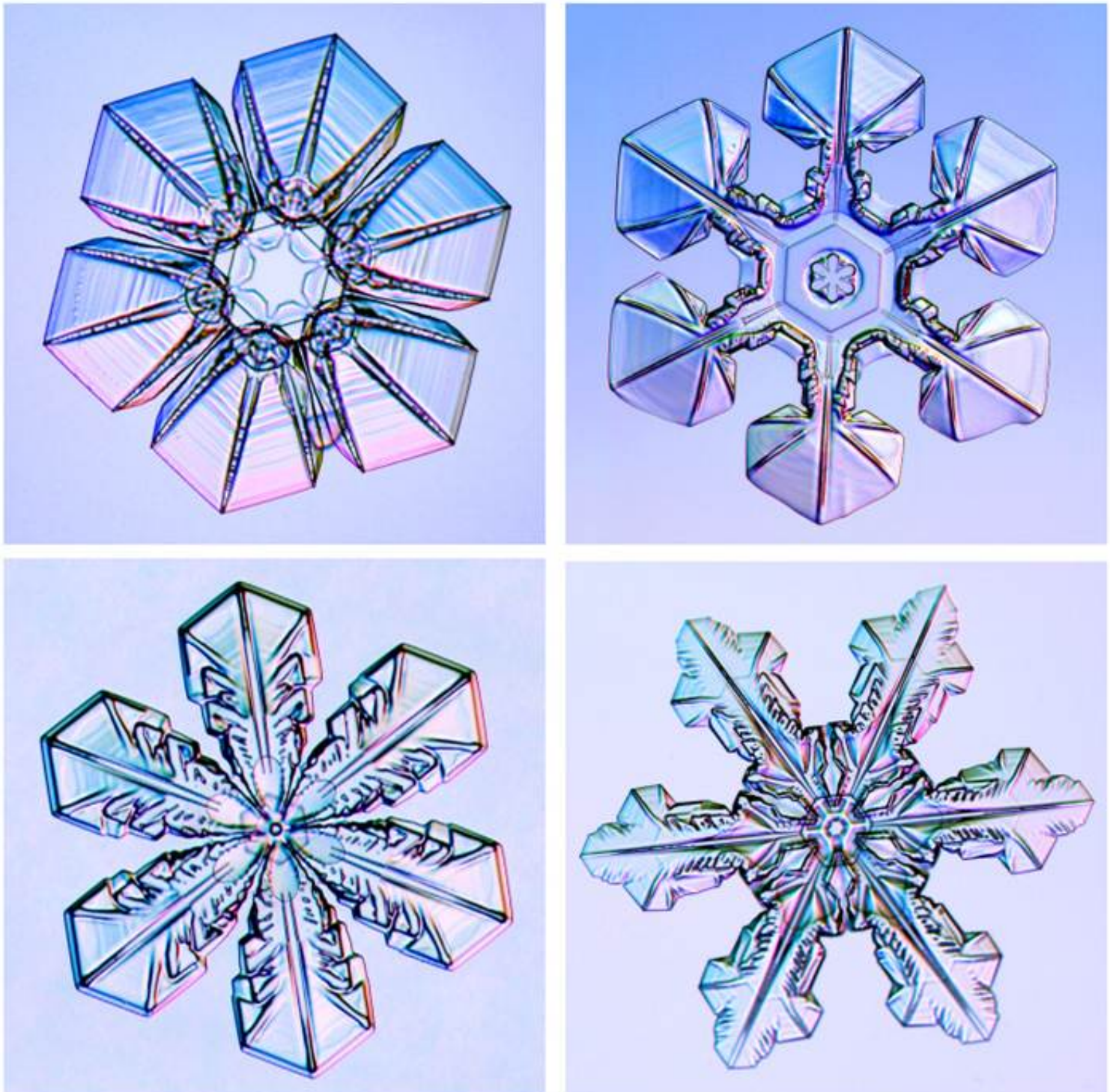


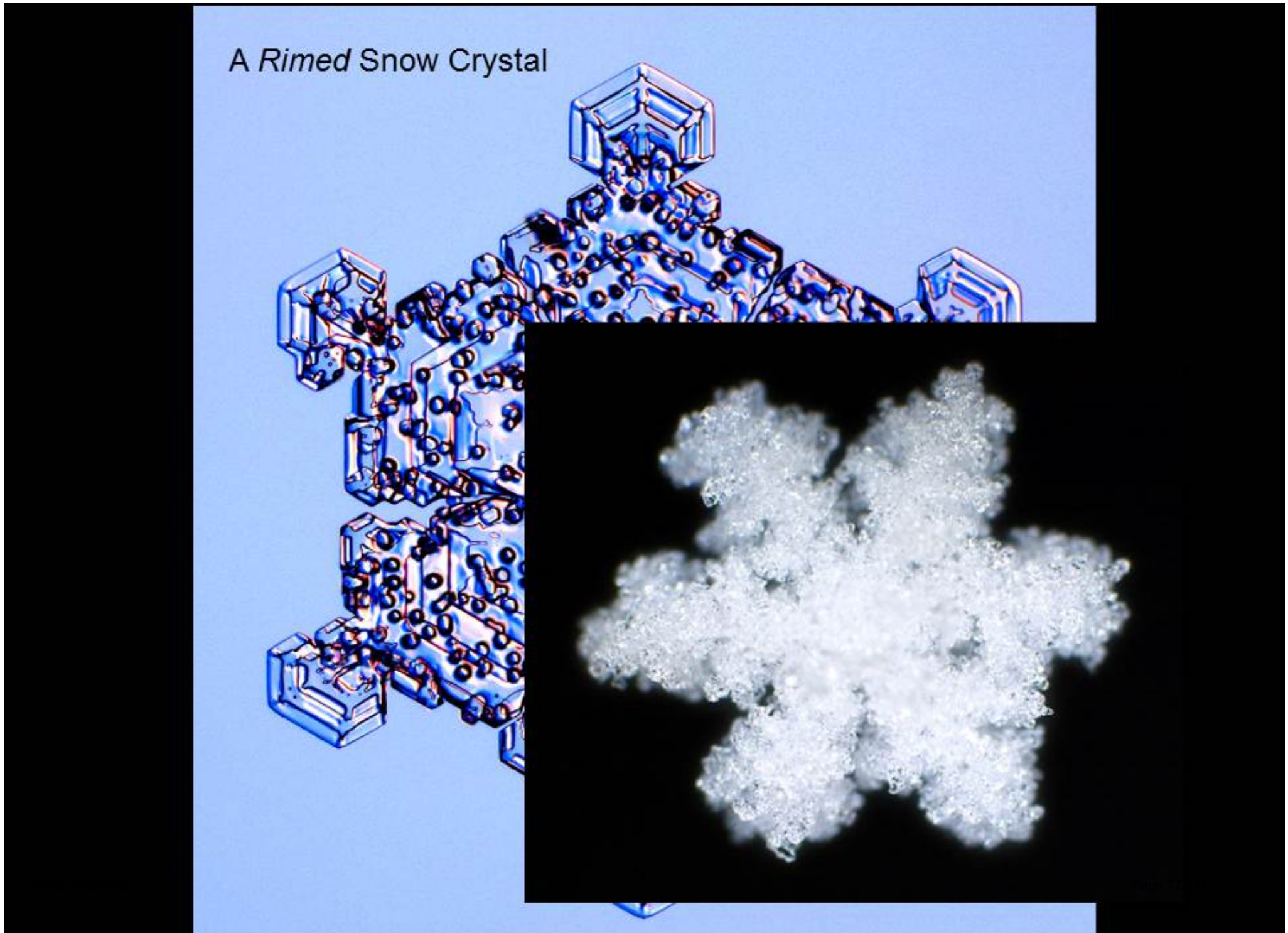
Ridges at corners between facets divides branches into sectors




"duck feet"






A *Rimed* Snow Crystal

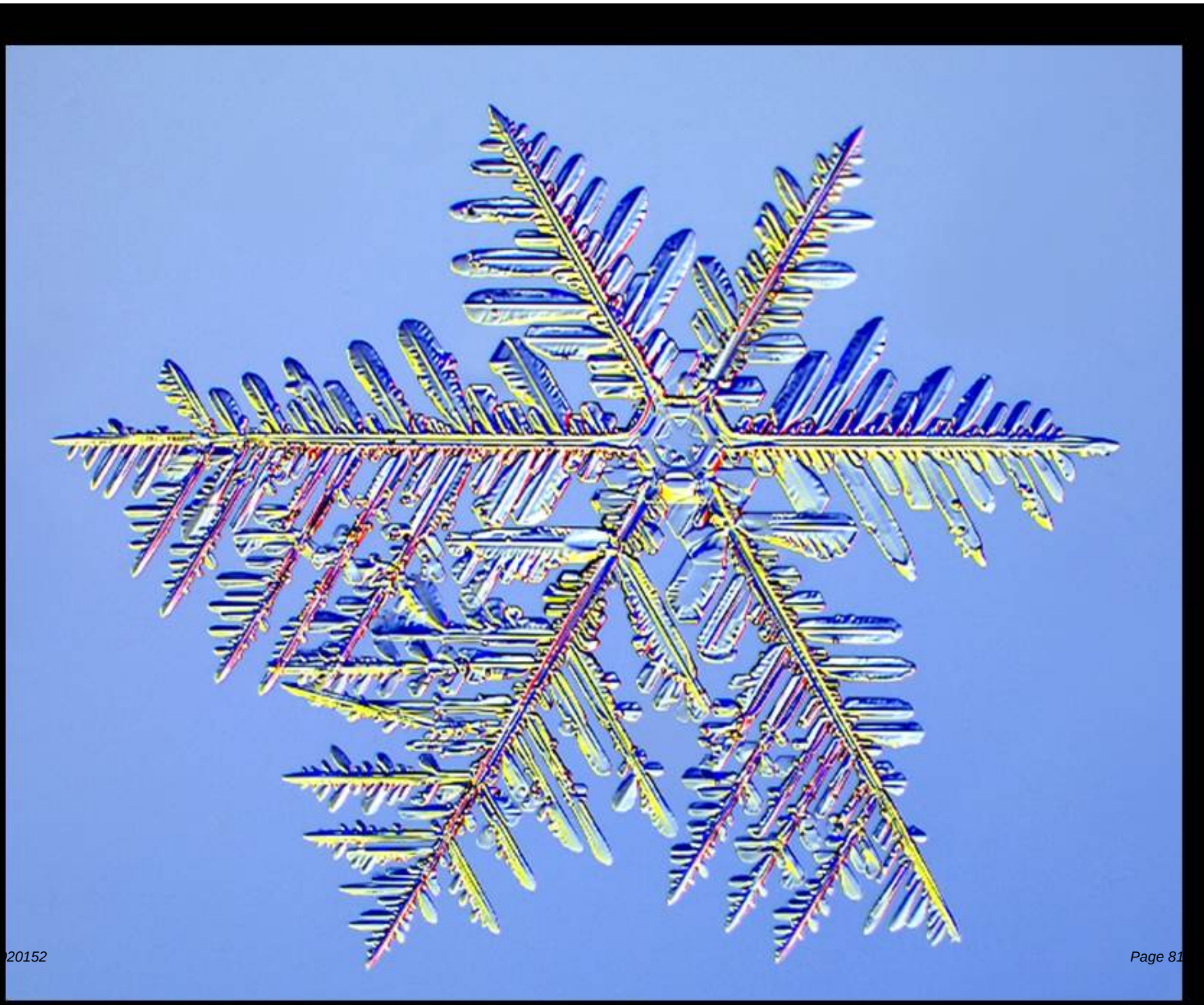
What Falls from the Sky...

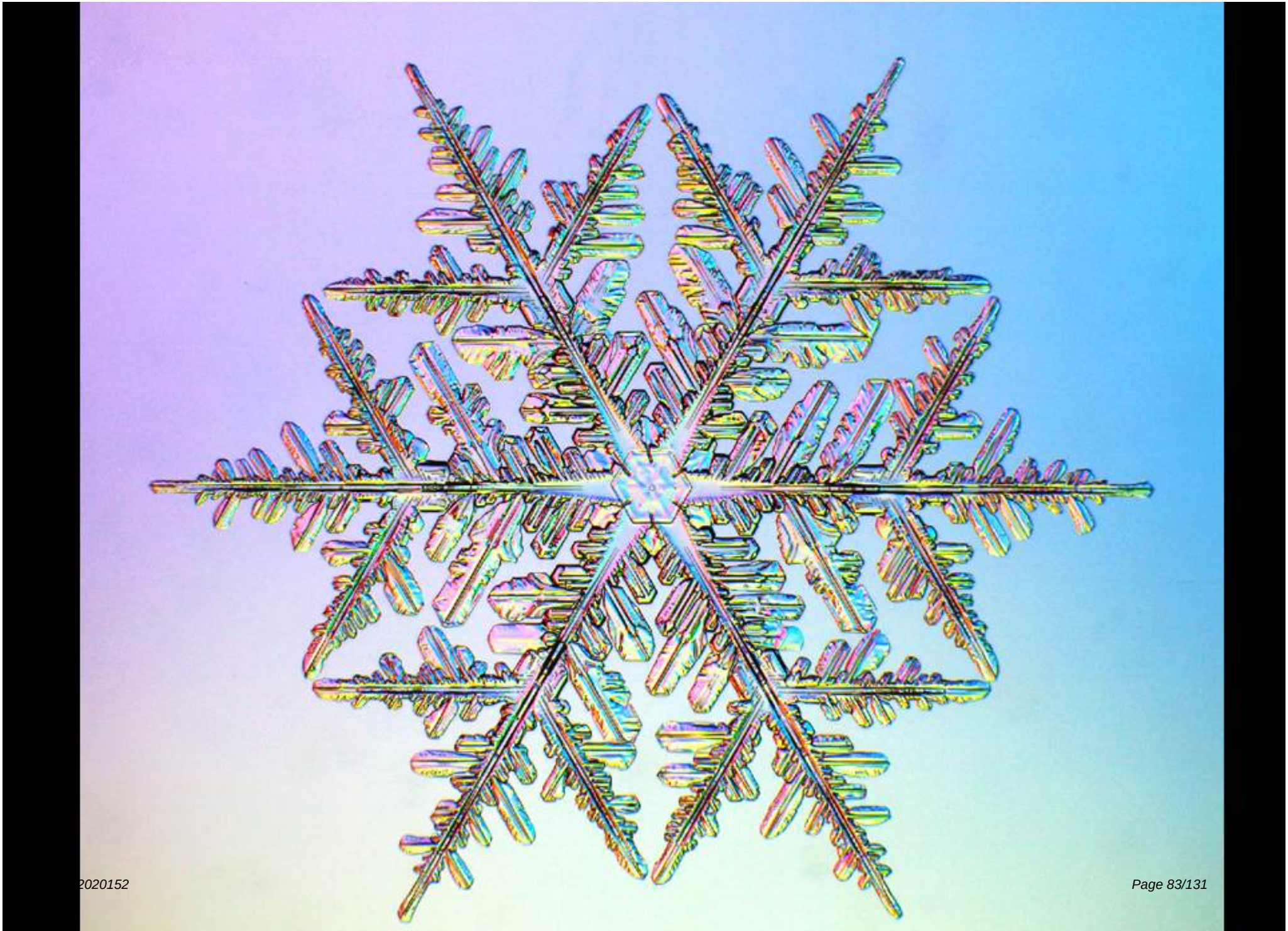
Stellar Dendrites

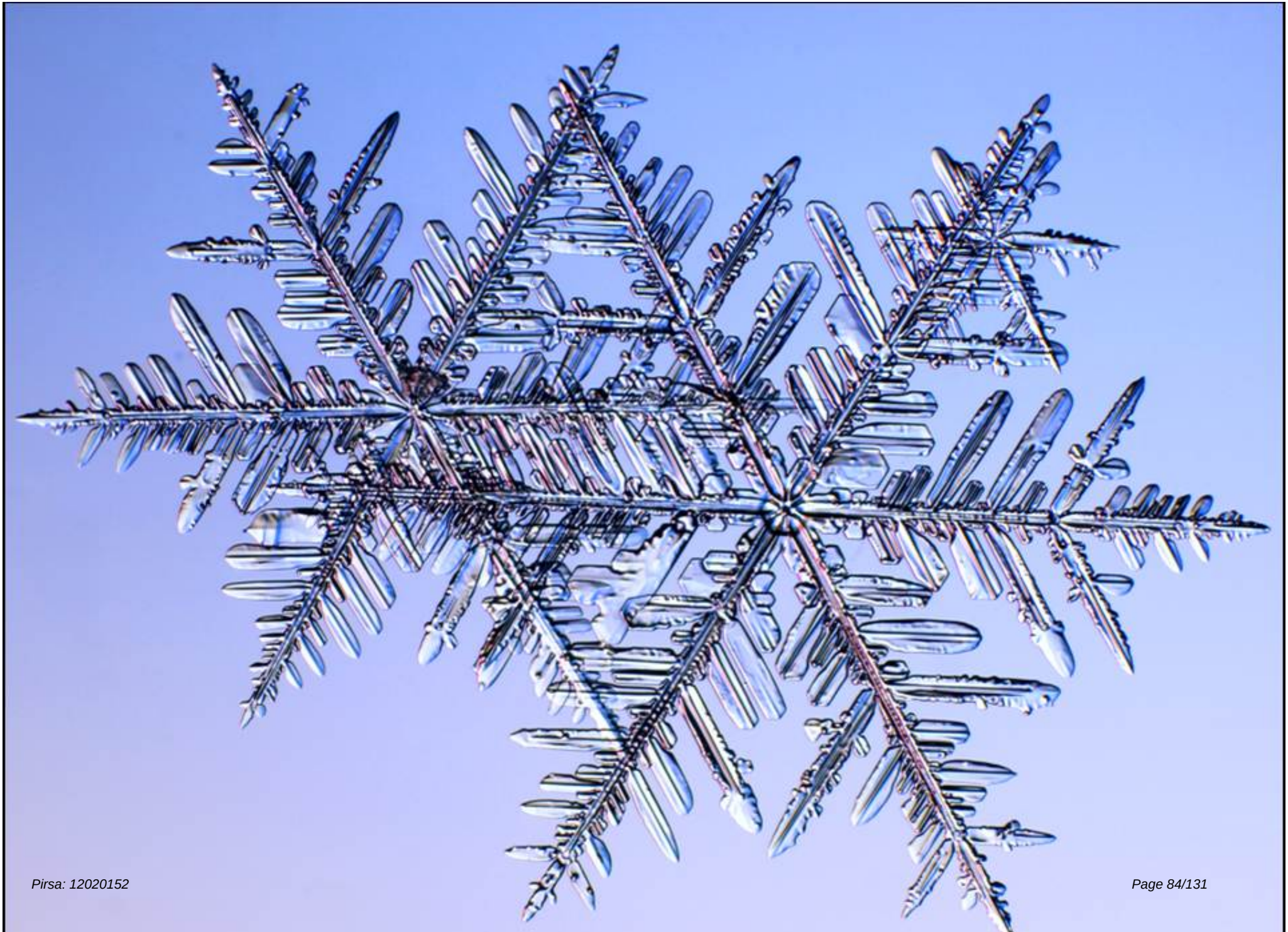
"dendrite" = "tree-like"
multiple branches and sidebranches
still thin plates

