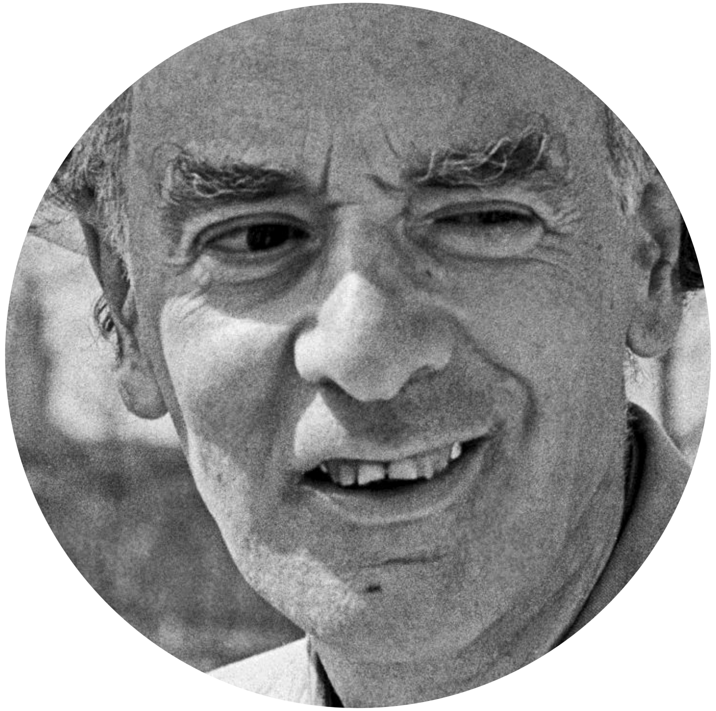


MORE IS DIFFERENTLY DIFFERENT

The multiphaseted nature of condensed matter

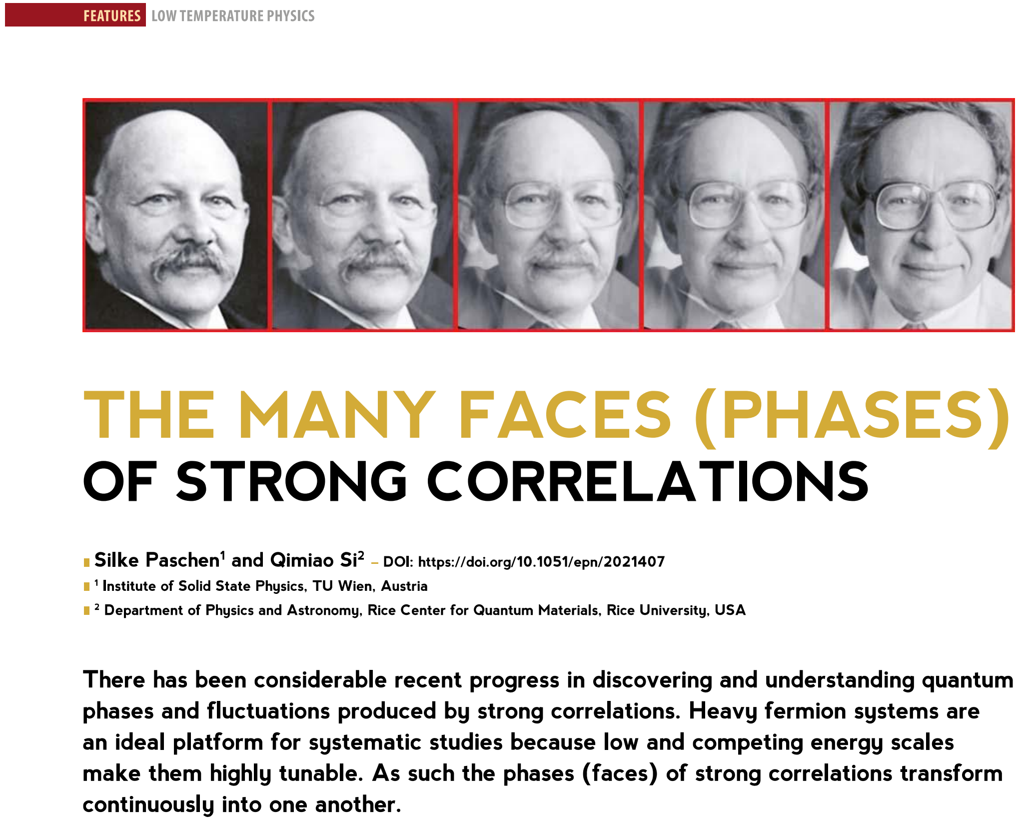
Jacopo Fiore
PhD seminars – S06E01
February 8th 2023

SAPIENZA
UNIVERSITÀ DI ROMA

Summary

- Introduction: how differently?
- Multiphaseted materials and superconductivity
- Probing phases and their signatures
- Examples: phase coexistence in $NbSe_2$ and LSCO
- Conclusion: same phase… different faces

(I did not come up with this title…)


