My more than three-decade physics collaboration with Aron Pinczuk

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Princeton University

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In 1987 Aron Pinczuk and I were both at Bell Labs in New Jersey.

Aron was one of the resident experts in optical studies of 2D electron systems
at the Holmdel campus,
And I was at Murray Hill, just starting to grow 2D electron systems using
gallium arsenide Molecular Beam epitaxy.

As my MBE quantum wells began to show more interesting
magneto-transport mobilities,
Bell Labs management brought the two of us together.

And a decades-long collaboration began!

Over the years I designed and grew by Molecular Beam Epitaxy
many quantum well structures for Aron.
And he rewarded me with detailed physics analysis
through his light-scattering experiments.

In this remembrance
I am going to focus on how Aron Pinczuk's ideas
and profound knowledge of optics,
deepened my understanding of the many imperfections
in the Q-well structures that I grew,
and helped me to improve my MBE techniques.

An early surprise I noticed in working with Aron, was that
he could deduce with his optics methods
the 2D-electron density
in the quantum wells that I grew for him,
so that my magneto-transport-density measurements
tended to confirm his optics-densities.

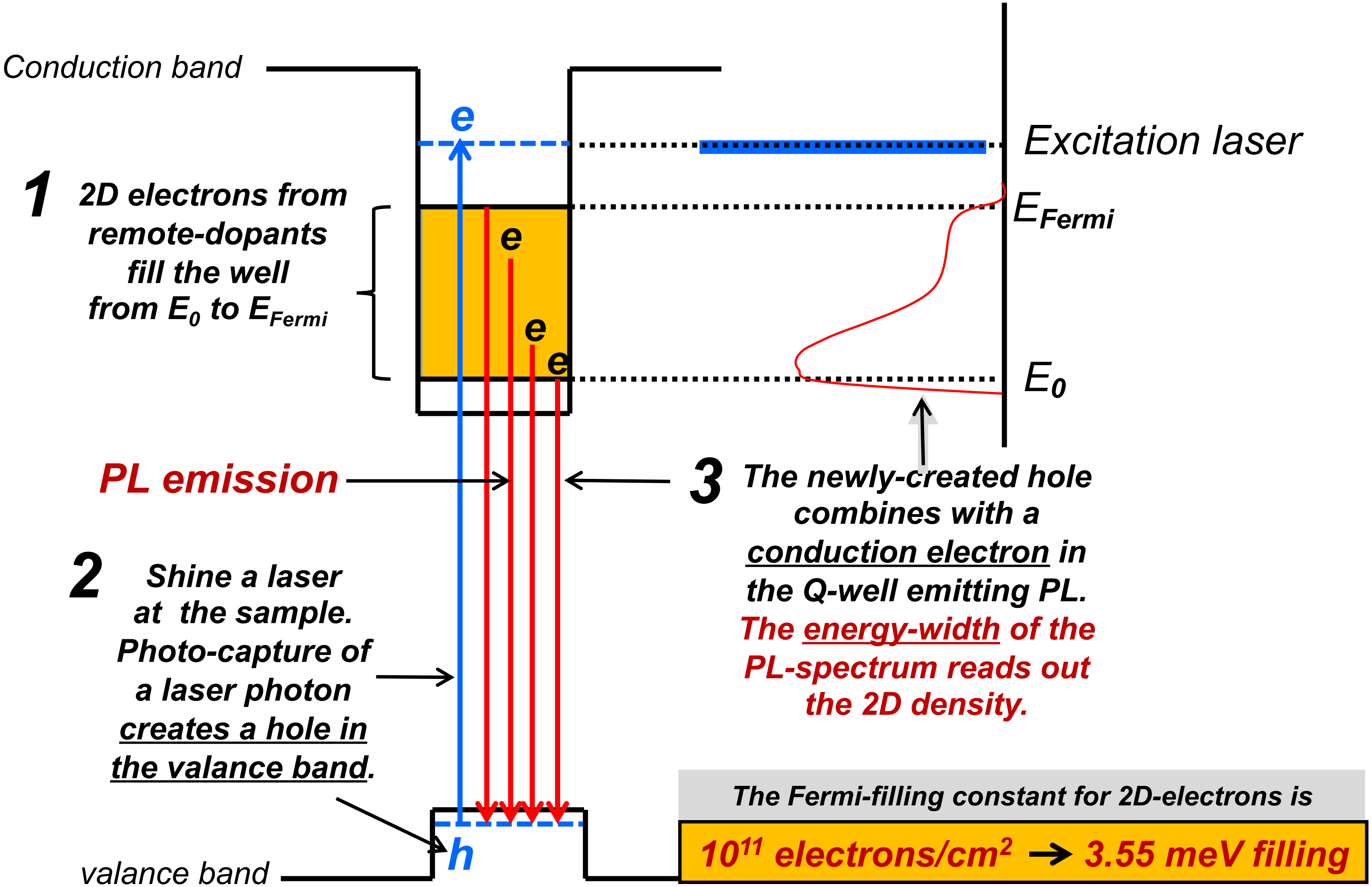
When I asked Aron about this,
he referred me 1984 paper he had written:

