Room-temperature superconductivity - or not?

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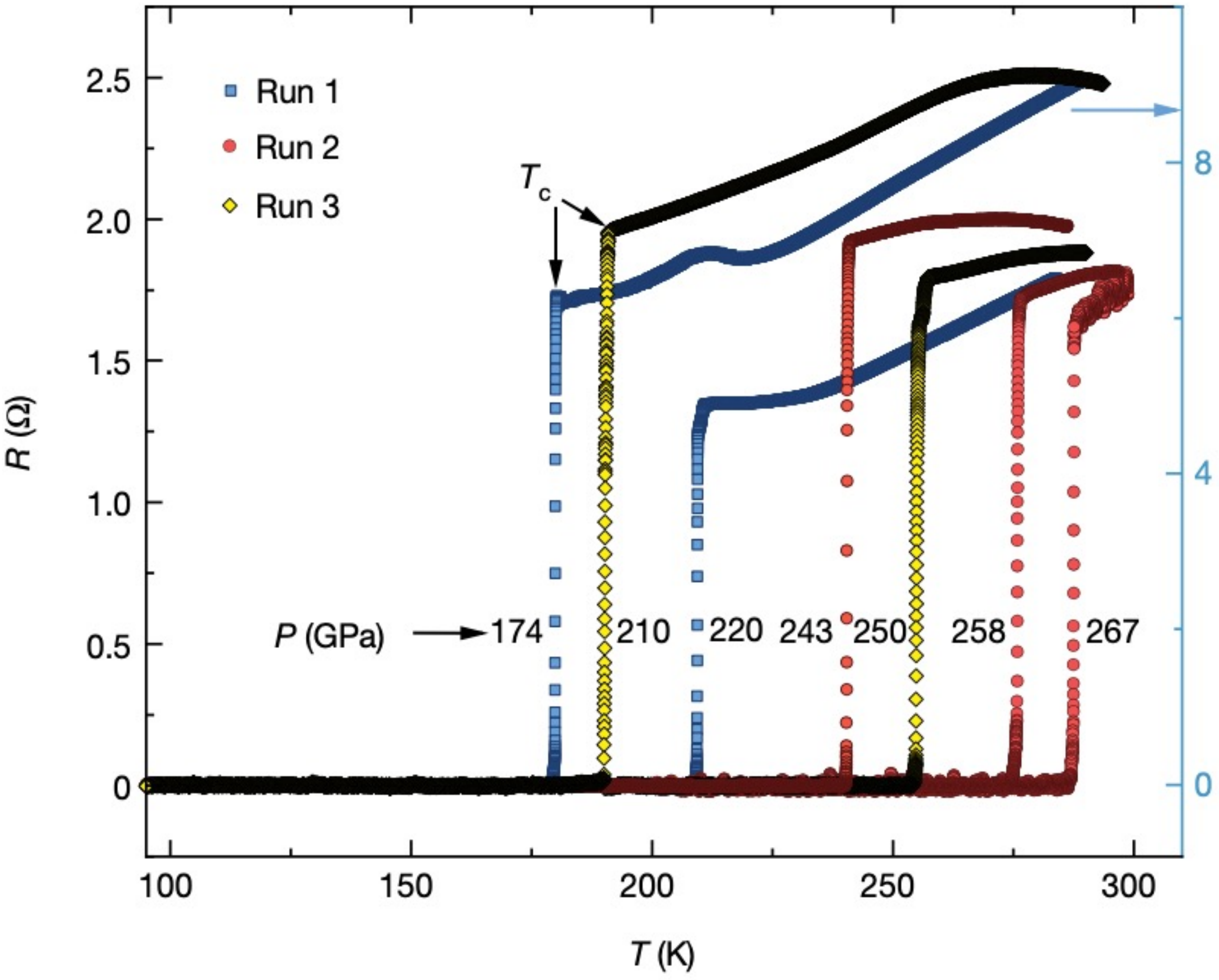
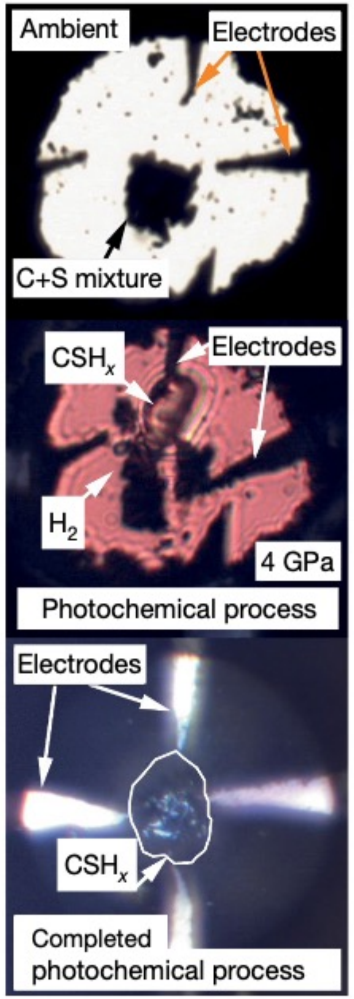
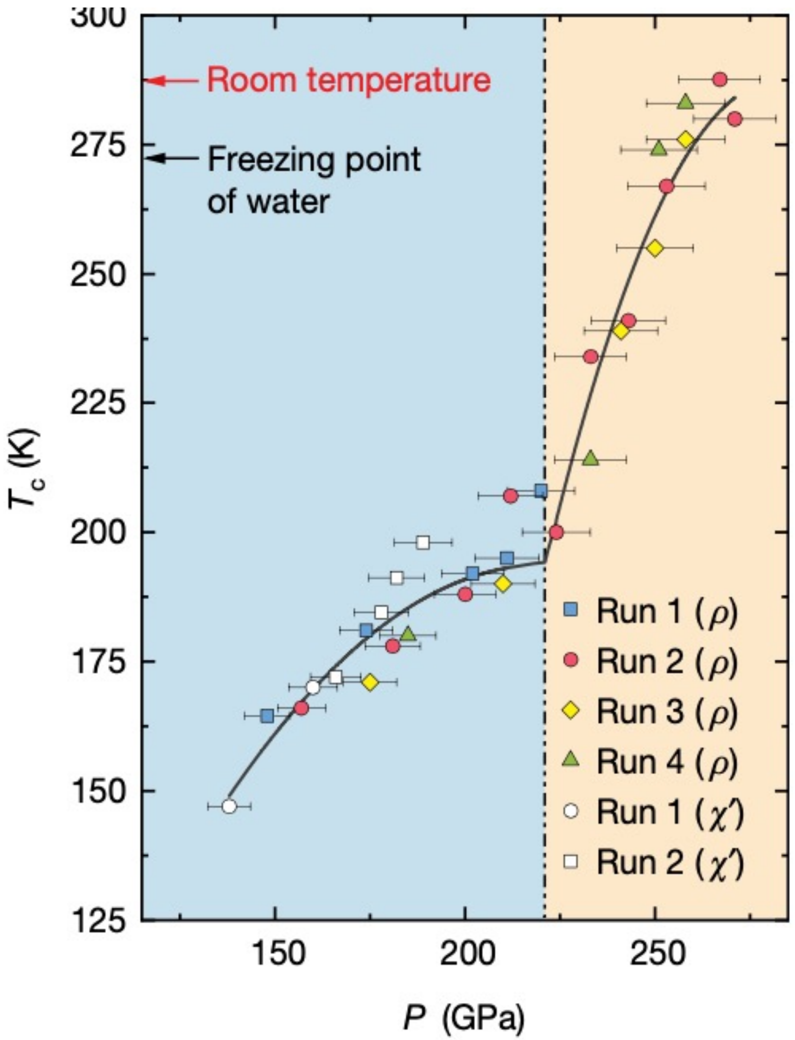
Dirk van der Marel, Jorge E Hirsch
Comment on Nature 58, 373 (2020) by E. Snider et al
arXiv:2201.07686 *(19.1.2022 - 10.4.2022)*

Room-temperature superconductivity in a carbonaceous sulfur hydride, E. Snider, N. Dasenbrock-Gammon, R. McBride, M. Debessai, H. Vindana, K. Vencatasamy, K. V. Lawler, A. Salamat & R. P. Dias, *Nature* **586**, 373 (14.10.2020).

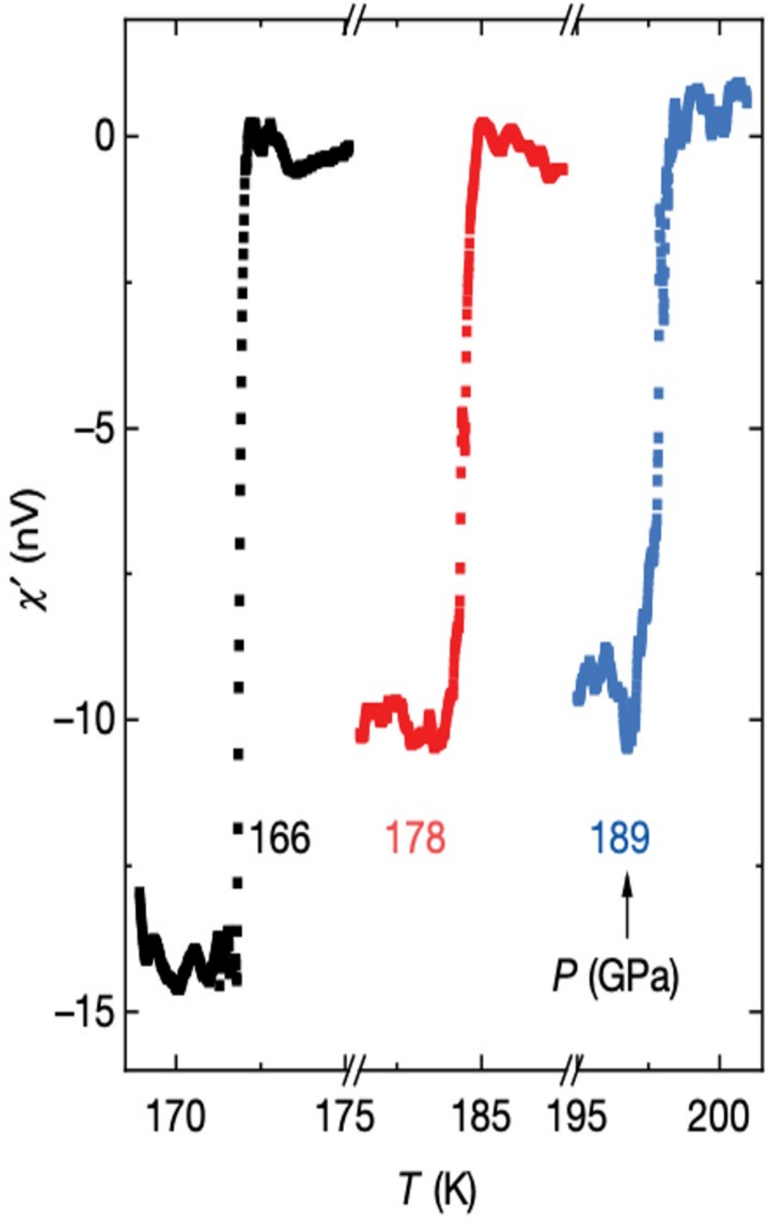


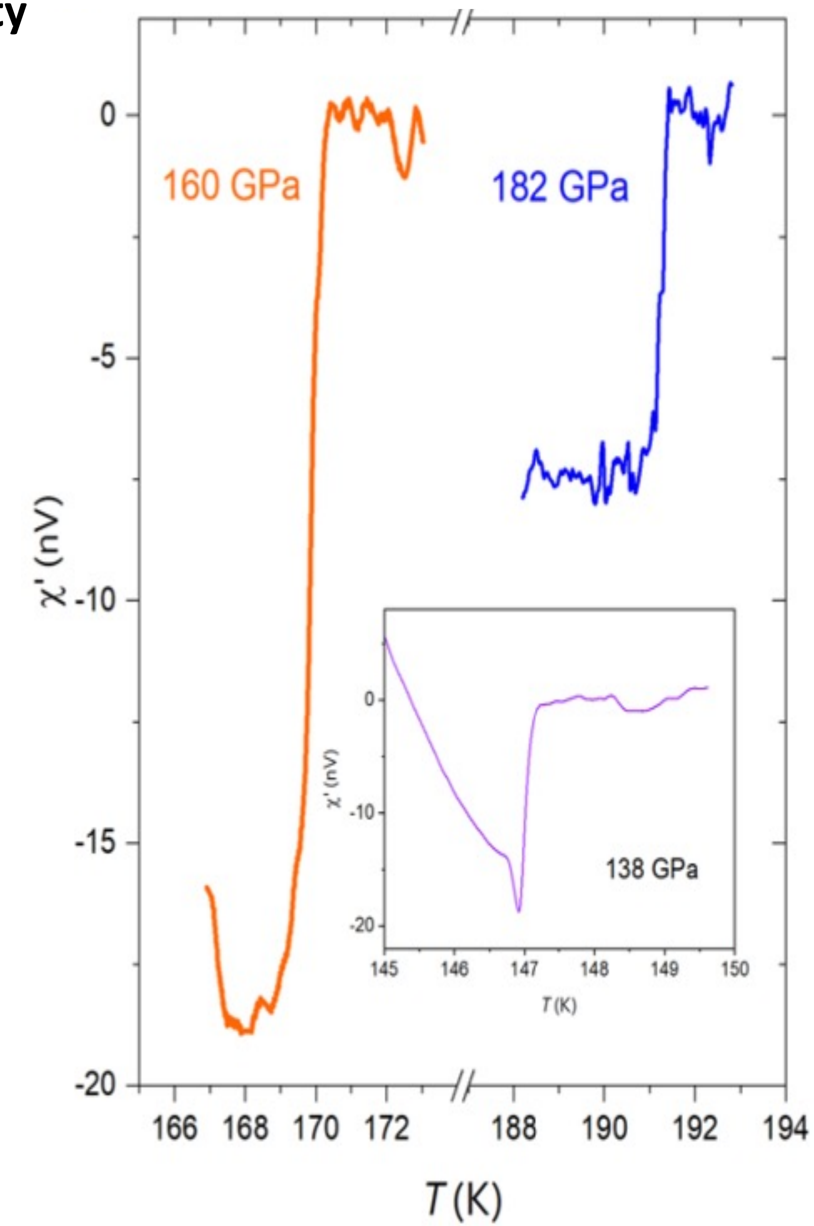




Room-temperature superconductivity in a carbonaceous sulfur hydride, E. Snider et al , *Nature* **586**, 373 (14.10.2020)

AC susceptibility





"The background signal, determined from a non-superconducting C–S–H sample at 108 GPa, has been subtracted from the data."

Nomenclature

Background corrected data = "Superconducting Signal" = $\chi_{sc}(T)$

Raw data = "Measured Voltage" = $\chi_{mv}(T)$

Background data = $\chi_{bg}(T)$

E. Snider et al , *Nature* **586**, 373 (2020):

"The background signal, determined from a non-superconducting C–S–H sample at 108 GPa, has been subtracted from the data."

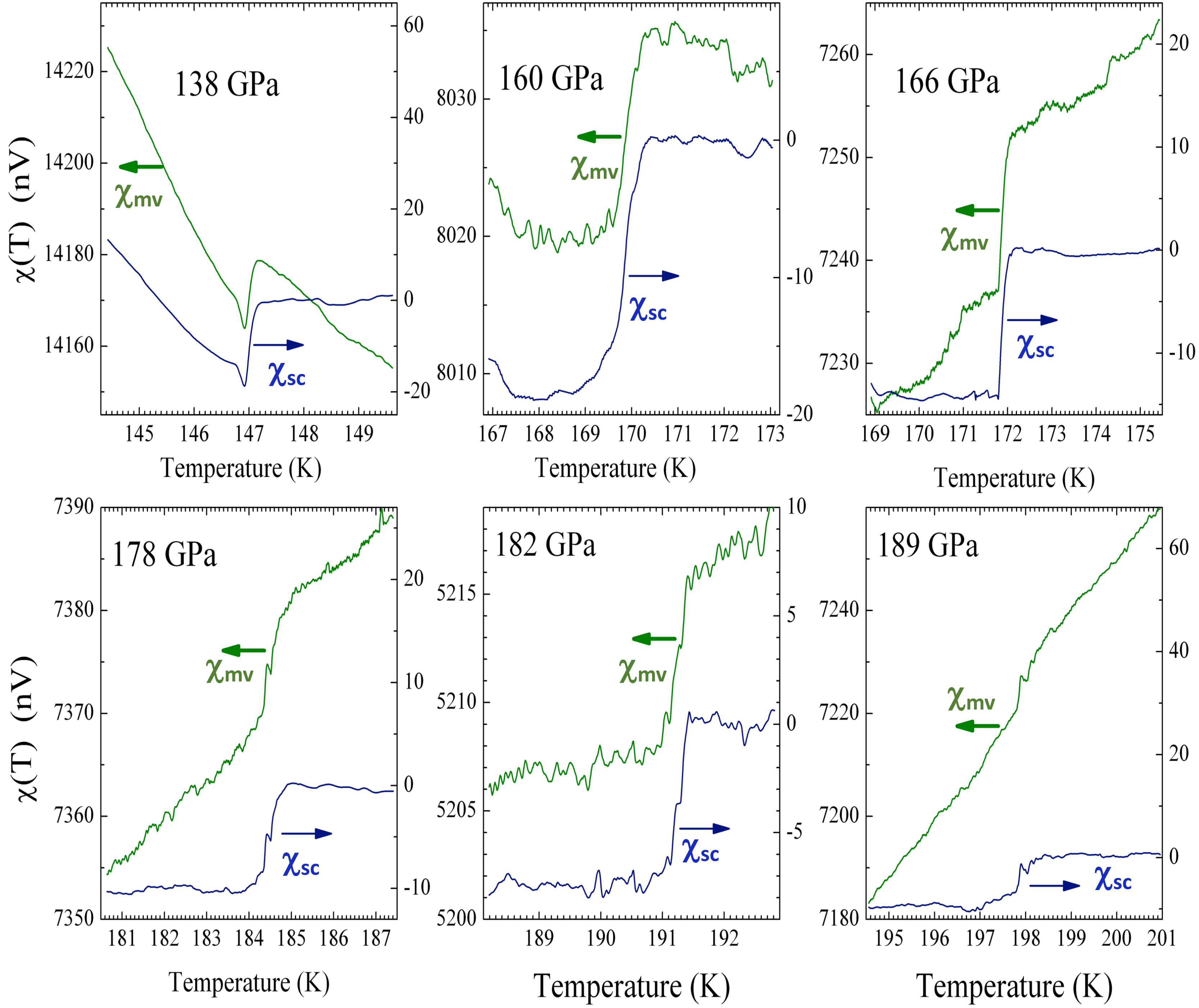
$$\chi_{sc}(T) = \chi_{mv}(T) - \chi_{bg}(T)$$

Provided in tables : $\chi_{sc}(T)$, $\chi_{mv}(T)$

Not provided : $\chi_{bg}(T)$ { but readily obtained from $\chi_{bg}(T) = \chi_{mv}(T) - \chi_{sc}(T)$ }

JE Hirsch, *Preprints* , 202112.0115 (2021)

The noise conundrum



The data indicate

noise$_{sc}$ < noise$_{mv}$

$\chi_{sc} = \chi_{mv} - \chi_{bg}$

χ_{mv} and χ_{bg} **are supposedly independent**

=> **noise$_{sc}$ ≥ noise$_{mv}$, noise$_{bg}$**

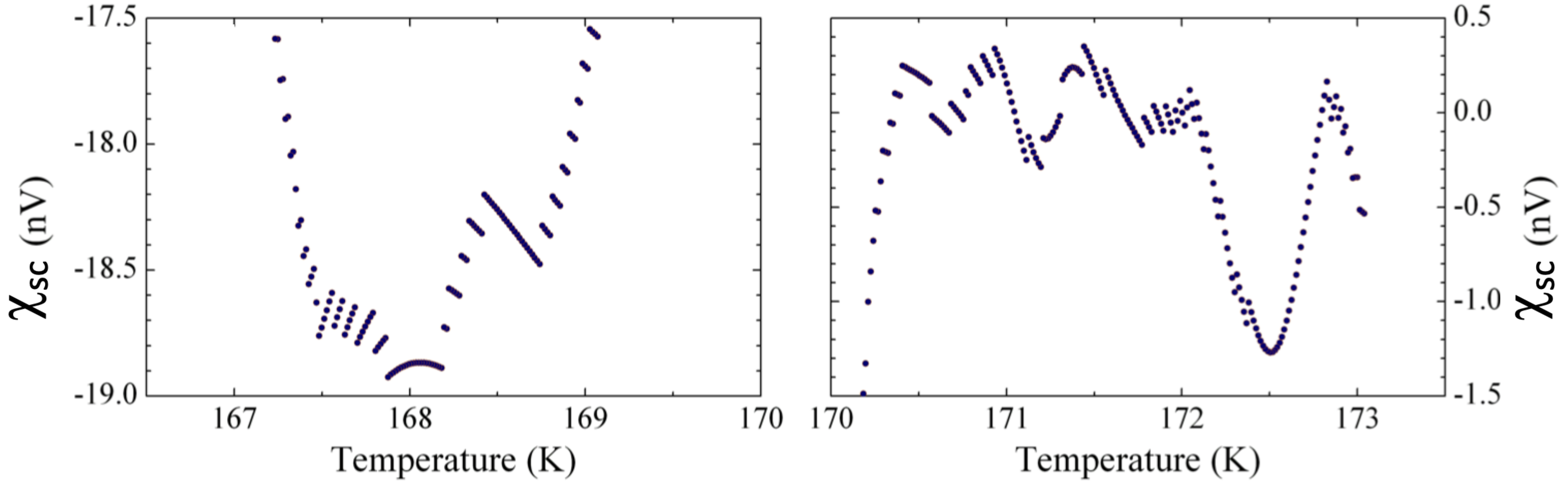
Possible solution: Perhaps χ_{sc} has been smoothed ?

