

# Emission is complicated: the beauty of resonant inelastic light scattering - in the lab with Aron

**Ursula Wurstbauer** 

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www.wurstbauer-nanoelectronics.d









"when can you start at Columbia - in 3 months or sooner?"

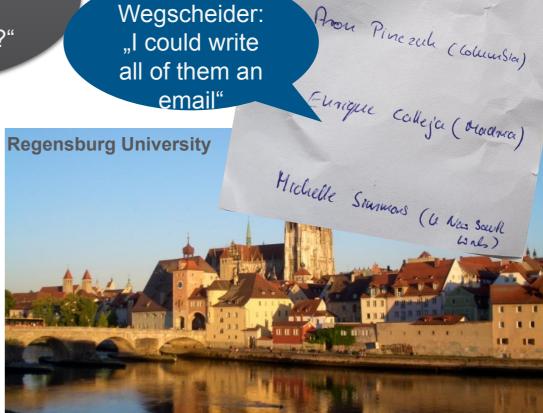
... the way my journey with Aron started

Joshua Folh (UBA)

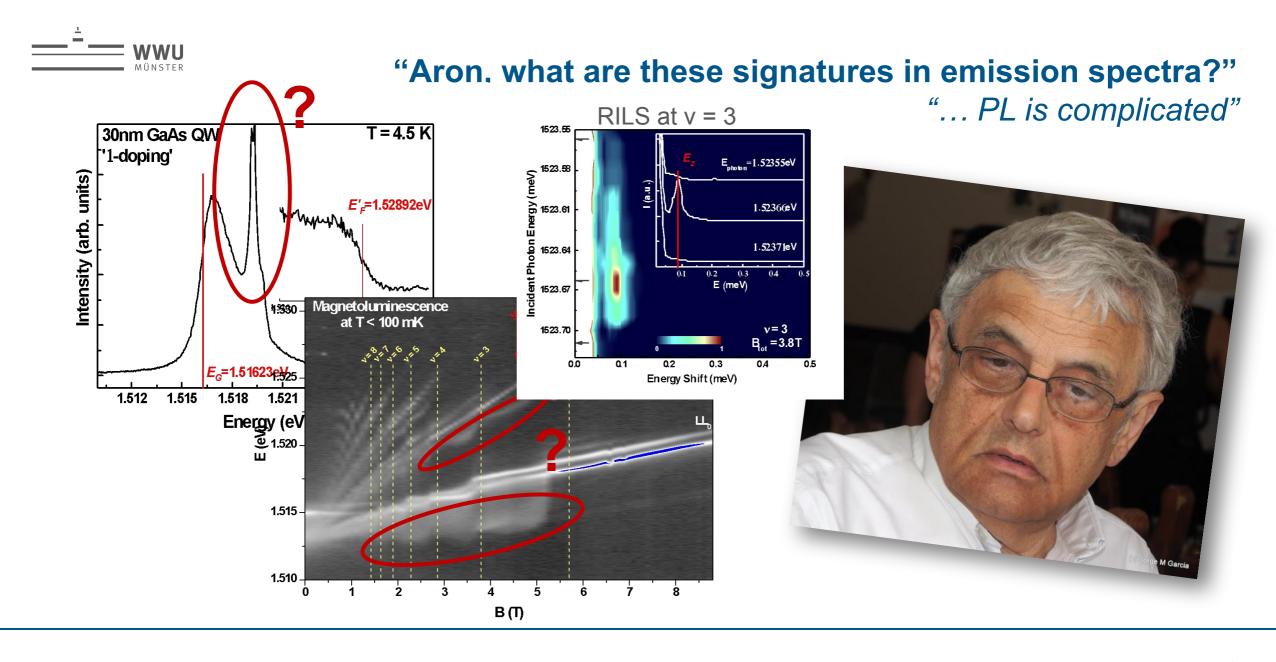


to do a postdoc broad. Do you ere I could go?"