FEATURES LOW TEMPERATURE PHYSICS

THE MANY FACES (PHASES) OF STRONG CORRELATIONS

Silke Paschen[1] and Qimiao Si[2] – DOI: https://doi.org/10.1051/epn/2021407

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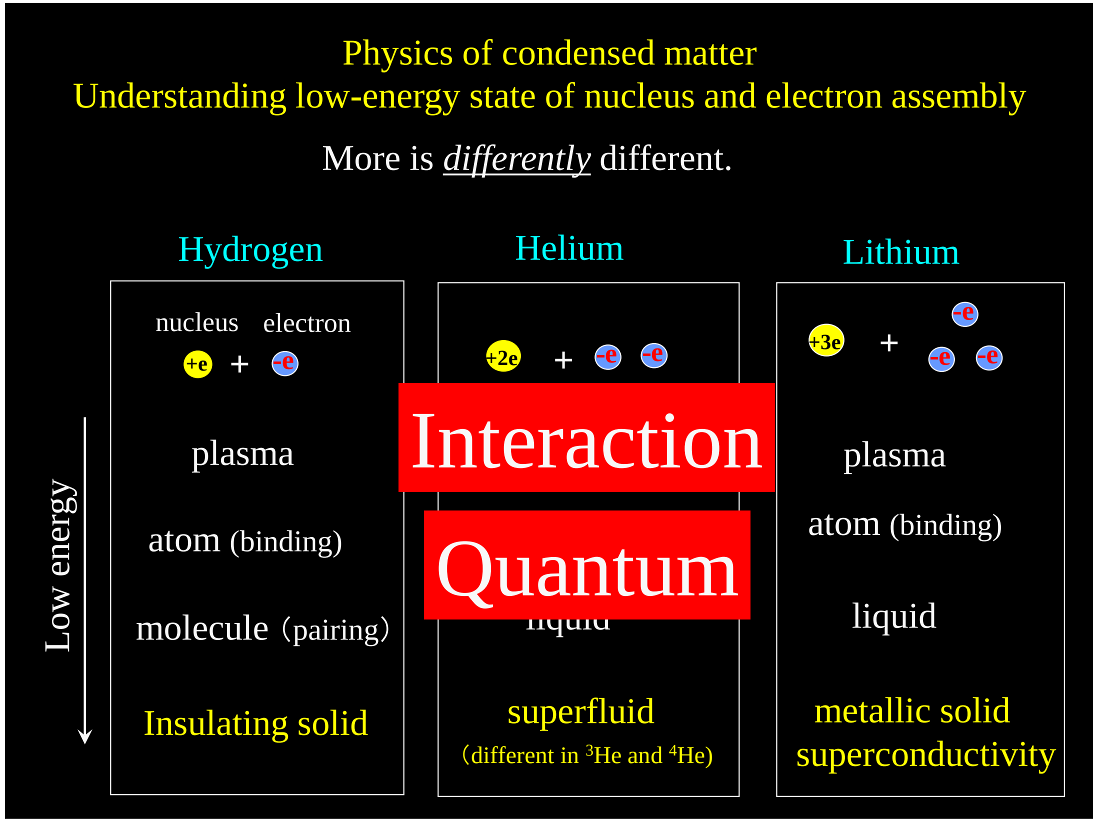
There has been considerable recent progress in discovering and understanding quantum phases and fluctuations produced by strong correlations. Heavy fermion systems are an ideal platform for systematic studies because low and competing energy scales make them highly tunable. As such the phases (faces) of strong correlations transform continuously into one another.

Paschen&Si, 2021



Kanoda, 2022

Explaining the –ly

The constructionist hypothesis breaks down when confronted with the twin dificulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is ***not*** *to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research […] inspiration and creativity to just as great a degree as in the previous one.*

4 August 1972, Volume 177, Number 4047 SCIENCE

More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson

The reductionist hypothesis may still be a topic for controversy among philosophers, but among the great majority of active scientists I think it is accepted without question. The workings of our minds and bodies, and of all the animate or inanimate matter of which we have any detailed knowledge, are assumed to be controlled by the same set of fundamental laws, which except under certain extreme conditions we feel we know pretty well.

It seems inevitable to go on uncritically to what appears at first sight to be an obvious corollary of reductionism: that if everything obeys the same fundamental laws, then the only scientists who are studying anything really fundamental are those who are working on those laws. In practice, that amounts to some astrophysicists, some elementary particle physicists, some logicians and other mathematicians, and few

planation of phenomena in terms of known fundamental laws. As always, distinctions of this kind are not unambiguous, but they are clear in most cases. Solid state physics, plasma physics, and perhaps also biology are extensive. High energy physics and a good part of nuclear physics are intensive. There is always much less intensive research going on than extensive. Once new fundamental laws are discovered, a large and ever increasing activity begins in order to apply the discoveries to hitherto unexplained phenomena. Thus, there are two dimensions to basic research. The frontier of science extends all along a long line from the newest and most modern intensive research, over the extensive research recently spawned by the intensive research of yesterday, to the broad and well developed web of extensive research activities based on intensive research of past decades.

The effectiveness of this message may be indicated by the fact that I heard it quoted recently by a leader in the field of materials science, who urged the

less relevance they seem to have to the very real problems of the rest of science, much less to those of society.

The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. That is, it seems to me that one may array the sciences roughly linearly in a hierarchy, according to the idea: The elementary entities of science X obey the laws of science Y.

X	Y
solid state or many-body physics	elementary particle physics
chemistry	many-body physics
molecular biology	chemistry
cell biology	molecular biology
⋮	⋮
psychology	physiology
social sciences	psychology

But this hierarchy does not imply that science X is "just applied Y." At each stage entirely new laws, concepts, and generalizations are necessary, requiring inspiration and creativity to just as great a degree as in the previous one. Psychology is not applied biology, nor is biology applied chemistry.

Anderson, 1972

Explaining the –ly… Fifty years later

Strongly correlated electron systems host a tremendous variety of fascinating __macroscopic__ phenomena […] the essential physics of many of these systems is still not understood, and we do not have a overall __perspective__ on strong electron correlations. Moreover, our __predictive__ power for such systems is lacking. […] Is a unified perspective even possible? Or is the "Anna Karenina Principle" in effect – all non-interacting systems are alike; each strongly correlated system is strongly correlated in its own way?