Objection: Smoothing is incompatible with sharp features in some of the χ_{sc} data, *e.g.* the jump at 171.8 K for 166 GPa

“Superconducting Signal” at 160 GPa

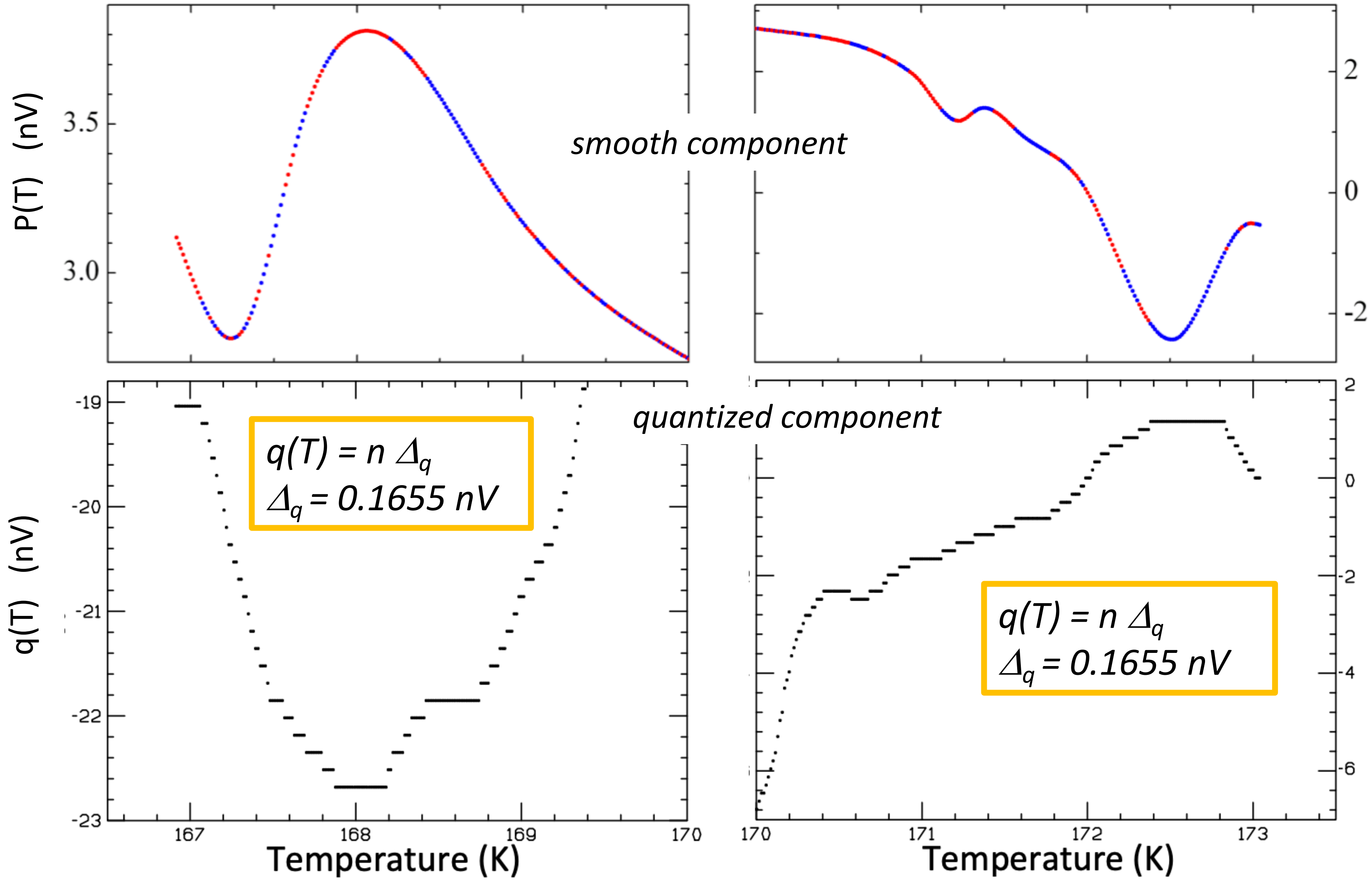
Table 5 from R. P. Dias and A. Salamat, *arXiv*:**2111**.15017v2 (2021)

Smoothing is also incompatible with this....



“Superconducting Signal” at 160 GPa

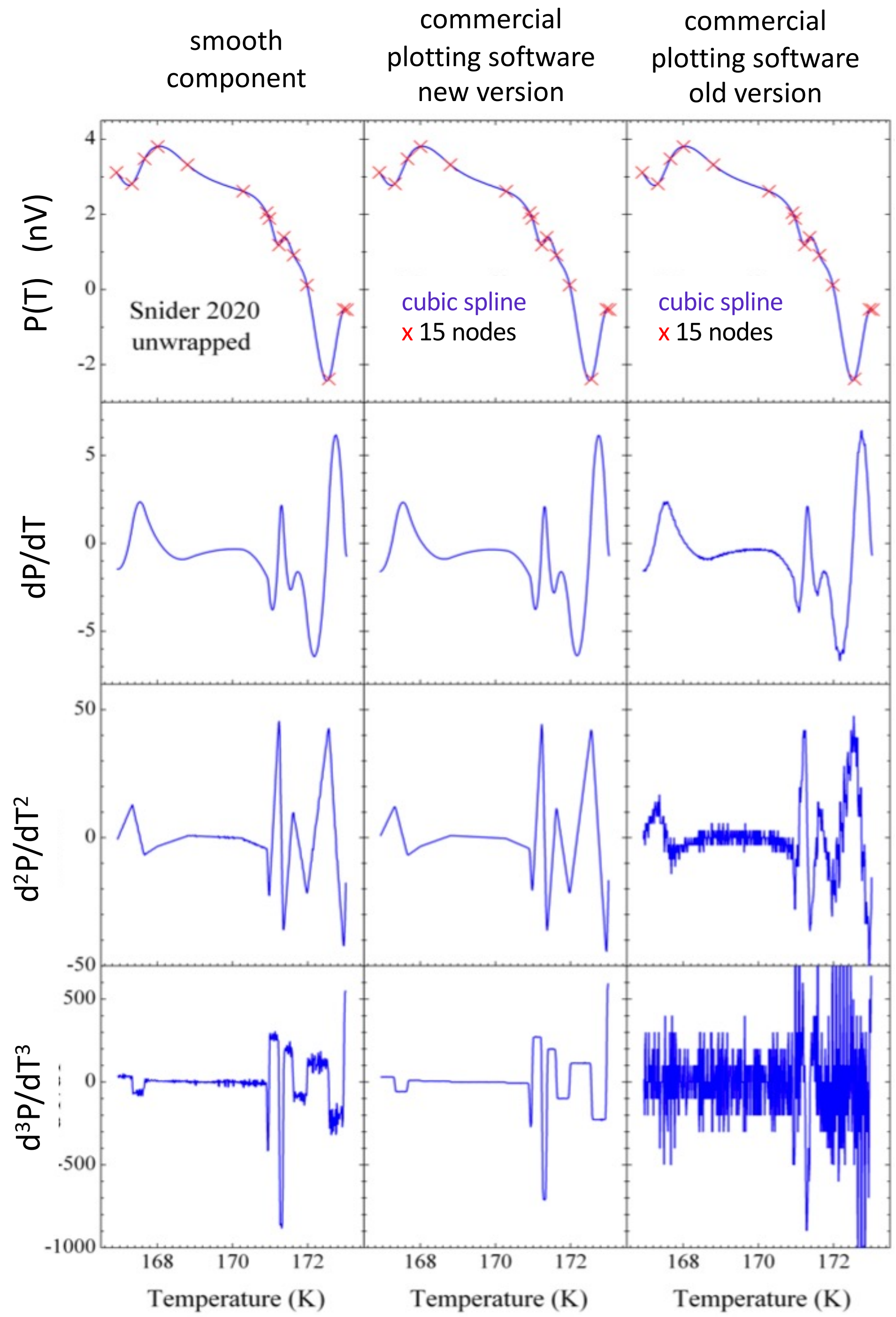
Superconducting Signal = quantized component + smooth component : $\chi_{sc}(T) = q(T) + P(T)$



DvdM&JE Hirsch https://arxiv.org/abs/2201.07686v1

Properties of the smooth component

- *spline*
- *number of segments: 14*
- *number of nodes: 15*
- *order: cubic*
- *boundary conditions: natural*

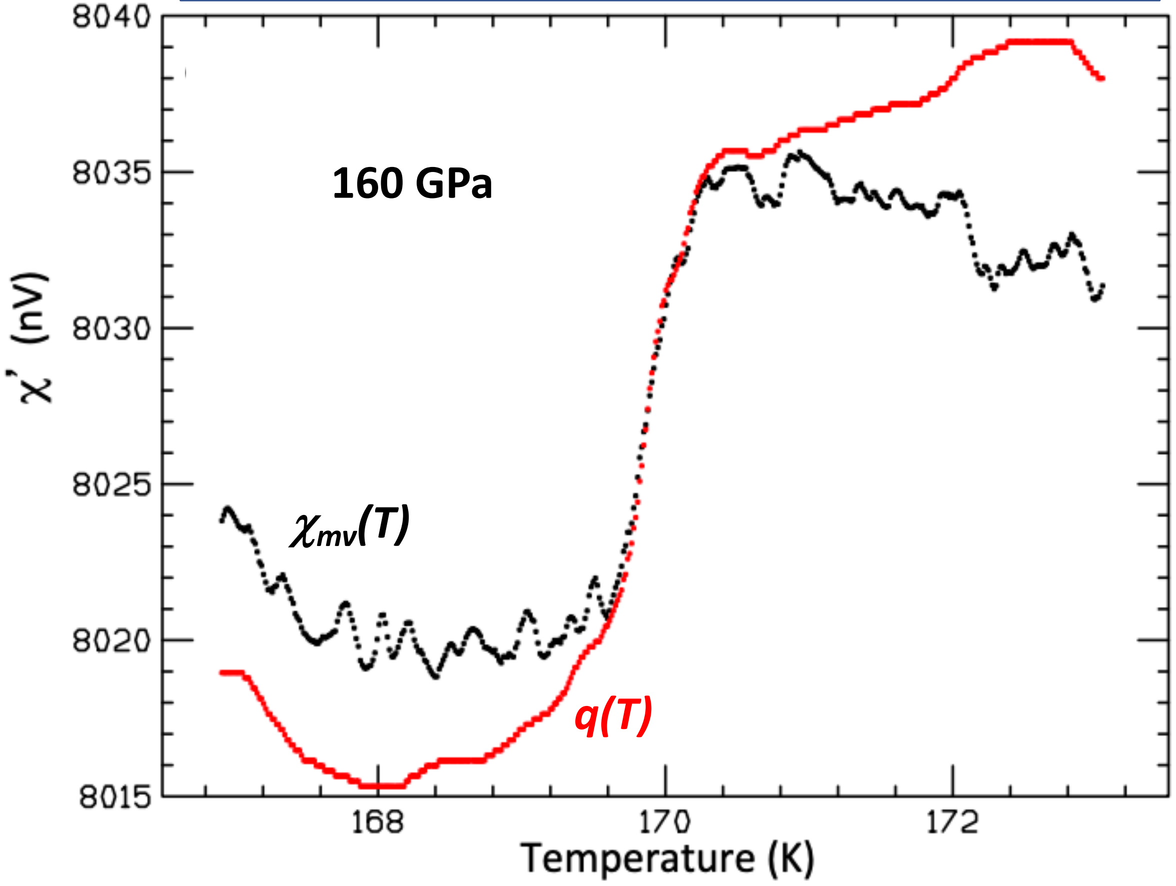


DvdM&JE Hirsch https://arxiv.org/abs/2201.07686v4

What is the nature of the **“quantized component”** ?
Raw data recorded with 3 digit precision ?

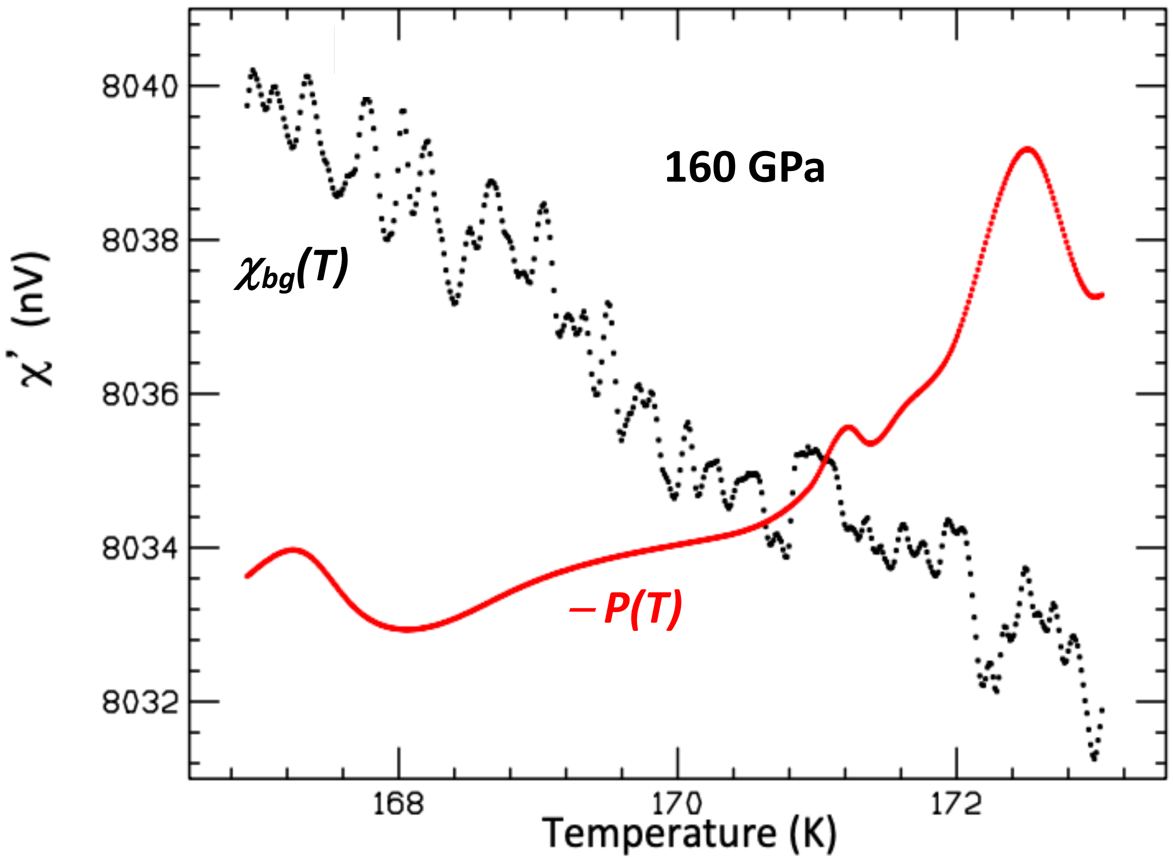
What is the nature of the **“smooth component”** ?
-1 x fitted (or otherwise smooth) “User Defined Background”?

Comparison of **“quantized component”**
and **“Measured Voltage”**



The **“quantized component”** is ***not*** the raw data

Comparison of **“smooth component”**
and **“User Defined Background”**



The **“smooth component”** is ***not*** the background

DvdM&JE Hirsch https://arxiv.org/abs/2201.07686v4

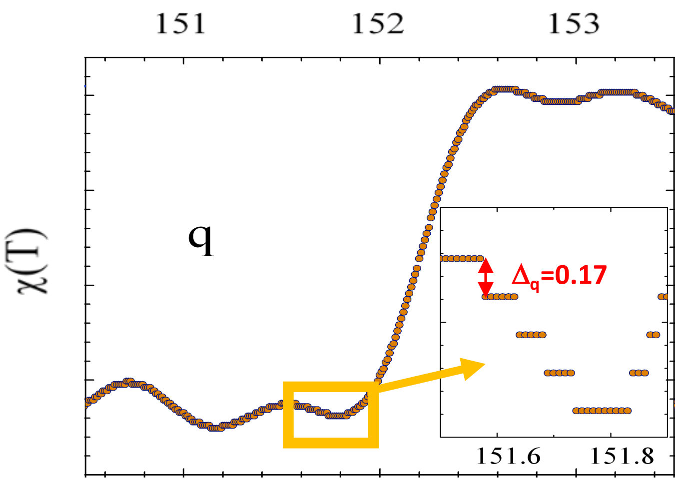
Diagnostic tool. Discrete first and second derivatives

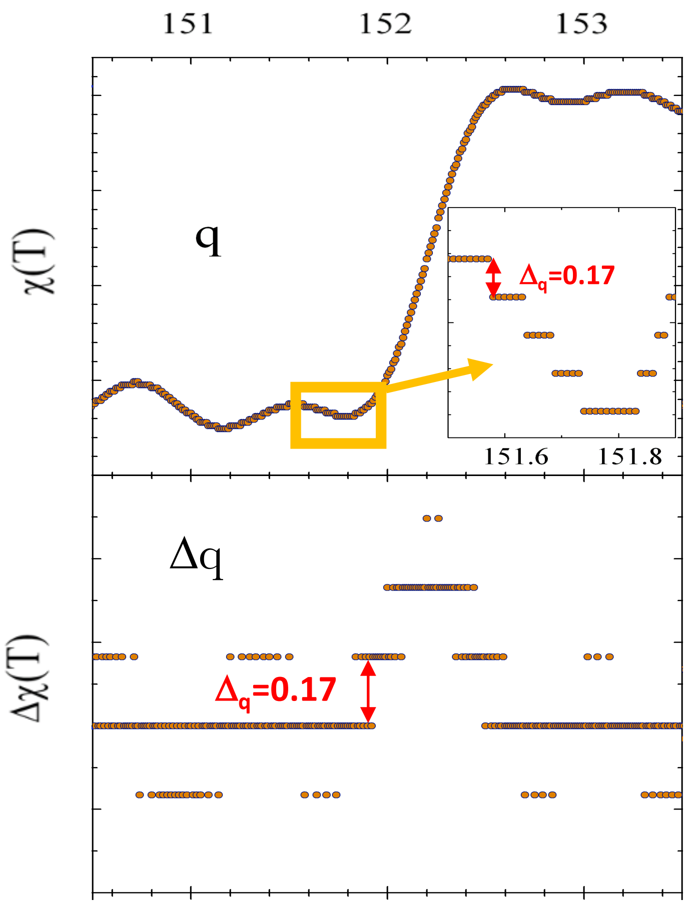
JE Hirsch, *Europhys. Lett.* **137**, 36001 (2022)