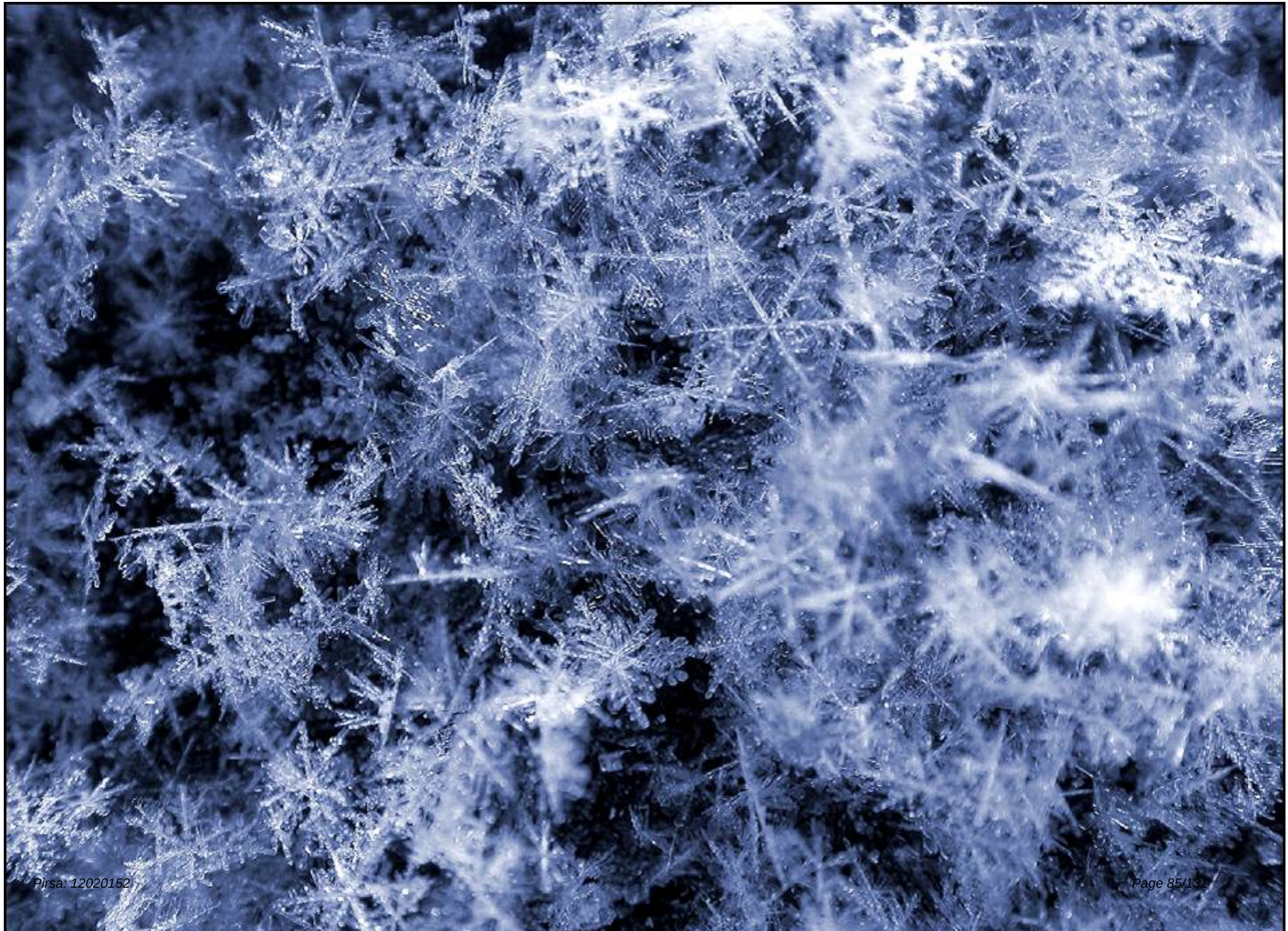
stellar dendrites

fern-like stellar dendrites
are still single crystals





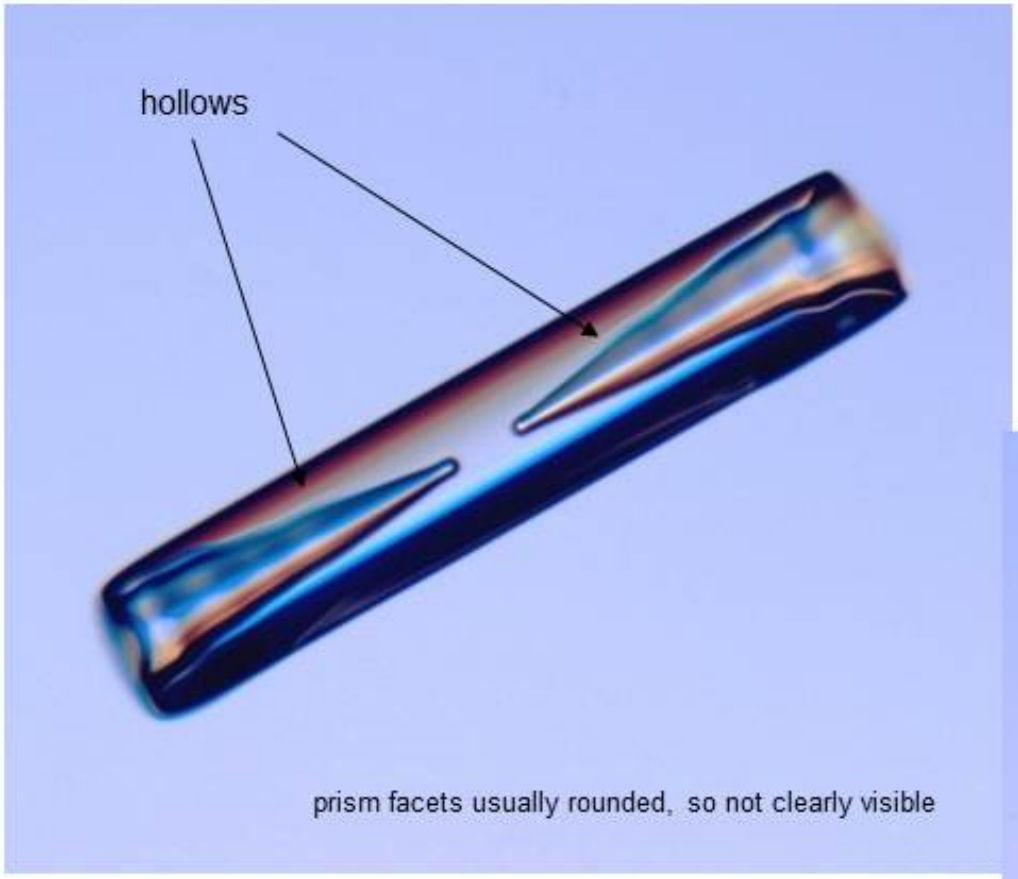


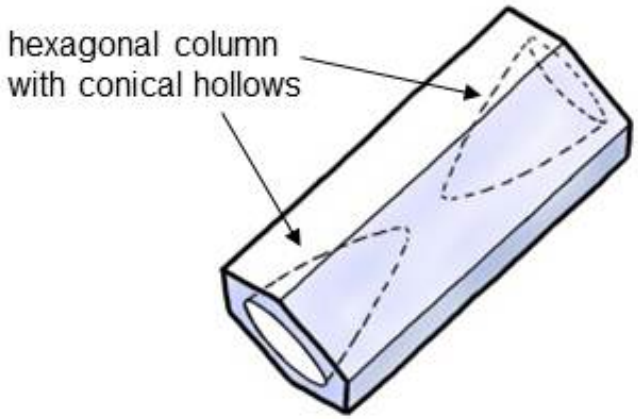


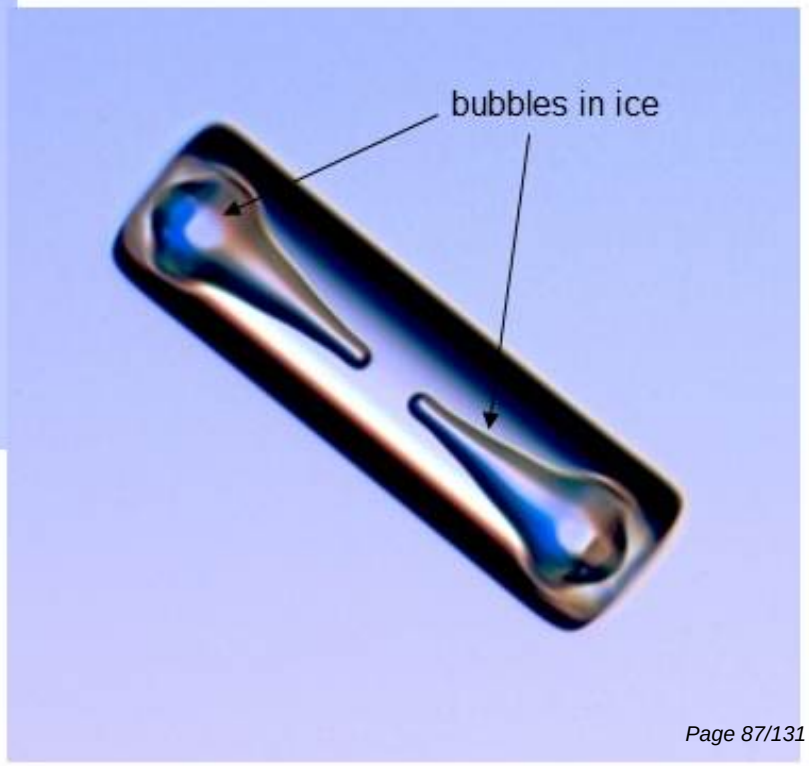

An exceptionally large
snow crystal
size: 10 mm

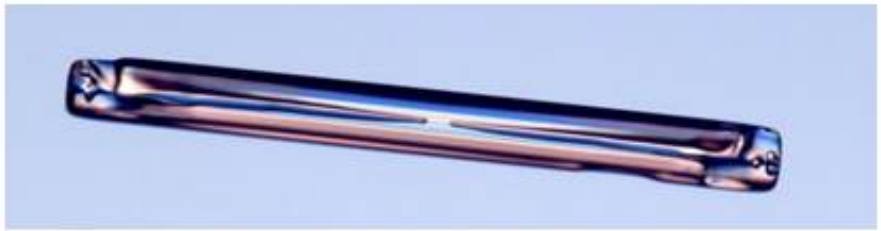
What Falls from the Sky...

Hollow Columns



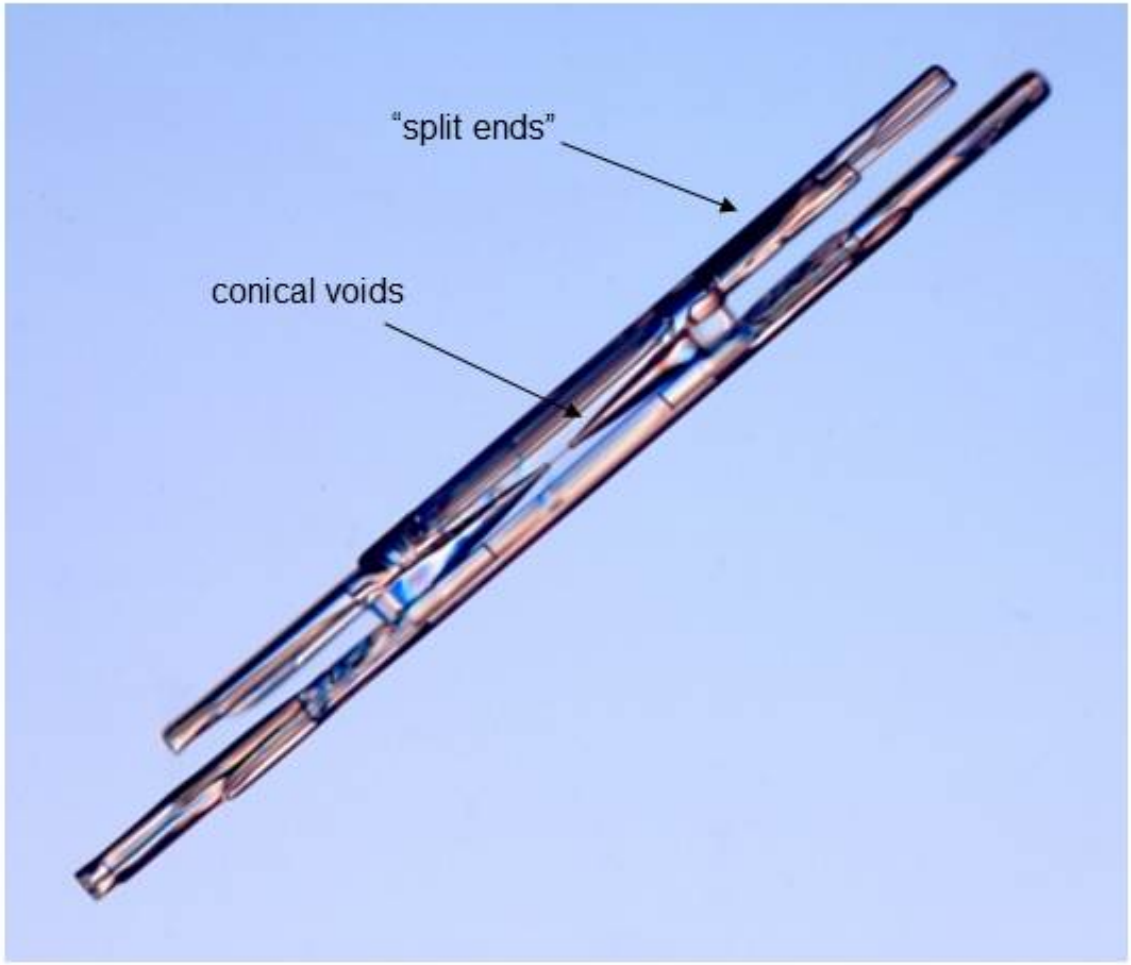


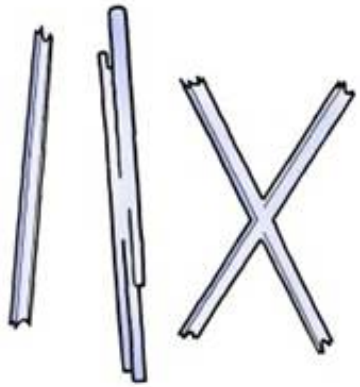




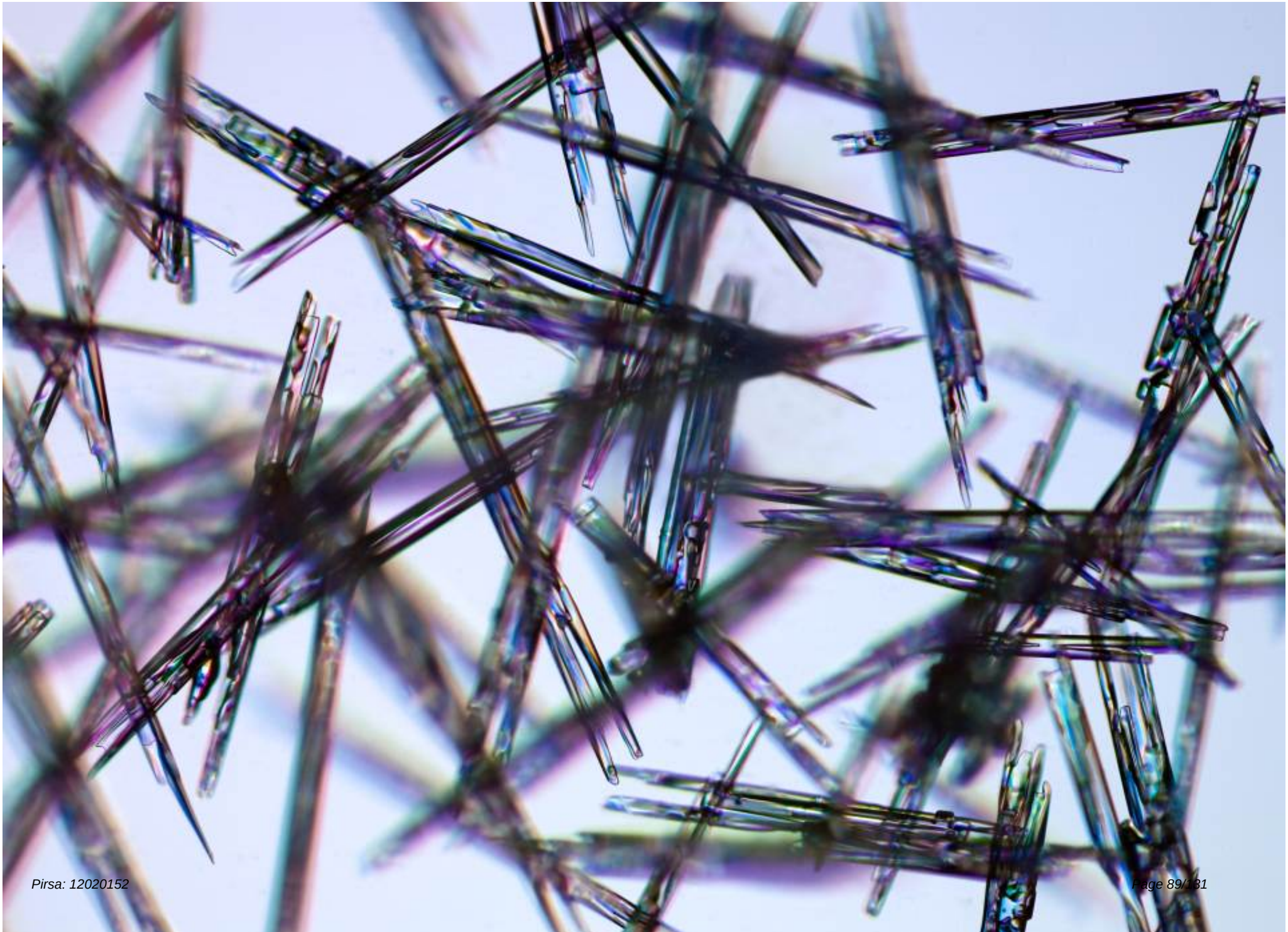
What Falls from the Sky...