The Future of the Correlated Electron Problem

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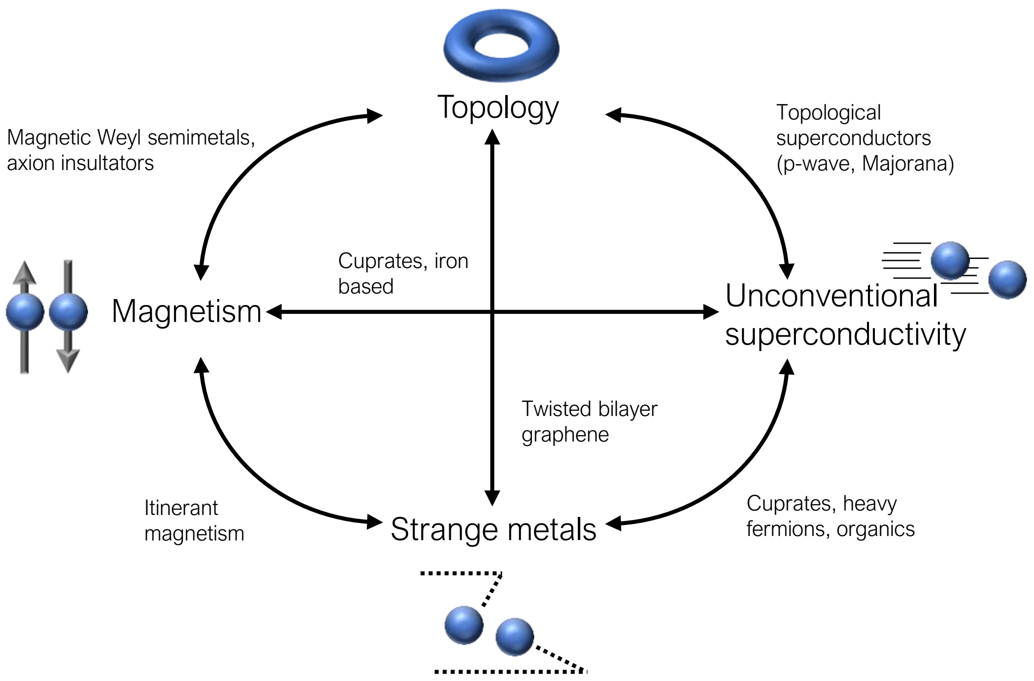
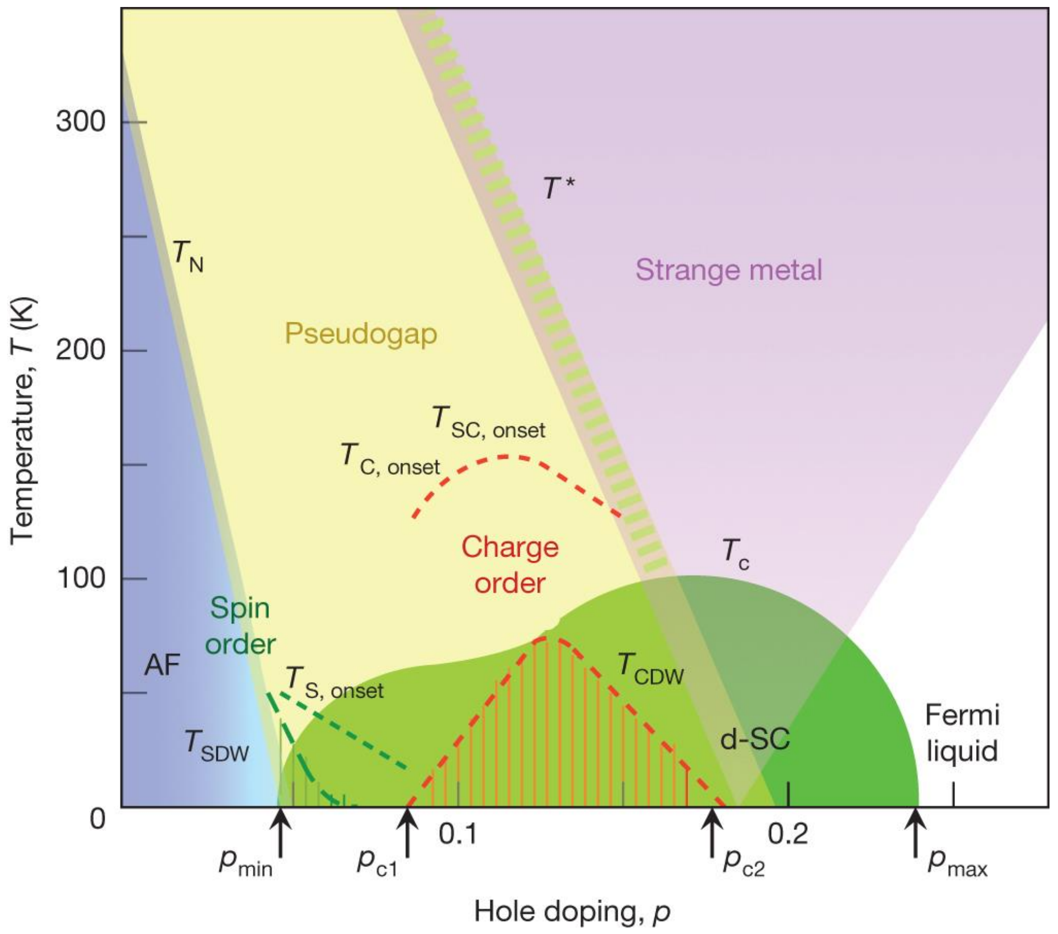
Alexandradinata&al., 2020

Multiphaseted materials

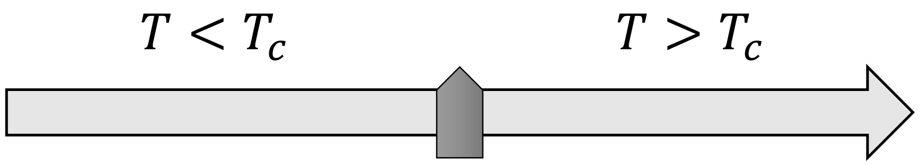




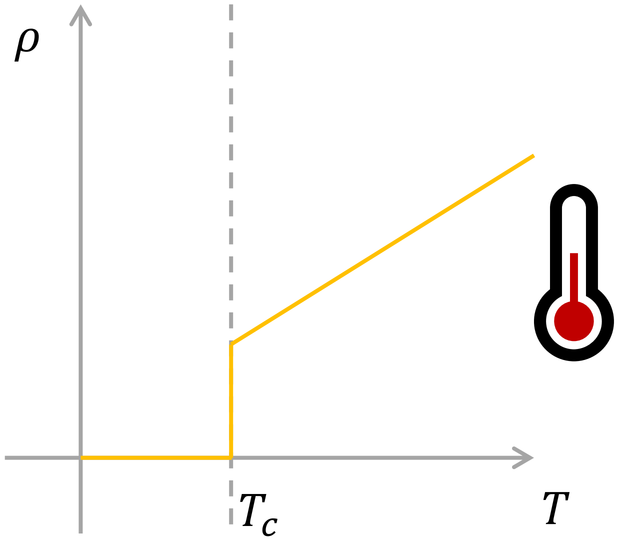
[Alexandradinata&al., 2020](#)

[Keimer&al., 2015](#)