$$\Delta\chi(T_j) = \chi(T_j) - \chi(T_{j-1})$$

$$\Delta^2\chi(T_j) = \Delta\chi(T_j) - \Delta\chi(T_{j-1})$$

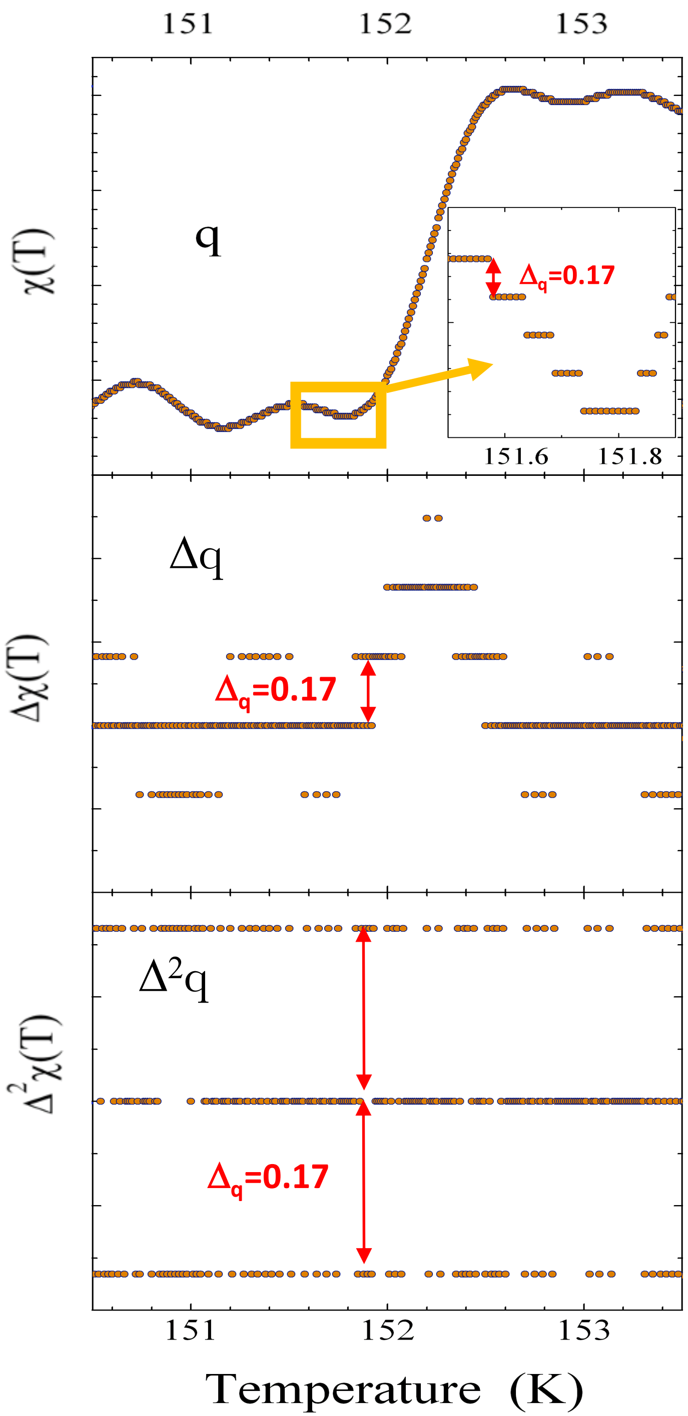
simulated data



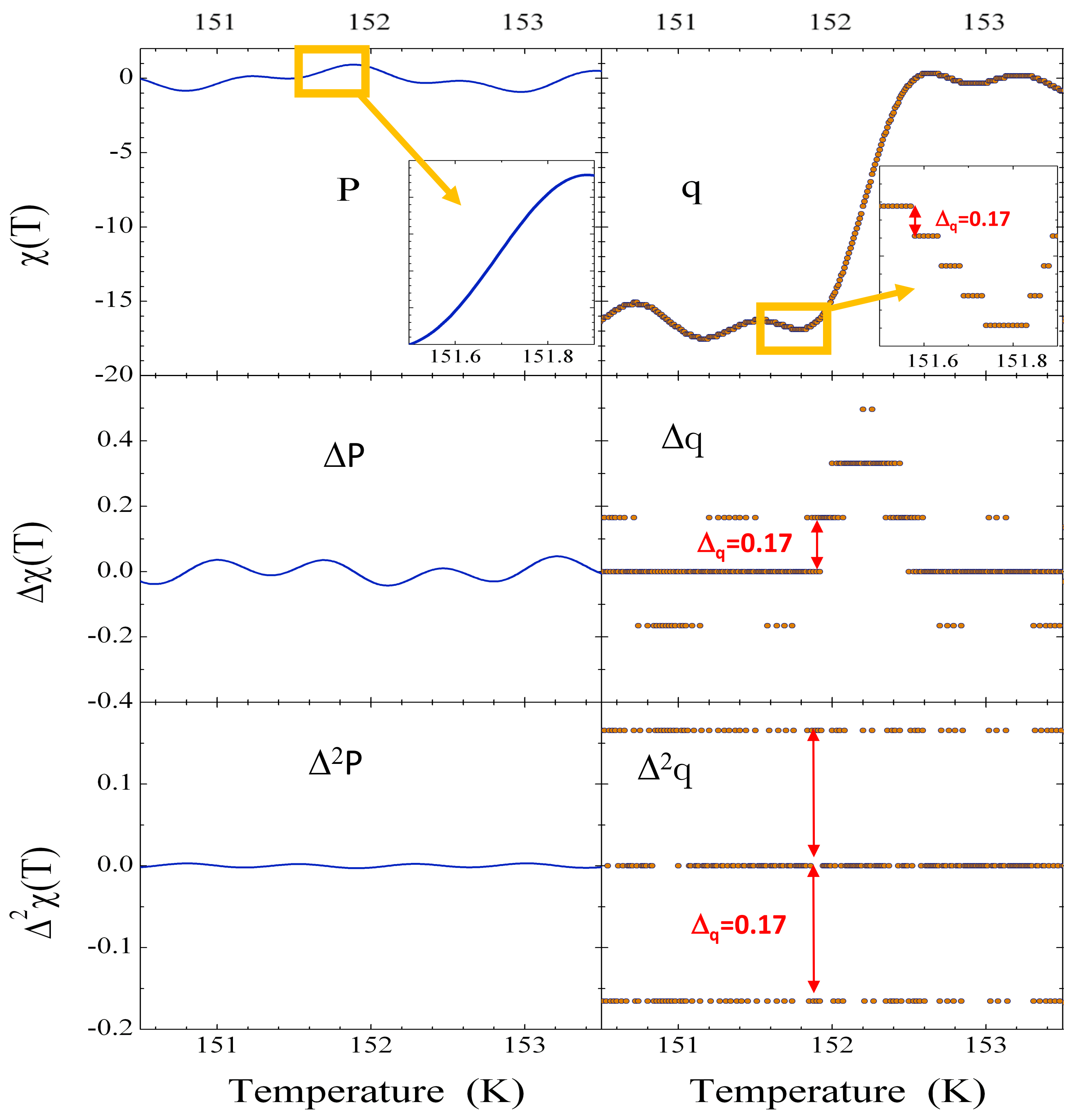


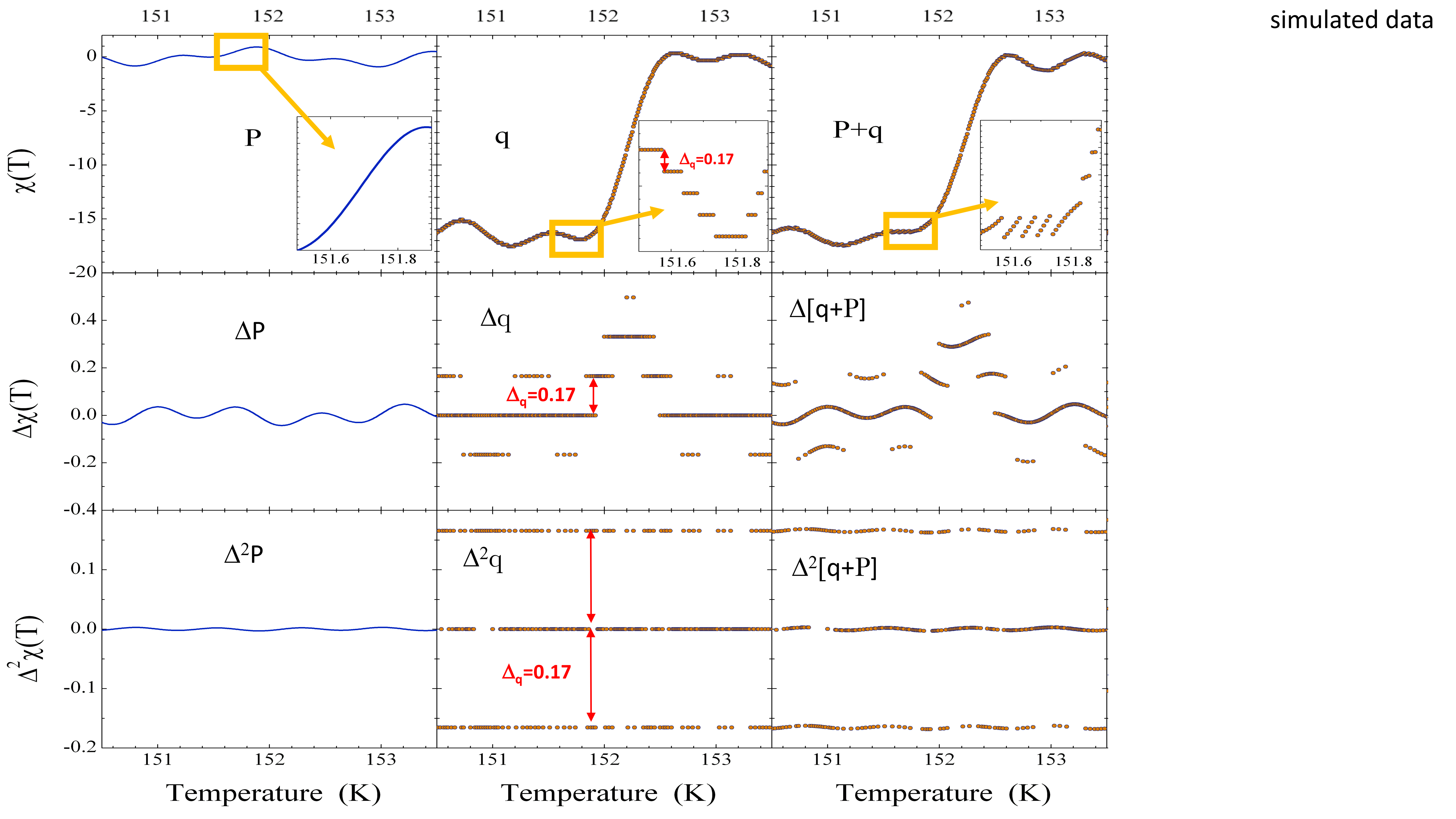
simulated data

simulated data



simulated data




simulated data
P
q
P+q
Δ$_q$=0.17
ΔP
Δq
Δ[q+P]
Δ^{2}P
Δ^{2}q
Δ^2[q+P]
χ(T)
Δχ(T)
Δ^{2}χ(T)
Temperature (K)
151.6
151.8

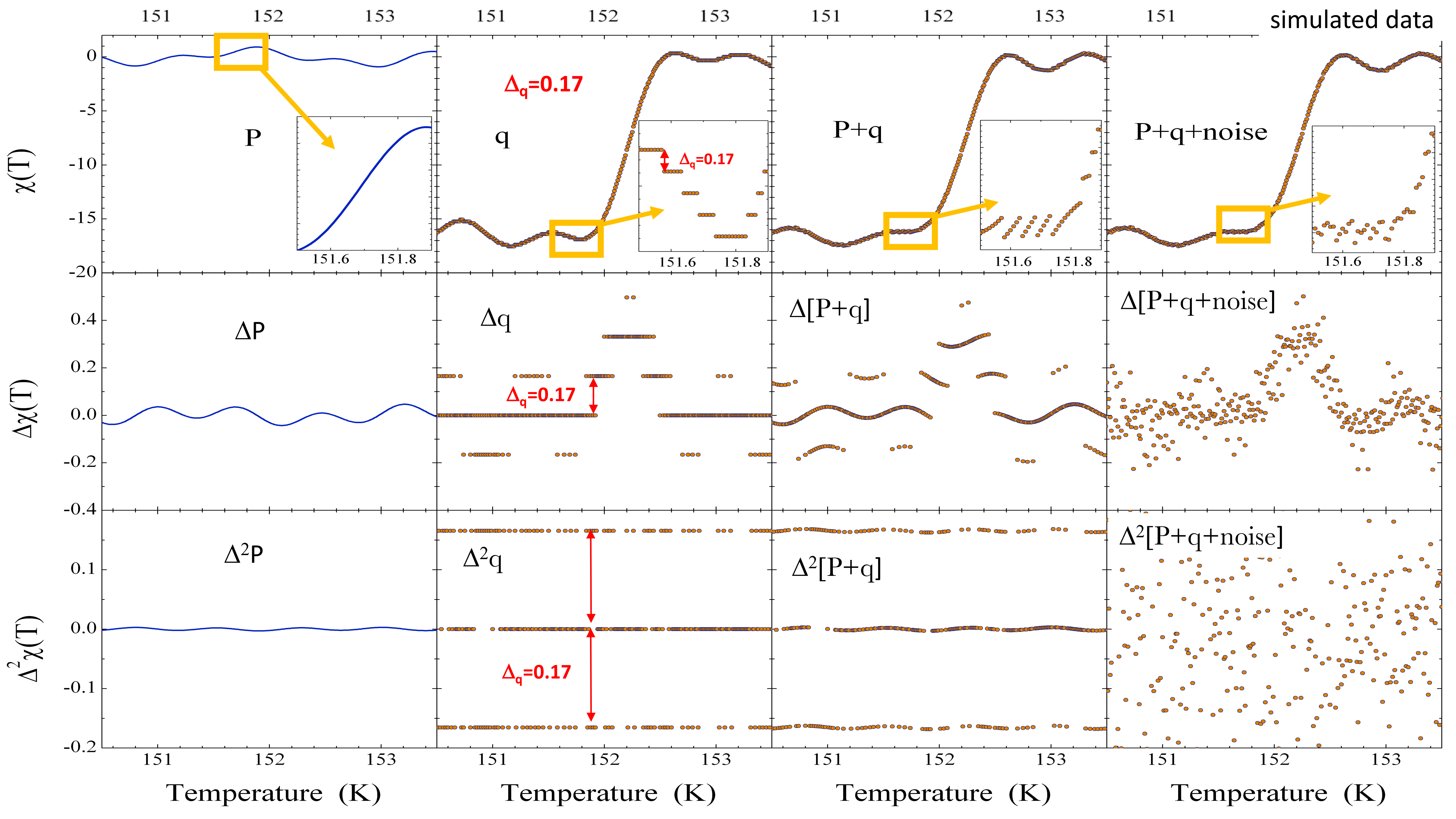
Diagnostic tool. Discrete first and second derivatives

JE Hirsch, *Europhys. Lett.* **137**, 36001 (2022)

$$\Delta\chi(T_j) = \chi(T_j) - \chi(T_{j-1})$$

$$\Delta^2\chi(T_j) = \Delta\chi(T_j) - \Delta\chi(T_{j-1})$$

Quantized steps Δ_q, if present, show up in $\Delta^2\chi(T_j)$ as weakly temperature dependent flat curves, with aliases shifted along y with integer multiples of Δ_q



simulated data
P
q
P+q
P+q+noise
Δ_q=0.17
ΔP
Δq
Δ[P+q]
Δ[P+q+noise]
Δ^2P
Δ^2q
Δ^2[P+q]
Δ^2[P+q+noise]
χ(T)
Δχ(T)
Δ^2χ(T)
Temperature (K)

Diagnostic tool. Discrete first and second derivatives

JE Hirsch, *Europhys. Lett.* **137**, 36001 (2022)

$$\Delta\chi(T_j) = \chi(T_j) - \chi(T_{j-1})$$

$$\Delta^2\chi(T_j) = \Delta\chi(T_j) - \Delta\chi(T_{j-1})$$

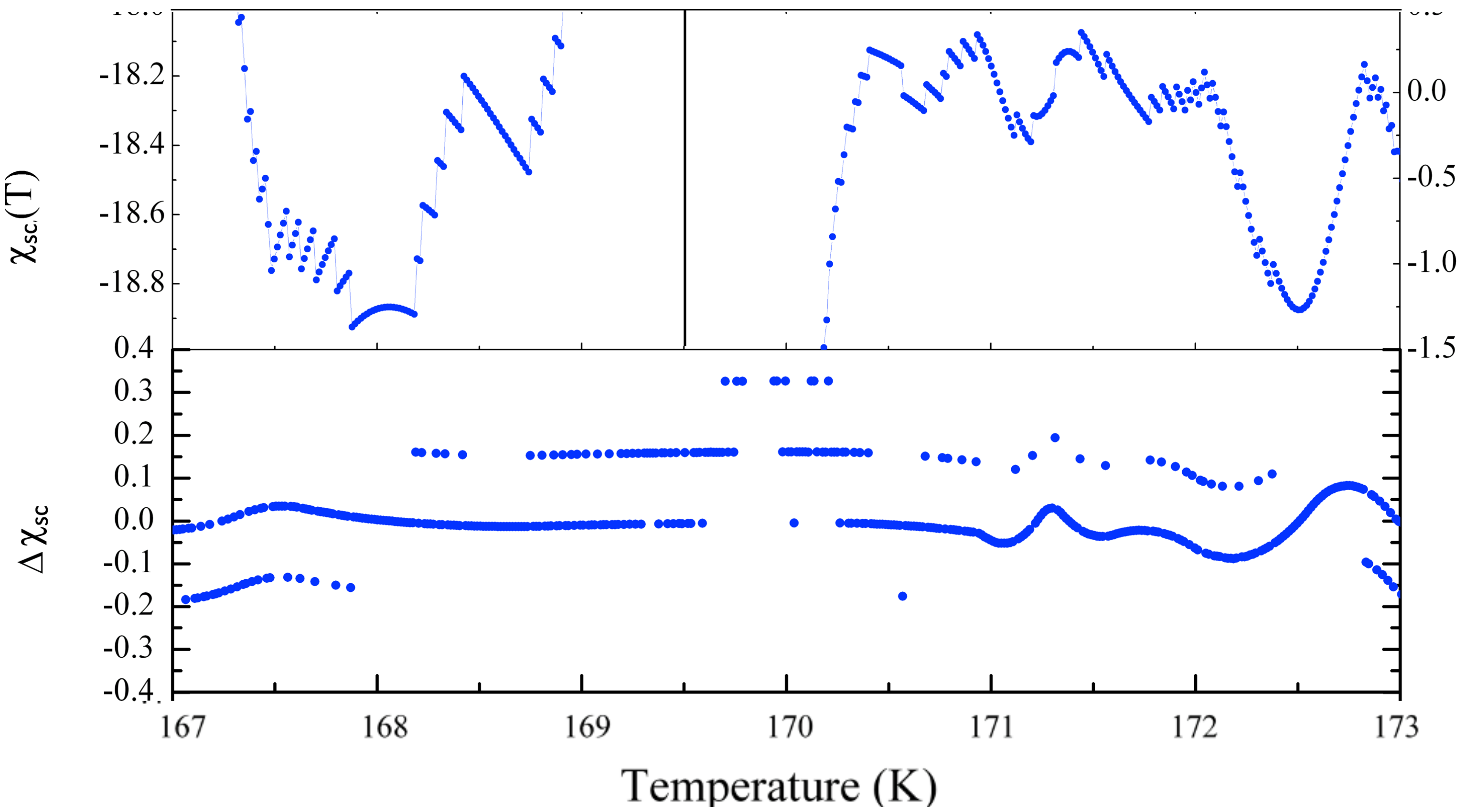
Noise amplitude of about $\Delta_q/2$ suffices to scramble the aliasing structure in $\Delta^2\chi(T_j)$.

In other words, **if** $\Delta^2\chi(T_j)$ has aliasing structure, **this implies** that random noise is absent or has amplitude below $\Delta_q/2$.

The "Superconducting Signal"

$$\Delta\chi(j) = \chi(j) - \chi(j-1)$$

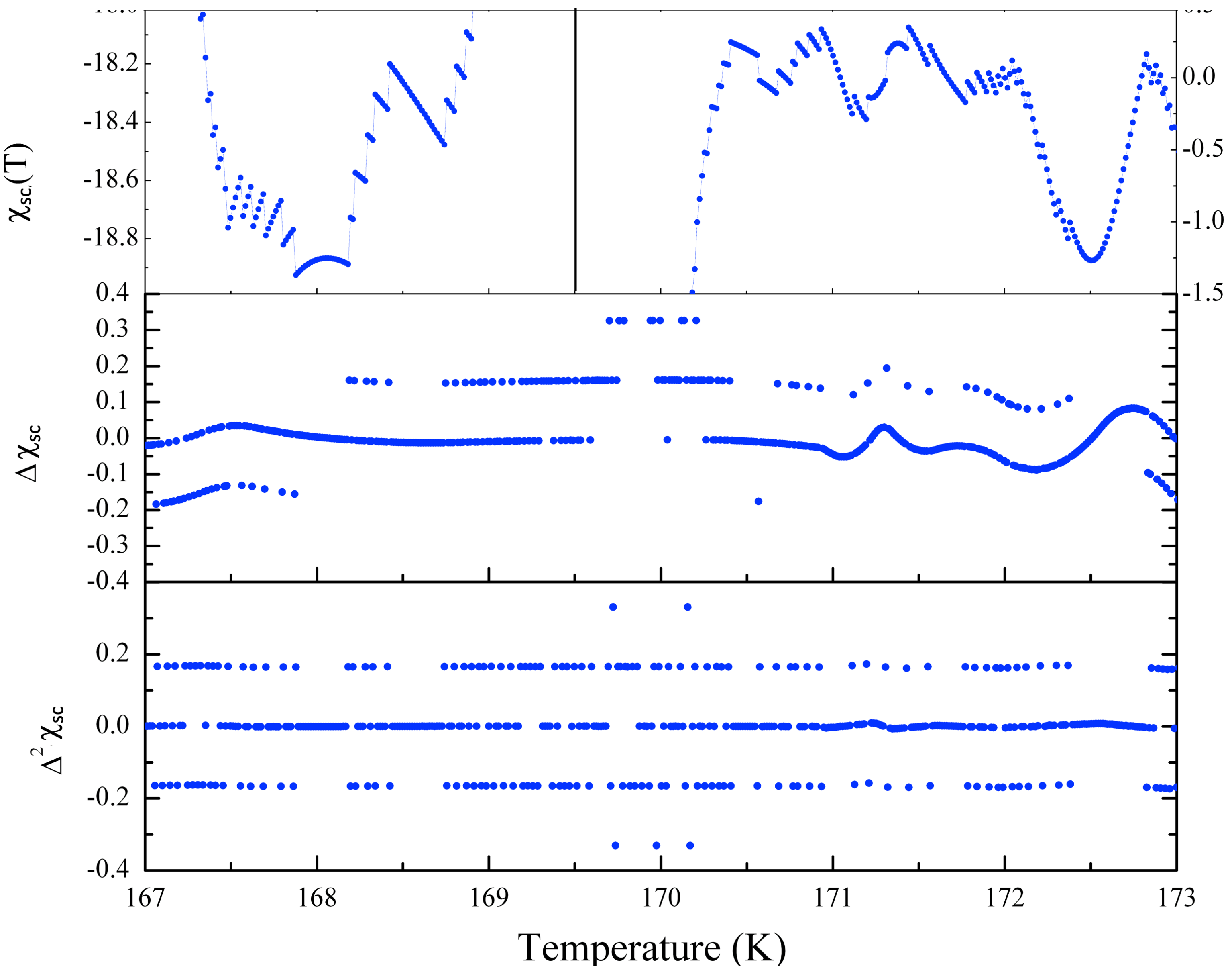
160 GPa



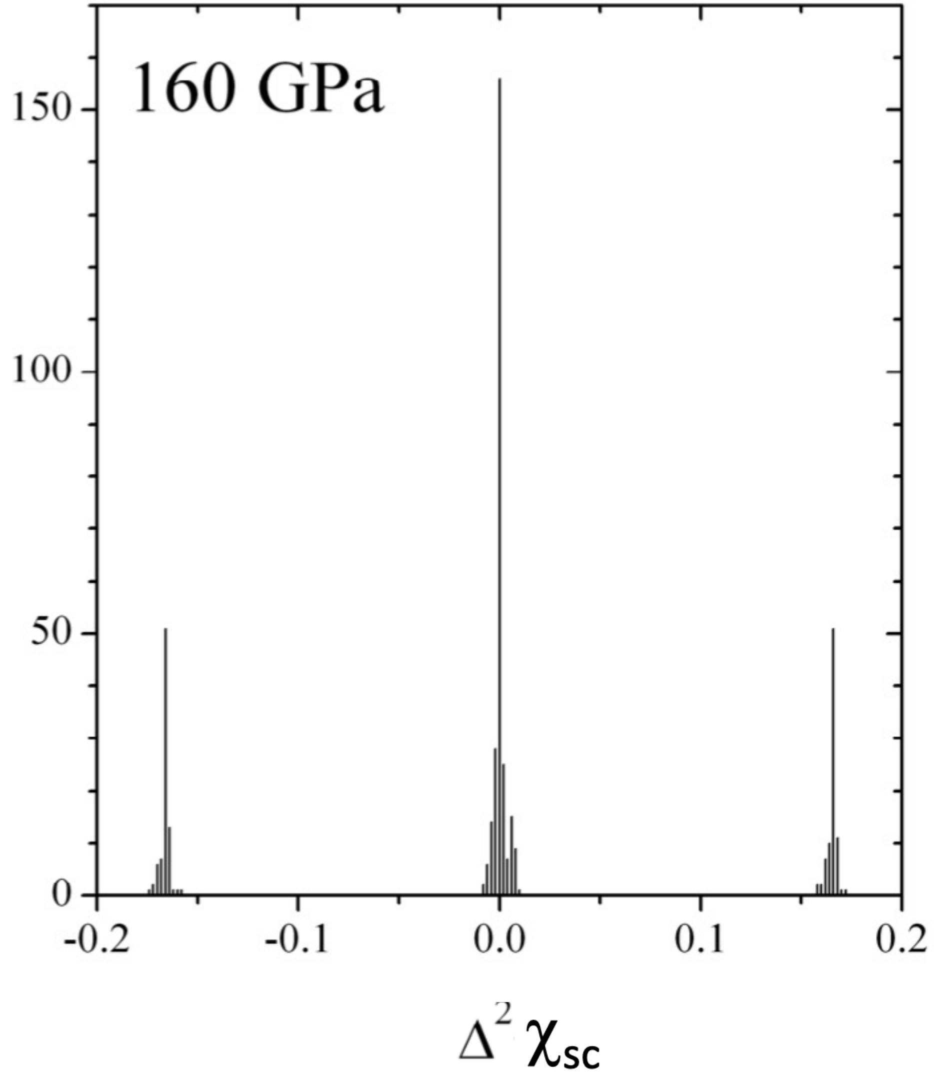
The “Superconducting Signal”

$$\Delta\chi(j) = \chi(j) - \chi(j-1)$$
$$\Delta^2\chi(j) = \Delta\chi(j) - \Delta\chi(j-1)$$

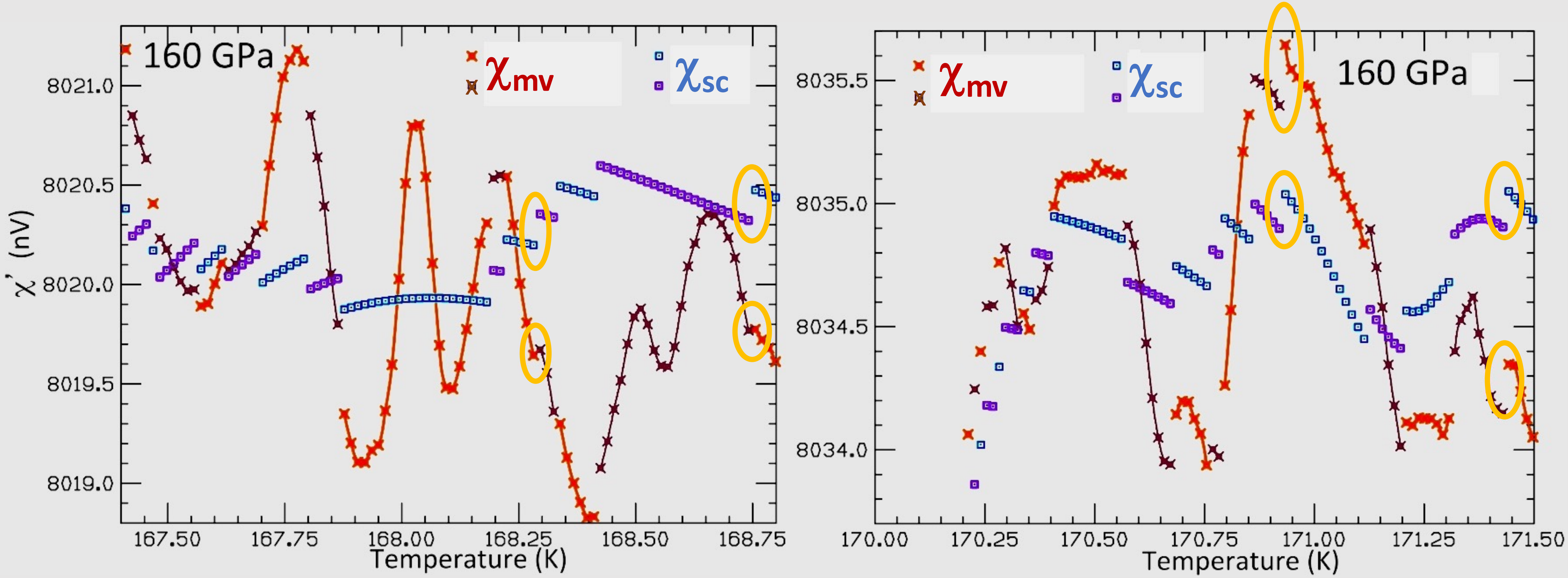
160 GPa



Dukwon, https://imgur.com (2022)