Wegscheider:
"I could write
all of them an

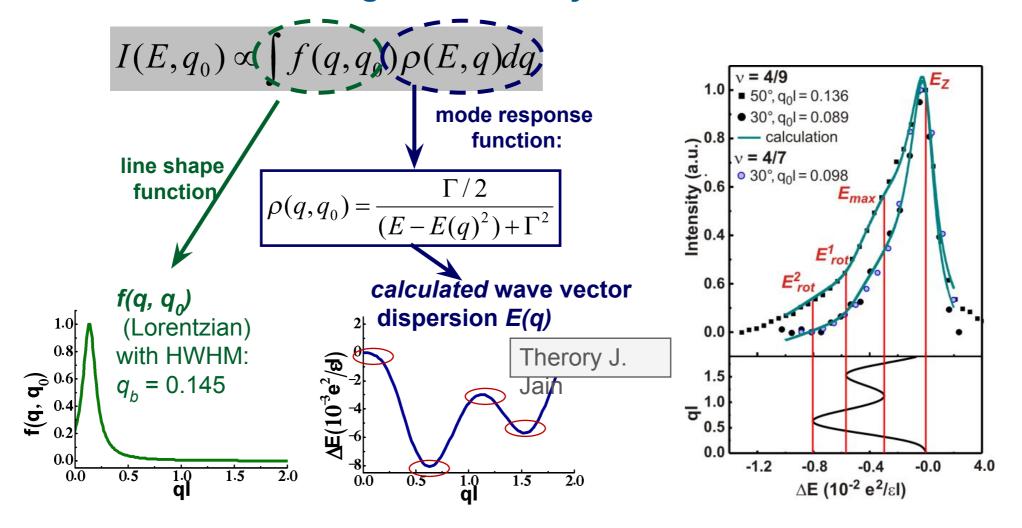








## "the strength and beauty of RILS on collective excitations"



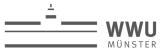


# "running on sugar"

# dark, because it is healthier – but not too dark ⊕



Ursula Wurstbauer 5



# "running on sugar"

# Transforming dark swiss chocolate in PRL and other paper

week ending 5 AUGUST 2011

PHYSICAL REVIEW LETTERS

Observation of Nonconventional Spin Waves in Composite-Fermion Ferromagnets PRL 107, 066804 (2011)

U. Wurstbauer, 1,\* D. Majumder, 2 S. S. Mandal, 2 I. Dujovne, 3 T. D. Rhone, 1 B. S. Dennis, 4 A. F. Rigosi, 1 J. K. Jain, 5 L. Wurstbauer, 1, 2 Dinoval, 1, 6 K. W. Wood, 7 and 1 N. Pfaiffor, 7 <sup>1</sup>Department of Physics, Columbia University, New York, New York 10027, USA

<sup>2</sup>Department of Theoretical Physics, Indian Association for the Cultivation of Science, Jadavpur, Kolkata 700 032, India

<sup>3</sup>Chemistry Department. University of Massachusetts. Amherst. Massachusetts 01003. \*Department of Physics and Astronomy, Rutgers University, Piscataway, New Jersey 08854, USA

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\*Department of Physics Department, Pennsylvania State University, University Park, Pennsylvania University, University Park, New York 10027. USA

\*Department of Annied Physics and Annied Math. Columbia University. New York New York 10027. Chemistry Department, University of Massachusetts, Amherst, Massachusetts 01003, USA
 Department of Physics and Astronomy, Rutgers University, Piscataway, New Jersey 08854, USA
 Laboratory, Dissiparations, Population State Haisarcine, University Park, Pomoulvania 169

Davey Laboratory, Physics Department, Pennsylvania State University, University Park, Pennsylvania 16802, USA

Davey Laboratory, Physics Department, Pennsylvania State University, New York, New York 10027, USA

Columbia University, New York, New York 10027, USA

Department of Applied Physics and Applied Math, Columbia University, Princeton, New Jersey 08544, USA

Department of Applied Physics and Applied Math, Columbia University, Princeton, New Jersey 08544, USA

Department of Applied Physics Department, Princeton University, Published 2 August 2011)

PRL 110, 026801 (2013)

PHYSICAL REVIEW LETTERS

Resonant Inelastic Light Scattering Investigation of Low-Lying Gapped Excitations

U. Wurstbauer, 1,\* K. W. West, 2 L. N. Pfeiffer, 2 and A. Pinczuk 1.3 <sup>1</sup>Department of Physics, Columbia University, New York, New York 10027, USA <sup>2</sup> Electrical Engineering Department, Princeton University, Princeton, New Jersey 08544, 212-1 Physics and Applied Math, Columbia University, New York, New York A 20 April 2012; published 7 January 2013)

ressible quantum Hall fluid at

PHYSICAL REVIEW B 92, 241407(R) (2015) RAPID COMMUNIO

Gapped excitations of unconventional fractional quantum Hall effect states in the second Landau level

U. Wurstbauer, <sup>1,2,4</sup> A. L. Levy, <sup>3</sup> A. Pinczuk, <sup>3,4</sup> K. W. West, <sup>5</sup> L. N. Pfeiffer, <sup>5</sup> M. J. Manfra, <sup>6,7,8</sup>

Walter Schottky Institut and Physik-Department, Technische Universität München, 85748 Garching, Germany <sup>2</sup>Nanosystems Initiative Munich (NIM), Schellingstraße 4, 80799 München, Germany <sup>3</sup> Department of Physics, Columbia University, New York, New York 10027, USA

<sup>4</sup>Department of Applied Physics and Applied Mathematics, Columbia University, New York, New York 10027, USA <sup>3</sup>Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA

Department of Physics and Astronomy, Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, USA School of Materials Engineering, Birck Nanotechnology Center, Purdue University, West LaJayette, Indiana 47907, USA School of Electrical and Computer Engineering, Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, USA

We report the observation of low-lying collective charge and spin excitations in the second Landau level at  $\nu=2+1/3$  and also for the very fragile states at  $\nu=2+2/5$  and 2+3/8 in inelastic light scattering experiments. These modes exhibit a clear dependence on filling factor and temperature substantiating the unique access to the characteristic neutral excitation spectra of the incompressible fractional quantum Hall effect (FQHE) states. A detailed mode analysis reveals low-energy modes at around 70 reV and a sharn mode slightly below the