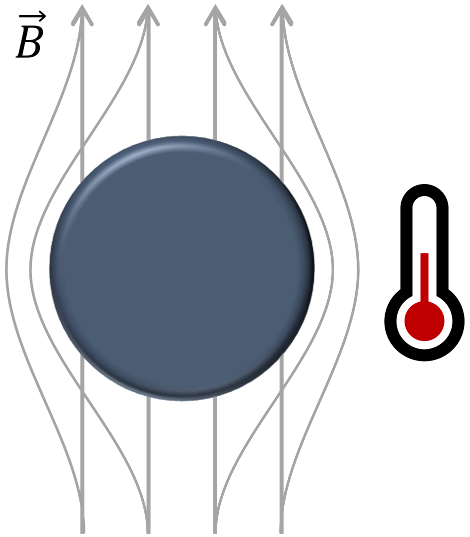
The superconducting state



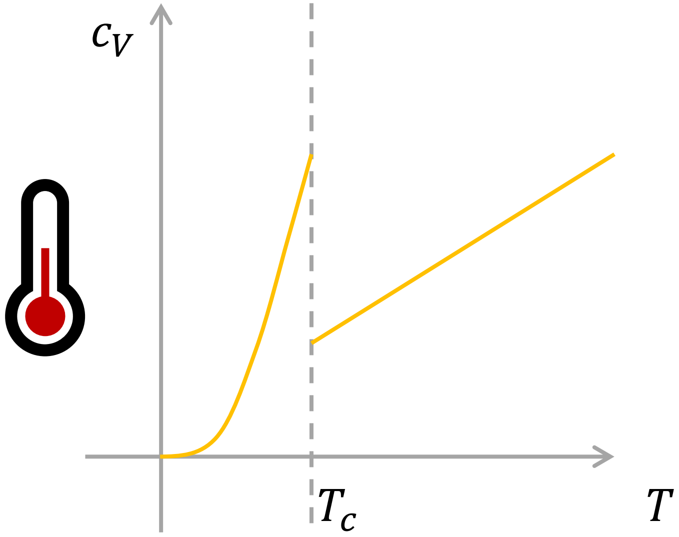
Breakdown of resistivity



Meissner effect



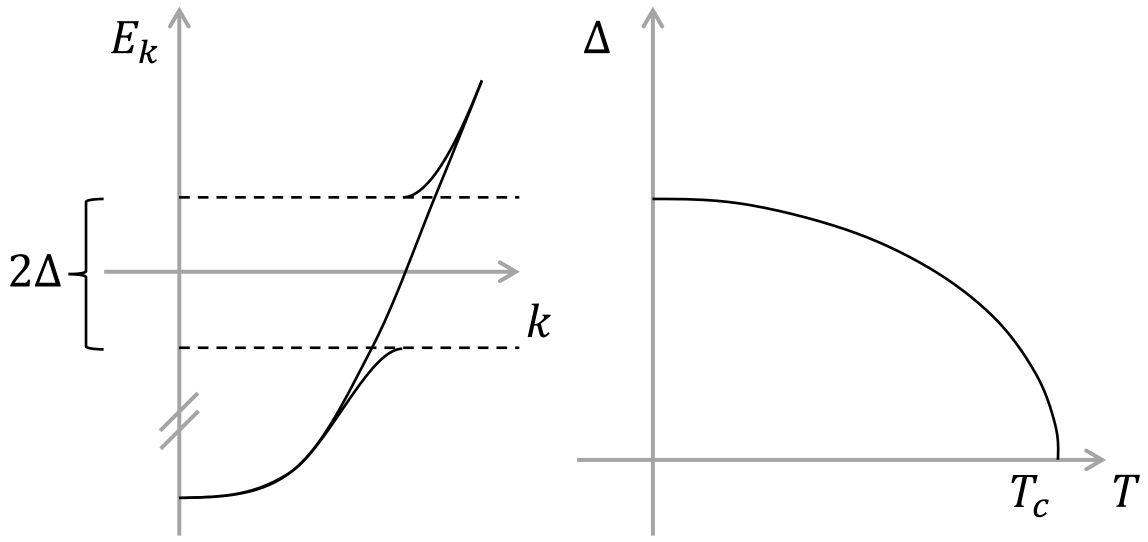
Discontinuity of specific heat



The superconducting state

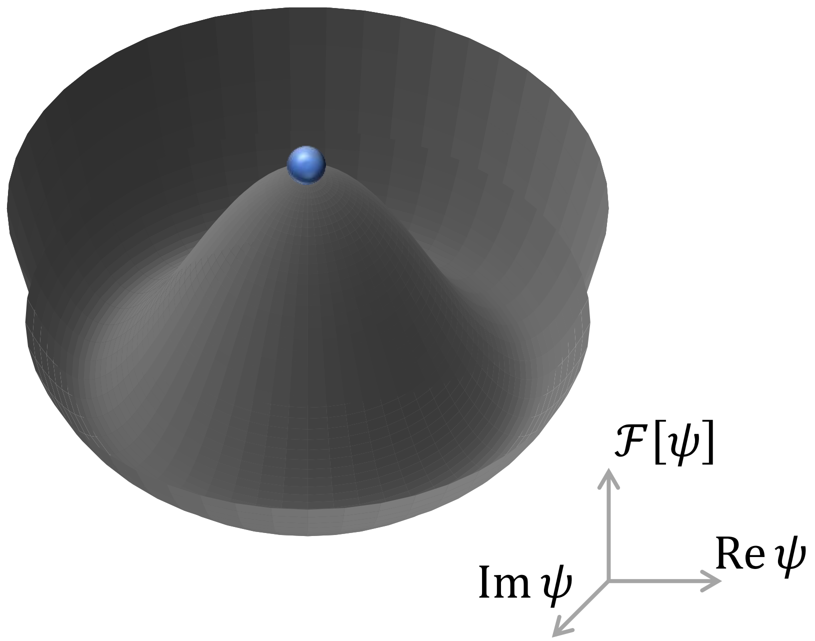
Bardeen, Cooper&Schrieffer, 1957

$$H = \sum_{\boldsymbol{k}\sigma} \xi_{\boldsymbol{k}} c^\dagger_{\boldsymbol{k}\sigma} c_{\boldsymbol{k}\sigma} - \sum_{\boldsymbol{k}\boldsymbol{k}'} V_{\boldsymbol{k}\boldsymbol{k}'} c^\dagger_{\boldsymbol{k}\uparrow} c^\dagger_{-\boldsymbol{k}\downarrow} c_{-\boldsymbol{k}'\downarrow} c_{\boldsymbol{k}'\uparrow}$$



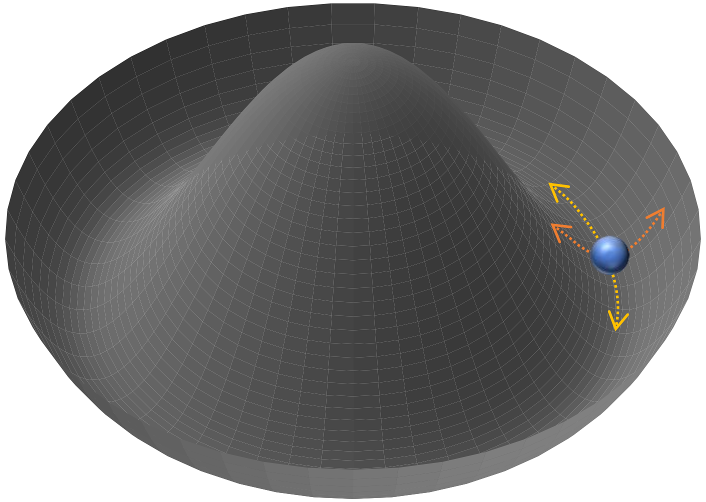
Ginzburg&Landau, 1950

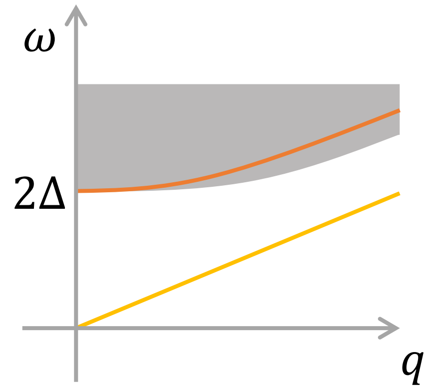
$$\mathcal{F}[\psi] = \mathcal{F}_n + \alpha(T - T_c)|\psi|^2 + \frac{\beta}{2}|\psi|^4$$