Comparison of Raw Data and Superconducting Signal



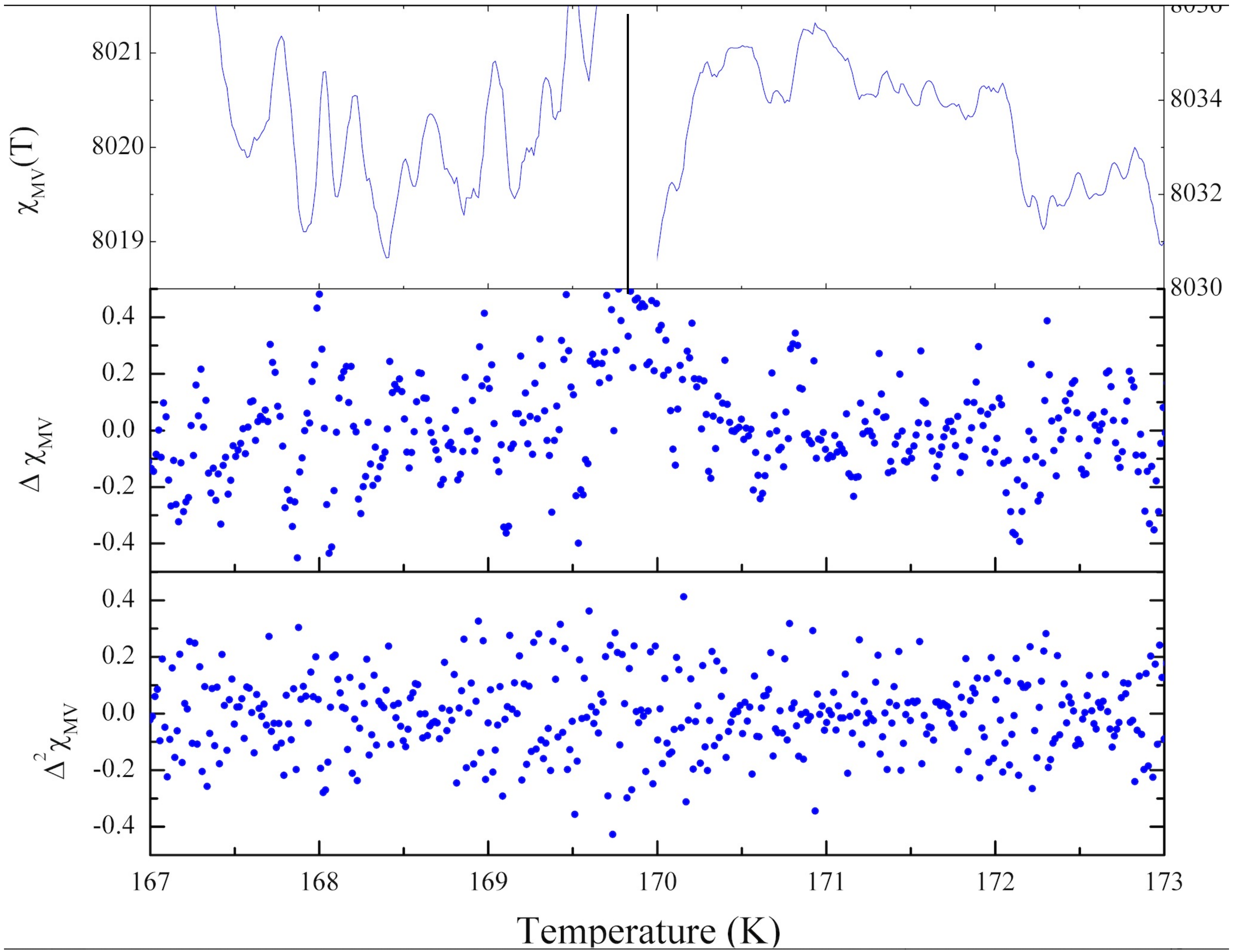
Observation: The quantized component q(T) also shows up in the "Measured Voltage"

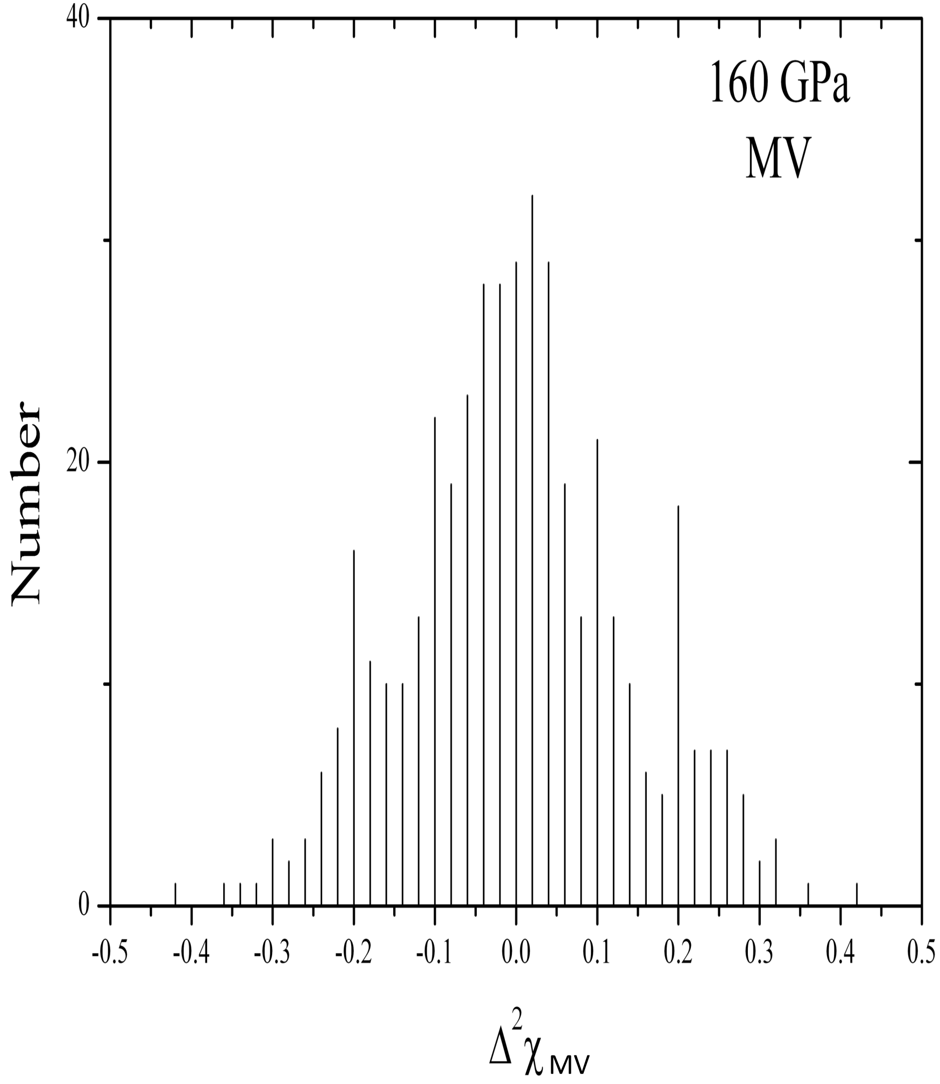
Is this statistically significant ?

The “Measured Voltage”

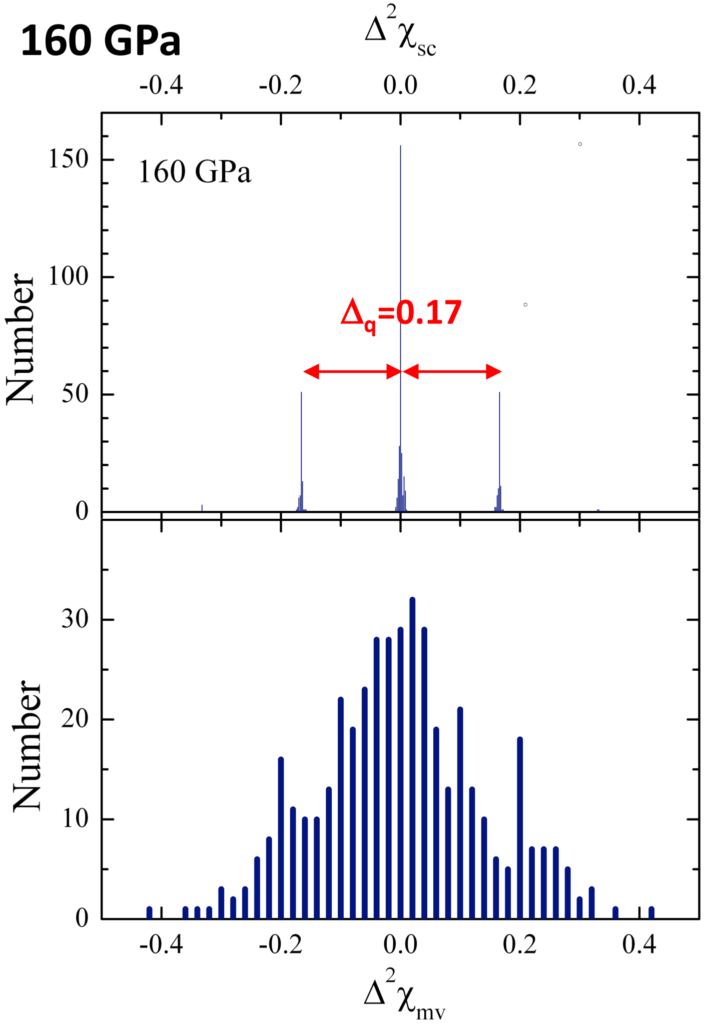
160 GPa

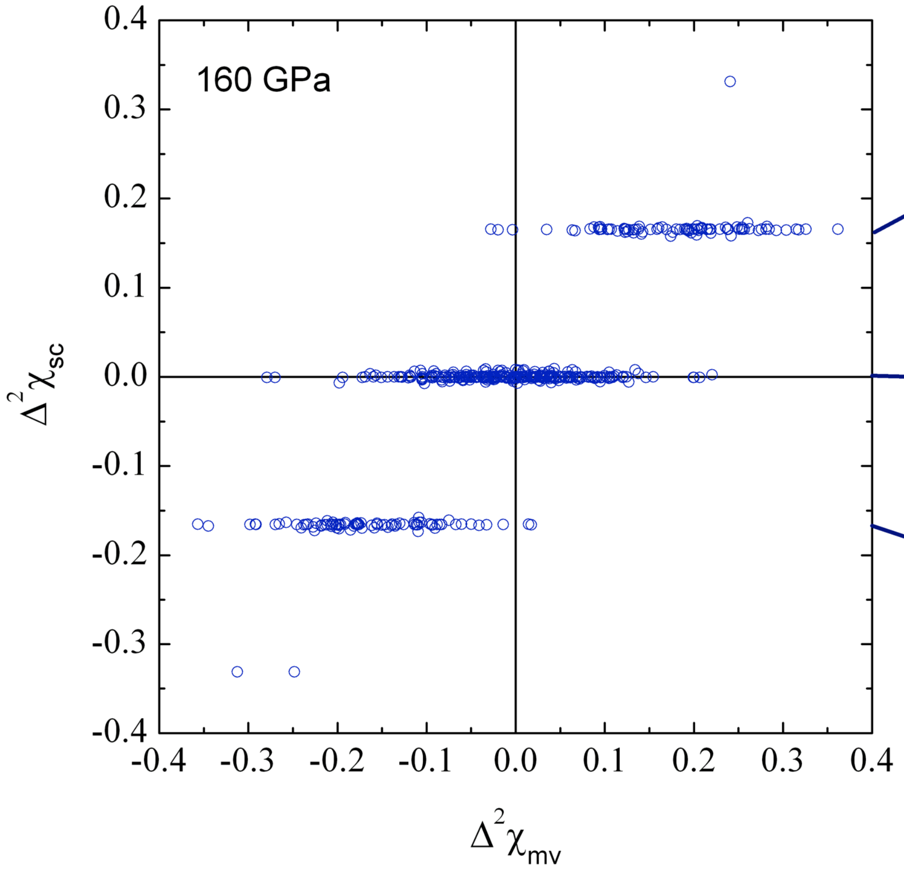
$$\Delta\chi(j) = \chi(j) - \chi(j-1)$$
$$\Delta^2\chi(j) = \Delta\chi(j) - \Delta\chi(j-1)$$

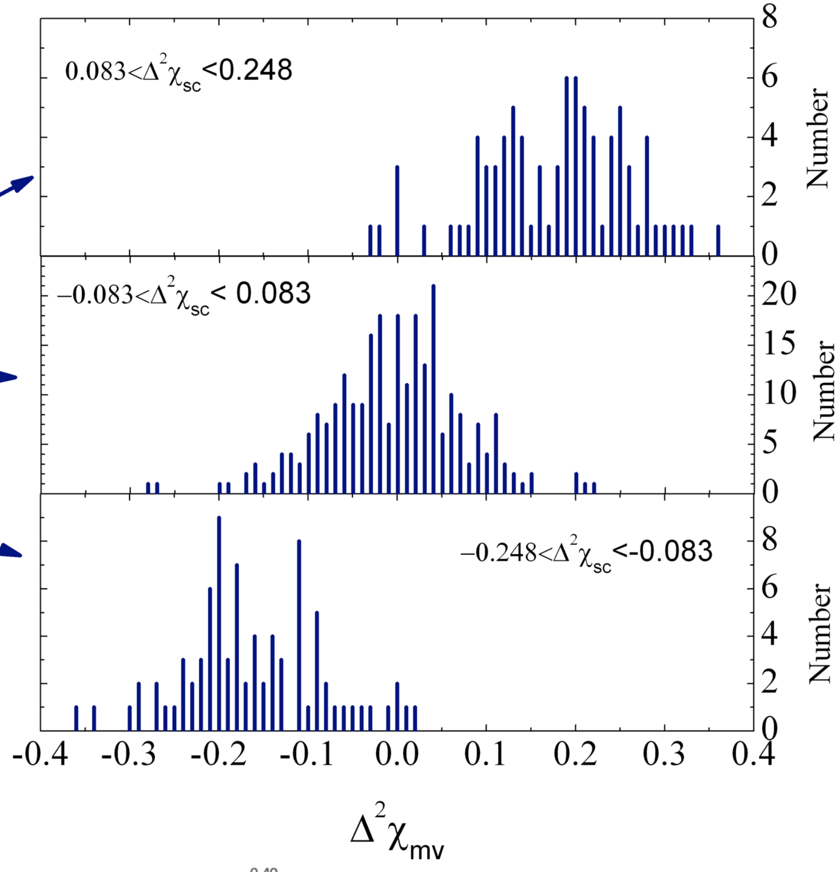


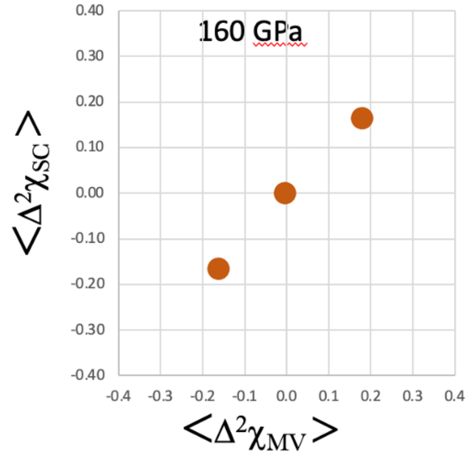


Correlation between $\Delta^2\chi_{mv}$ and $\Delta^2\chi_{sc}$









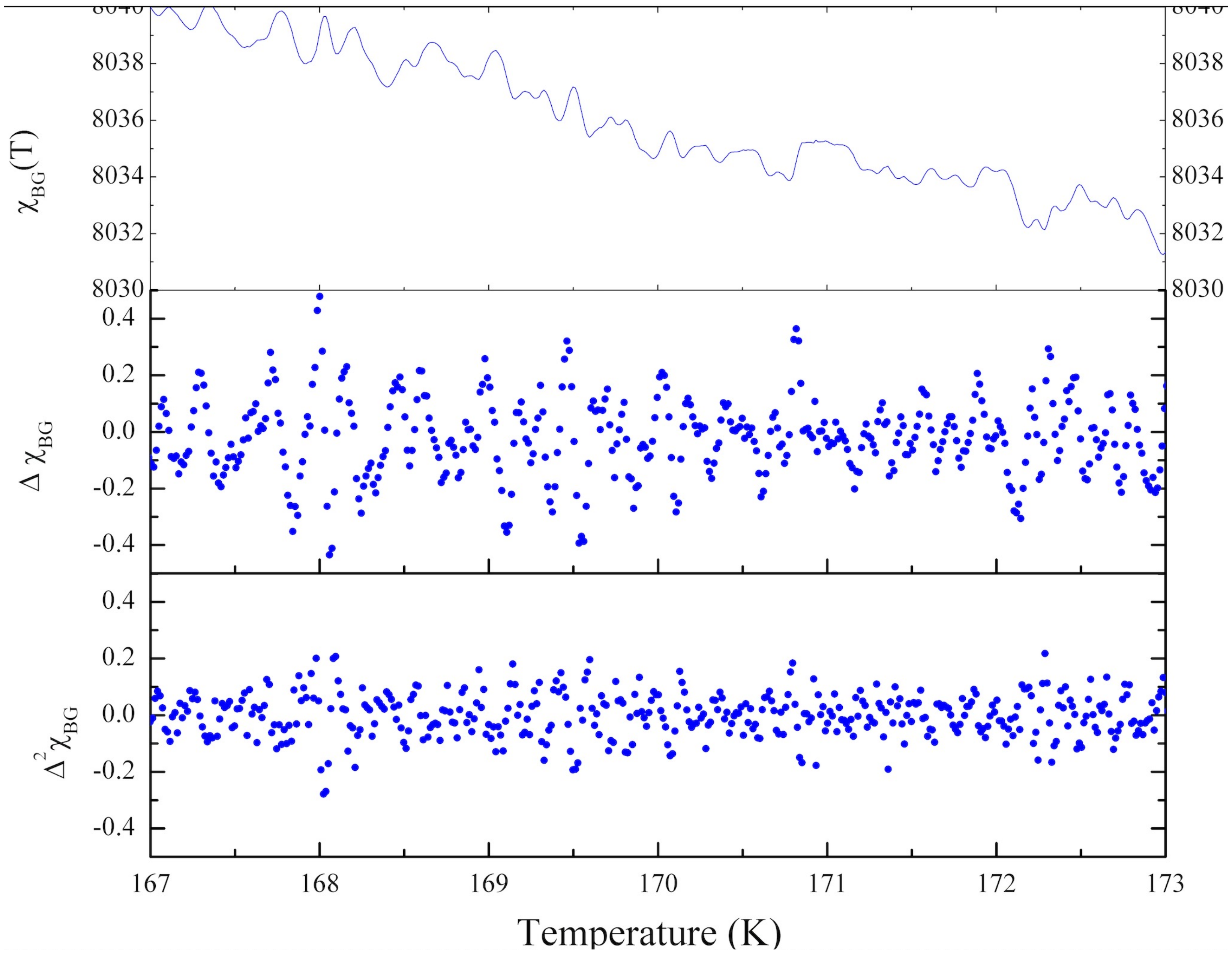
- The 0.17 nV steps are also present in χ_{mv}
- The steps in χ_{mv} and in χ_{sc} occur for the same temperatures
- They have, apart from noise in χ_{mv}, the same vertical step-size

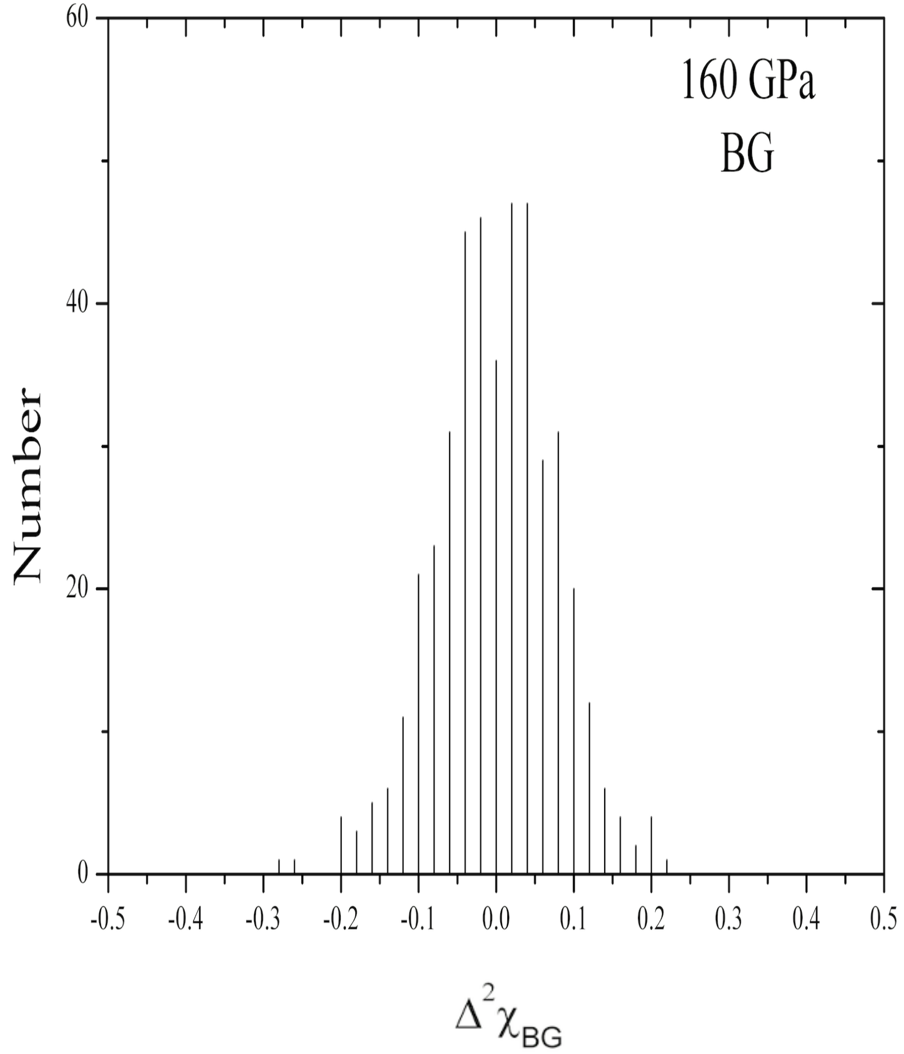
The q(T) component of χ_{sc} is equally strong in χ_{mv}