COMMUNICATIONS

ARTICLE

Received 22 Mar 2015 | Accepted 22 Oct 2015 | Published 26 Nov 2015

Fractionally charged skyrmions in fraction quantum Hall effect

Ajit C. Balram<sup>1</sup>, U. Wurstbauer<sup>2,3</sup>, A. Wójs<sup>4</sup>, A. Pinczuk<sup>5</sup> & J.K. Jain<sup>1</sup>

week ending 11 JANUARY 2013 excitations, composite fermions, abelian and Fractionally charged skyrmions, which support c-like spin structure, have also been predicted to vest Landau level. The fractional skyrmions. agile, suppressed by very small Zeeman ener-1/3 filling, the smallest manifestations of the ctrum for a broad range of Zeeman energies, ring experiments as well-defined resonances ande. The spectroscopy of these exotic bound g the residual interaction between composite

I quantum Hall states in this filling factor

pired searches for exotic emergent topological

PHYSICAL REVIEW B 95, 085312 (2017)

Collective electronic excitation in a trapped ensemble of photogenerated holes revealed by inelastic light scattering

Sebastian Dietl, <sup>1,2</sup> Sheng Wang, <sup>3</sup> Dieter Schuh, <sup>4</sup> Werner Wegscheider, <sup>5</sup> Jörg P. Kottha Alexander W. Holleitner, 1.2.\* and Ursula Wurstbauer 1.2.1 Walter Schottky Institut und Physik Department, Am Coulombwall 4a, Technische Universität Münch <sup>2</sup>Nanosystems Initiative Munich (NIM), Schellingstrasse 4, 80799 München, Ge Department of Applied Physics and Applied Mathematics, Columbia University, New York, Anstitute of Experimental and Applied Physics, University of Regensburg, D-93040 Rege <sup>6</sup>Center for Nanoscience and Fakultät für Physik, Ludwig-Maximilians-Universität, Geschwister-Scholl-Pl Department of Physics, Columbia University, New York, New York 10027, 1 (Received 13 December 2016; published 27 February 2017)

 $Photogenerated\ excitonic\ ensembles\ confined\ in\ coupled\ GaAs\ quantum\ wells\ were\ probed\ by$ approach of emission spectroscopy and resonant inelastic light scattering. Lateral electron were used to create dense systems of spatially indirect excitons and excess holes with similar der of 10<sup>11</sup> cm<sup>-2</sup>. Inelastic light scattering spectra reveal a very sharp low-lying collective mode th of to chi . The most content is specific to the a very small non-ying contents have an energy of 0.44 meV and a full width at half maximum of only  $\sim$ 50  $\mu$ eV. This mode is interp excitation of the excess hole system coupled to the photogenerated indirect excitons. The emisindirect excitons shifts under the application of a perpendicular applied electric field, with the qu Stark effect unperturbed from the presence of free charge carriers. Our results illustrate the potential of studying low-lying collective excitations in photogenerated exciton systems to explore the many-body phase diagrams

DOI: 10.1103/PhysRevB.95.085312

PHYSICAL REVIEW LETTERS 128, 017401 (2022)

Domain Textures in the Fractional Quantum Hall Effect

Ziyu Liu, 1,4 Ursula Wurstbauer, 2 Lingjie Du, 3 Ken W. West, 4 Loren N. Pfeiffer, 4 Danaster, 2 Observator Calumbia University New York Many York 19927 1984 Michael J. Manira, and Aron Pinczuke

Department of Physics, Columbia University, New York, New York 10027, USA

Department of Physics, Columbia University, New York, New York 1002/, USA
Institute of Physics, University of Münster, Wilhelm-Klemm-Straße 10, 48149 Münster, Germany \*\*Institute of Physics, University of Minster, Withelm-Klemm-Straße 10, 48149 Minster, Germany School of Physics, and National Laboratory of Solid State Microstructures, Nanjing University, Nanjing 210093, China Princeton University Princeton New Inventor 19844 1184 Physics, and National Laboratory of Solid State Microstructures, Nanying University, Nanying 2100 Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA

Spepariment of Physics and Astronomy, School of Materials Engineering, and School of Electrical and Computer Engineering,

Burdue University, Weet Laborate Indiana 47007 IVA

Department of Applied Physics and Applied Mathematics, Columbia University, New York, New York 1

issed 4 August 2021; revised 18 October 2021; accepted 12 December 2021; published 6 January 2022) Impacts of domain textures on low-tying in

(FQHE) systems are probed by resonant inelastic light scattering. We demonstrate that large domains of quantum fluids support long-wavelength neutral collective excitations with well-defined wave vector quantum minus support iong-wavelengui neutral conective exchancias with wear-termed v (momentum) dispersion that could be interpreted by theories for uniform phases. Access to dis-

PRL 116, 016801 (2016)

PHYSICAL REVIEW LETTERS

### Optical Emission Spectroscopy Study of Competing Phases of Electrons in the Second Landau Level

A. L. Levy, 1,4 U. Wurstbauer, 2,3 Y. Y. Kuznetsova, A. Pinczuk, 1,4 L. N. Pfeiffer, 5 K. W. West, M. J. Manfra, 6,7,8 G. C. Gardner, and J. D. Watson<sup>6</sup> Department of Physics, Columbia University, New York, New York 10027, USA

<sup>2</sup>Walter Schottky Institut and Physik-Department, Technische Universität München, Am Coulombwall 4a, 85748 Garchine, Germany <sup>3</sup>Nanosystems Initiative Munich (NIM), Munich, Germany

<sup>4</sup>Department of Applied Physics and Applied Mathematics, Columbia University, New York, New York 10027, USA <sup>5</sup>Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA

<sup>6</sup>Department of Physics and Astronomy, Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, USA School of Materials Engineering, Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, USA <sup>8</sup>School of Electrical and Computer Engineering, Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, USA

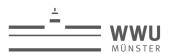
(Received 27 March 2015; published 8 January 2016)

Ouantum phases of electrons in the filling factor range  $2 \le \nu \le 3$  are probed by the weak optical emission from the partially populated second Landau level and spin wave measurements. Observations of

optical emission include a multiplet wave measurements by resonant ine are used to link this optical emission between emission peak intensities i

only one paper on PL!