Needles



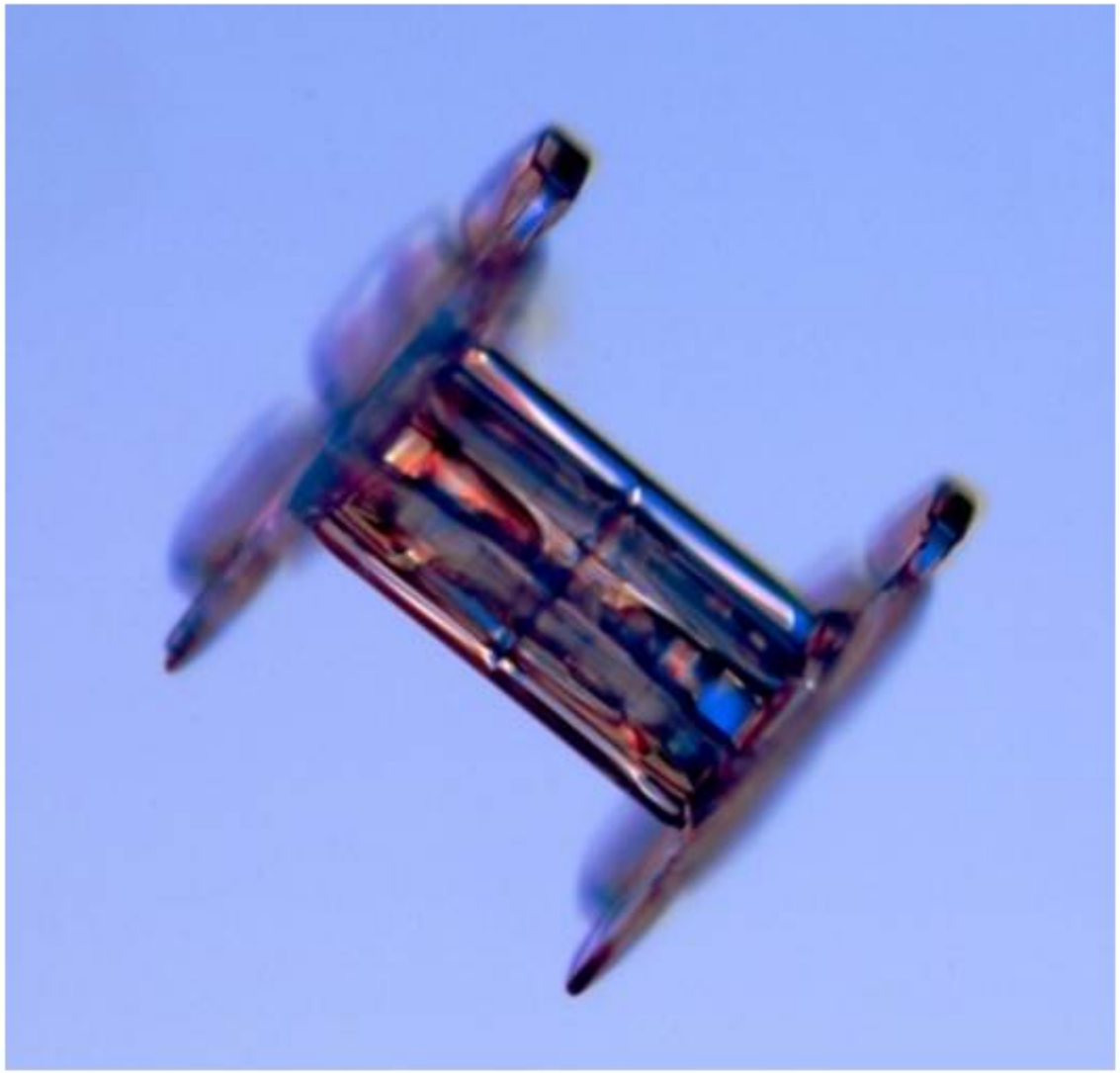


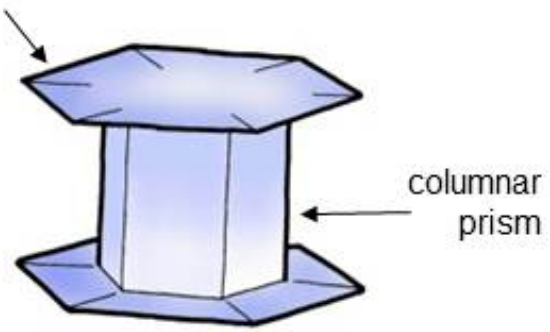
longest of the columnar crystals, up to 2-3 mm long
often find in clusters



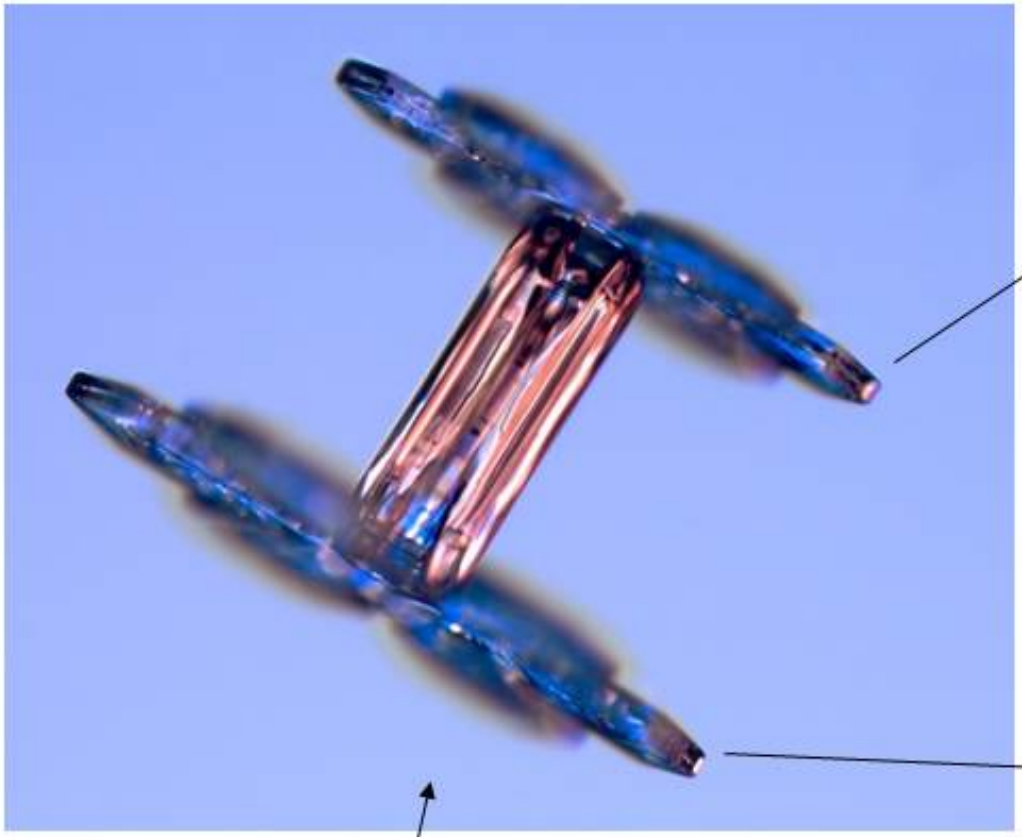
What Falls from the Sky...

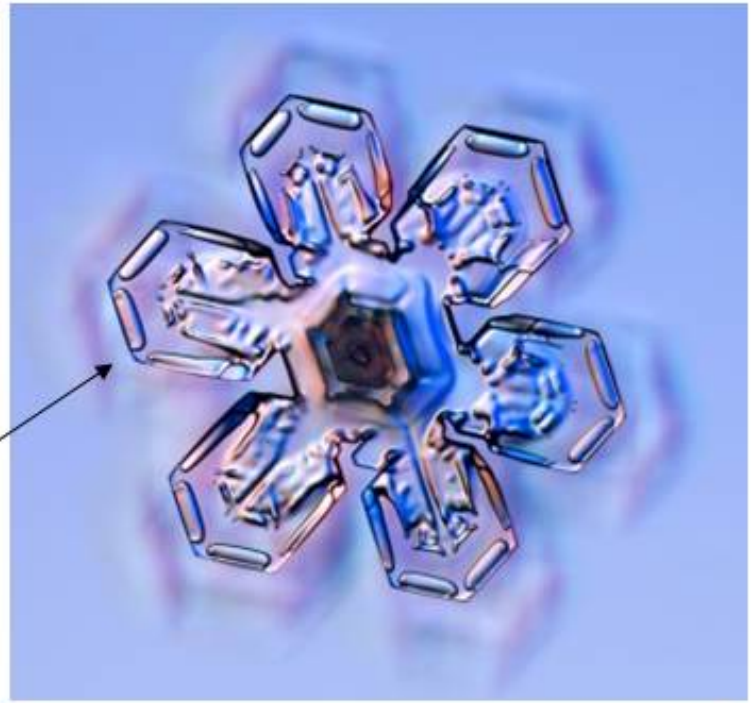
Capped Columns



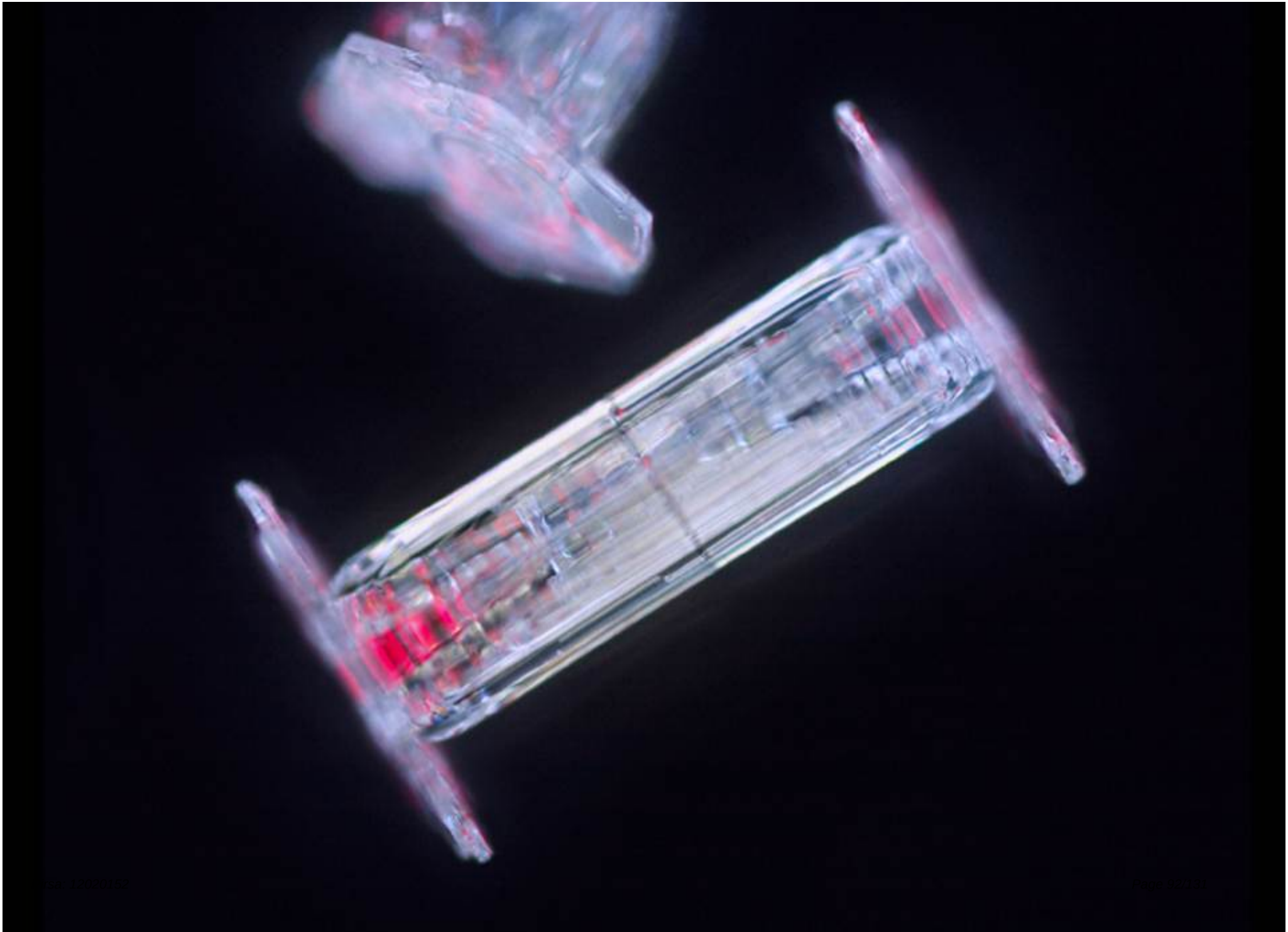


Another Capped Column

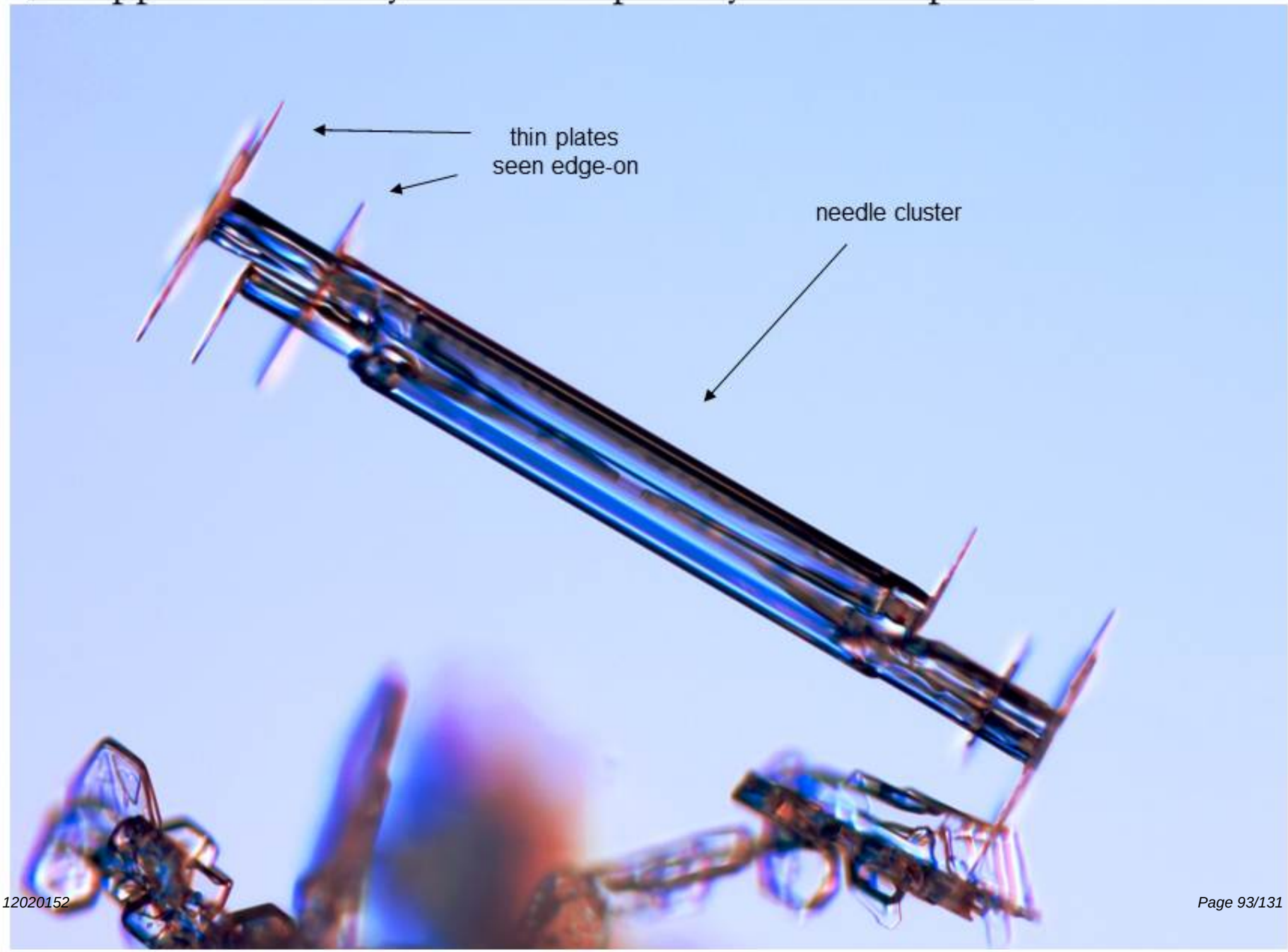




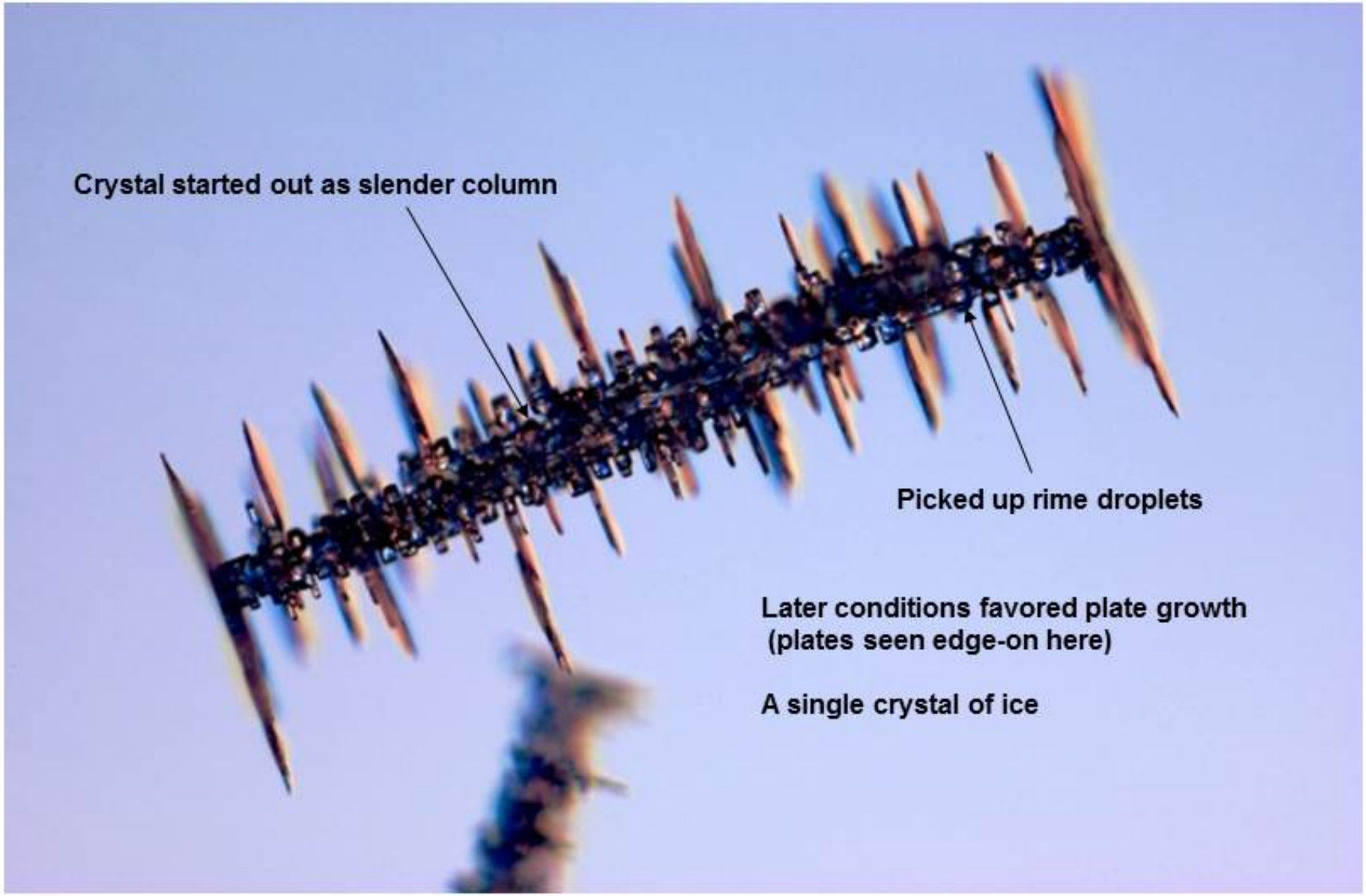
First took picture above
Then flipped crystal on end, focused on top plate
... and then focused on bottom plate