Collective modes of superconductors

- Fluctuations of the complex order parameter
  $$\psi \rightarrow |\psi_0 + \delta\psi| e^{i(\theta_0 + \delta\theta)}$$
- $\delta\psi$ amplitude or Higgs fluctuations have mass 2Δ
- $\delta\theta$ phase or Goldstone fluctuations are massless
- Do not miss the quasiparticle continuum!





Probing collective modes…

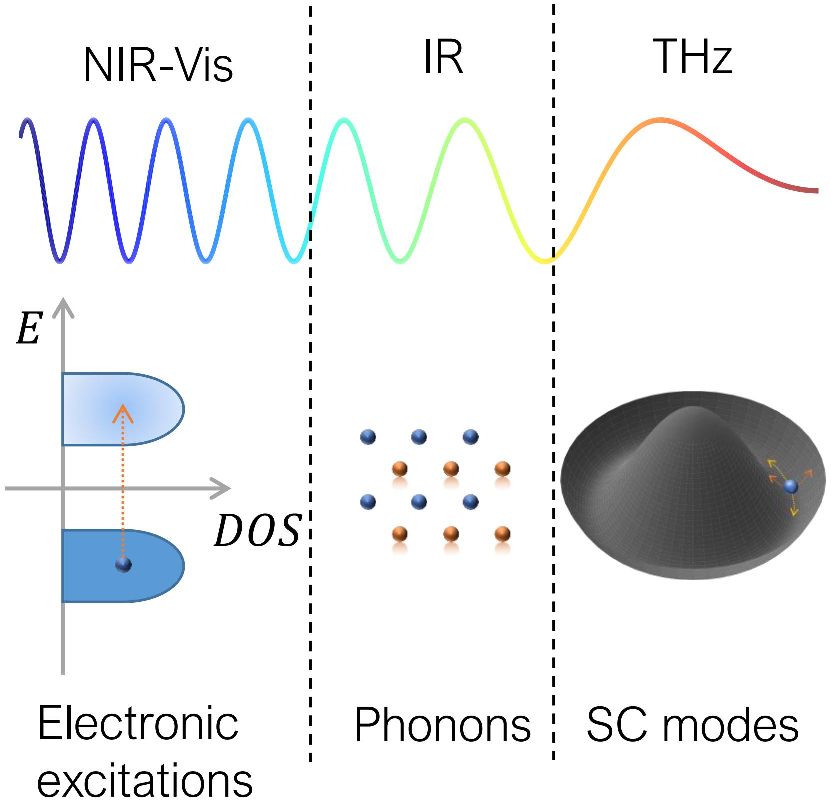
Storie Scientifiche
3 g ·

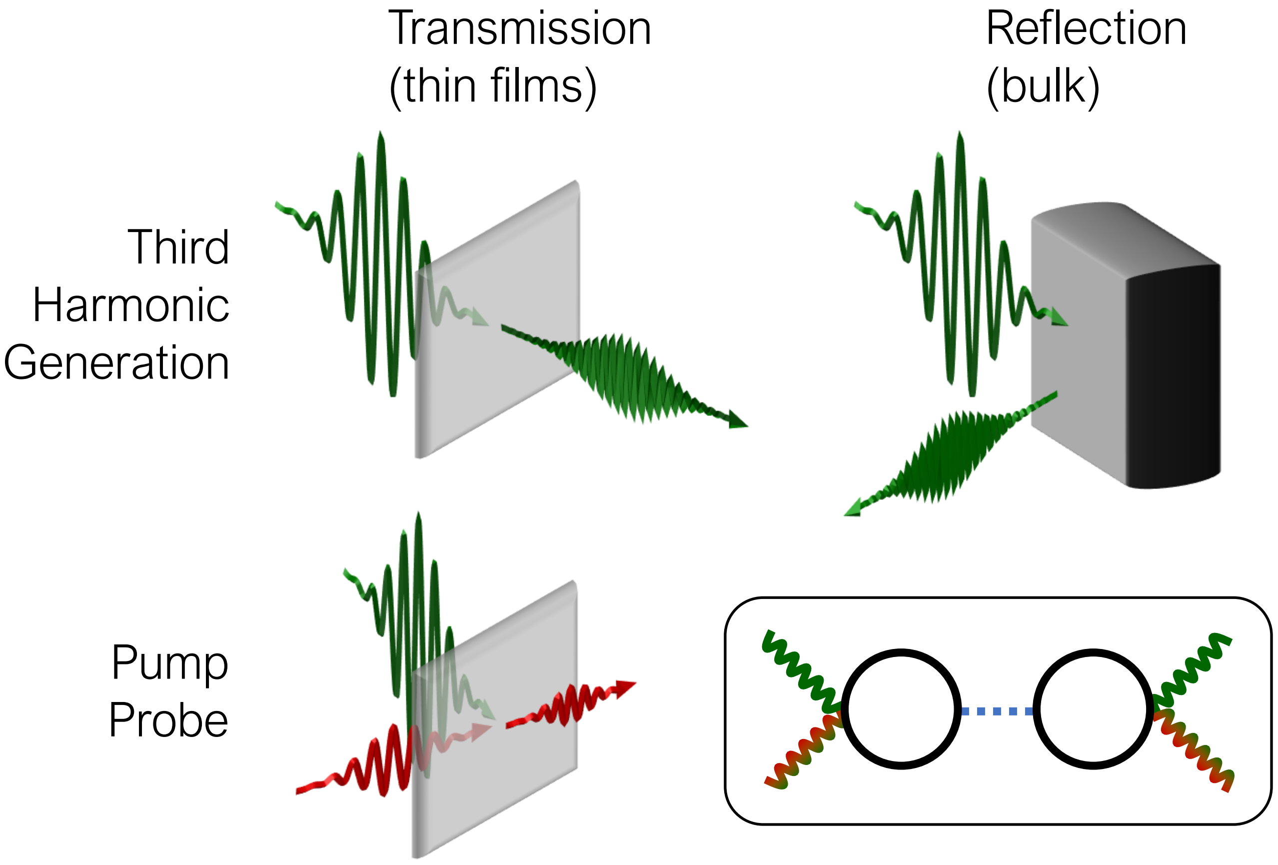
La fisica spiegata con le mani.