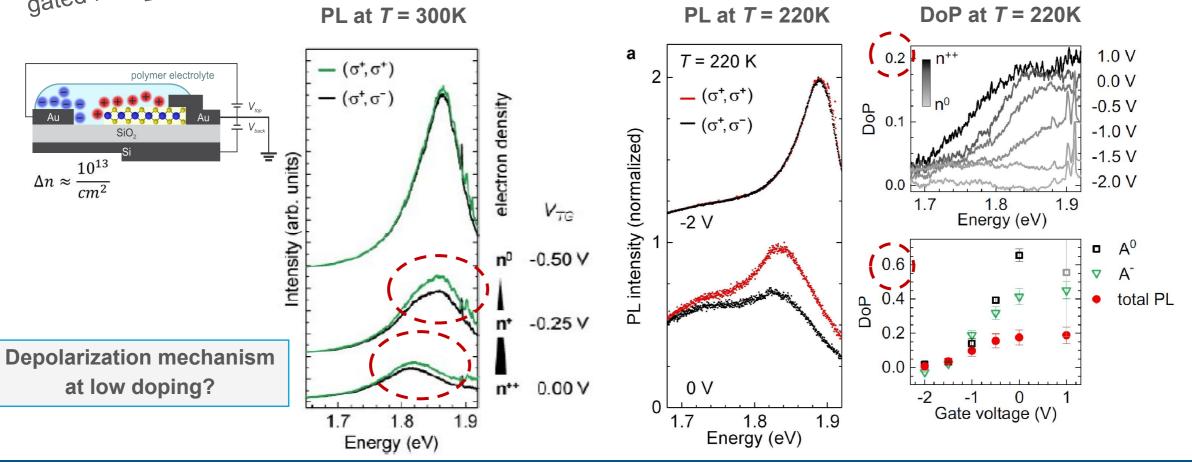
DOI: 10.1103/PhysRevLett.116.01680



# "PL is complicated"

Circularly polarization PL on gated MoS<sub>2</sub> monolayers

"... I am fully convinced and telling it to my students"

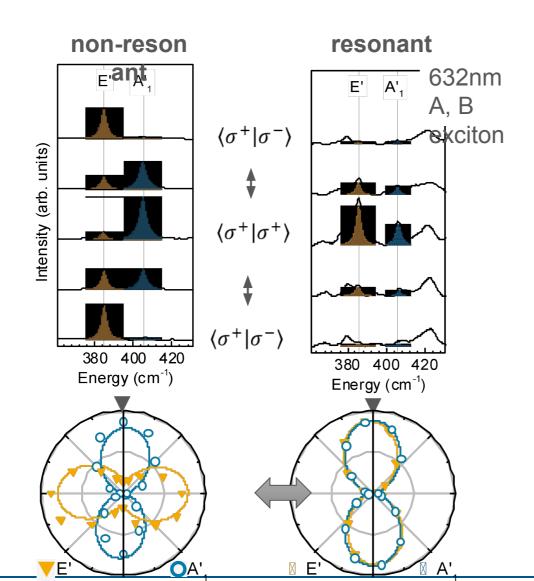


B. Miller, UW et al. APL. 106, 122103 (2015)

B. Miller, UW et al. Nature Commun. 10, 807 (2019).

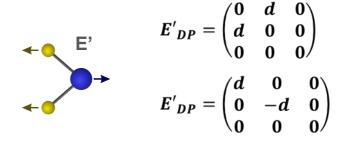


Circularly polarized Raman

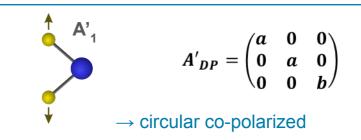


# "Insights from (R)ILS"

$$I \propto |e_s \cdot R \cdot e_i|^2$$



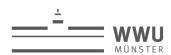
→ circular cross-polarized



Fröhlich coupling

$$E_{Fr\ddot{o}hlich} = \begin{pmatrix} c & 0 & 0 \\ 0 & c & 0 \\ 0 & 0 & c \end{pmatrix}$$

 $\rightarrow$  circular co-polarized



# Fröhlich exciton-phonon coupling

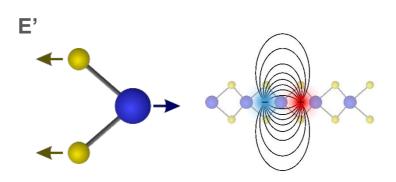
Circularly polarized Raman

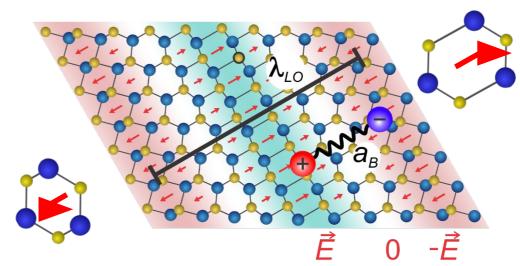
LO mode, polar

1s exciton

Fröhlich exciton-LO phonon coupling

(long range → macroscopic E-field)