A capped needle crystal with especially thin end plates

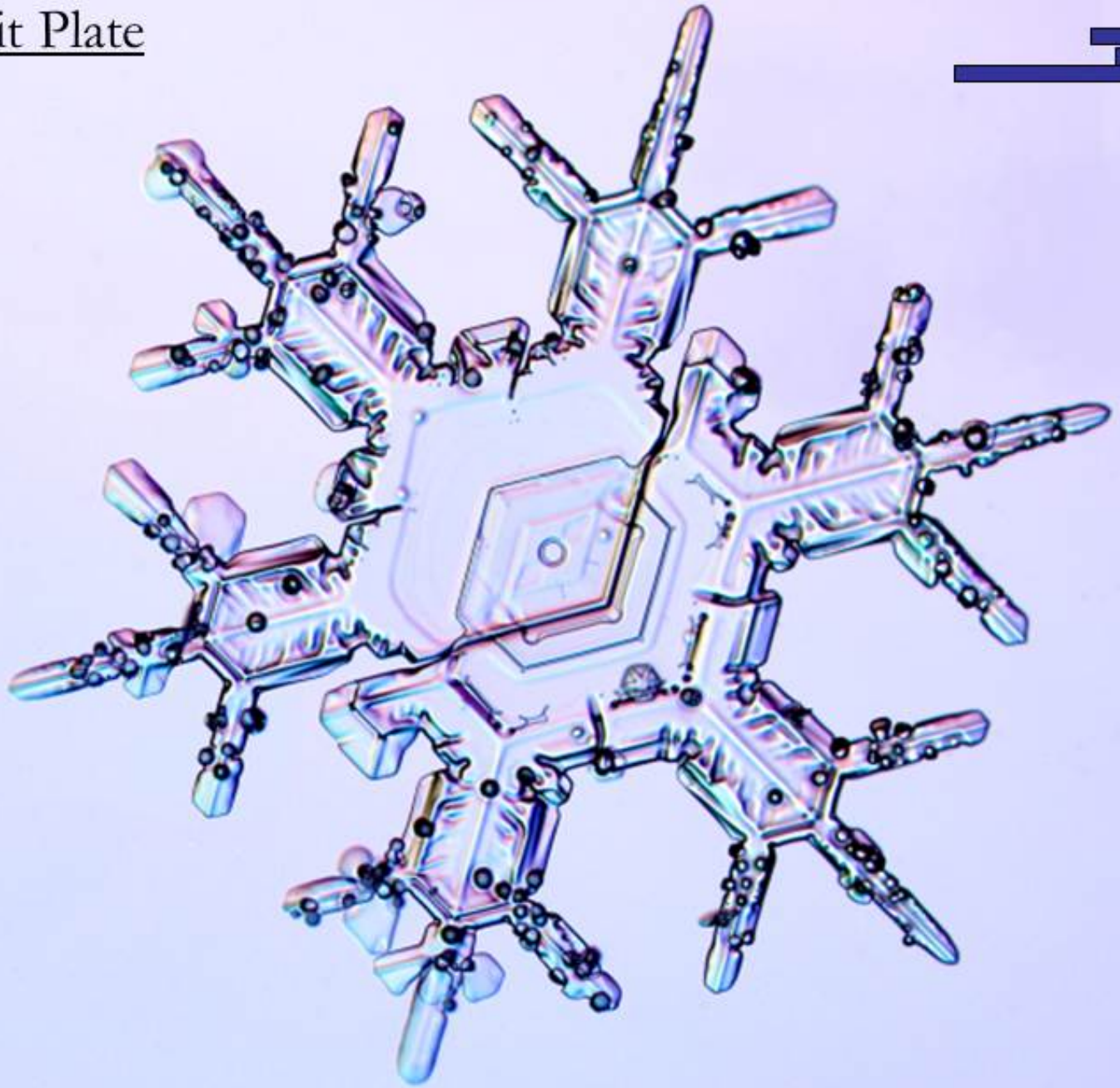


A Multiply Capped Column



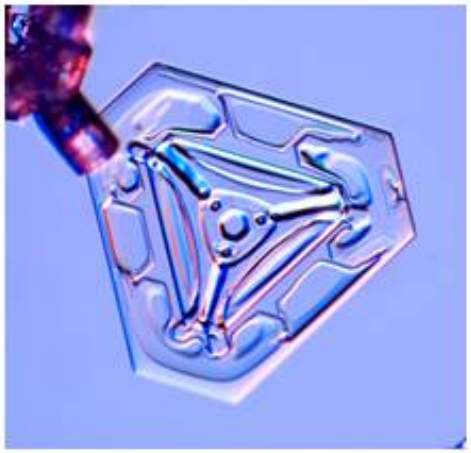

A Double Plate

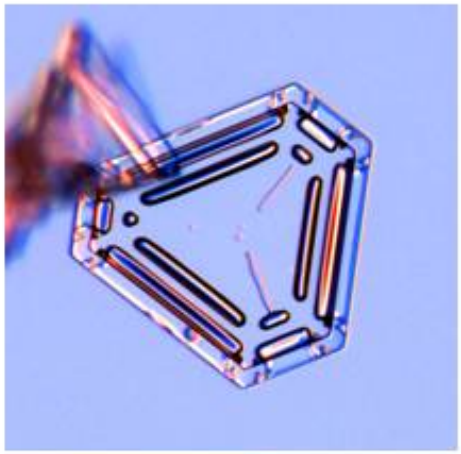
A Split Plate

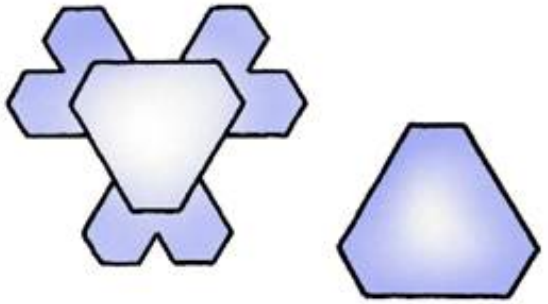


What Falls from the Sky...

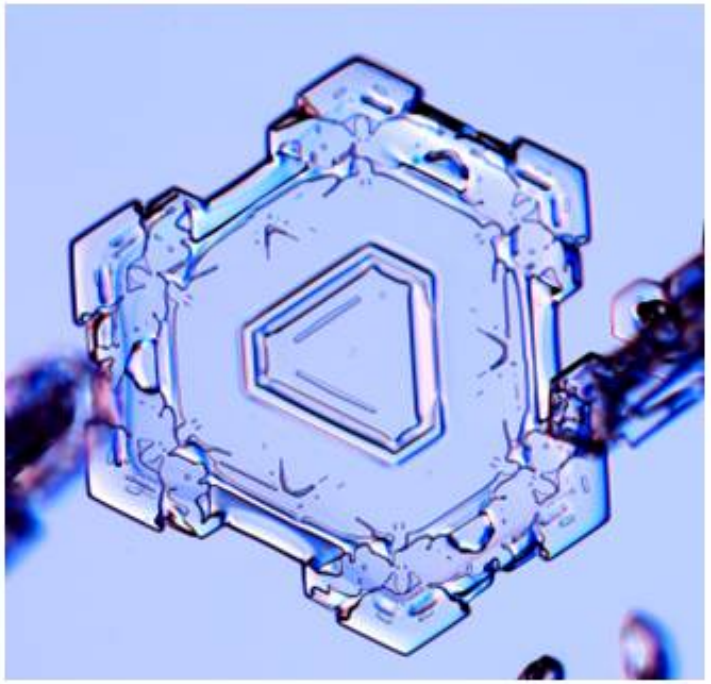
Triangular Crystals

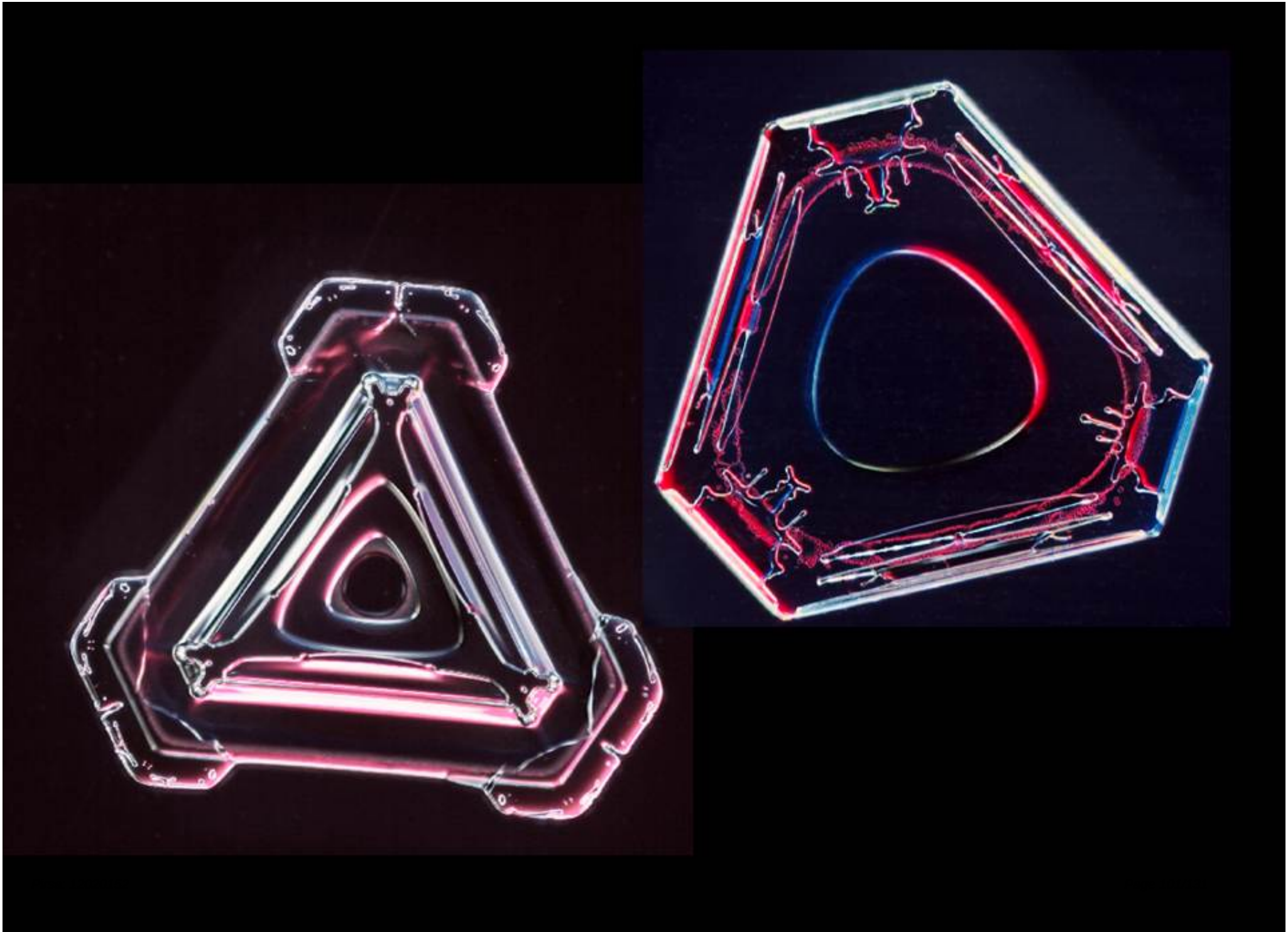






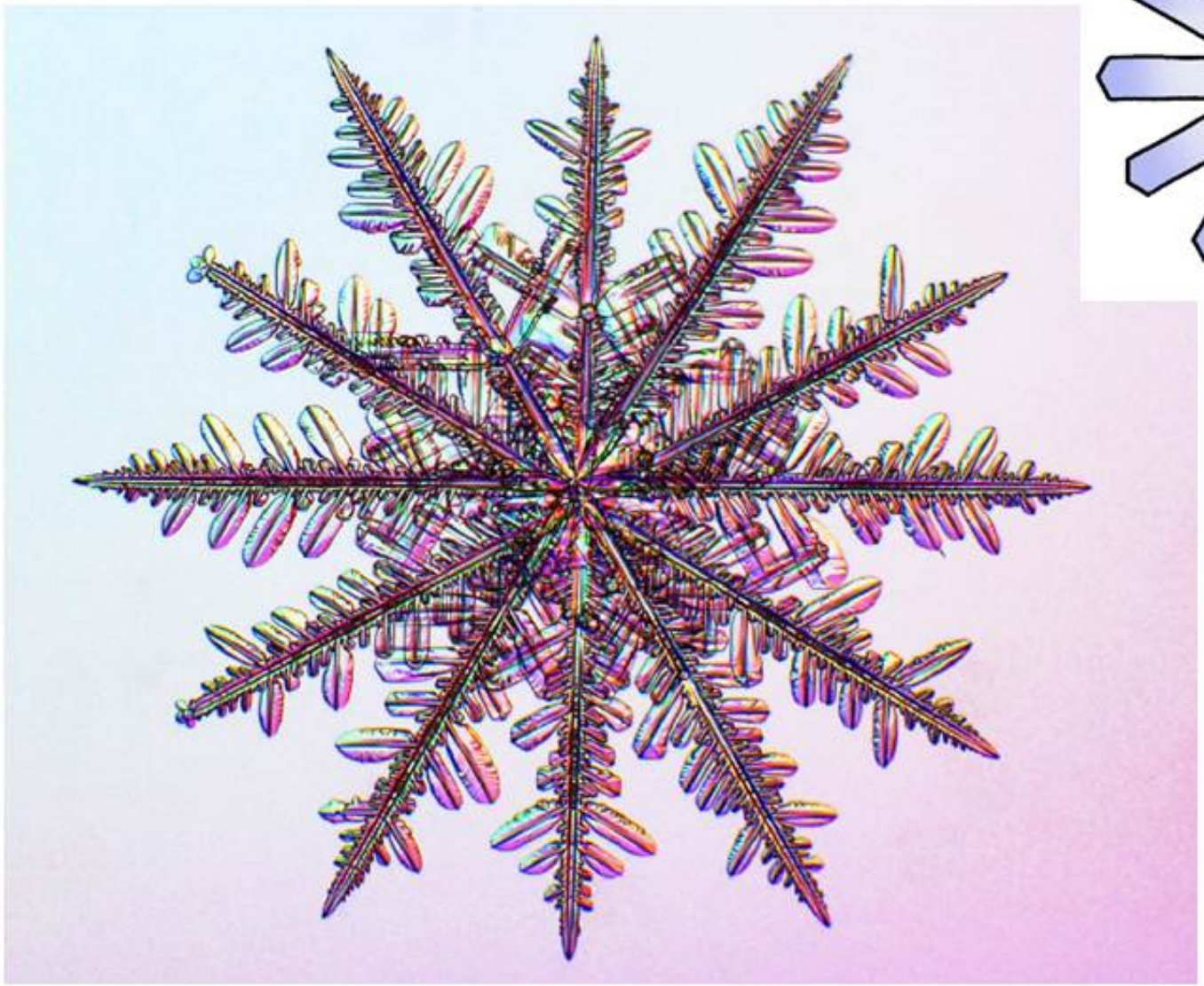
Uncommon,
but there if you look...