The "background": $\chi_{bg}=\chi_{mv}-\chi_{sc}$

160 GPa

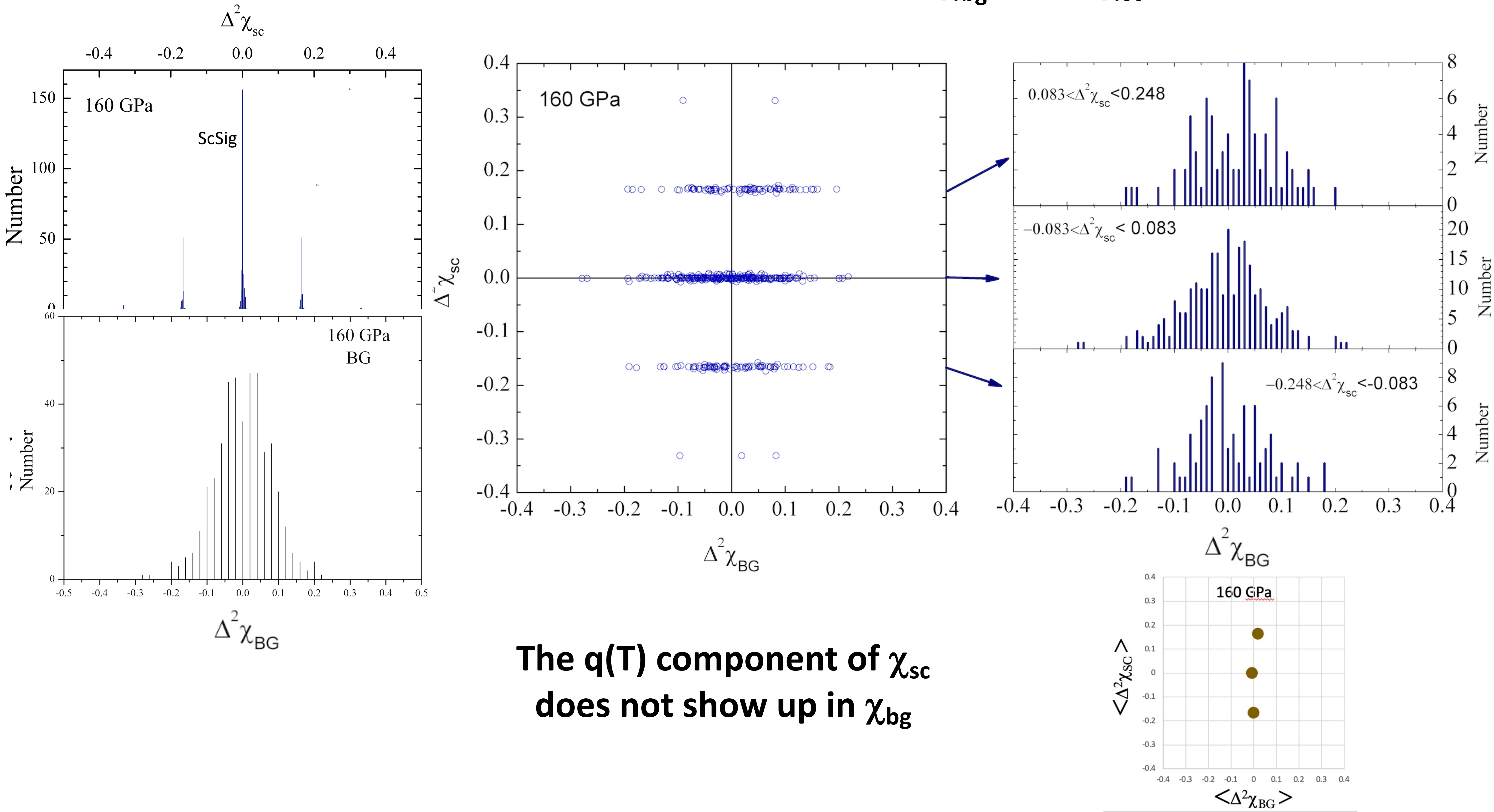
$$\Delta\chi(j)=\chi(j)-\chi(j-1)$$
$$\Delta^2\chi(j)=\Delta\chi(j)-\Delta\chi(j-1)$$





160 GPa

Absence of correlation between $\Delta^2\chi_{bg}$ and $\Delta^2\chi_{sc}$



The q(T) component of χ_{sc} does not show up in χ_{bg}

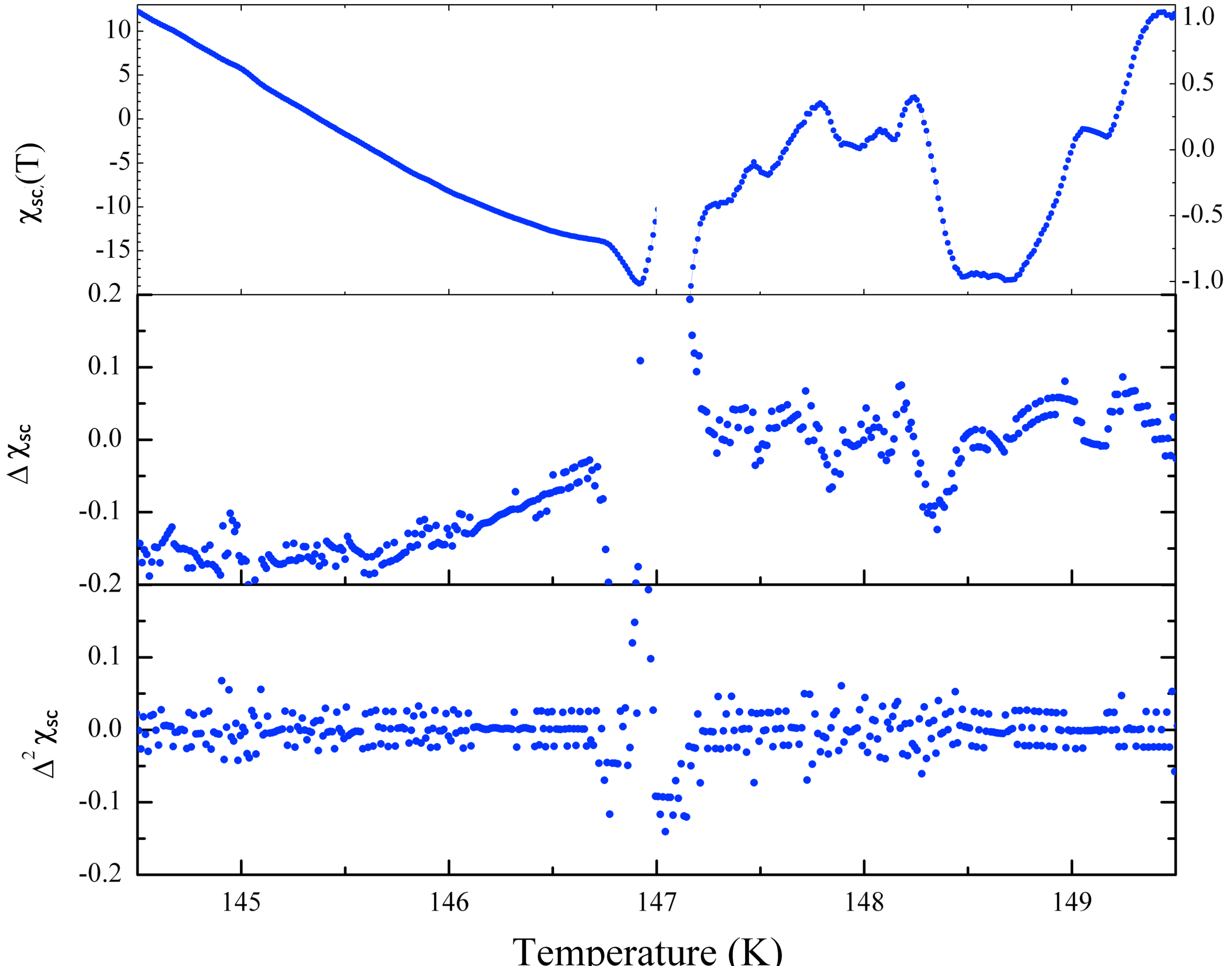
All 6 pressures

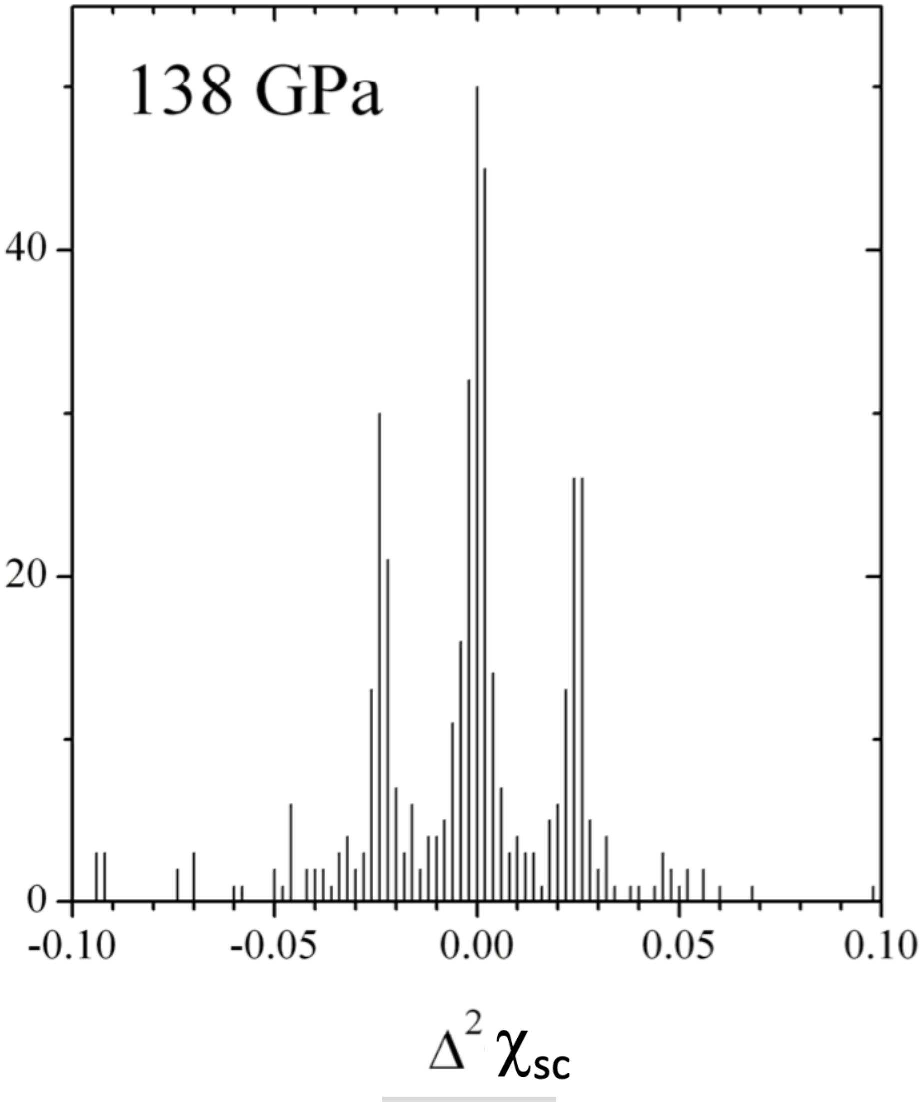
1) Superconducting signal

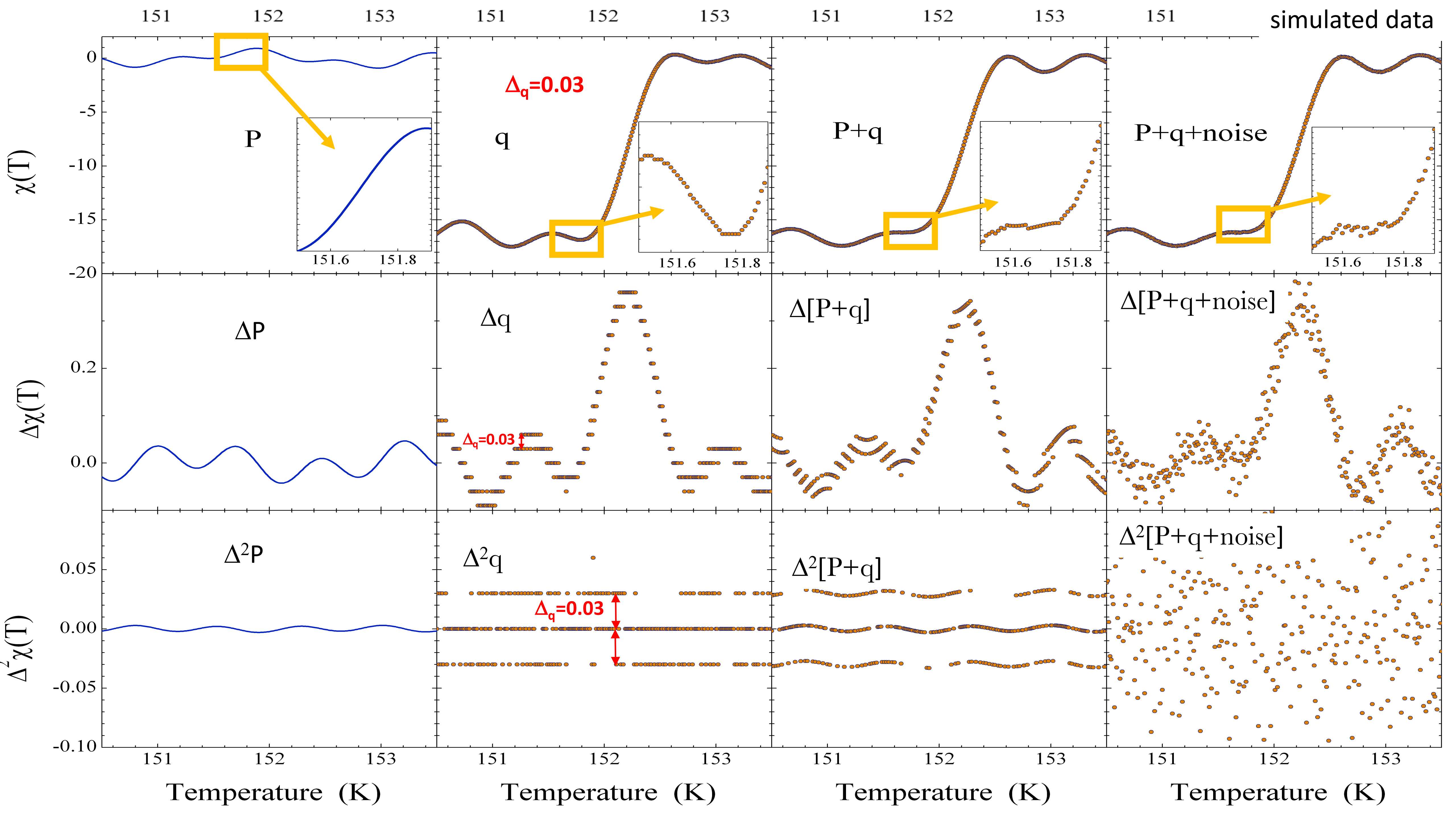
The "Superconducting Signal"

$$\Delta\chi(j) = \chi(j) - \chi(j-1)$$
$$\Delta^2\chi(j) = \Delta\chi(j) - \Delta\chi(j-1)$$

138 GPa





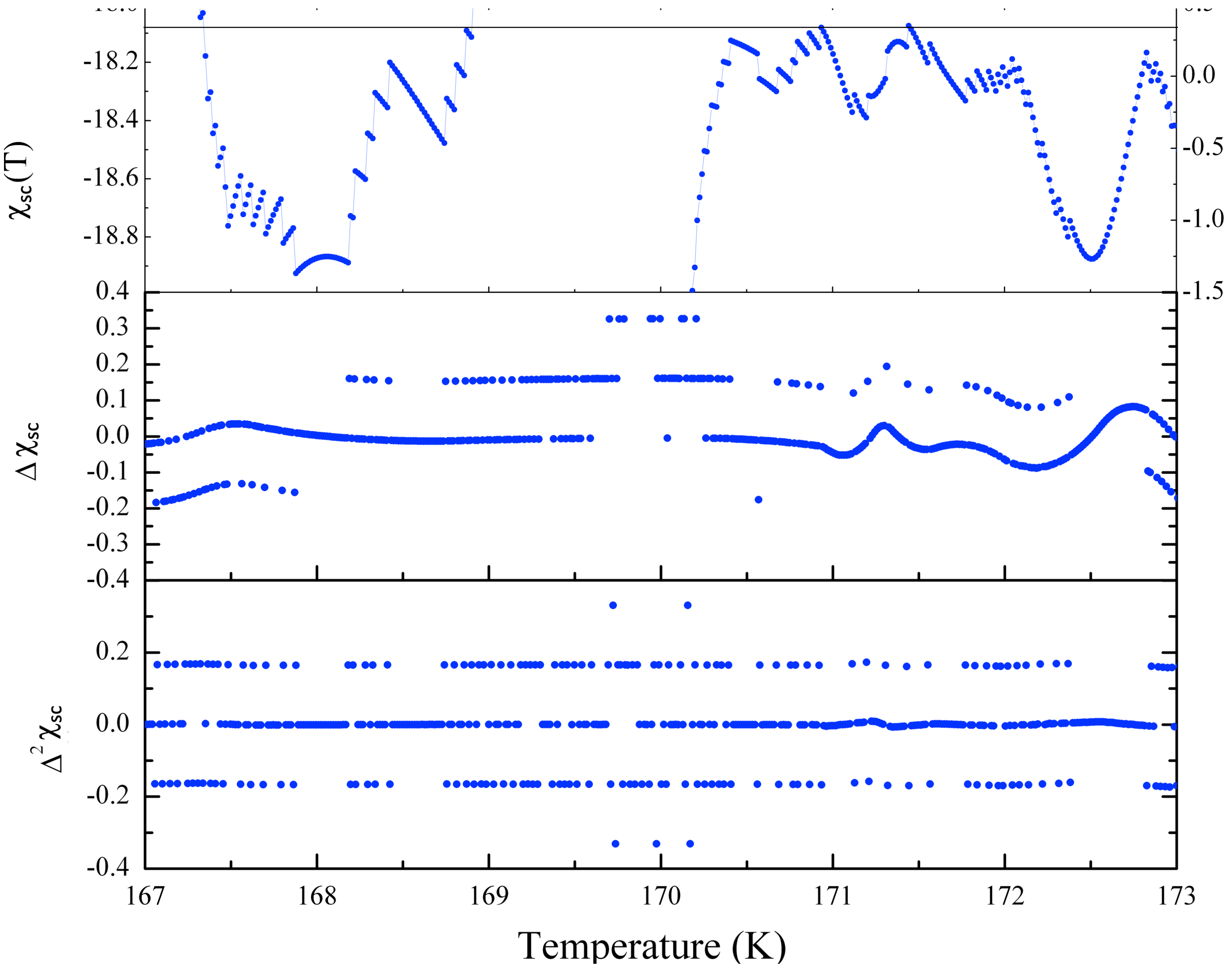


simulated data
P
q
P+q
P+q+noise
Δq=0.03
ΔP
Δq
Δ[P+q]
Δ[P+q+noise]
Δ²P
Δ²q
Δ²[P+q]
Δ²[P+q+noise]
χ(T)
Δχ(T)
Δ²χ(T)
Temperature (K)

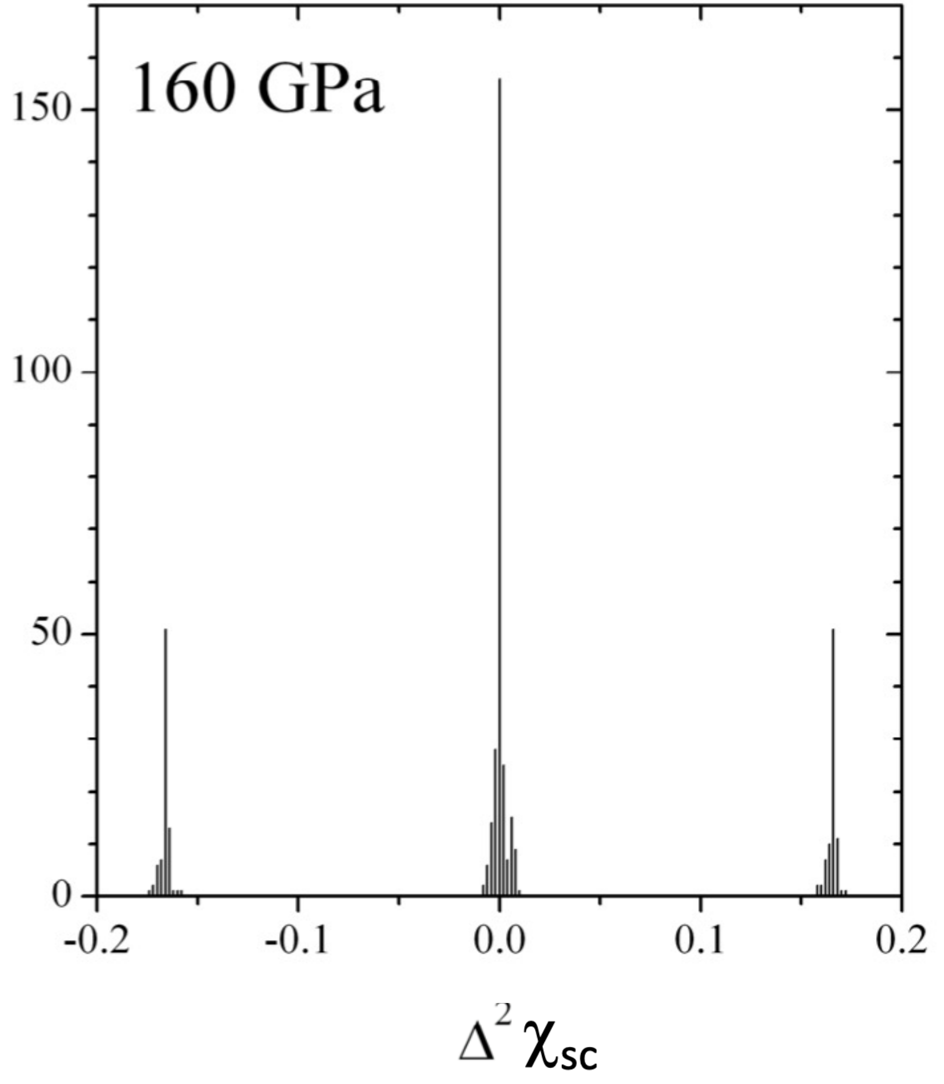
The "Superconducting Signal"

$$\Delta\chi(j) = \chi(j) - \chi(j-1)$$
$$\Delta^2\chi(j) = \Delta\chi(j) - \Delta\chi(j-1)$$

160 GPa



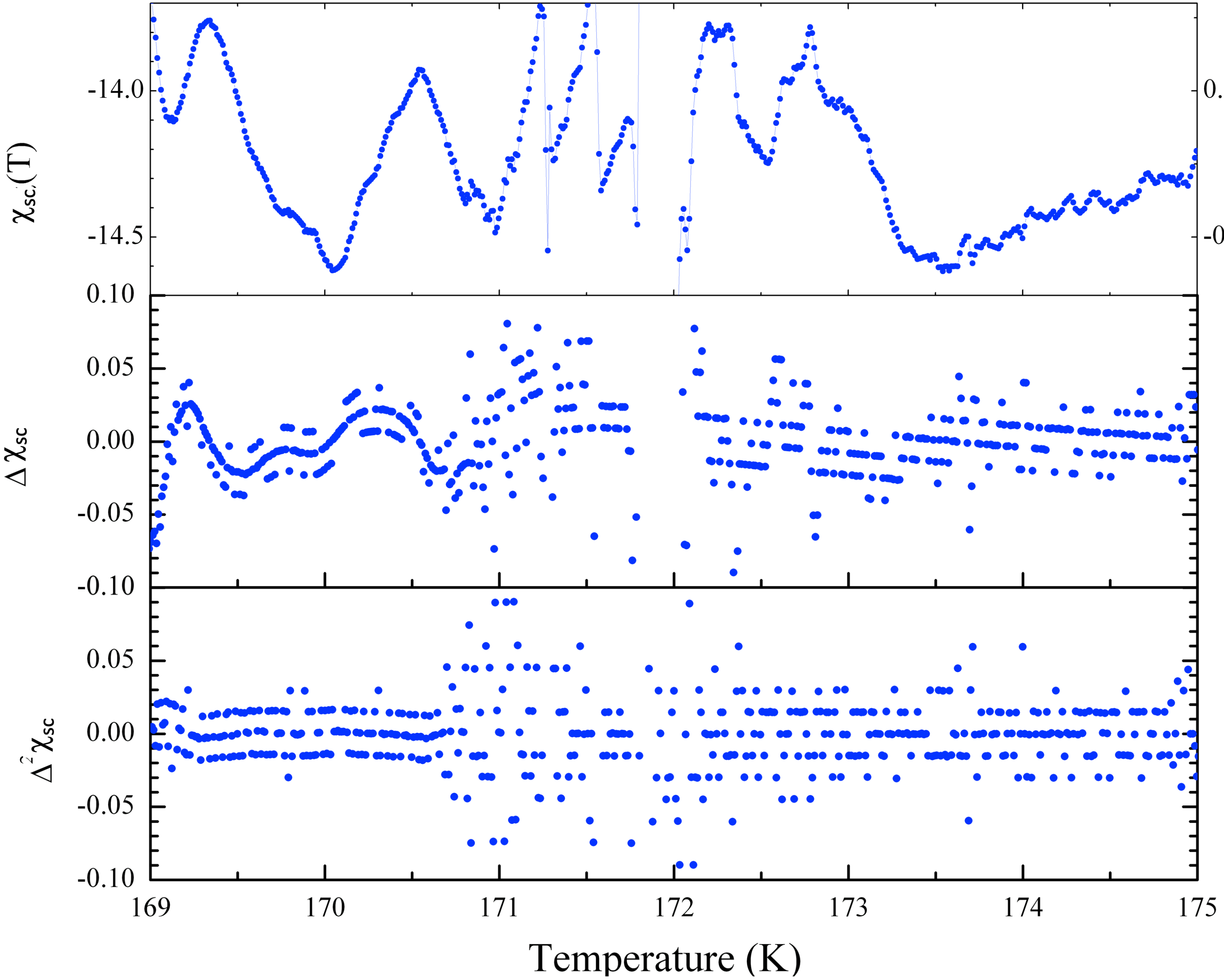
Dukwon, https://imgur.com (2022)