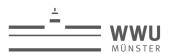




Fröhlich coupling

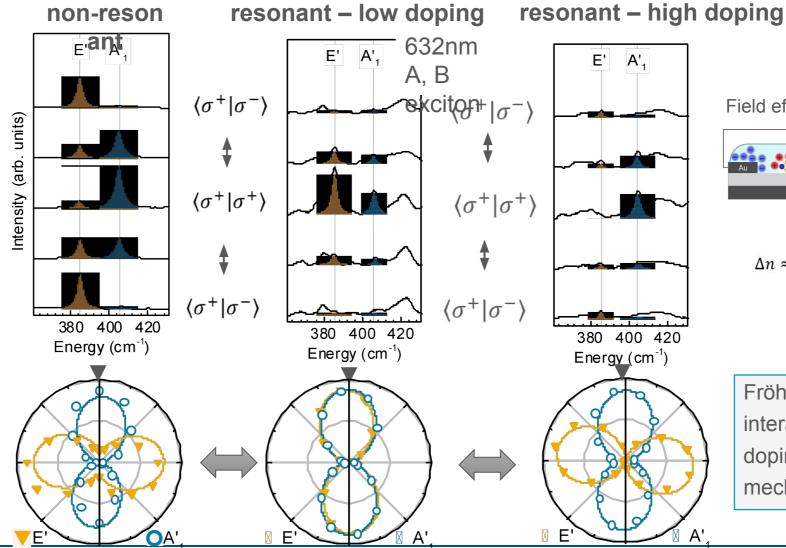
$$E_{Fr\ddot{o}hlich} = \begin{pmatrix} c & 0 & 0 \\ 0 & c & 0 \\ 0 & 0 & c \end{pmatrix}$$

→ circular co-polarized

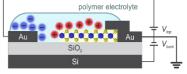


# "Insights from (R)ILS"

Circularly polarized Raman



Field effect devices:



$$\Delta n \approx \frac{10^{13}}{cm^2}$$

Fröhlich exciton-phonon interaction suppressed by doping and depolarization mechanism.



# Fröhlich exciton-phonon coupling

Fröhlich exciton-LO phonon coupling

PHYSICAL REVIEW LETTERS

24 FEBRUARY 1969

EXCITON-ENHANCED RAMAN SCATTERING BY OPTICAL PHONONS

E. Burstein\*† and D. L. Mills‡ Physics Department, University of California, Irvine, California

and

A. Pinczuk\* and S. Ushioda\* ics Department and Laboratory for Research on the Structure of Matter, University of Pennsylvania, Philadelphia, Pennsylvania (Received 16 September 1968)

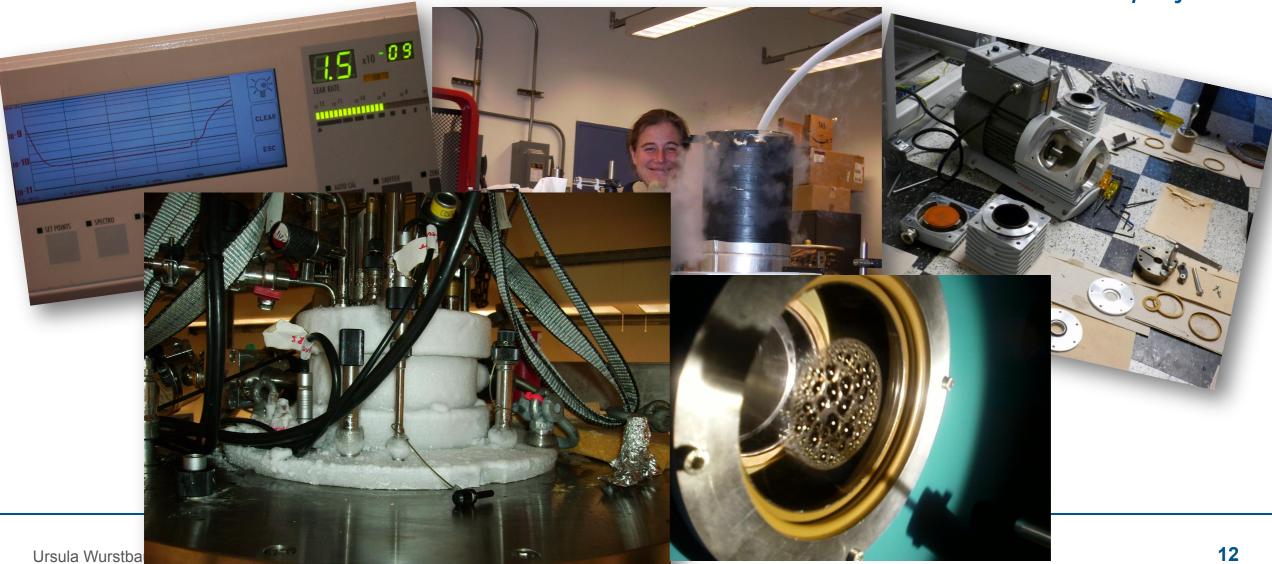
ne theory of exciton-enhanced Raman scattering is formulated in terms of the scattering of polaritons by optical phonons via the exciton part of the coupled modes. The expression for the exciton contribution to the scattering tensor is given, within a constant factor, in terms of the same parameters that determine the exciton contribution to the frequency-dependent dielectric constant. The theory also provides a new mechanism for