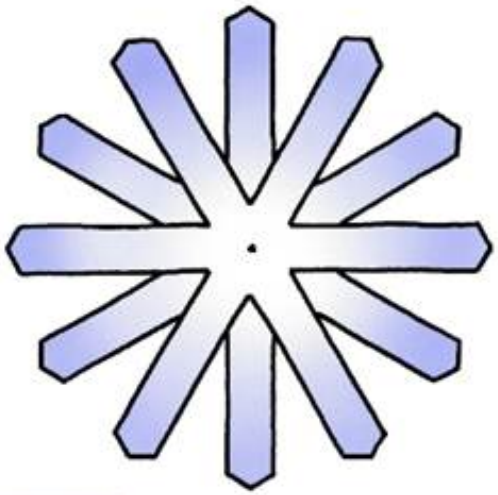


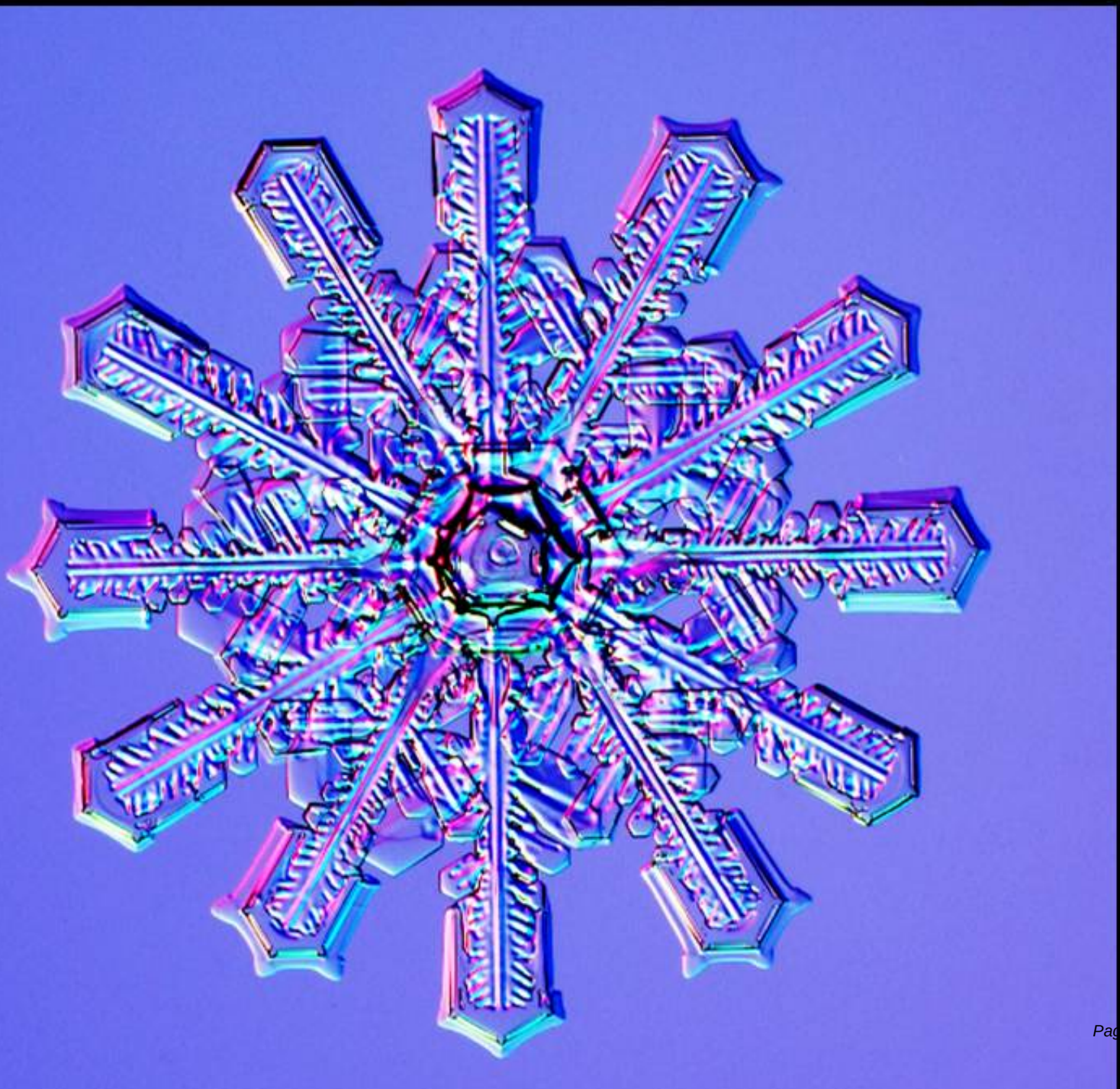


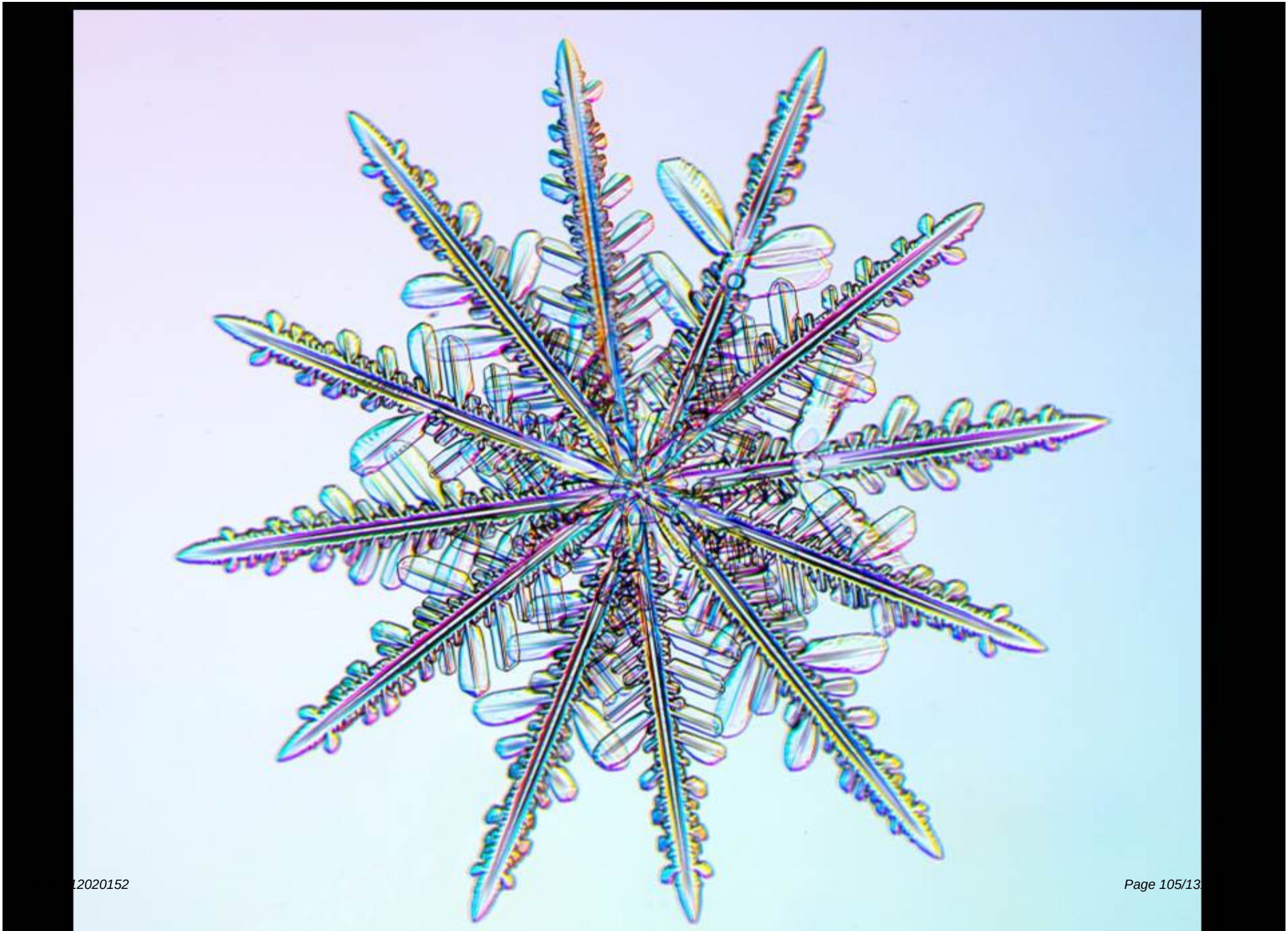
What Falls from the Sky...

Twelve-branched crystals



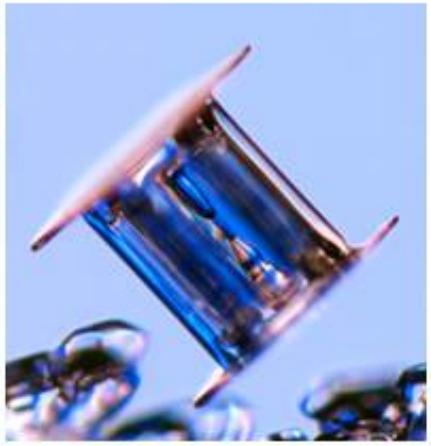


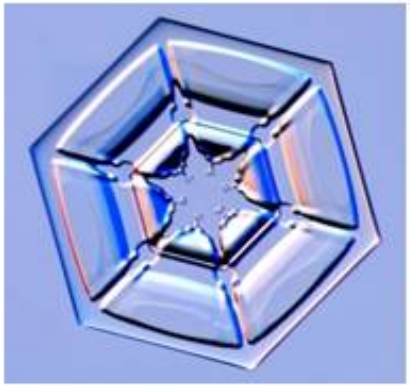


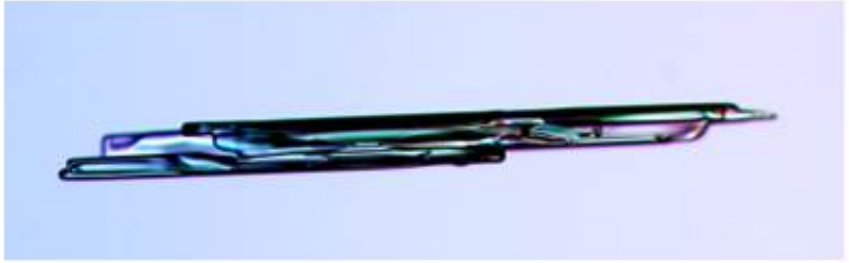



In the Field...

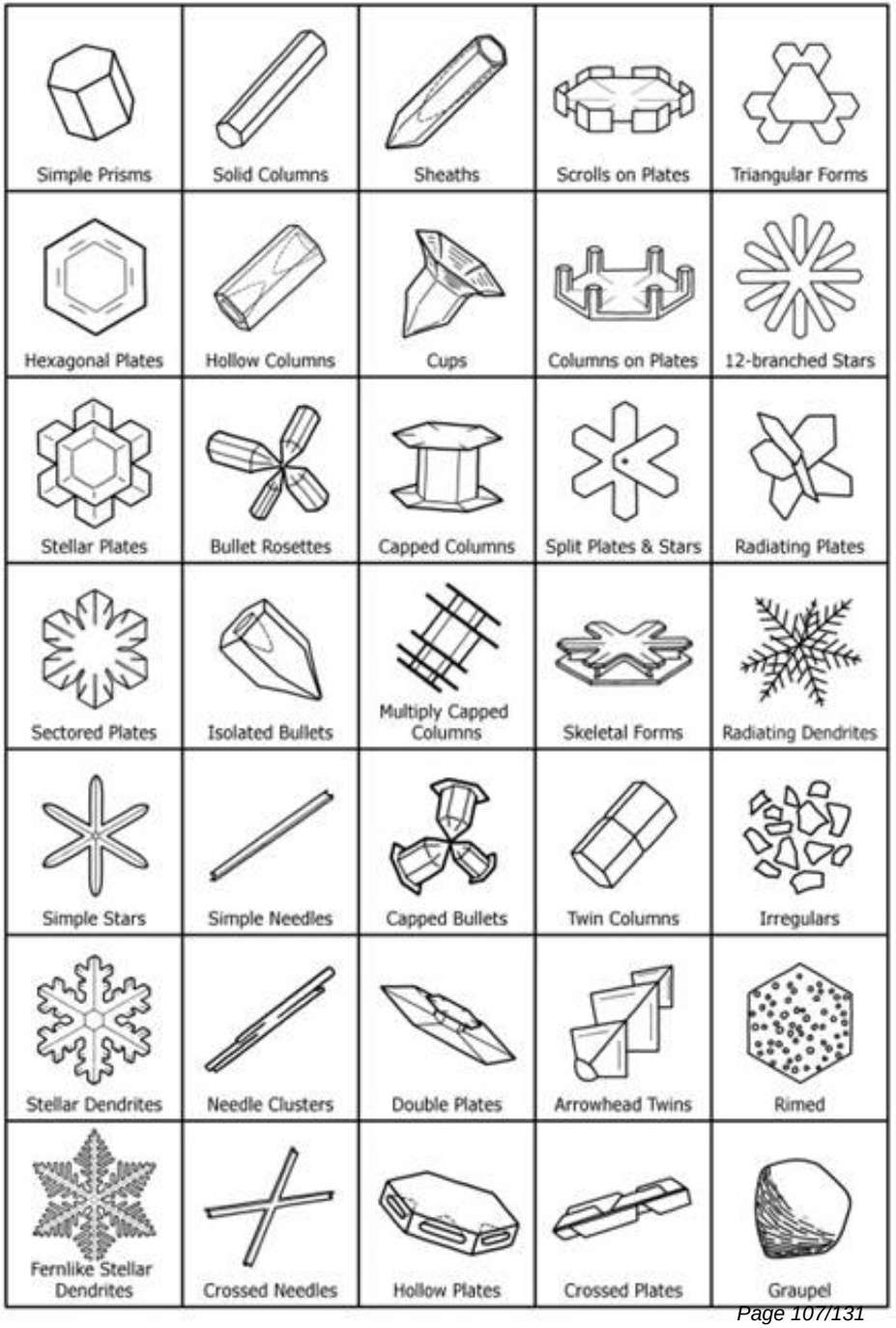
The Menagerie of Snow Crystal Types





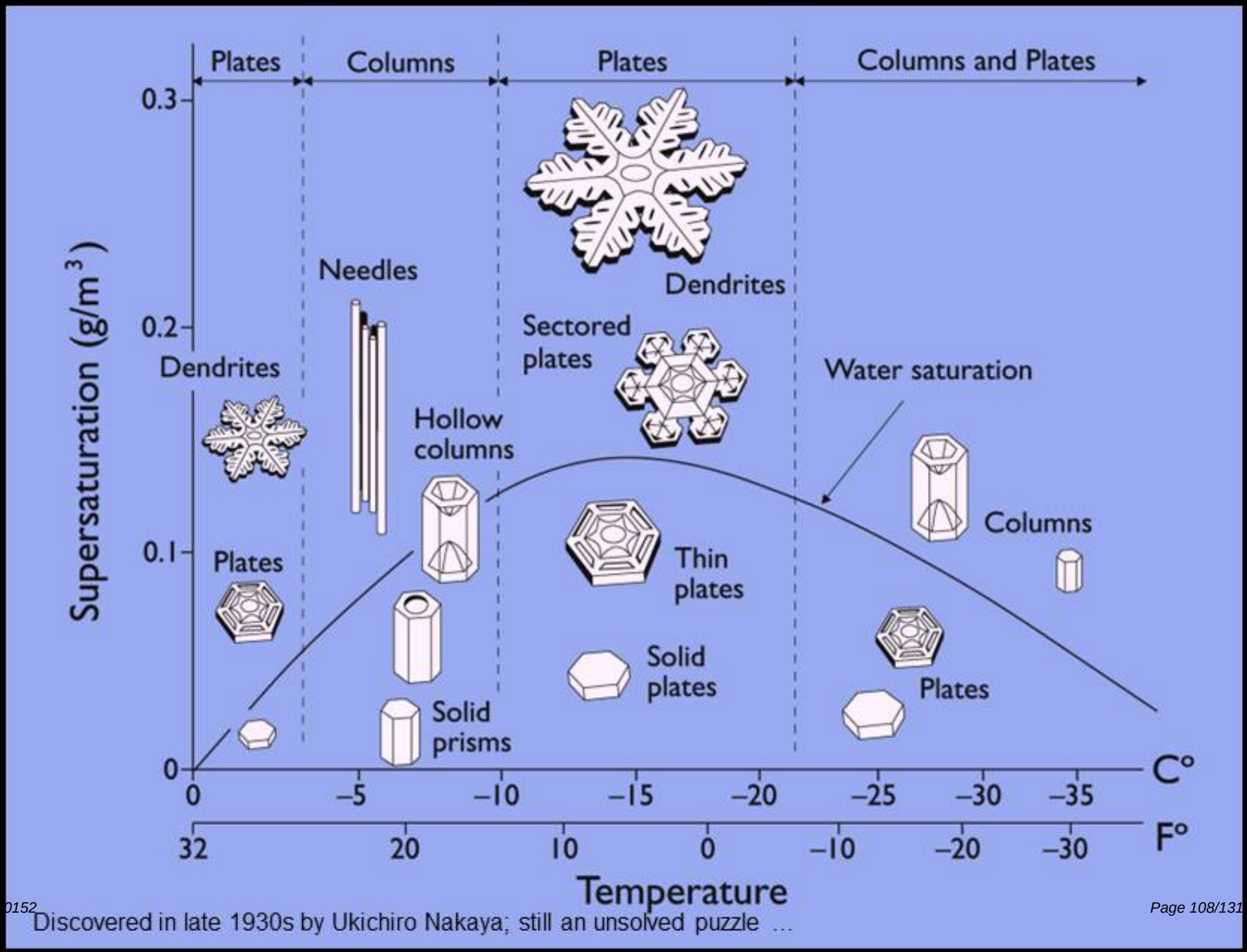


Why such diversity of shapes?
How do structures arise during crystal growth?
What is the underlying physics?



from *Ken Libbrecht's Field Guide to Snowflakes*

The Snow Crystal Morphology Diagram



Discovered in late 1930s by Ukichiro Nakaya; still an unsolved puzzle …

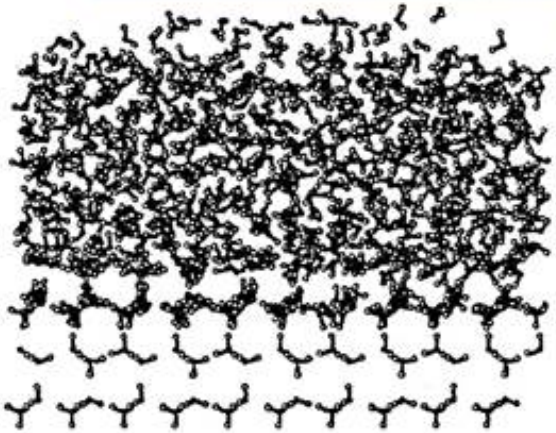
The Molecular Physics of Snow Crystal Formation

>> What does the ice surface look like at the molecular scale?

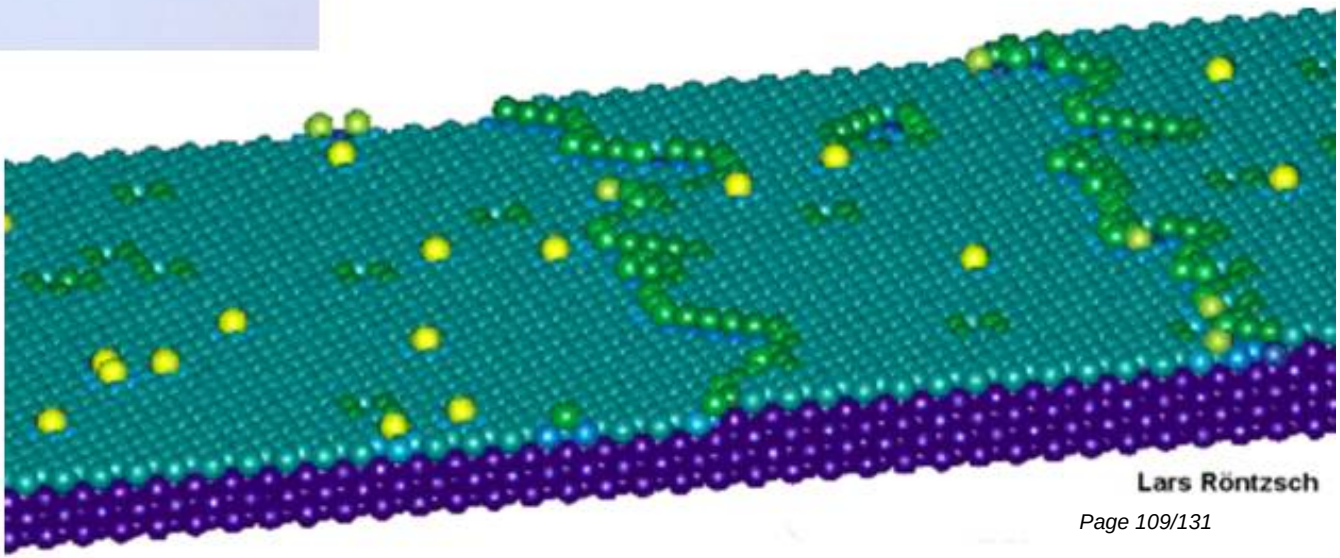
>> How to water molecules attach to the surface? How quickly?

>> How does the molecular-scale physics determine snow crystal shapes?