"Ve spiego qual è la rivoluzione più importante de la meccanica statistica de non equilibrio: non serve da no schiaffo in faccia ad un energumeno per sape che te crocchia de botte. Basta guardarlo prima in faccia. Ecco, non serve perturbà il sistema pe sape come risponde, basta guarda le fluttuazioni all'equilibrio. Tutto ciò però se rimanemo nel regime lineare, cioè se lo schiaffo che je date non è forte. Altrimenti non potete sape quello che succede, magari lo ammazzate"

233 Commenti: 27 Condivisioni: 22

Probing collective modes…

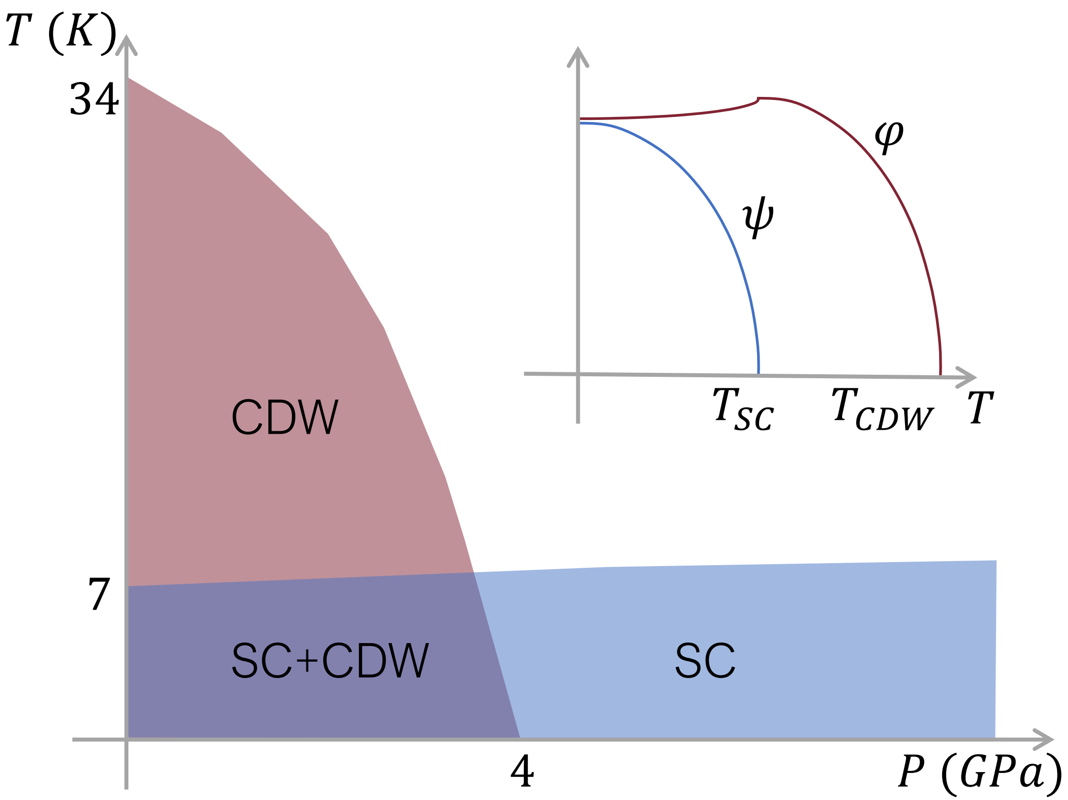




Nicoletti&Cavalleri, 2016

Udina&al., 2019/ Udina&al., 2022

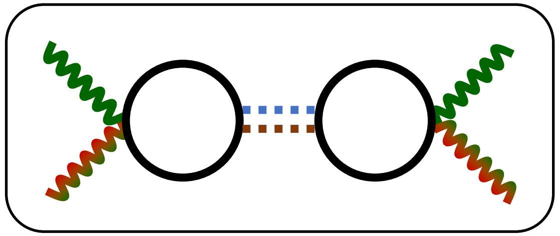
An example: $NbSe_2$



$$\mathcal{F}[\psi,\varphi] = \overbrace{-\alpha|\psi|^2 + \frac{\beta}{2}|\psi|^4}^{SC} \overbrace{-a|\varphi|^2 + \frac{b}{2}|\varphi|^4}^{CDW}$$

$$\underbrace{+\lambda|\psi|^2\ |\varphi|^2}_{coupling} + \underbrace{\varepsilon A^2|\varphi|}_{driving}$$

$$\begin{cases} (\omega^2 - \omega_\psi^2)|\psi| + \lambda|\varphi| = 0 \\ (\omega^2 - \omega_\varphi^2)|\varphi| + \lambda|\psi| = \varepsilon A^2 \end{cases}$$