In 1984 Aron Pinczuk with Jag Shah showed how
optical Photoluminescence (PL) could measure
the electron density in a quantum well.
Solid State Communications 50, 735 (1984)

Here is how the Pinczuk-Shah scheme works.

Measuring the electron density in a quantum well by photoluminescence.

Solid State Communications 50, 735 (1984)



1 ***2D electrons from remote-dopants fill the well from E_0 to E_{Fermi}***

PL emission

2 ***Shine a laser at the sample. Photo-capture of a laser photon <u>creates a hole in the valance band</u>.***

3 ***The newly-created hole combines with a <u>conduction electron</u> in the Q-well emitting PL. The <u>energy-width</u> of the PL-spectrum reads out the 2D density.***

The Fermi-filling constant for 2D-electrons is

10^{11} electrons/cm^2 → 3.55 meV filling

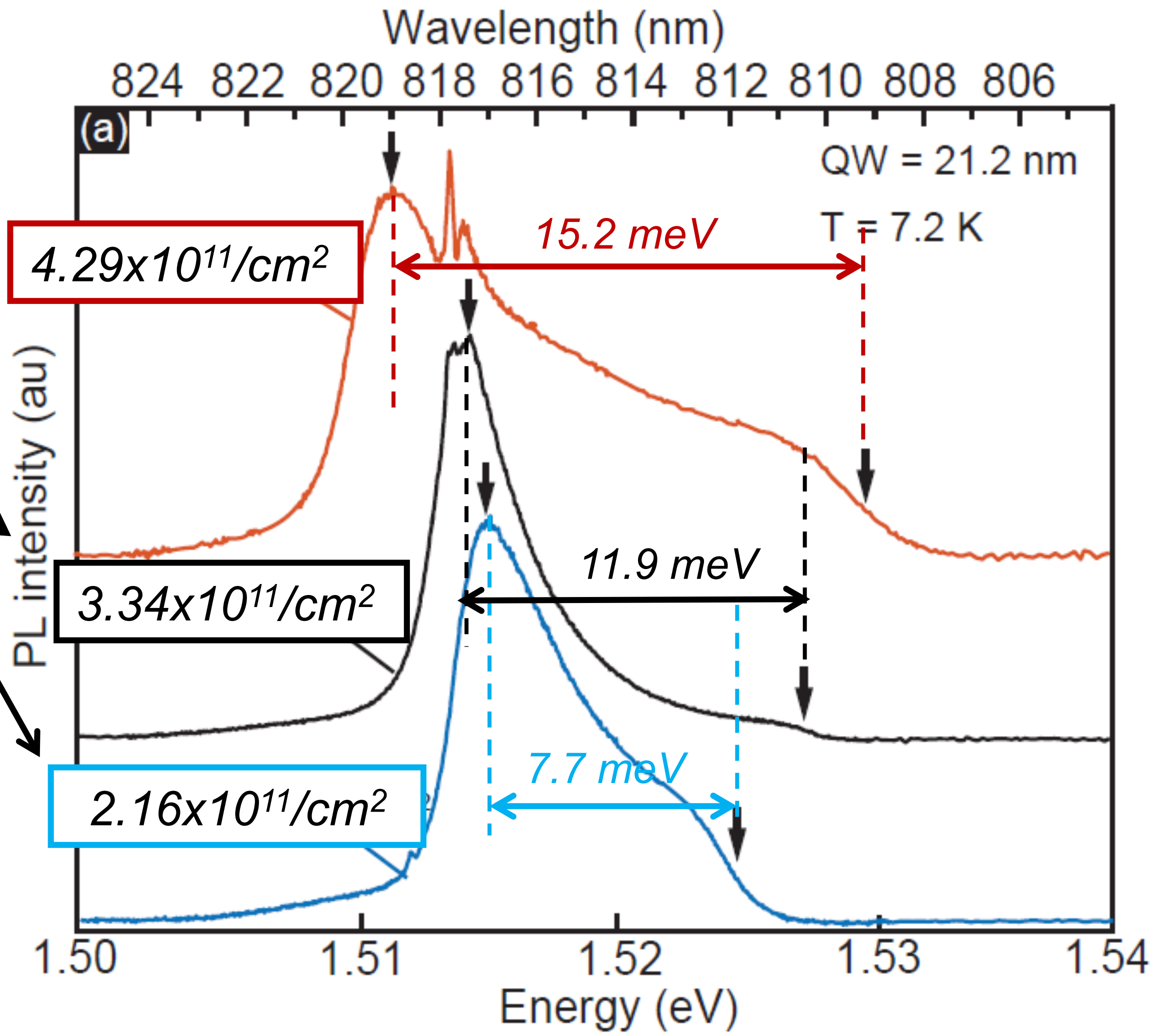
We used these ideas informally for years, but in 2017