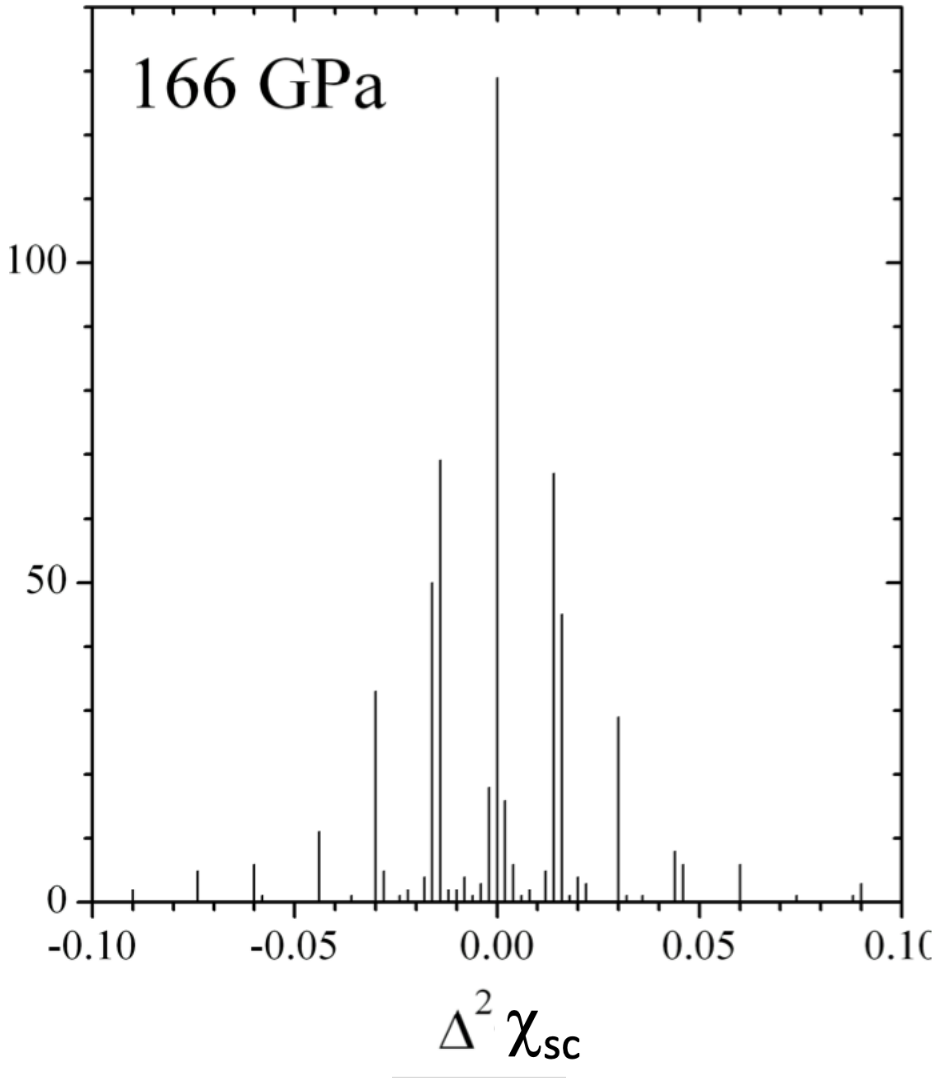


The "Superconducting Signal"

$$\Delta\chi(j) = \chi(j) - \chi(j-1)$$
$$\Delta^2\chi(j) = \Delta\chi(j) - \Delta\chi(j-1)$$

166 GPa

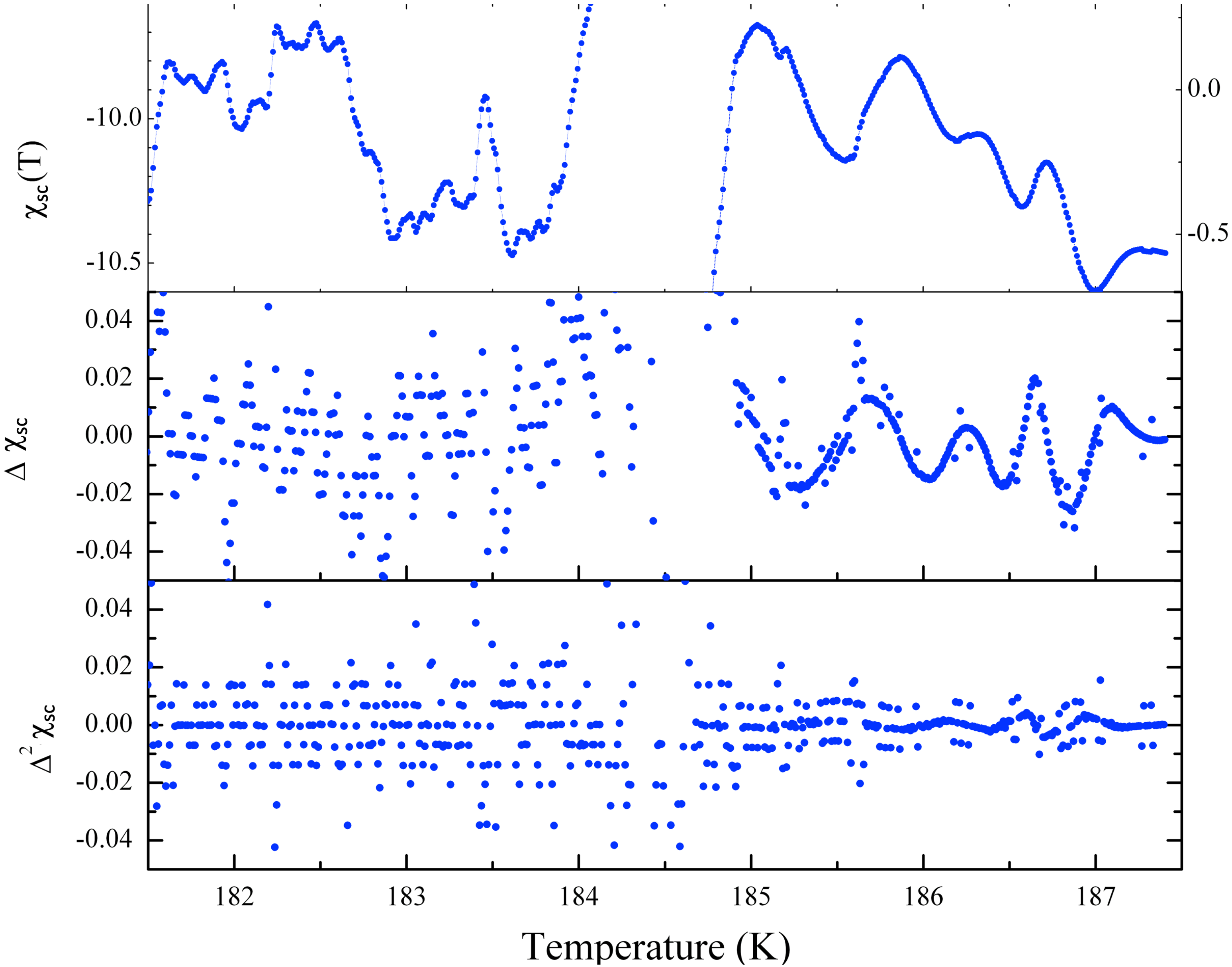


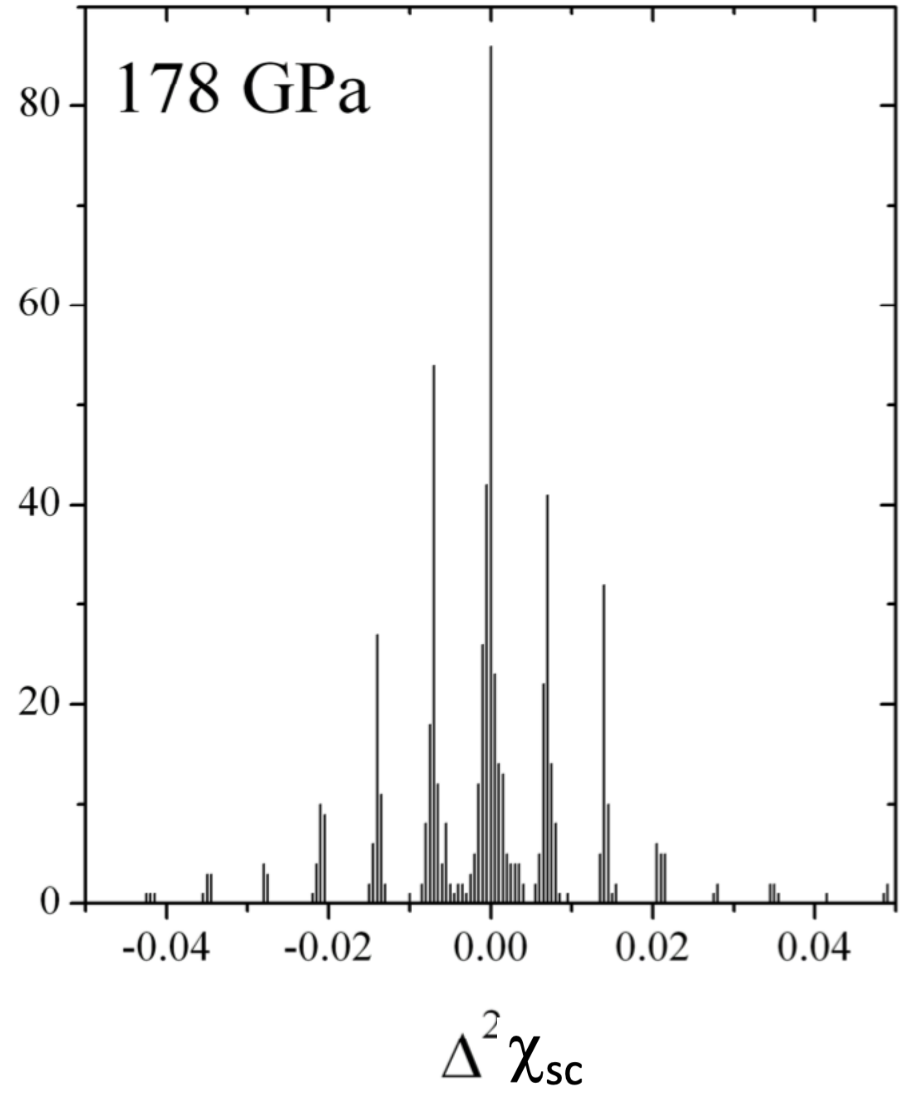


The “Superconducting Signal”

$$\Delta\chi(j) = \chi(j) - \chi(j-1)$$
$$\Delta^2\chi(j) = \Delta\chi(j) - \Delta\chi(j-1)$$

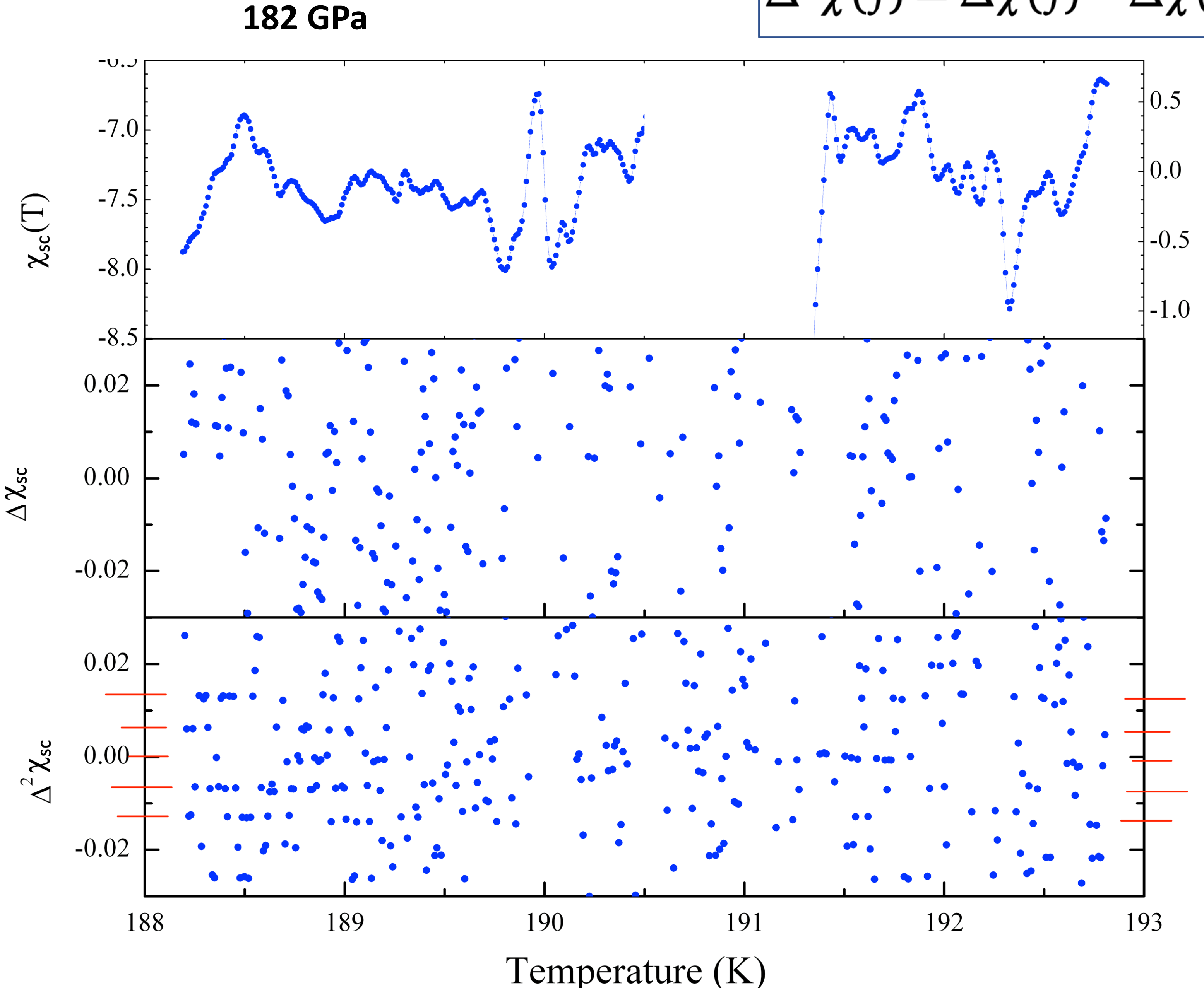
178 GPa

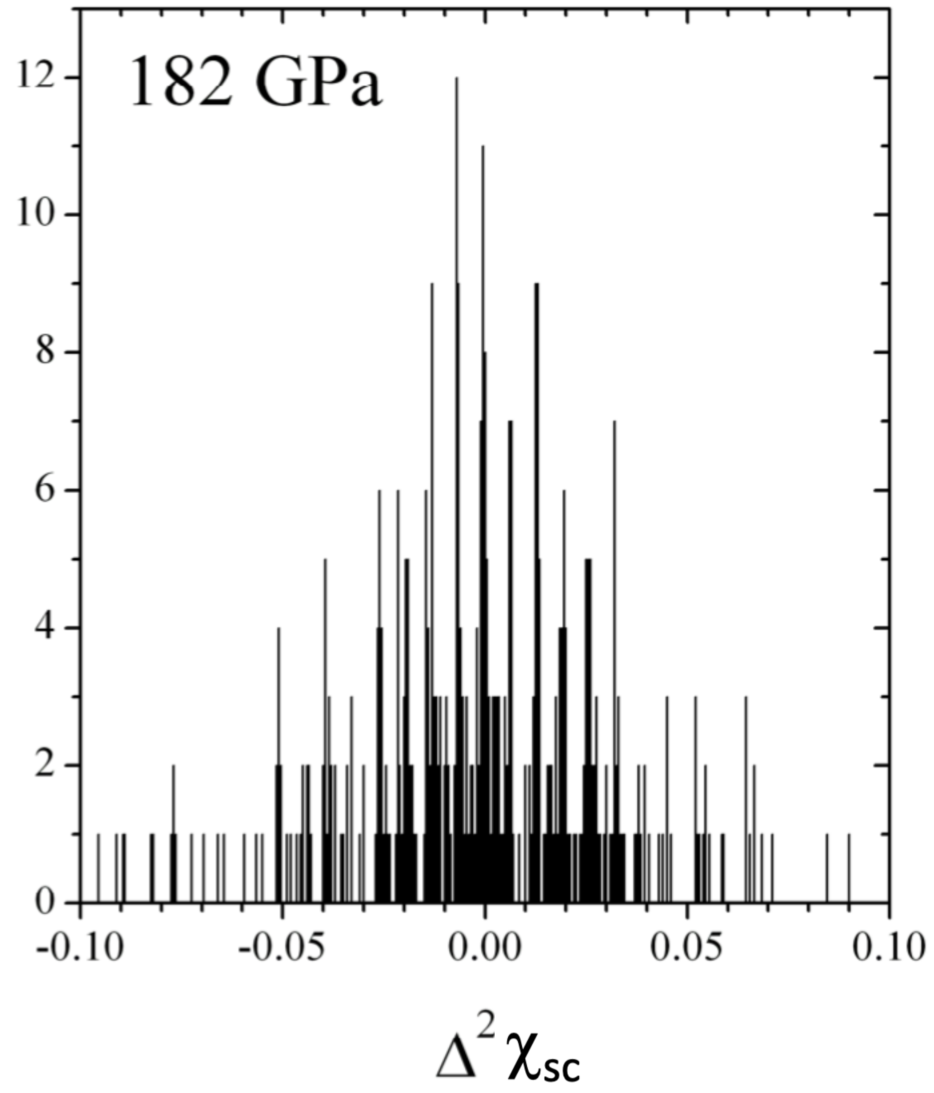




The "Superconducting Signal"

$$\Delta\chi(j) = \chi(j) - \chi(j-1)$$
$$\Delta^2\chi(j) = \Delta\chi(j) - \Delta\chi(j-1)$$





The "Superconducting Signal"

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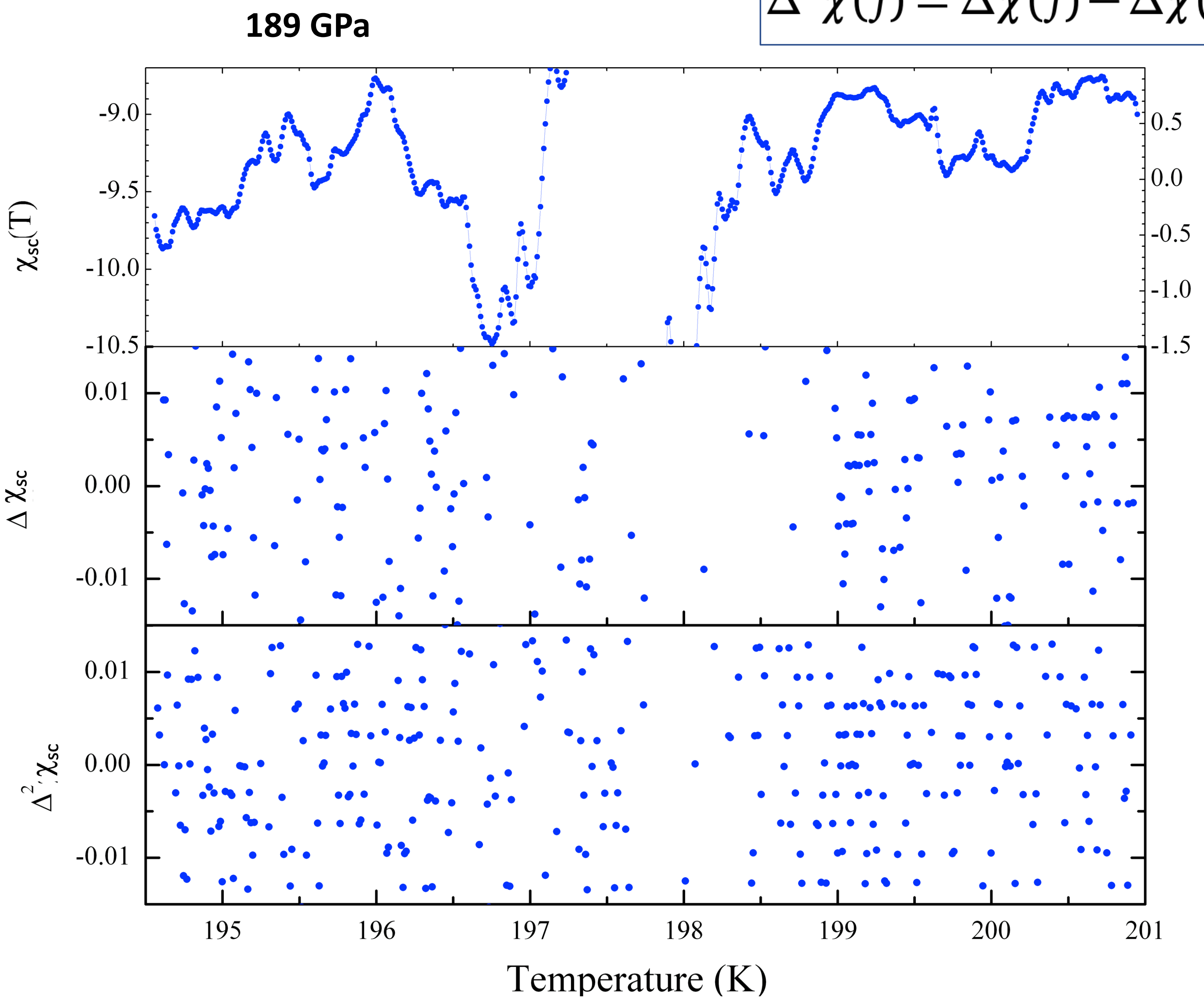
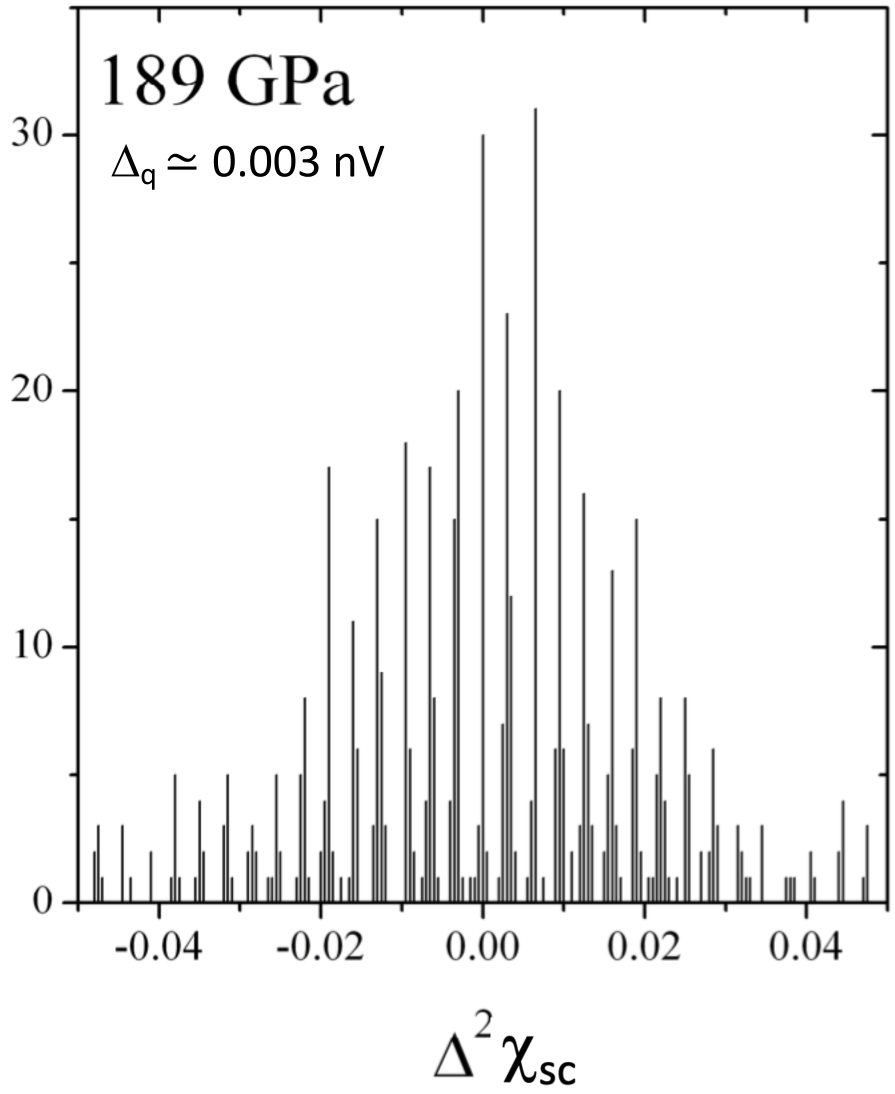
$$\Delta^2\chi(j) = \Delta\chi(j) - \Delta\chi(j-1)$$