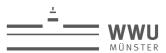
# in the lab with Aron



soccer, nuts, fun, tears and the question: "would you like to do a different

project"





### in the lab with Aron

soccer, nuts, fun, tears and lots of data





Ursula Wursi

# farewell celebrations from Columbia

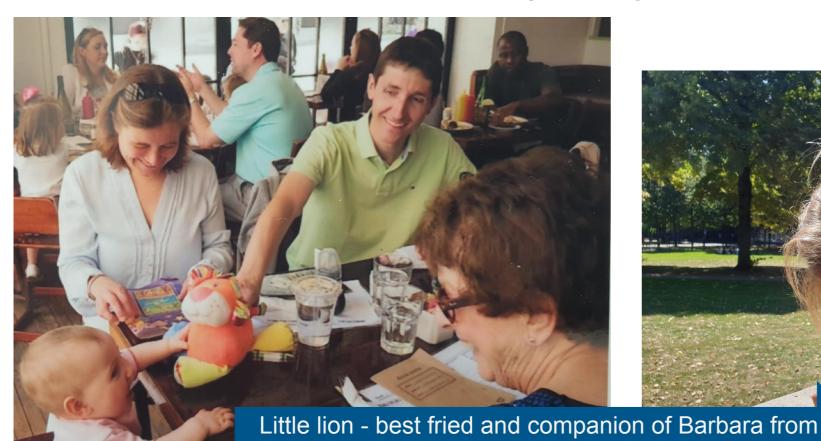
Going out for group lunch or dinner

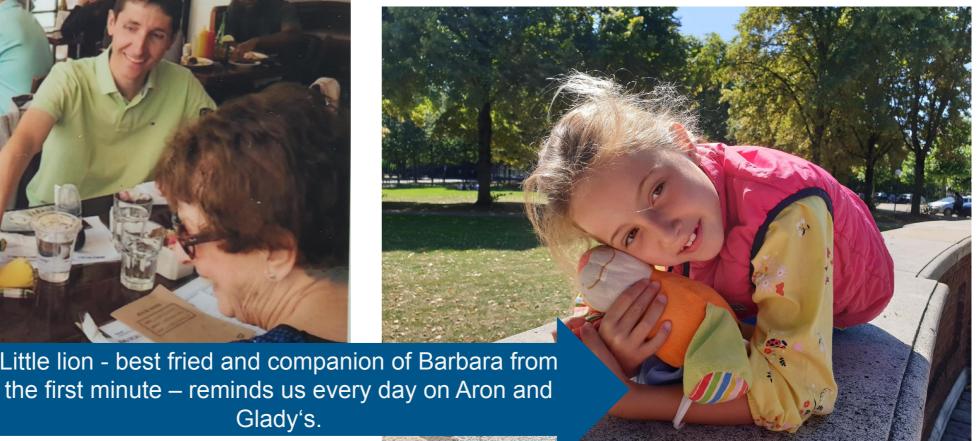




# Coming back to NYC after 2 years

immediately feeling welcome – thank you Aron and Glady's





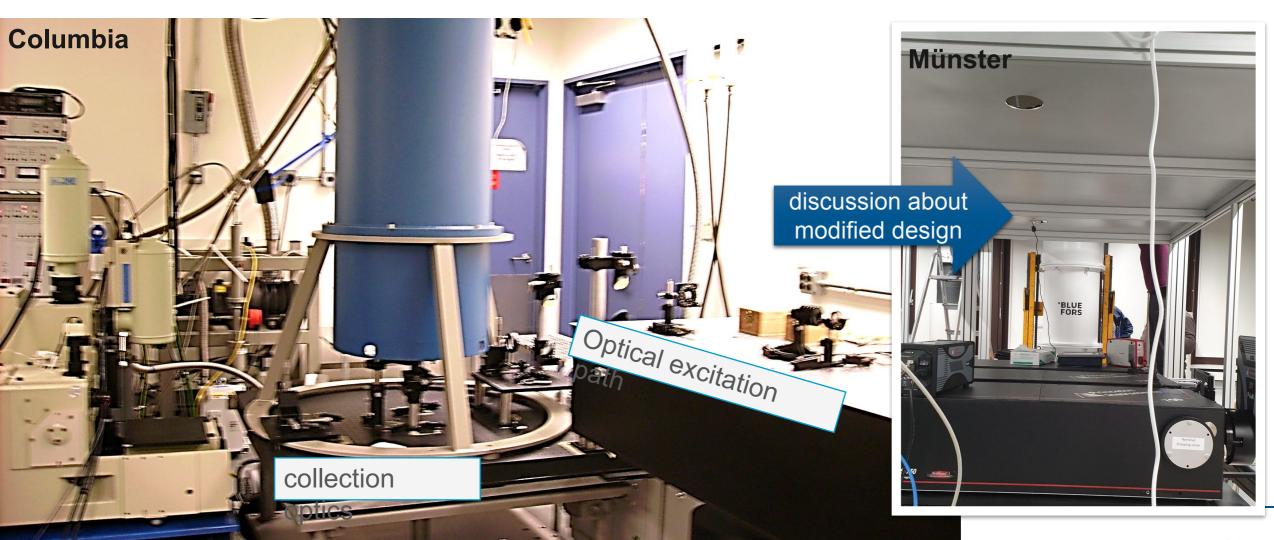
15 Ursula Wurstbauer

Glady's.