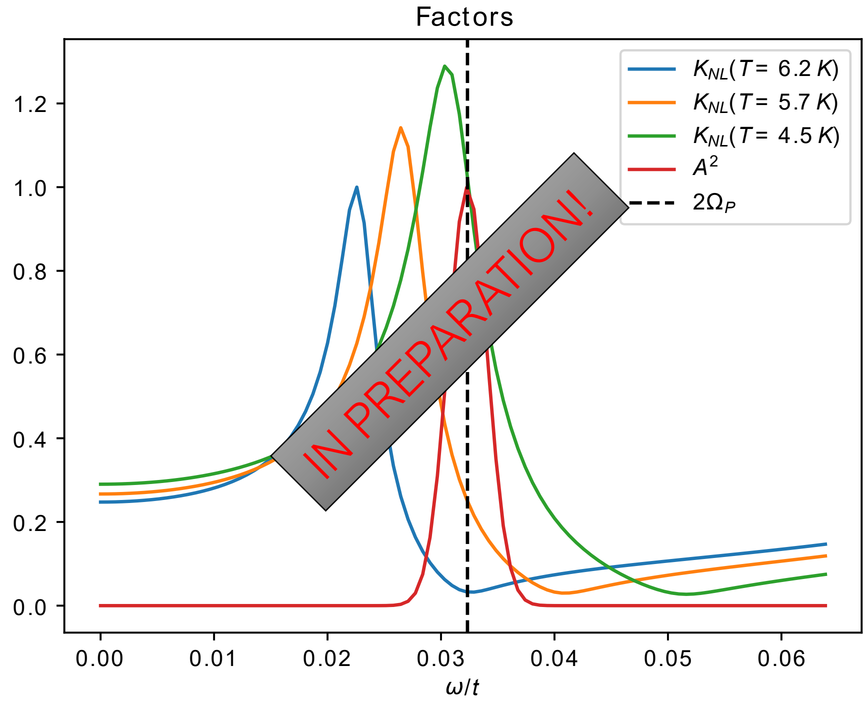
Grasset&al., 2018/ Cea&Benfatto, 2014

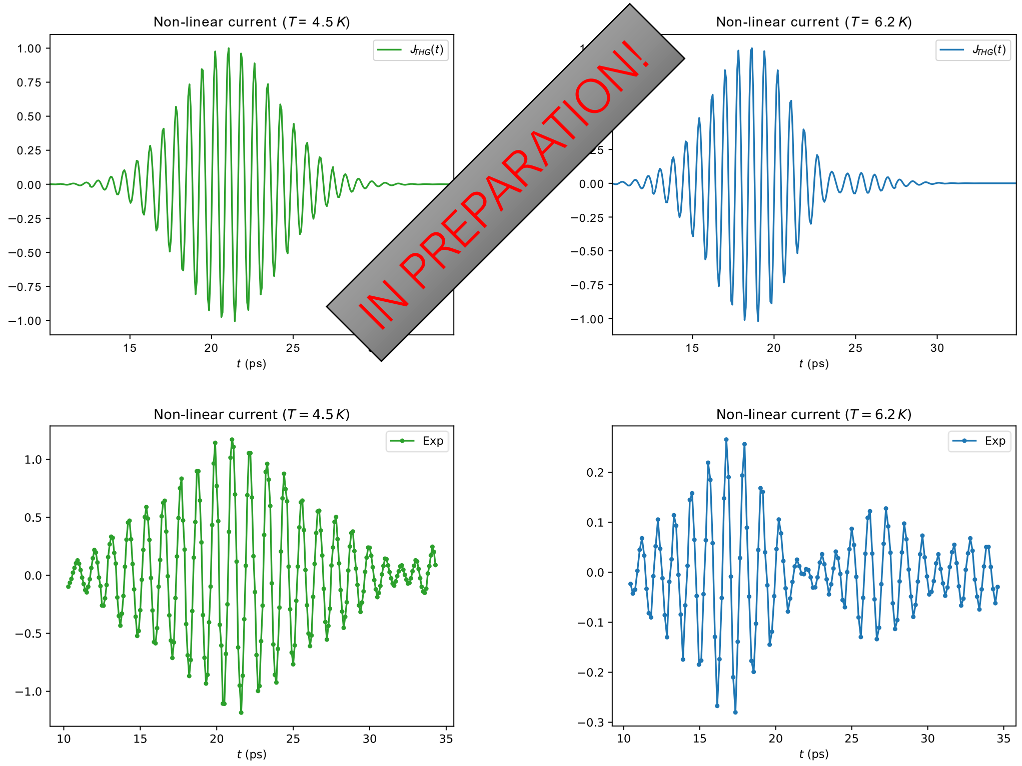
An example: $NbSe_2$

$$\delta A_{pp} \propto \frac{\partial \mathcal{F}}{\partial \varepsilon} = \underbrace{\frac{(\omega^2 - \omega_\psi^2)}{(\omega^2 - \omega_1^2)(\omega^2 - \omega_2^2)}}_{K_{NL}} A^2$$

$$K_{NL} \propto \frac{1}{\omega^2 - \omega_1^2}$$

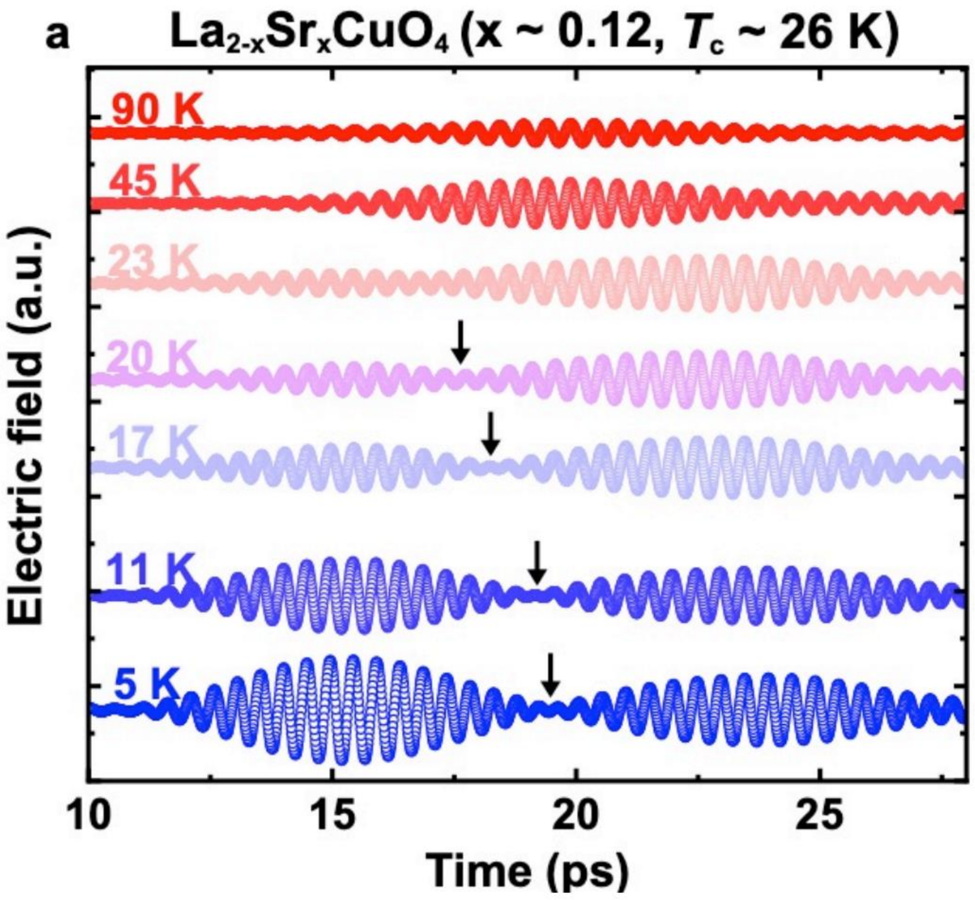
$$K_{NL} \propto \omega^2 - \omega_\psi^2$$