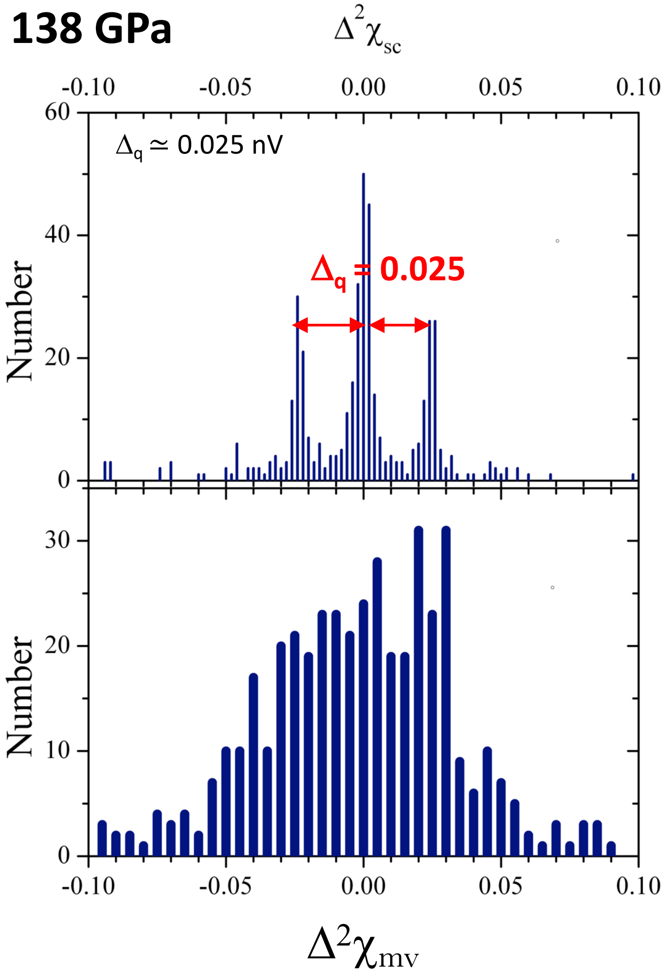


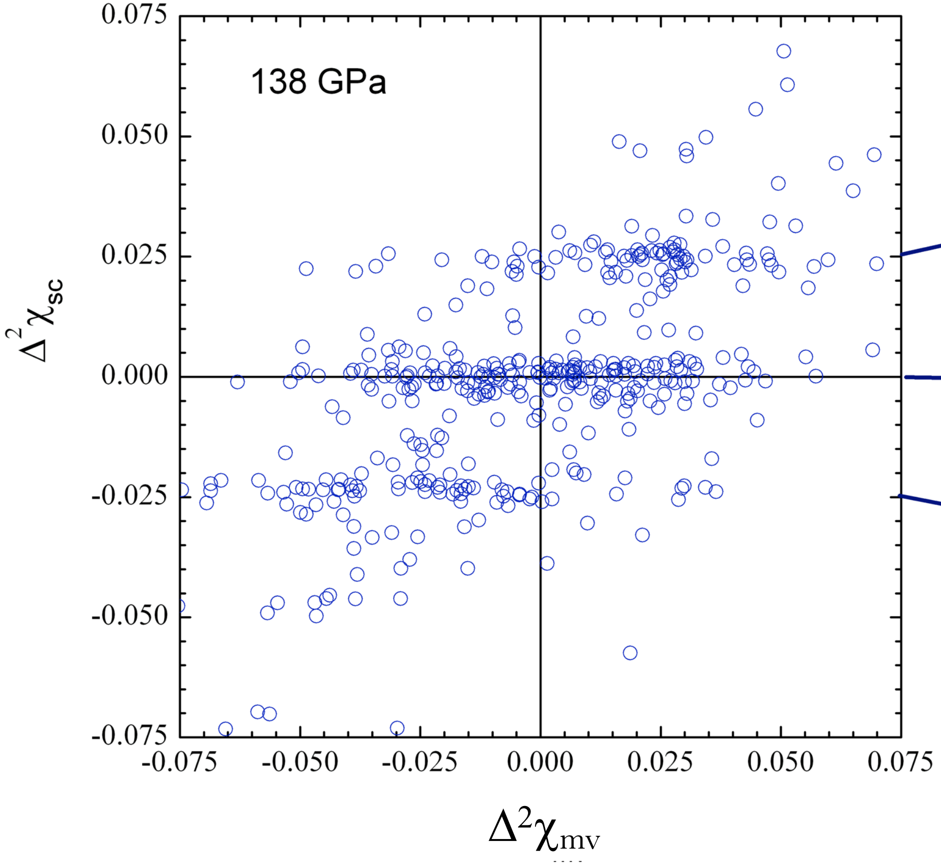


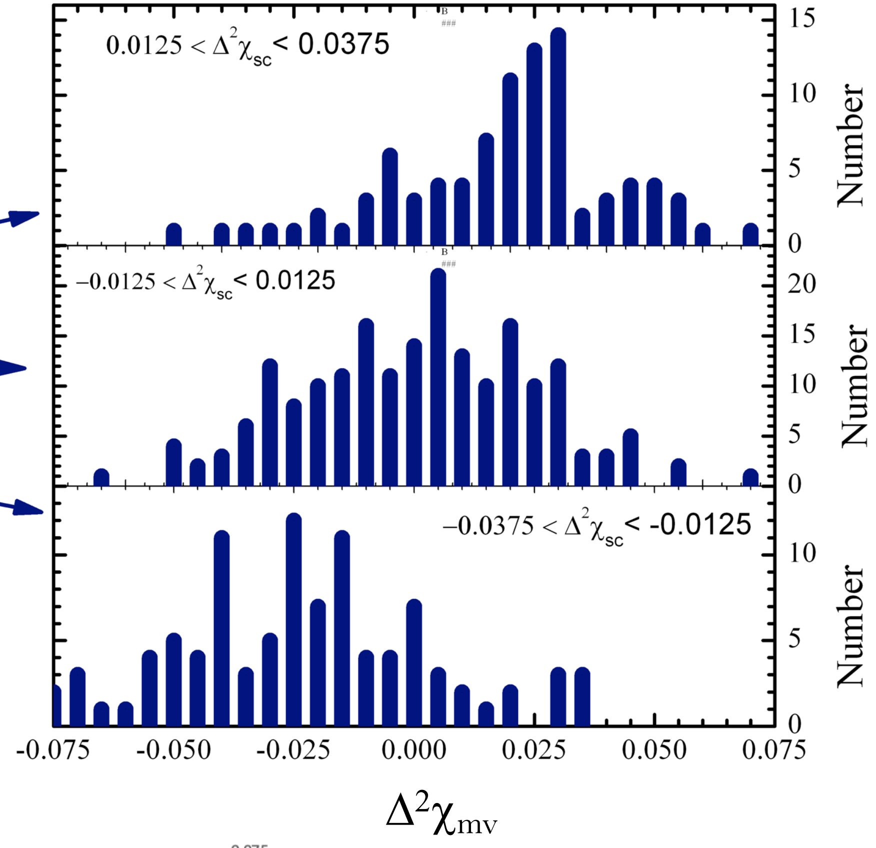
All 6 pressures

2) Measured Voltage («raw data»)

Correlation between $\Delta^2\chi_{mv}$ and $\Delta^2\chi_{sc}$

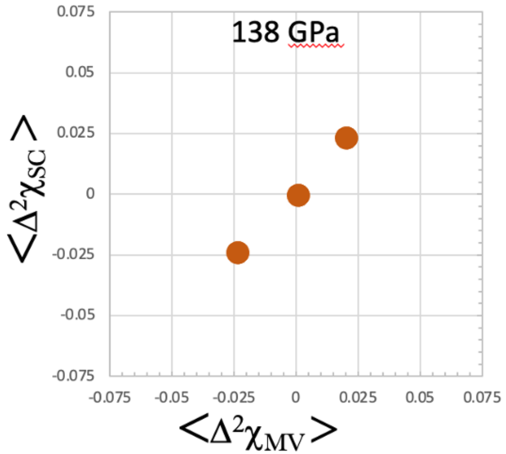




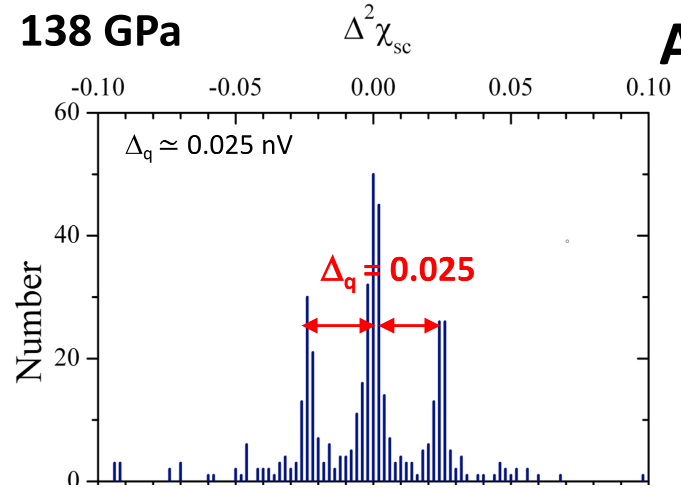


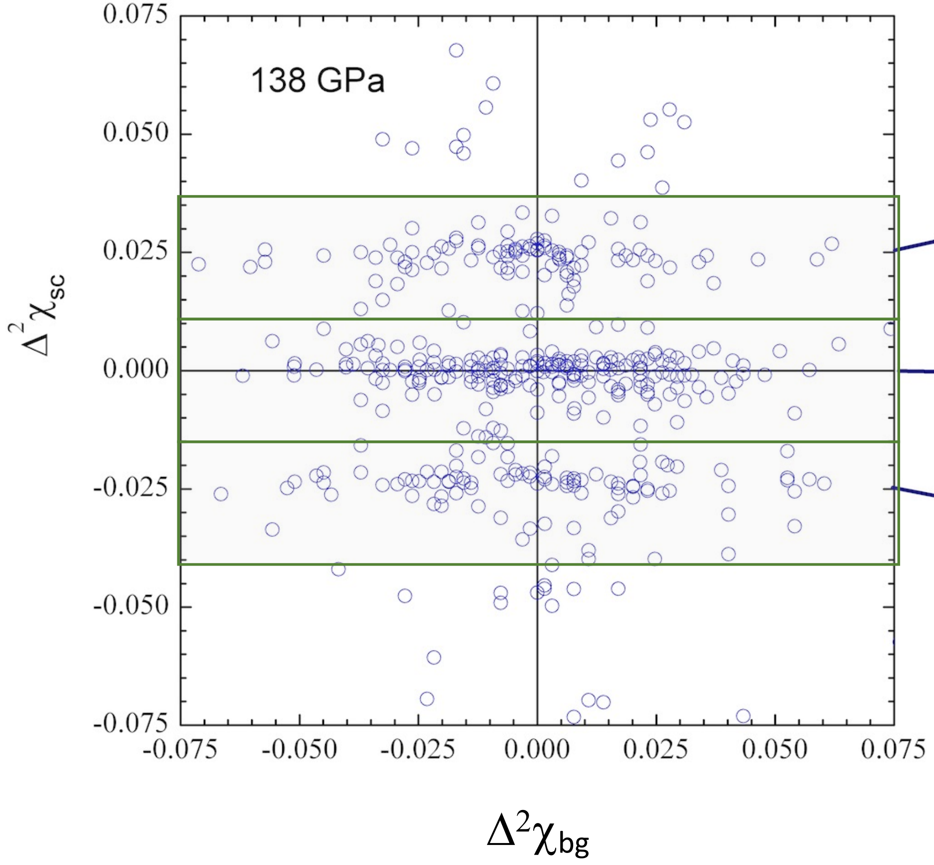
The q(T) component of χ_{sc} is equally strong in χ_{mv}

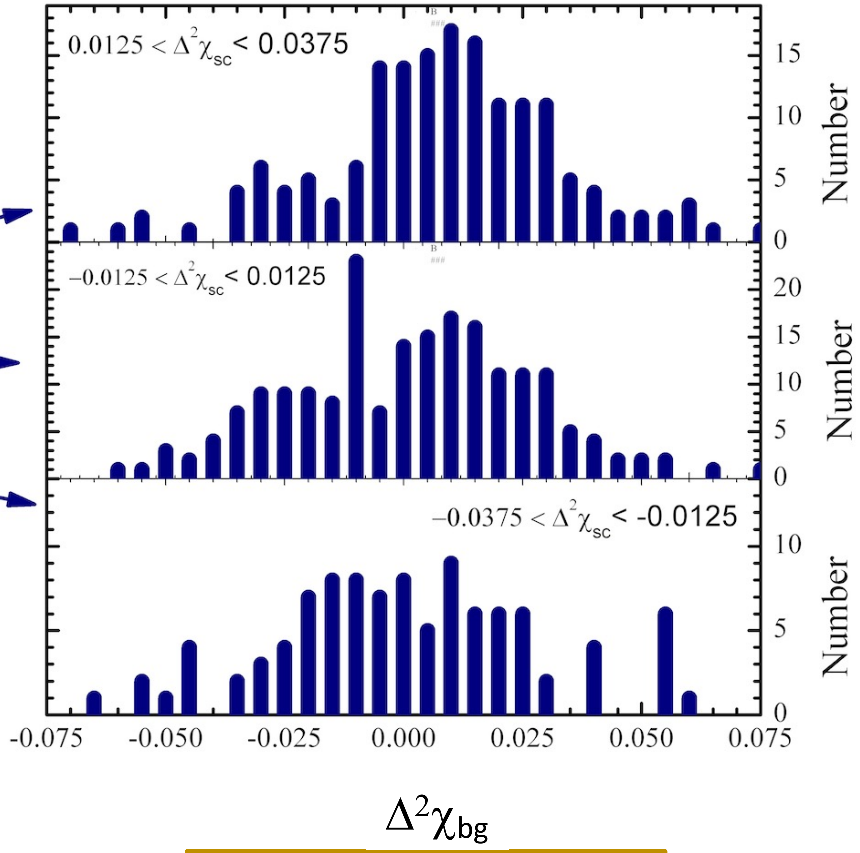
- The 0.025 nV steps are also present in χ_{mv}
- The steps in χ_{mv} and in χ_{sc} occur for the same temperatures
- They have, apart from noise in χ_{mv}, the same vertical step-size