# True mentorship and support

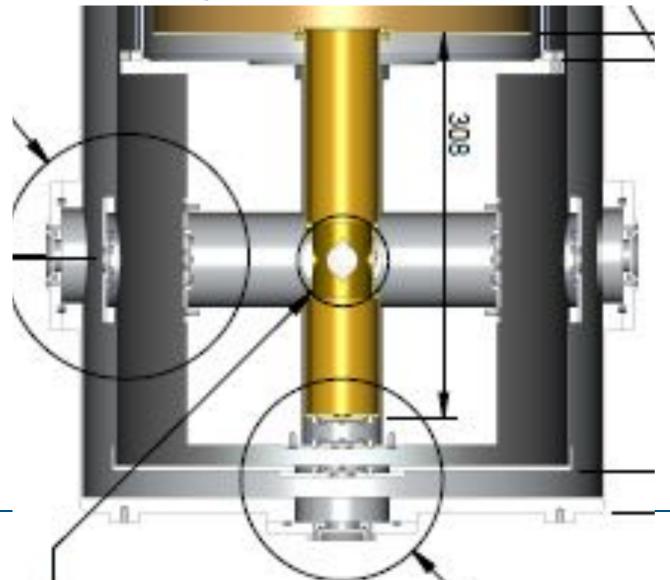
during a "lock-down" Zoom session between Pinczuk and Wurstbauer groups





# True mentorship and support

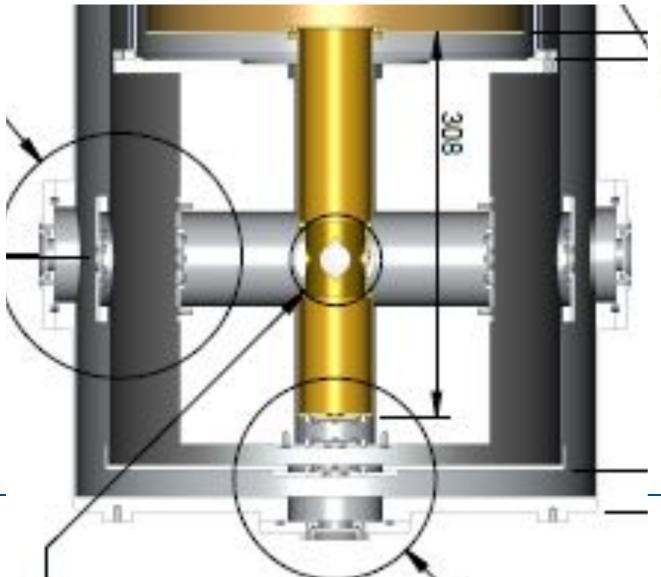
during a "lock-down" Zoom session between Pinczuk and Wurstbauer groups