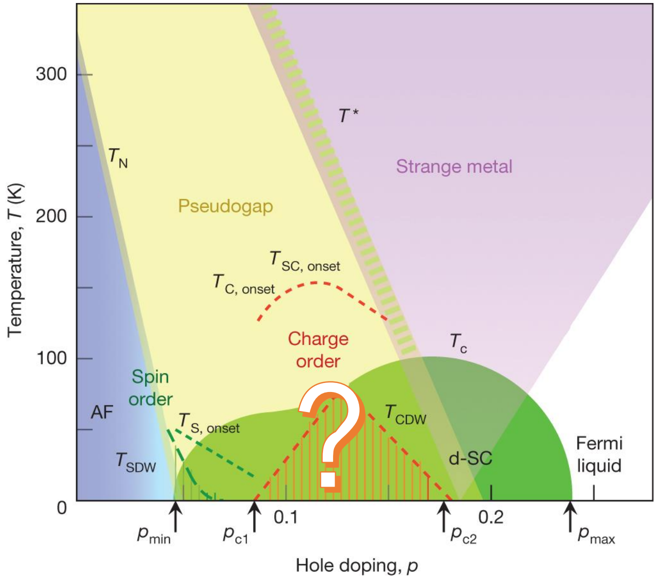


Feng&al.,2022

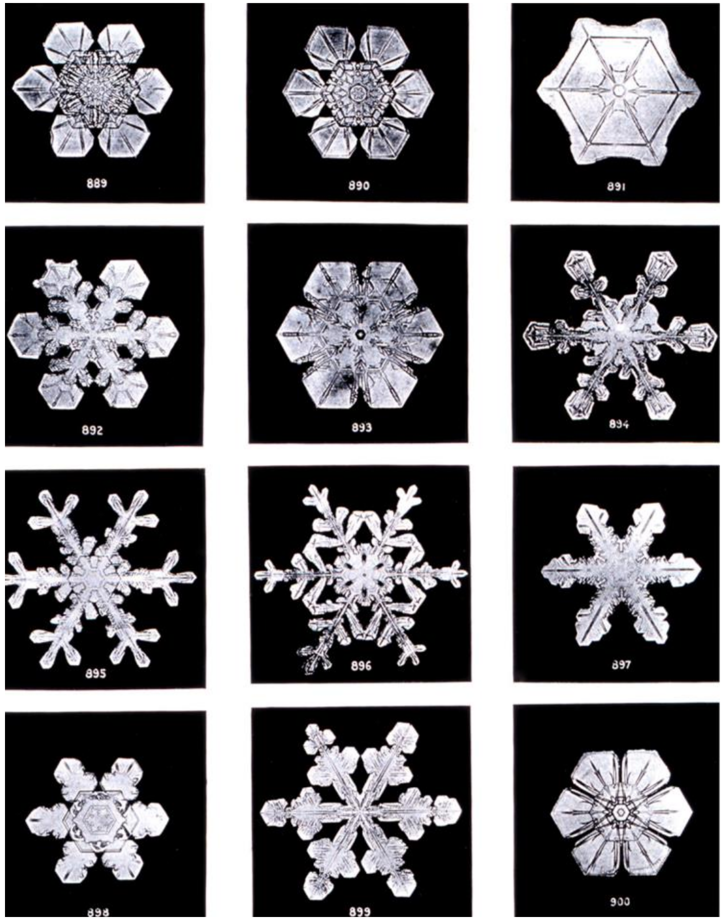
Perspective: LSCO



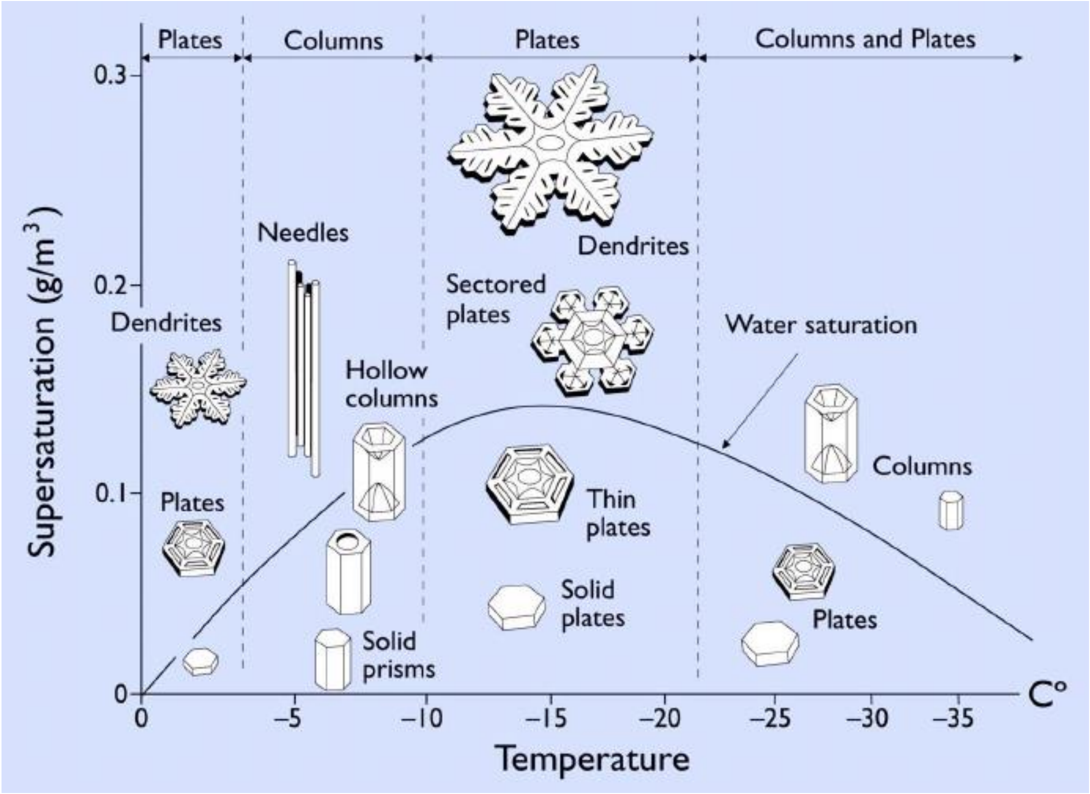
Feng&al.,2022



Conclusion: same phase… different faces



Bentley, 1902



Libbrecht, 2005