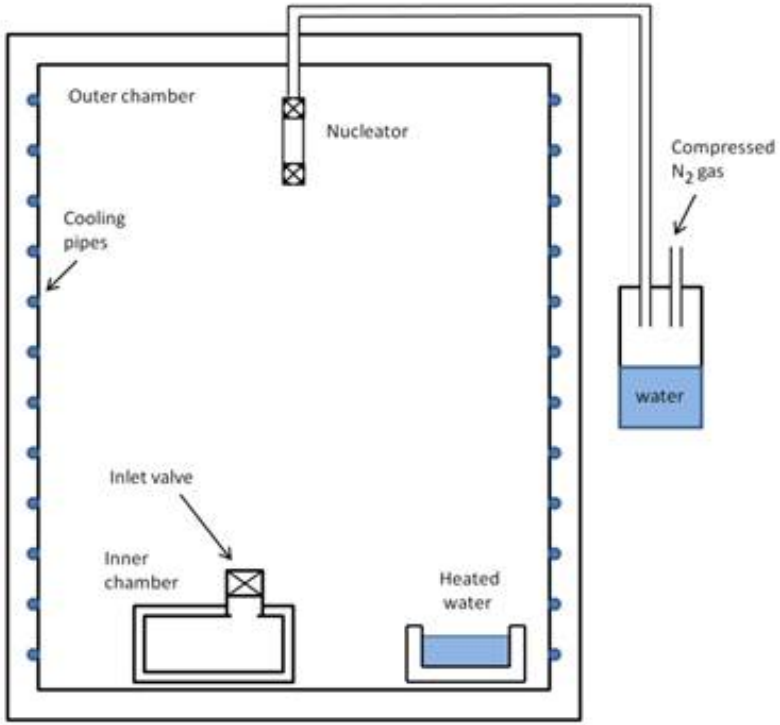
>> Why does the growth depend on temperature and other parameters?

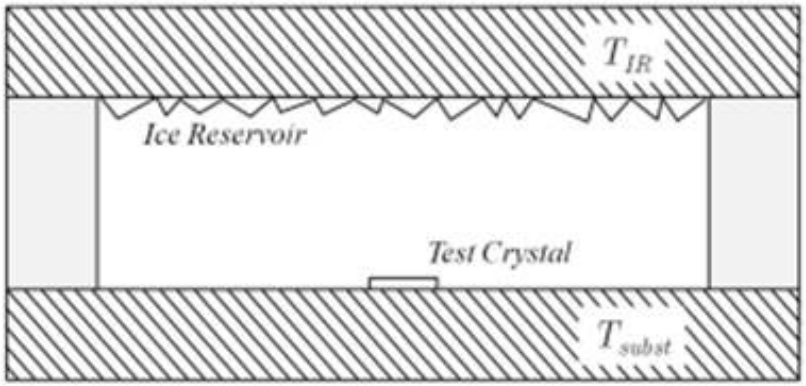


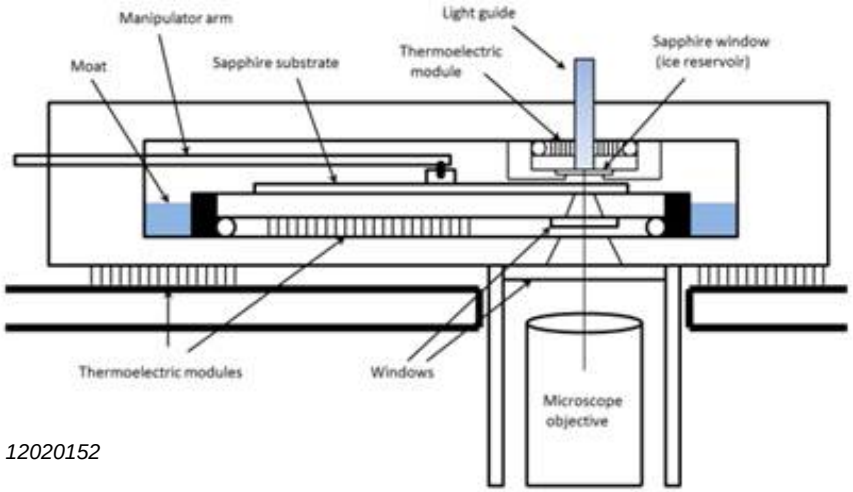
Surface melting in ice at -3C



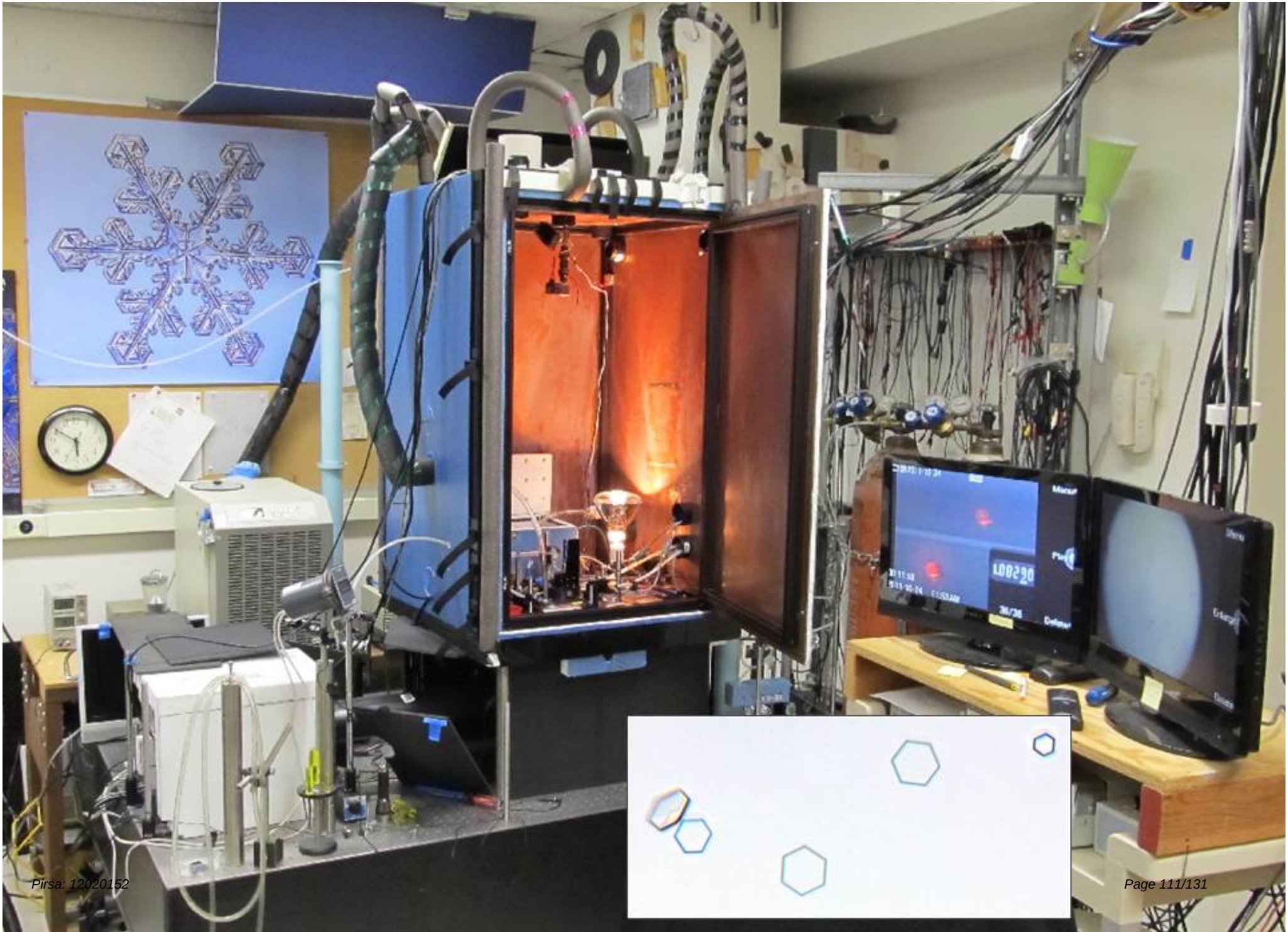
Controlled Ice Growth Experiments in a low-pressure environment







> Make crystals in main chamber
> Transfer some to smaller chamber
> Isolate single crystal on substrate
> Pump out small chamber
(fast particle diffusion → kinetics limited)
> Use optical interferometry to measure thickness vs time → growth velocity
> Supersaturation determined by T_{IR}, T_{subst}



SnowCrystals.com

... Your online guide to snowflakes, snow crystals, and other ice phenomena ...

"How full of the creative genius is the air in which these are generated! I should hardly admire more if real stars fell and lodged on my coat."
--Henry David Thoreau, 1856 [1]

Welcome to ***SnowCrystals.com!*** This site is all about snow crystals and snowflakes -- what they are, where they come from, and just how these remarkably complex and beautiful structures are created, quite literally, out of thin air.

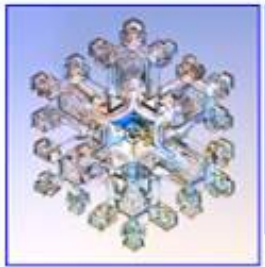
Snowflake News

NEW BOOK! SNOWFLAKES
Snowflakes is a chunky book book of terrific snowflake photographs and literary quotations. Fun to flip through! See more at Snowflake Books.

Or purchase snowflake cards, prints, and posters at the Snowflake Store.

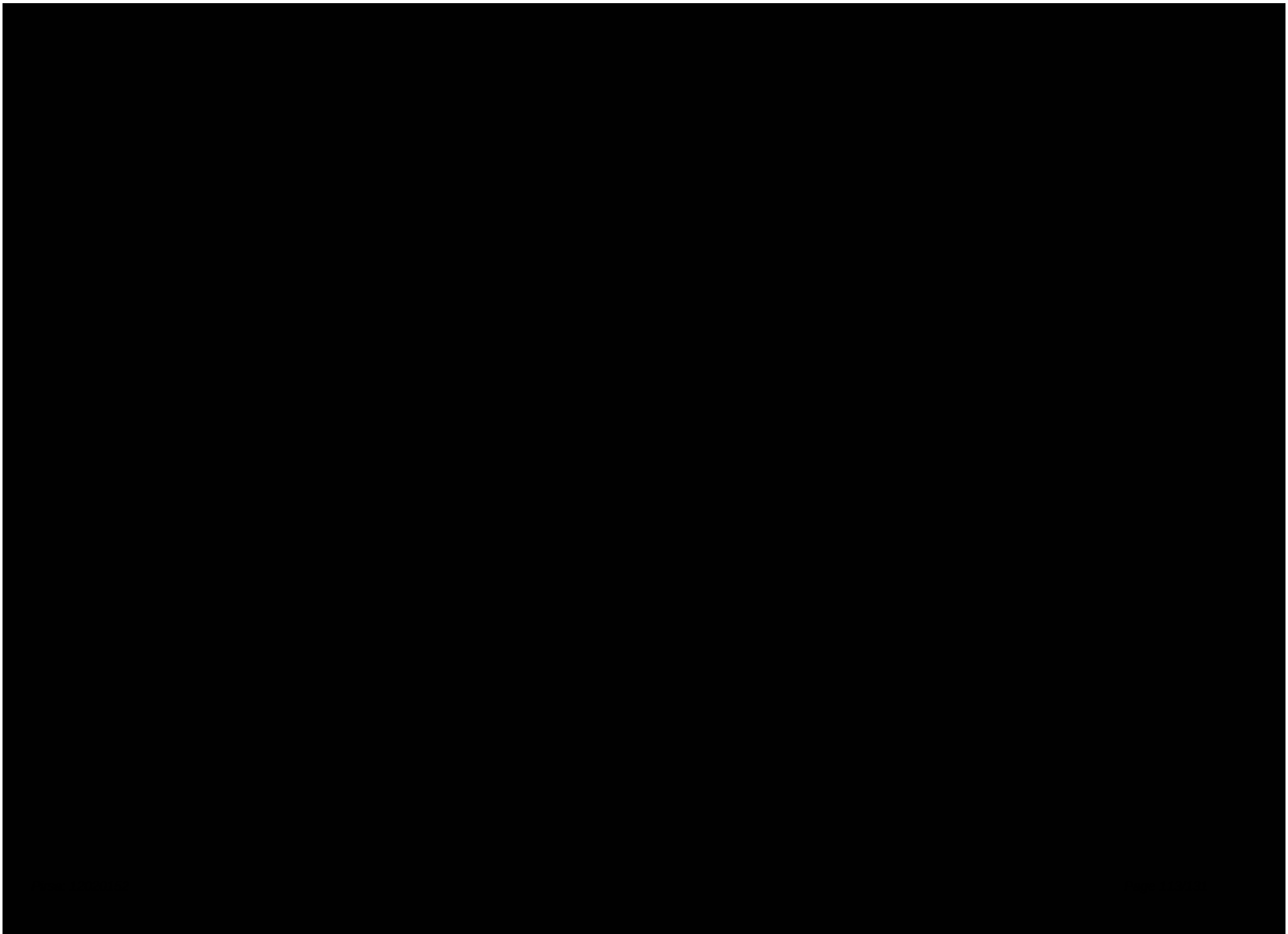
FREE! Snowflake Wallpaper. Put an awesome snowflake on your desktop -- guaranteed to make your computer run cooler! Click on the size appropriate for your computer screen: 640x480, 800x600, 1024x768, 1152x864, 1280x1024, 1400x1050, 1600x1200, 1680x1050.

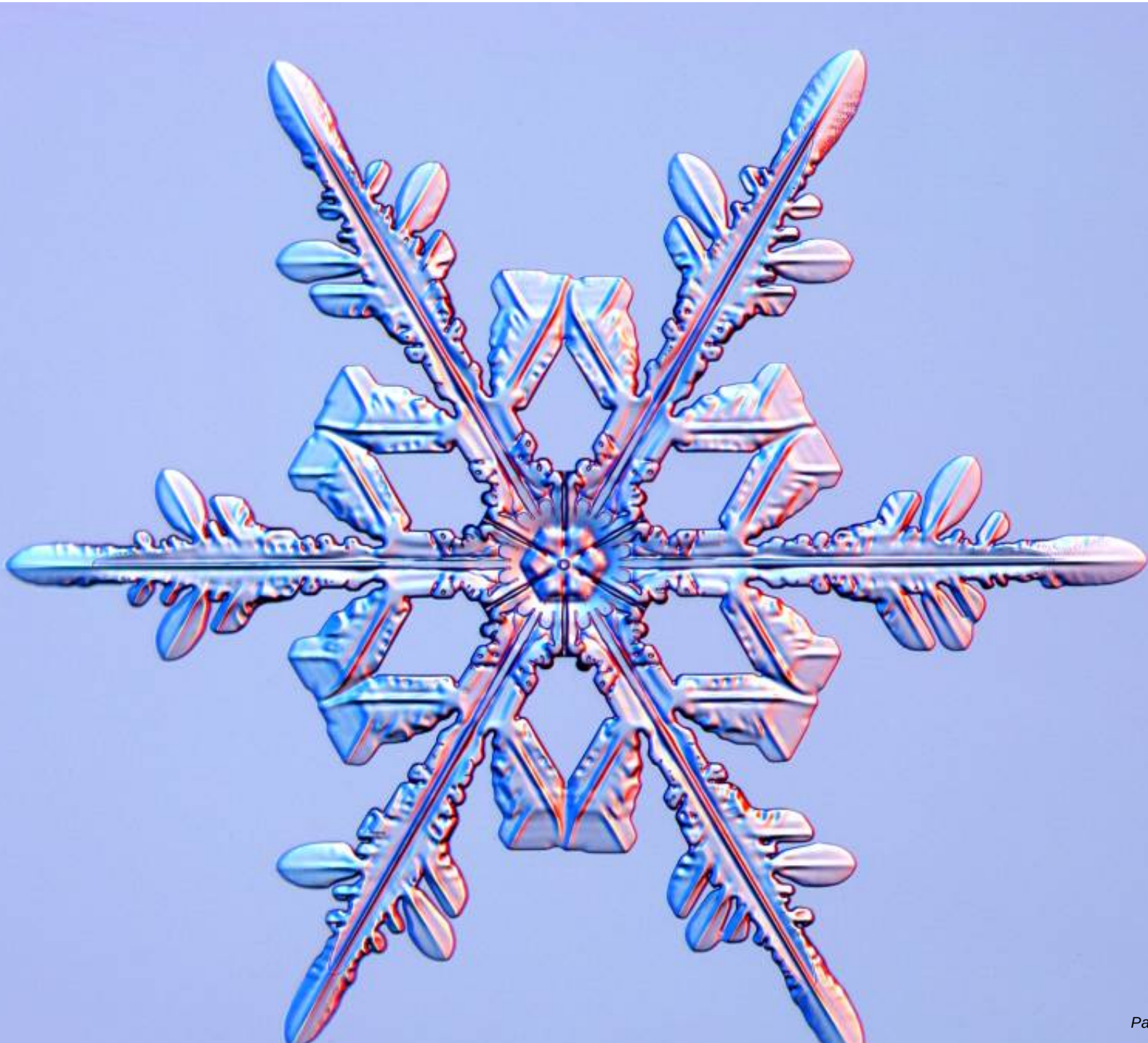
Natural Snowflakes

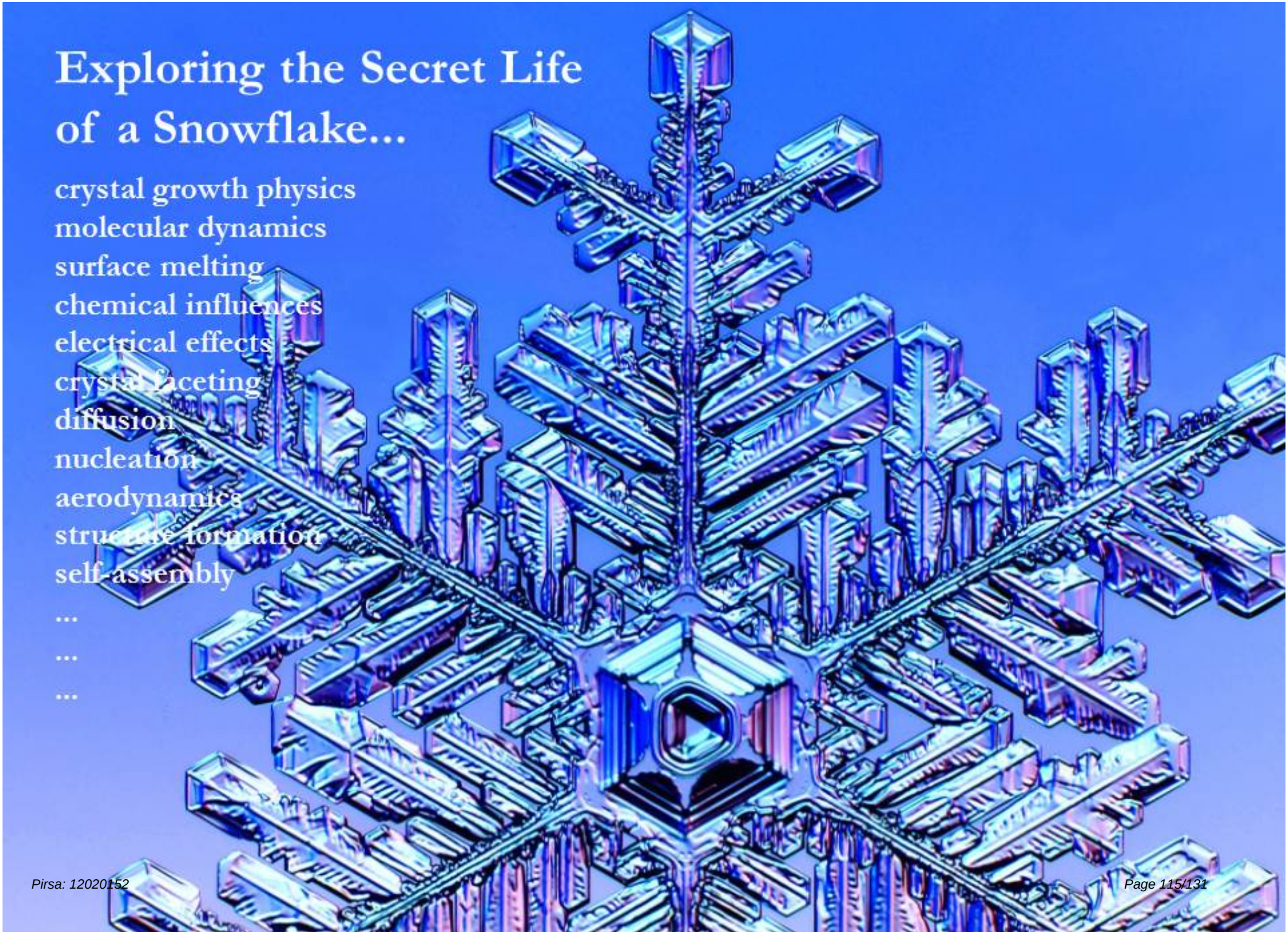


Pictures, pictures, pictures. Visit the three Photo Galleries to see some spectacular photographs of snow crystals.