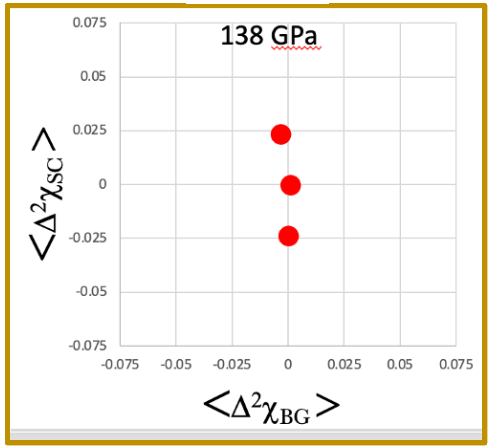


Absence of correlation between $\Delta^2\chi_{bg}$ and $\Delta^2\chi_{sc}$



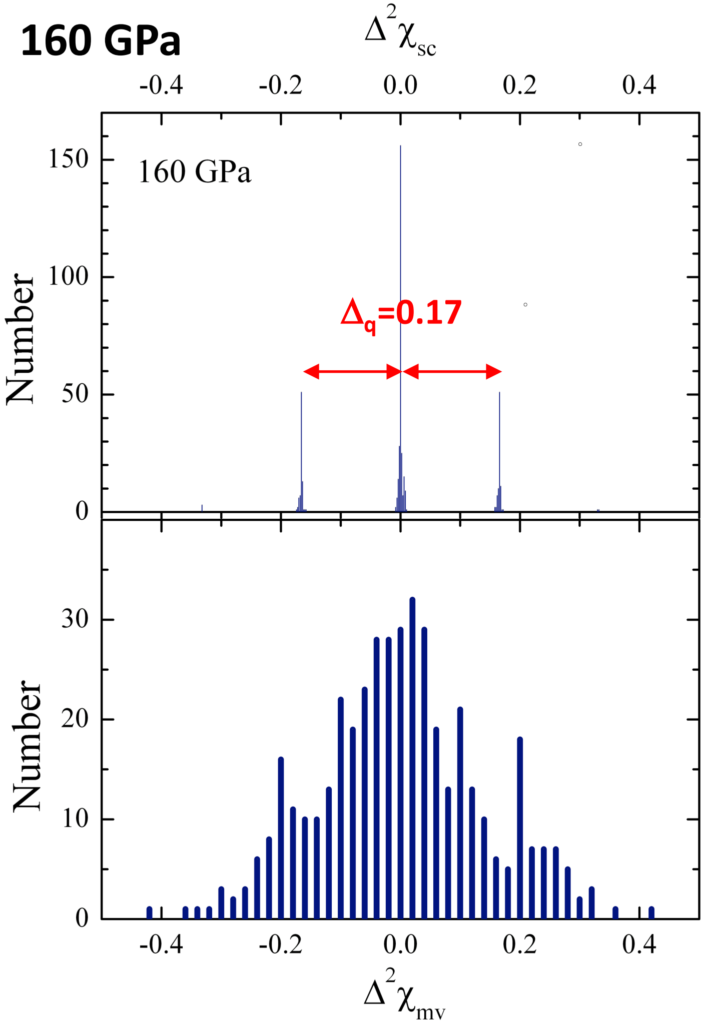


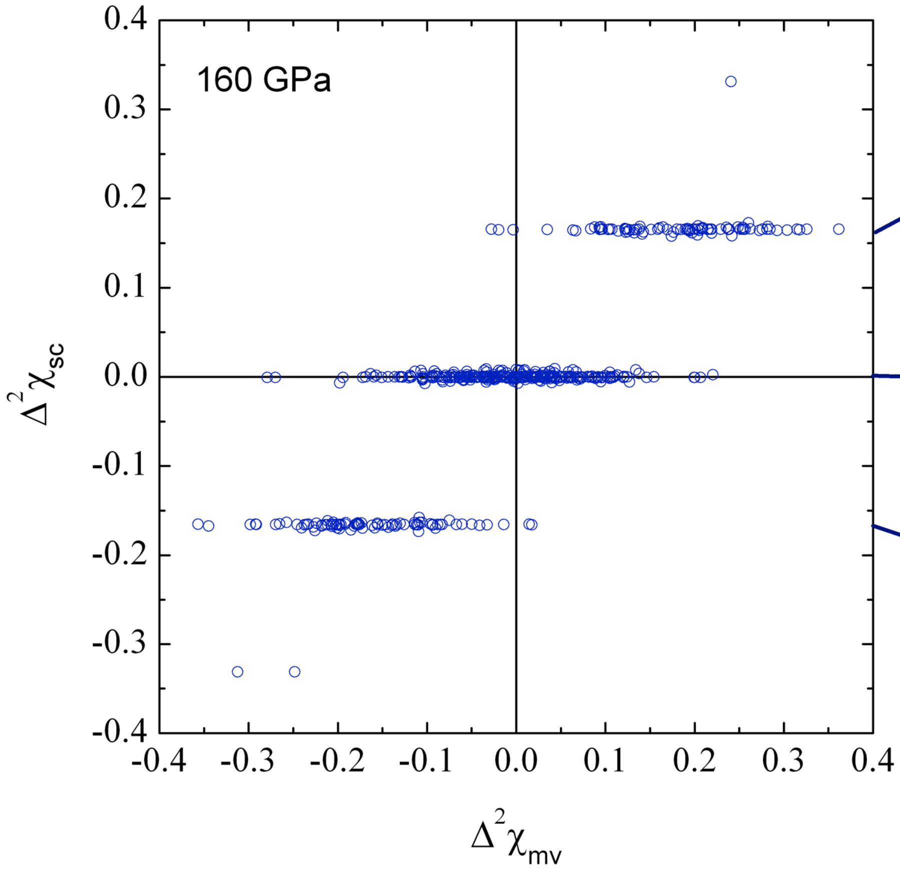


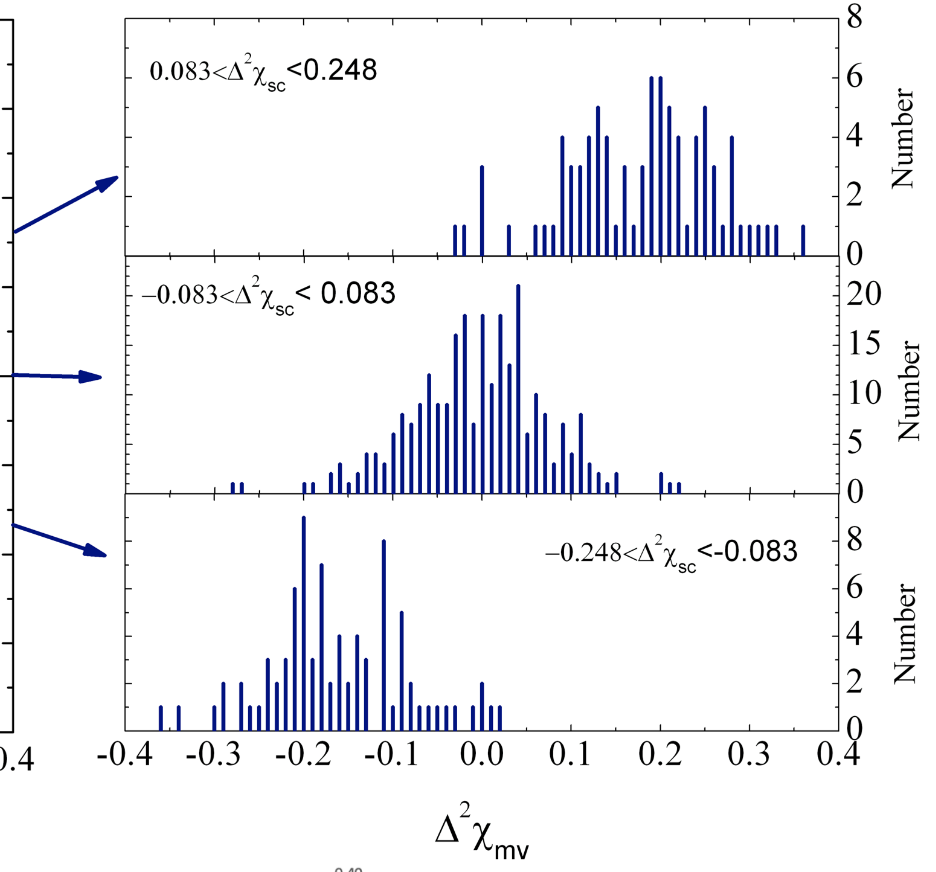


The q(T) component of χ_{sc} does not show up in χ_{bg}

Correlation between $\Delta^2\chi_{mv}$ and $\Delta^2\chi_{sc}$

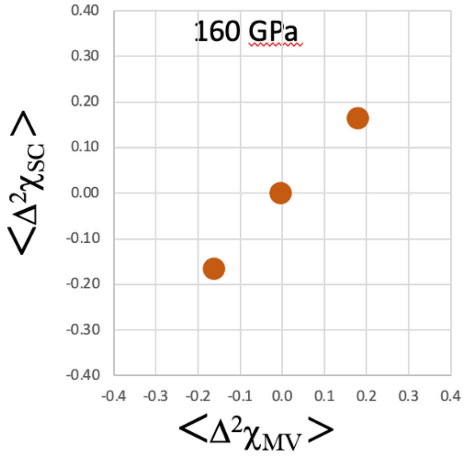






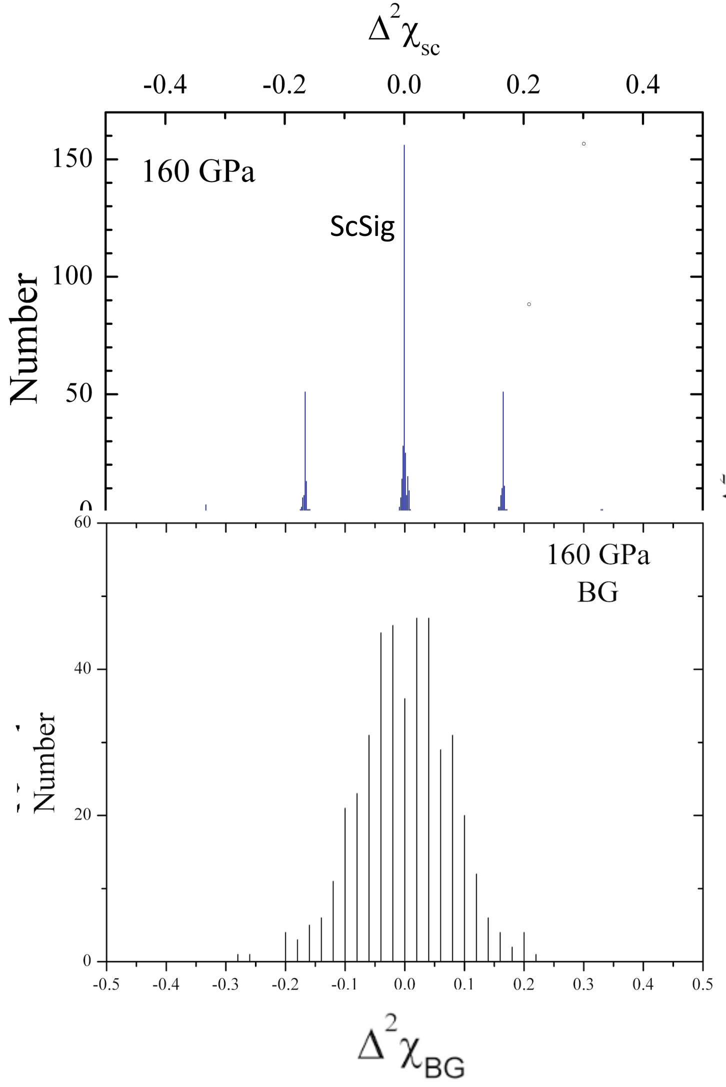
The q(T) component of χ_{sc} is equally strong in χ_{mv}

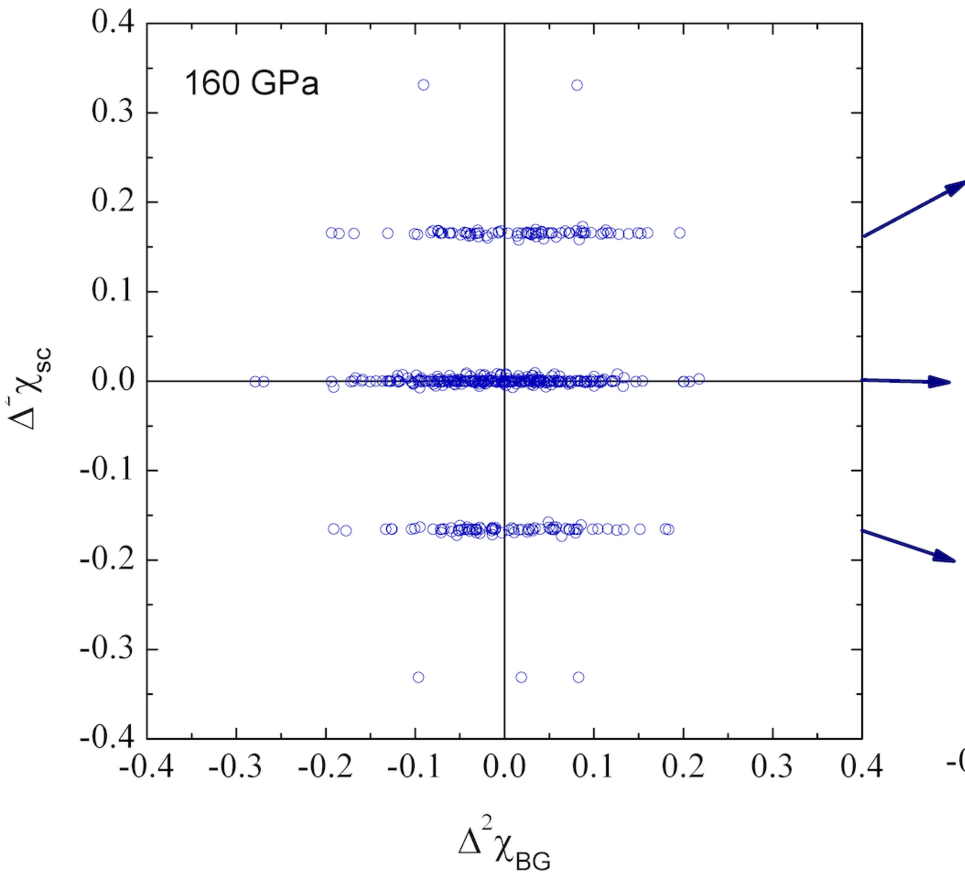
- The 0.17 nV steps are also present in χ_{mv}
- The steps in χ_{mv} and in χ_{sc} occur for the same temperatures
- They have, apart from noise in χ_{mv}, the same vertical step-size

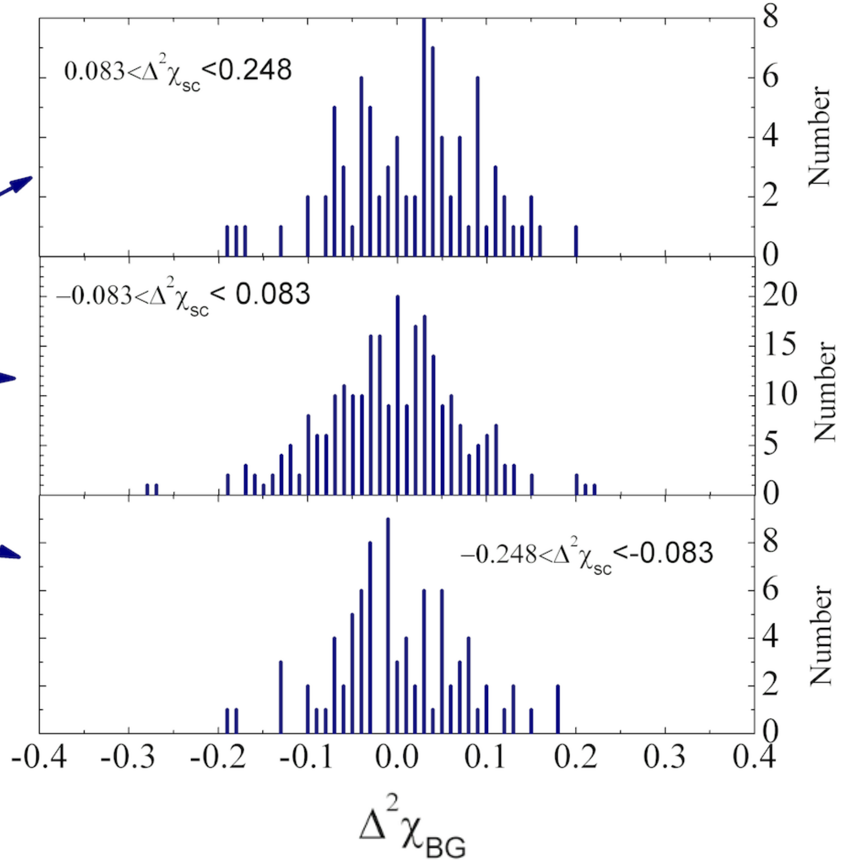


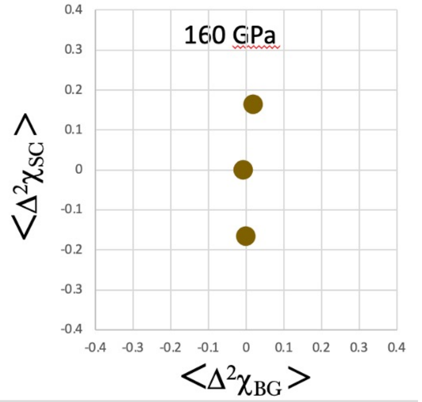
160 GPa

Absence of correlation between $\Delta^2\chi_{bg}$ and $\Delta^2\chi_{sc}$

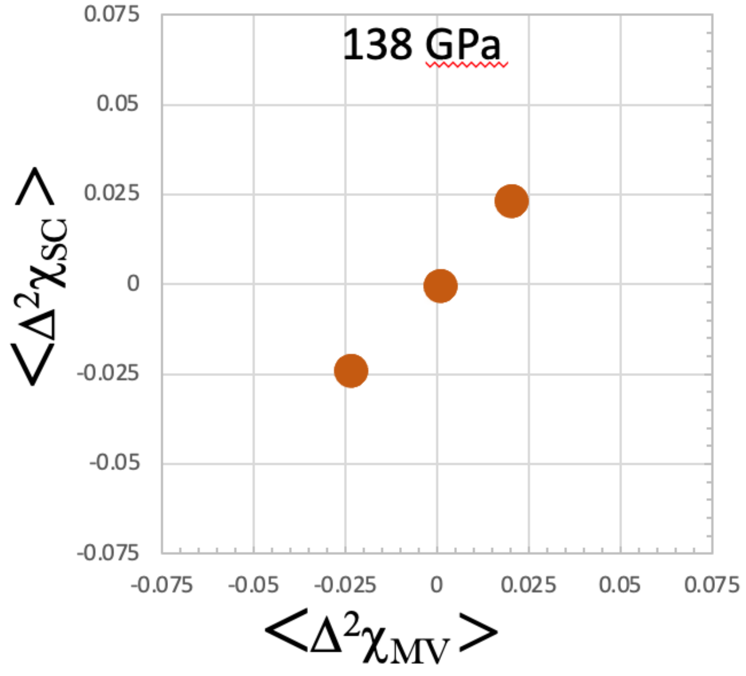


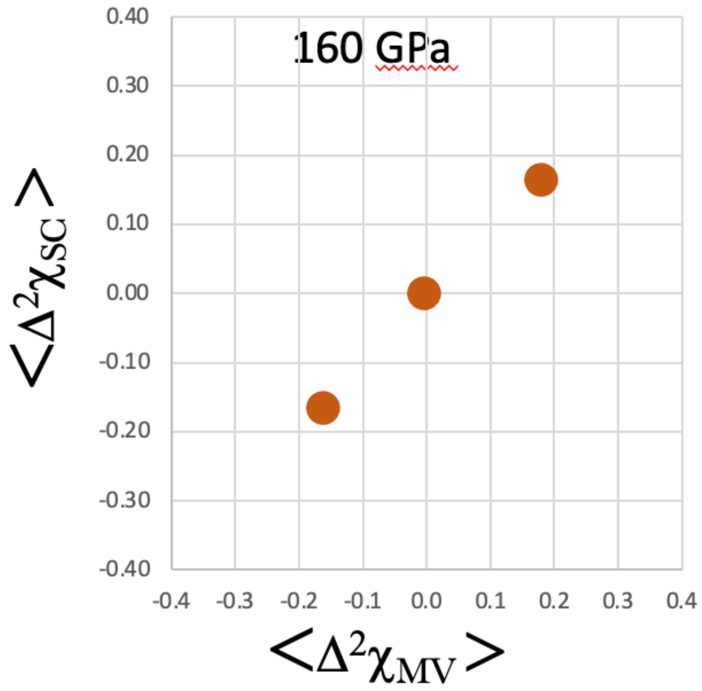




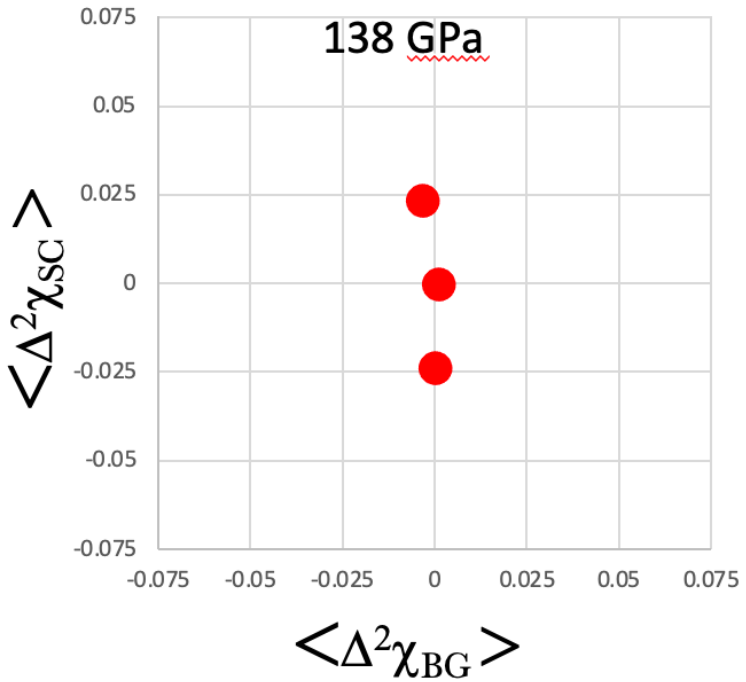


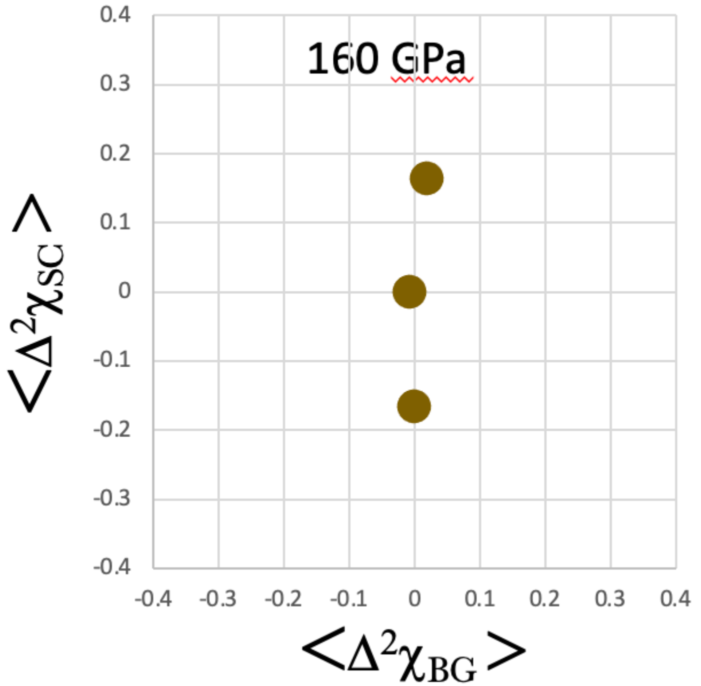
The q(T) component of χ_{sc} does not show up in χ_{bg}





The q(T) component of χ_{sc} is equally strong in χ_{mv}





The q(T) component of χ_{sc} does not show up in χ_{bg}

Summary for all 6 pressures

- While for each of the pressures 166, 178, 182 and 189 GPa χ_{sc} contains a component *q(T),* the noise of χ_{mv} is too strong to obtain a statistically significant signature of $q(T)$ in χ_{mv}.

- For 138 and 160 GPa χ_{mv} contains, superimposed on a noisy background signal, the steps of size Δ_q at the same temperatures as the steps of χ_{sc}.

- The background correction procedure $\chi_{sc} = \chi_{mv} - \chi_{bg}$ should somehow distill the pathological component $q(T)+P(T)$ out of χ_{mv}.

- The latter component is apparently identified as the superconducting signal: $\chi_{sc} = q(T) + P(T)$.

Protocol 1

E. Snider et al , *Nature* **586**, 373 (2020).

"The background signal, determined from a non-superconducting CSH sample at 108 GPa, has been subtracted from the data."

Protocol 2

R. P. Dias & A. Salamat, *arXiv*:**2201**.11883 (28.1.2022).

“We note here that we did not use the measured voltage values of 108 GPa as the background.”

“We use the temperature dependence of the measured voltage above and below the T_c of each pressure measurement and scale to determine a user defined background”

“The user defined background for subtraction is qualitative in nature and does not represent a physical quantity”

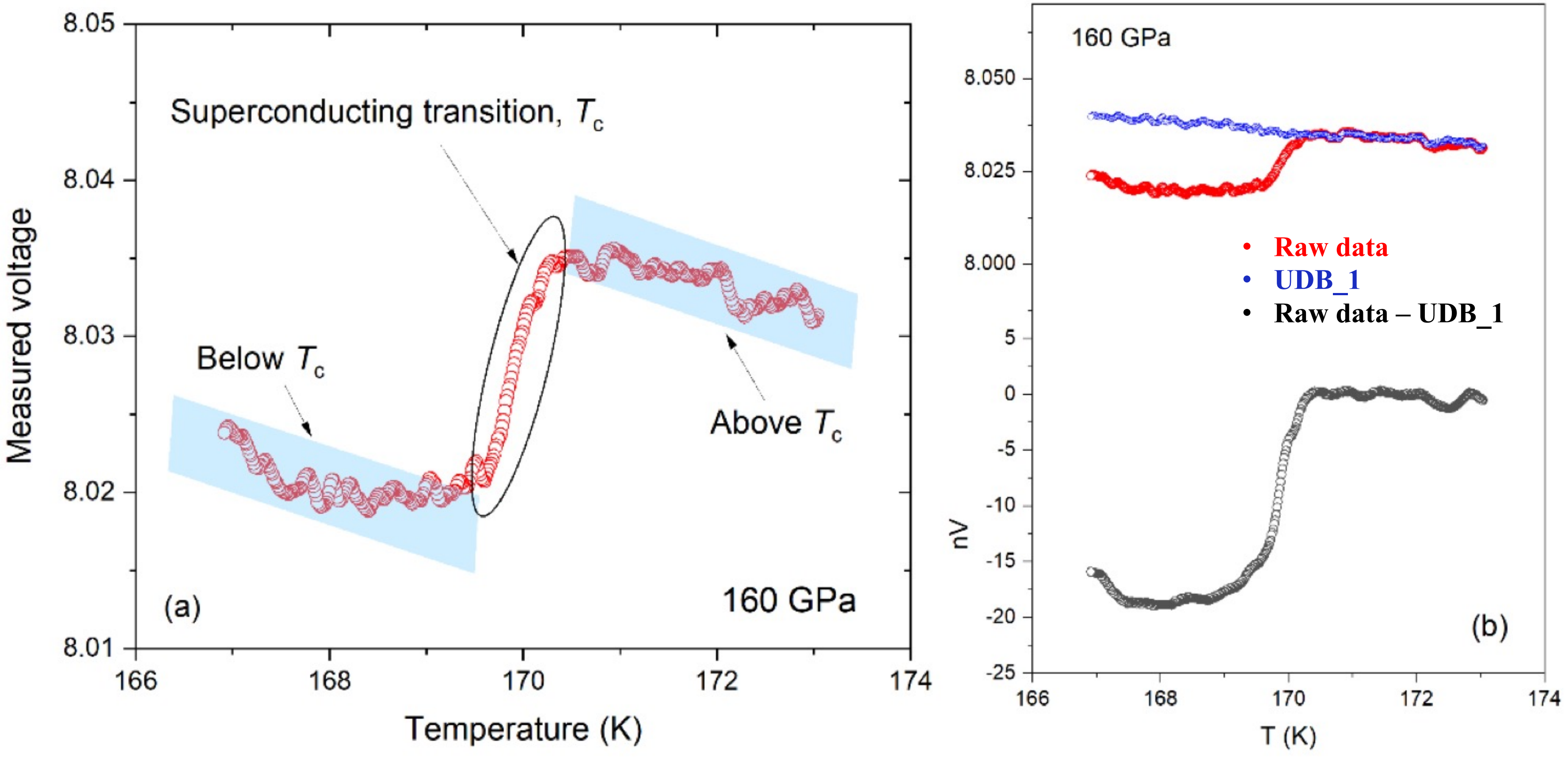


***Fig. 2** AC susceptibility data.*

(a) Raw data measured at 160 GPa. The profile of the regions highlighted in blue are used as part of the UDB_1.

(b) Measured voltage from the susceptibility measurement.

Protocol 3 is, to the best of our knowledge, the only protocol which is consistent with all the aforementioned properties of $\chi_{sc}(T)$ and $\chi_{mv}(T)$

- A "superconducting signal" $\chi_{sc}(T)$ is generated as the superposition of a quantized component $q(T)$ and a smooth function $P(T)$: $\chi_{sc}(T) = q(T)+P(T)$.

- A function $\chi_{bg}(T)$ is determined.

- The "measured voltage" $\chi_{mv}(T)$ is generated as the superposition of $\chi_{bg}(T)$ and the "superconducting signal": $\chi_{mv}(T) = \chi_{sc}(T) + \chi_{bg}(T)$.

Summary

- The susceptibility data in *Nature* **586**, 373 (2020) are pathological.

- The underlying raw data which were made publicly available one year later are, at least in part, also pathological.

- The method by which these data were obtained is not correctly described in the paper. One and half year after the publication two of the authors provided a different description of the analysis method which
  (i) is contrary to good practice
  (ii) is insufficiently documented, preventing others from reproducing the results
  (iii) doesn't explain the pathological nature of the published data and part of the underlying raw data.

Consequences for scientific progress

- Physics is about phenomena that can be reproduced under identical conditions. For this to be possible it is of crucial importance that scientific publications provide an accurate description of the methods of data acquisition and analysis, and of the data themselves. The incomplete and contradictory information provided in *Nature* **586**, 373 (14.10.2020), *arXiv*:**2111**.15017 (25.12.2021) and *arXiv*:**2201**.11883 (28.1.2022) prevents other scientists from reproducing and/or verifying the claimed room temperature superconductivity in CSH.

- Scientists worldwide, theoreticians as well as experimentalists, have been motivated to explain these results, reproduce these results, and to do new research motivated by the claim of room temperature superconductivity in *Nature* **586**, 373 (2020). This claim is, unfortunately, ill-substantiated.