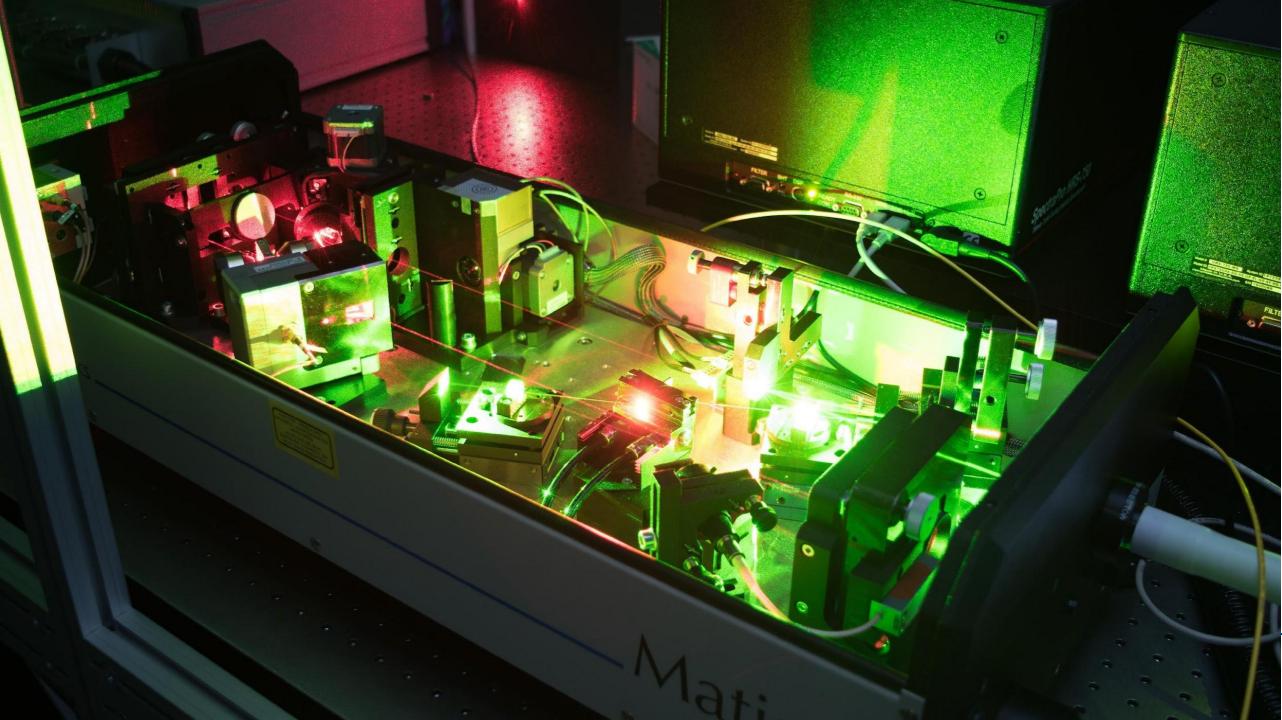


# True mentorship and support

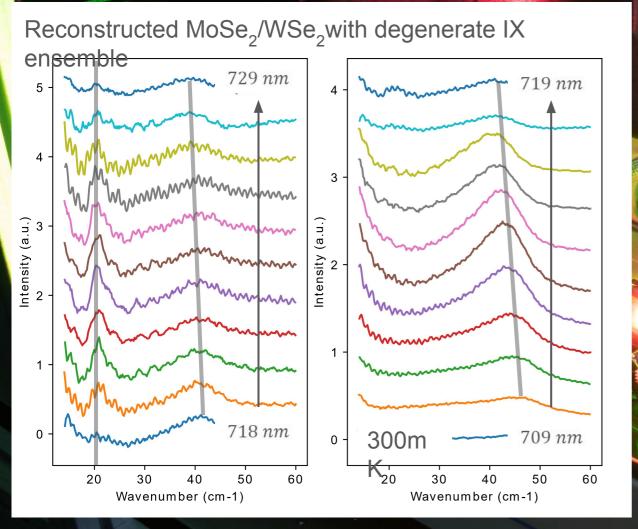
# during a "lock-down" Zoom session between Pinczuk and Wurstbauer groups



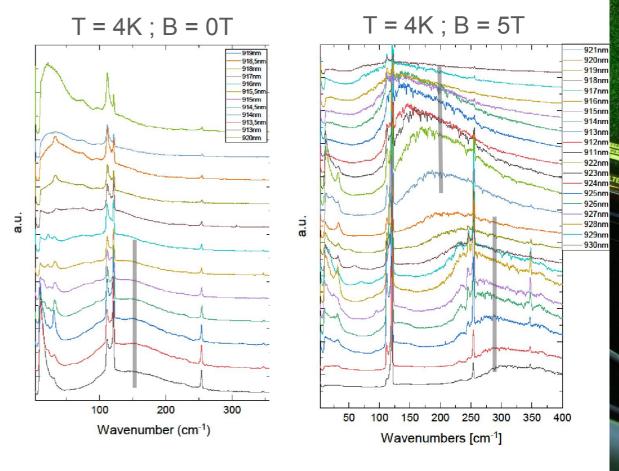
Optical Data	
clear aperture [mm]	4.7
focal length [mm]	2.87
numerical aperture(NA)	0.82
working distance	0.65 mm (1.40 mm)
Spectral Performance	
AR coating (> 80% trasnmission) [nm]	400 1000
apochromatic range (df < +/- delta) [nm]	565 770



fingerprints for collective excitation in van der Waals materials from mK-RILS



CrSBr – a layered magnetic semiconductor



Aron, thank you very much for teaching me and sharing the beauty of RILS – and for the continued support!



# A life for science and the science "family" & his students

AP

Mo 27.12.2021 16:11

Aron Pinczuk <ap359@columbia.edu>

Re: Season's Greetings

An ursula@wurstbauer.de

Cc apinczuk PNAS



is Sie haben am 29.12.2021 01:14 auf diese Nachricht geantwortet.

Dear Ursula,

Many thanks fo email and season's greeting You have a lovely family. You allook great!

This year my Holiday Season is complicated. This fall our teaching has been in-person. I am now very busy with calculating final grades and with related activities. In carrying out this work I neglected conventional contacts of the season.

Gladys and I hope you had a wonderful Christmas and Wish you a Very Happy New Year.

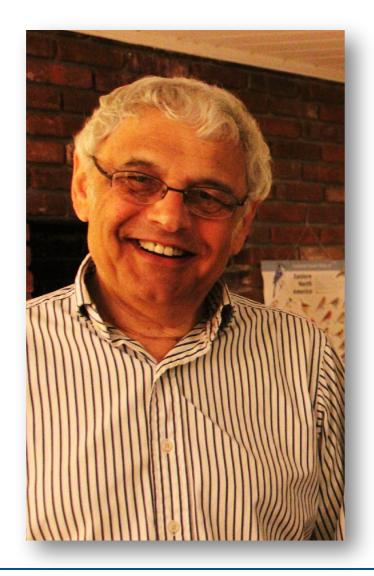
We got the NSF grant and Ziyu started training in the operation of the Kelvinox dil-fridge.

Shall we set up a Zoom session to talk about physics?

With kind regards,

Aron





Aron, I feel very privileged that I am part of your "science family". I truly acknowledge your great mentorship through all the years. Without you I would not be were I am now and I would not be the person I am today.

Thank you!

Ursula Wurstbauer 22