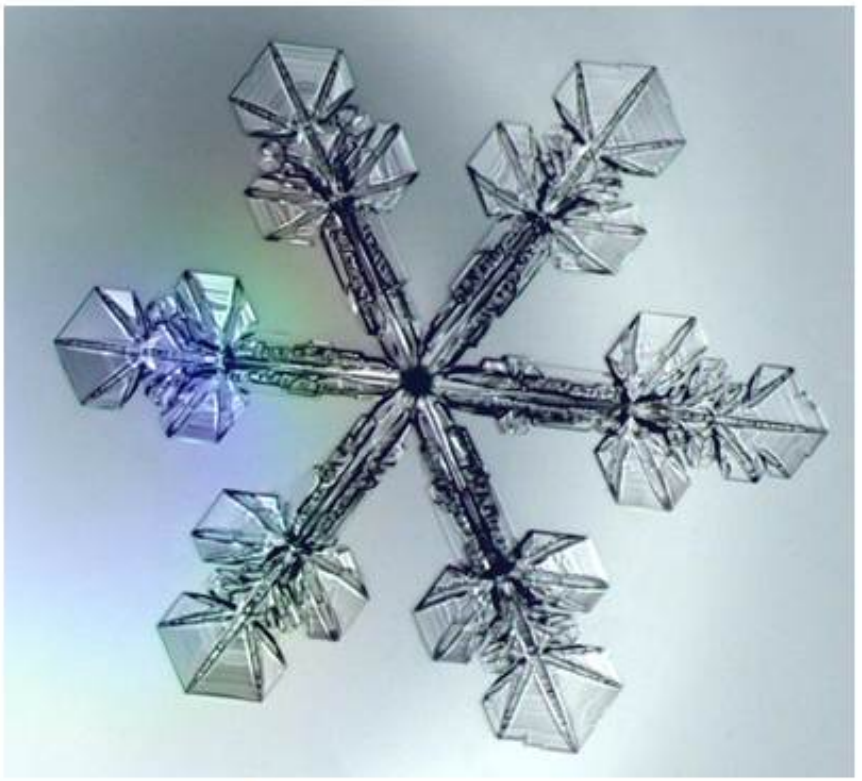
Don't know a stellar dendrite from a capped column? The Guide to Snowflakes shows different kinds of snow crystals that fall from the sky. Browse the other links at the far left to find out more about natural snowflakes.

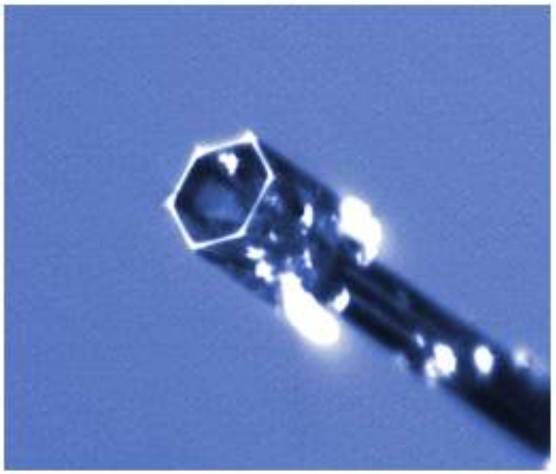


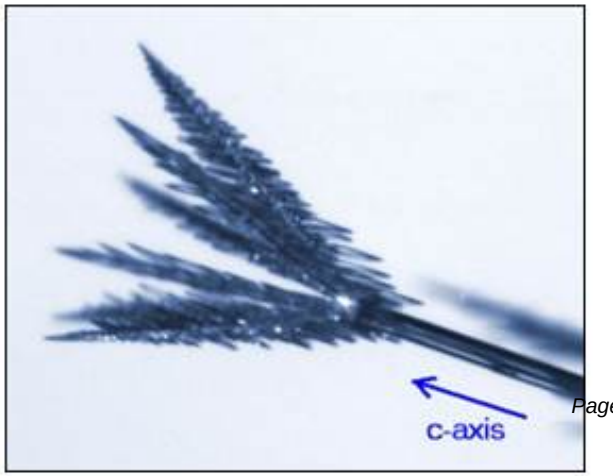



Exploring the Secret Life
of a Snowflake...
crystal growth physics
molecular dynamics
surface melting
chemical influences
electrical effects
crystal faceting
diffusion
nucleation
aerodynamics
structure formation
self-assembly
...
...
...

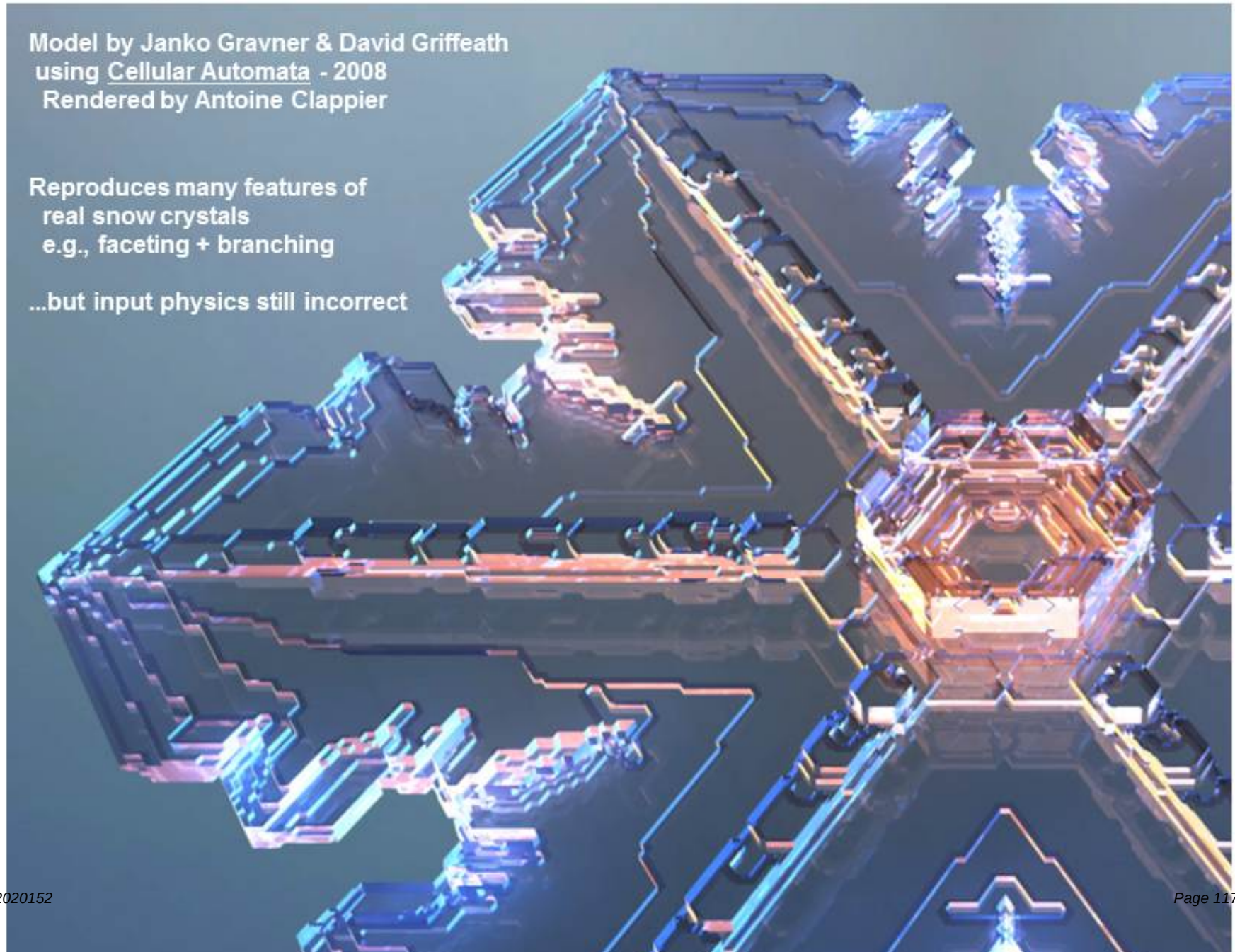
Some Laboratory-Grown Snowflakes





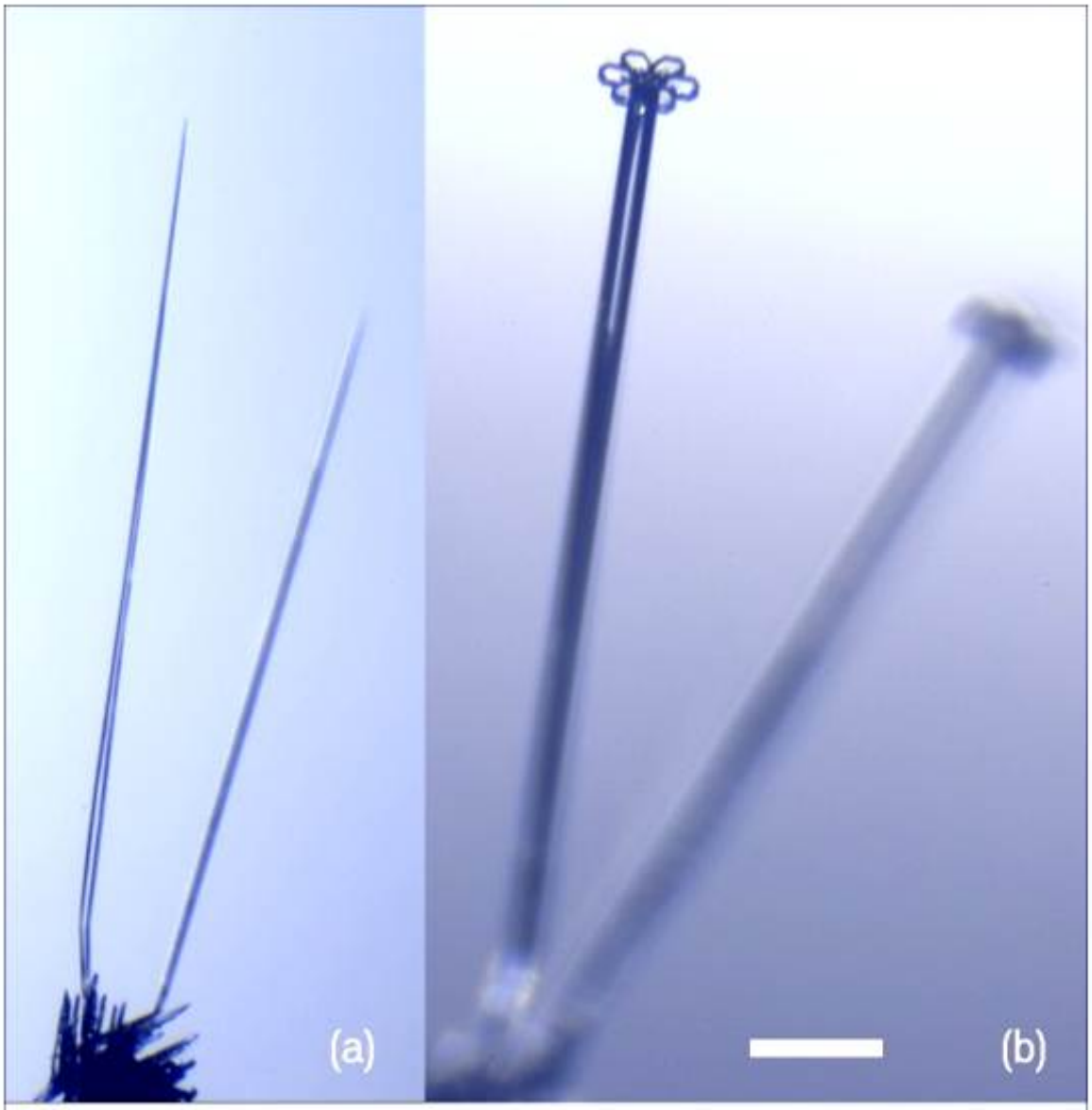


Growing Snowflakes on a Computer



Nature uses only the longest threads to weave her patterns, so that each small piece of her fabric reveals the organization of the entire tapestry.

-- Richard Feynman



Electric Ice. (a) Two crystalline needles exhibiting electrically enhanced growth, with tip velocities of 50 microns/second; (b) Normal crystal growth after the electrical potential was removed; end plates reveal that the electric needle growth was along the ice c-axis [0001]. Scale bar is 300 microns long.

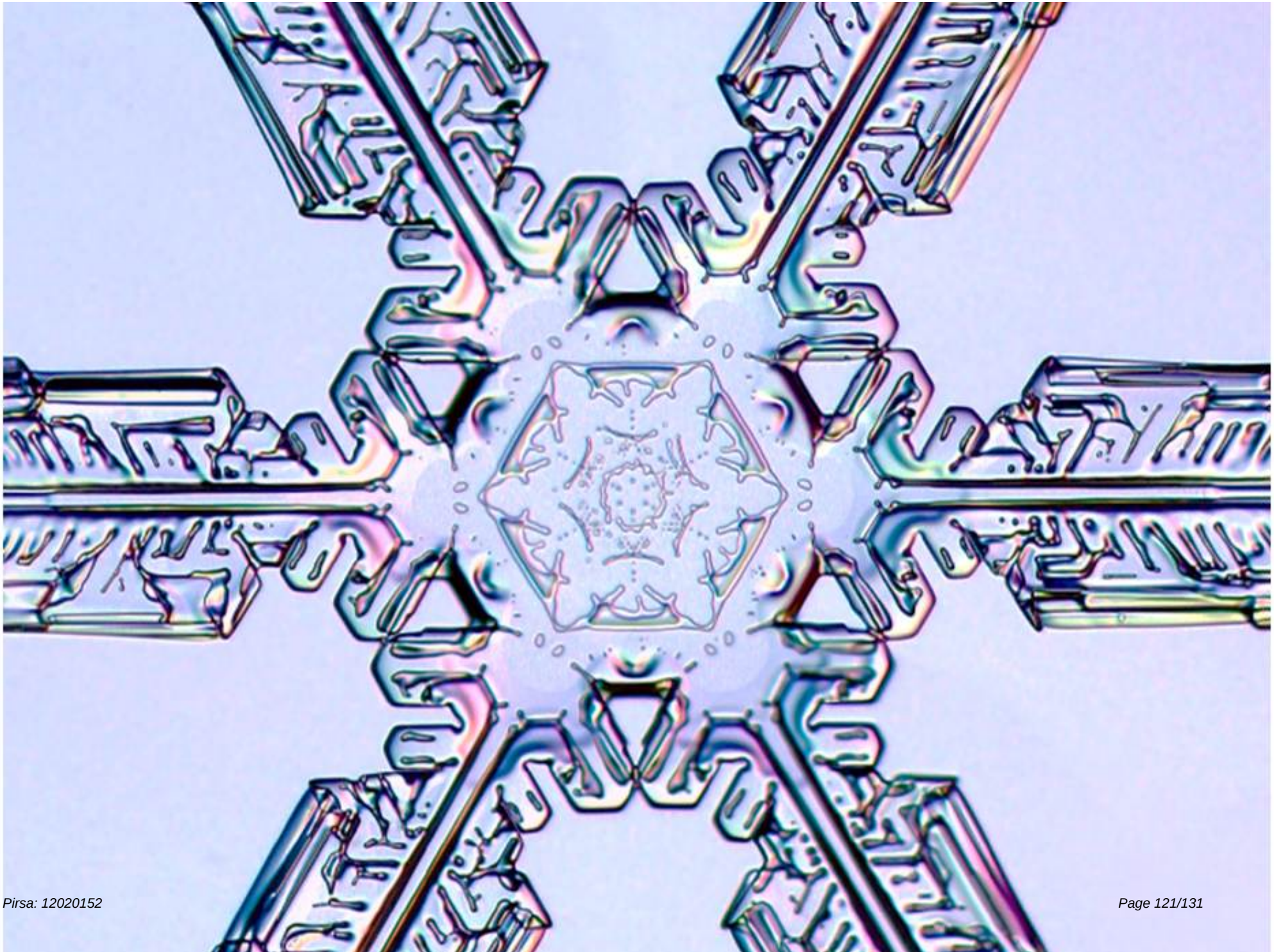
Electro-Chemically Modified Growth of Ice Needles