Aron and I wrote a paper that critically compared the PL and magneto-transport methods for 2D-density measurement.

*For 3-remotely-doped samples with different 2D densities, the **Fermi filling under the laser spot was read off from the energy differences between the arrows**, and then converted to **n_{PL} density** (using **3.55 meV = $10^{11}/cm^2$**).*

We found the PL densities agreed with electron transport densities n_{TR} to within 10%.

Appl. Phys. Lett. ***110,*** *262104 (2017)*



Question:

If PL-optics and magneto-transport are equally-good methods to measure the 2D-density,

Why do they sometimes disagree by up to10%?

2D electron systems are traditionally characterized by magneto-transport on millimeter-sized pieces,

with the electron density averaged over the large piece.

But suppose the 2D density is not constant across the large piece;

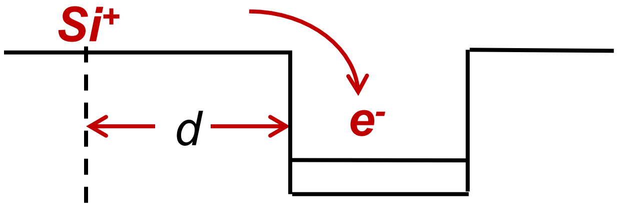
the PL-method which measures the local electron density at the laser spot could differ from this average.

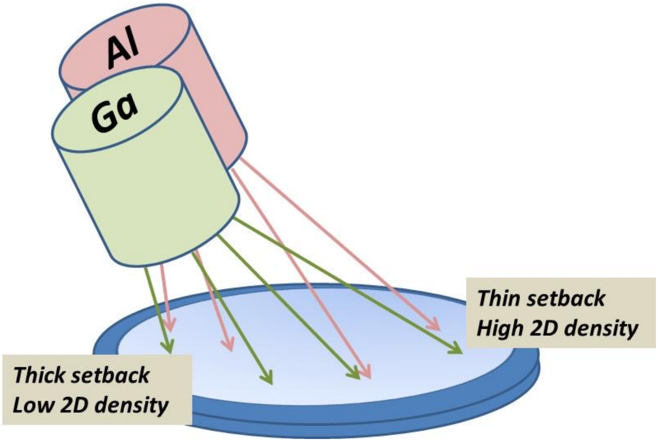
This triggered an idea:

By focusing the laser spot to a few microns in size, we could potentially raster-scan the µ-PL spot to measure local density variations in our samples on micron-sized length scales.