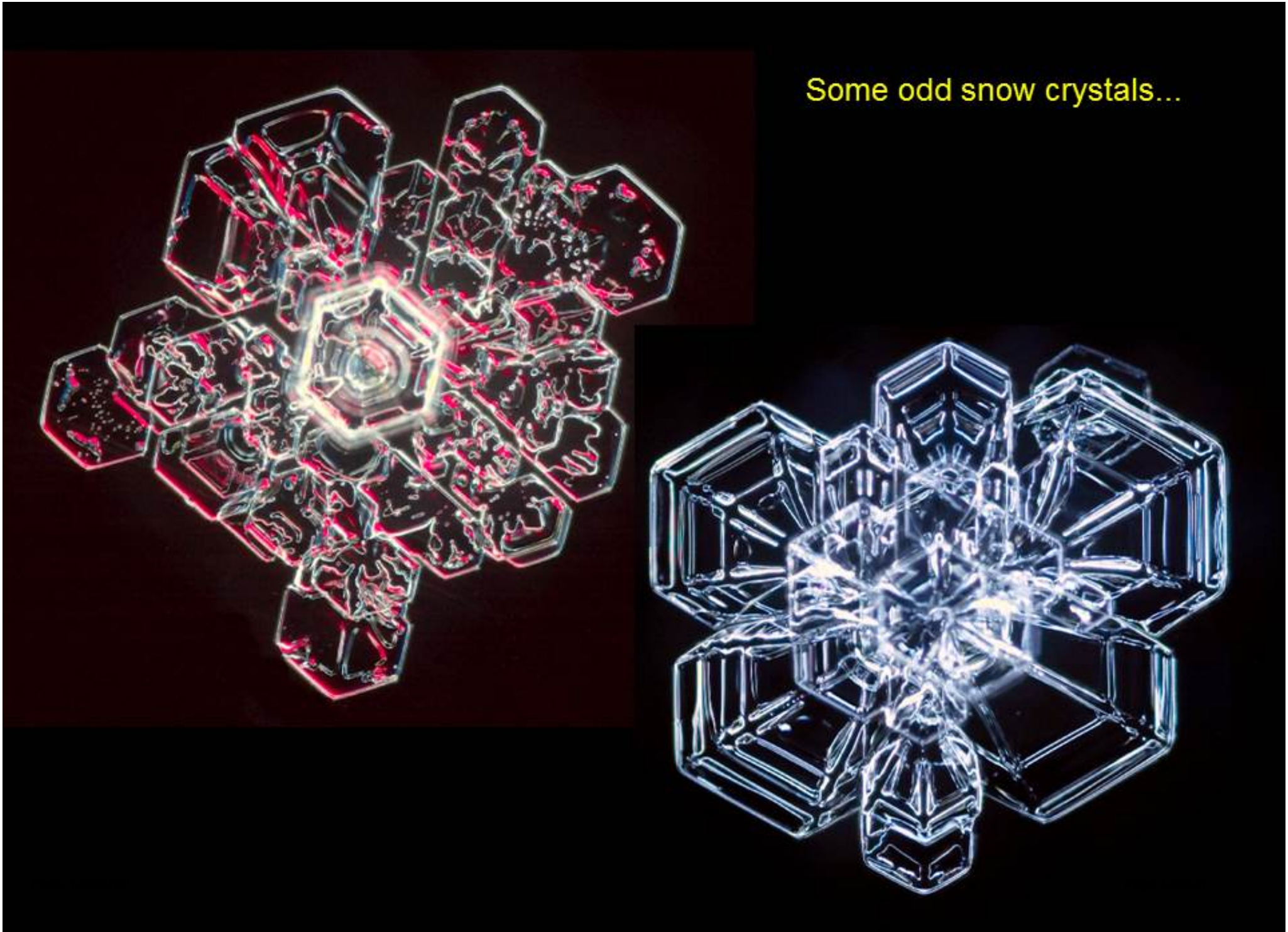
(better living through chemistry)

Recipe:
-Grow ice crystals on wire
-Apply 2000 volts to wire
-Add trace chemical additives
→ "Electric" Ice needles growth 10-100x faster

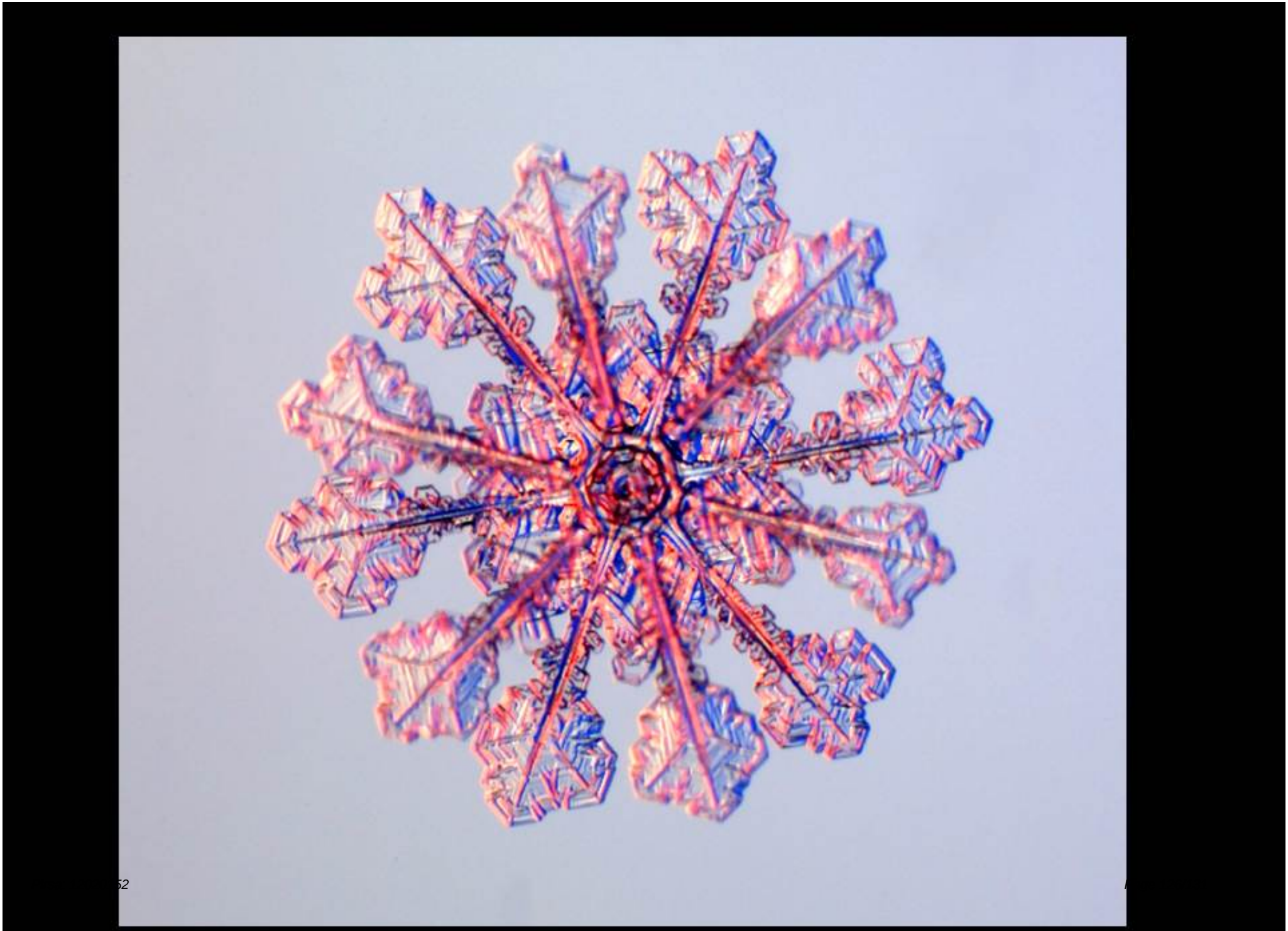
Remove high voltage
→ back to ordinary growth

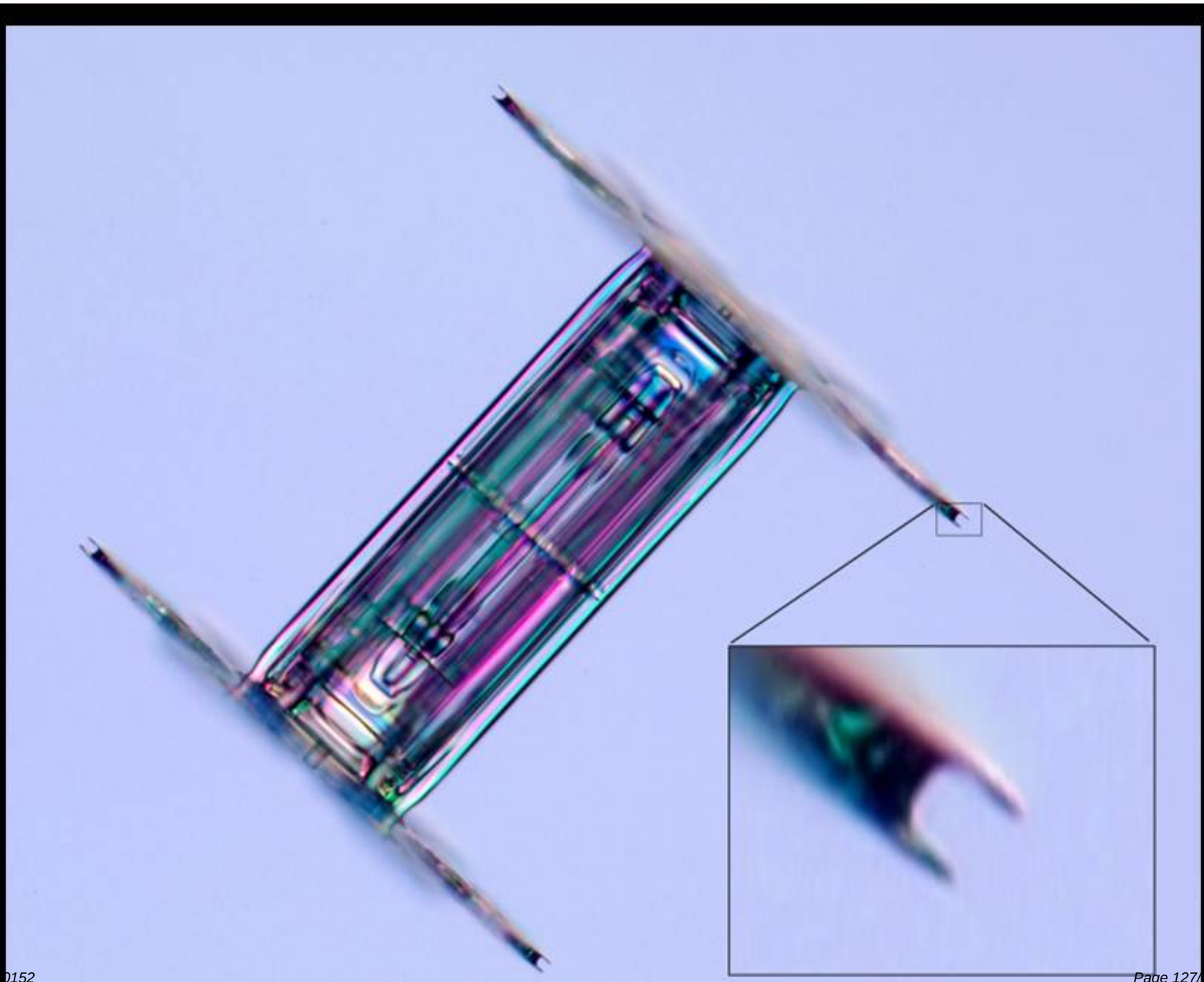
Snowflake on a stick...




Some odd snow crystals…


branches and sidebranches are parallel





The Molecular Physics of Snow Crystal Formation

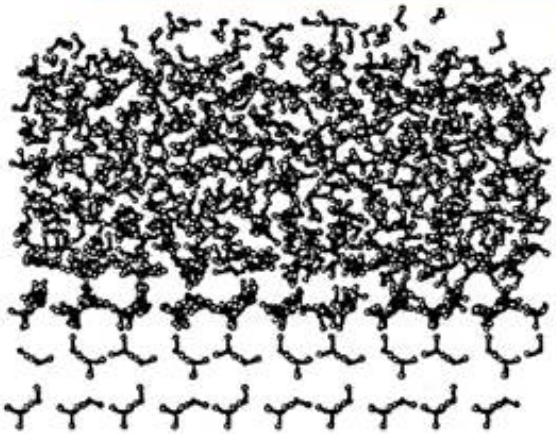
>> What does the ice surface look like at the molecular scale?

>> How to water molecules attach to the surface? How quickly?

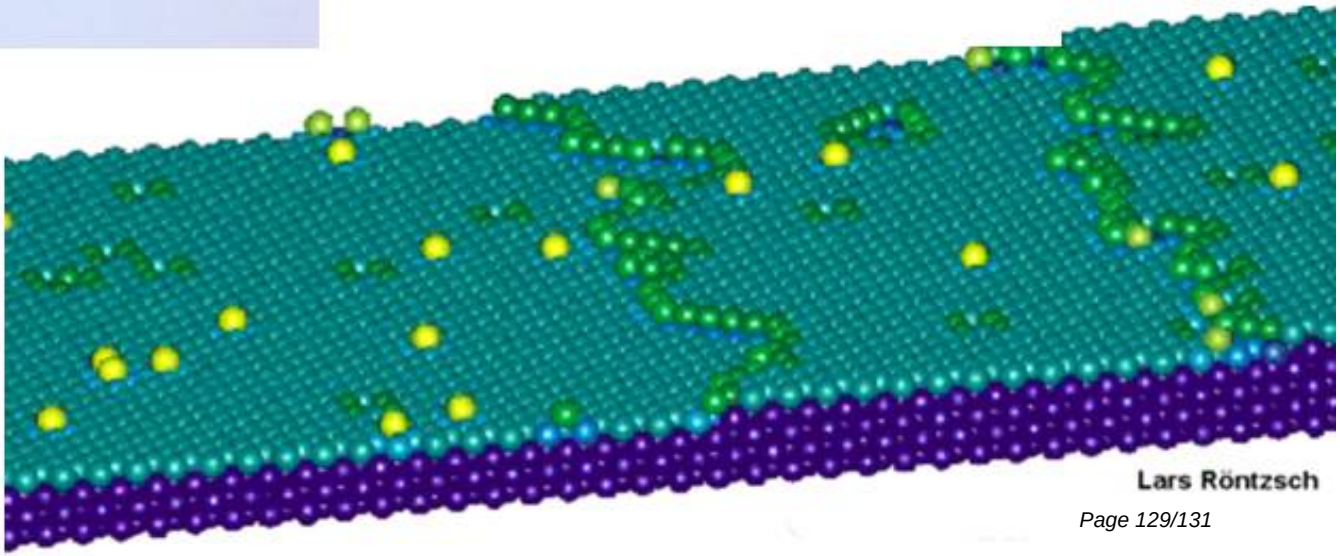
>> How does the molecular-scale physics determine snow crystal shapes?

>> Why does the growth depend on temperature and other parameters?

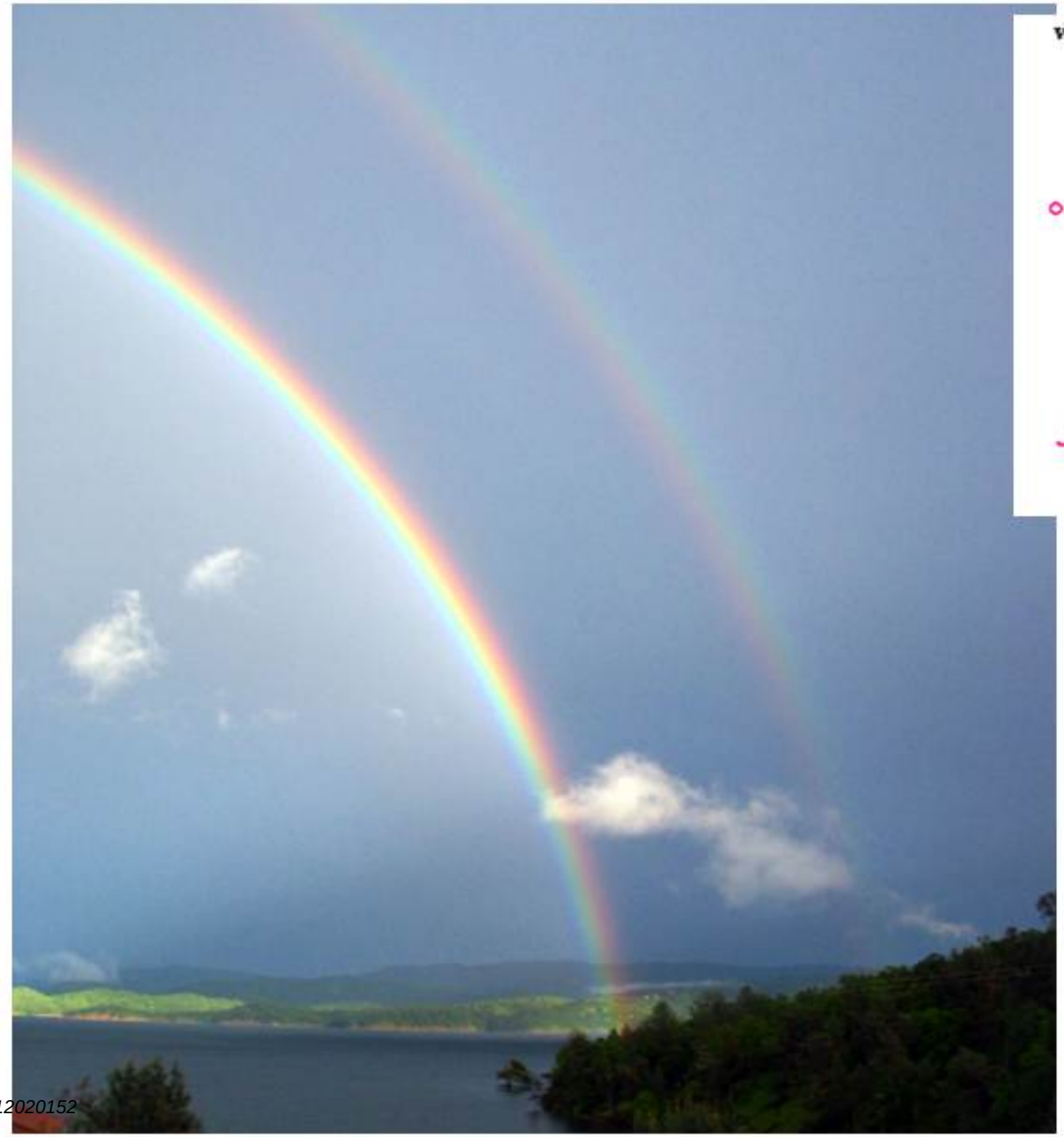
>> Applications?

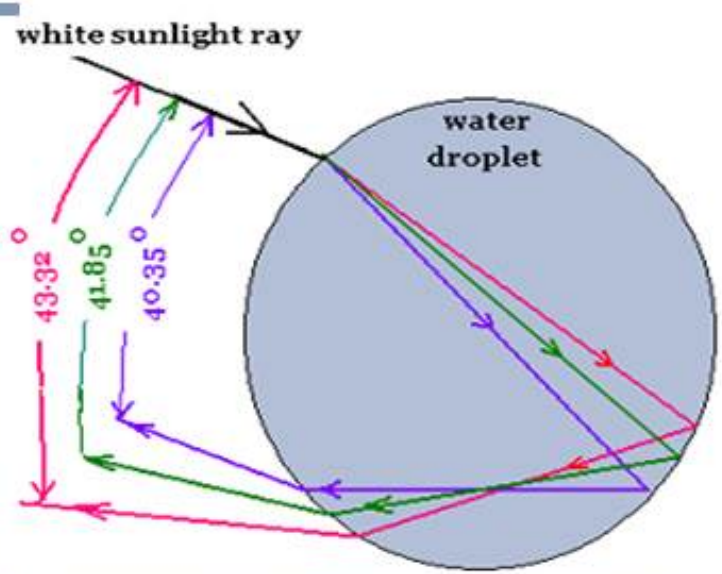


Surface melting in ice at -3C



Understanding Nature – How Things Work





Snow crystals are more complicated than rainbows …


The Art of the Snowflake
The Snowflake:
Winter's Secret Beauty
The Secret Life
of a Snowflake
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A Photographic Album
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