To TEST this idea we made a quantum well with a <u>calibrated</u> <u>spatial</u> <u>variation</u> in the 2D electron density

<u>The electron density in a remotely-doped well depends inversely</u> on the doping setback





Our MBE cells point 30°off from the substrate normal.

THUS we can <u>force</u> the electron density to show a spatial variation by <u>turning off the substrate rotation</u> during growth of the barrier separating the Si-dopant and the Q-well.

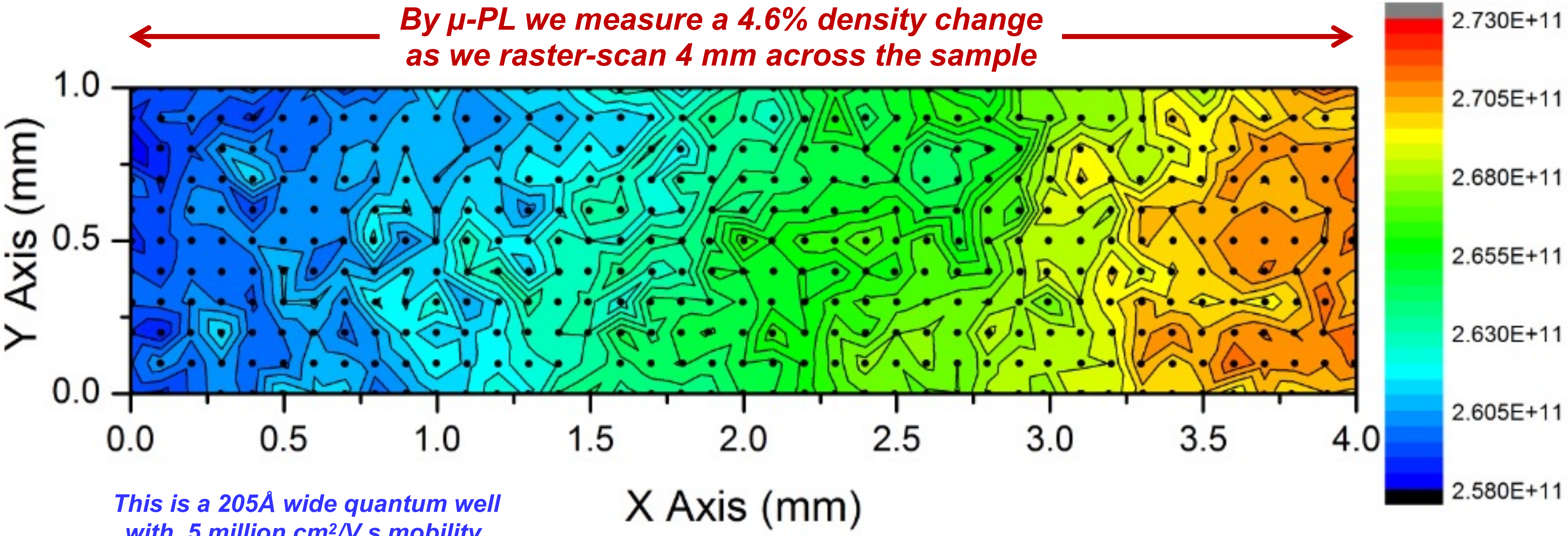
Then the 2D density in the quantum well must <u>increase</u>

by about 1% per mm as the setback across the sample decreases!

First micro-PL density scan of a quantum well

We expect a left-to-right 2D-density gradient since there was no rotation during growth of the setback.

The PL densities were measured only at the raster-grid of black dots.
The color-contours are self-consistent fits to the data.



By µ-PL we measure a 4.6% density change as we raster-scan 4 mm across the sample

This is a 205Å wide quantum well with 5 million cm^2/V s mobility.

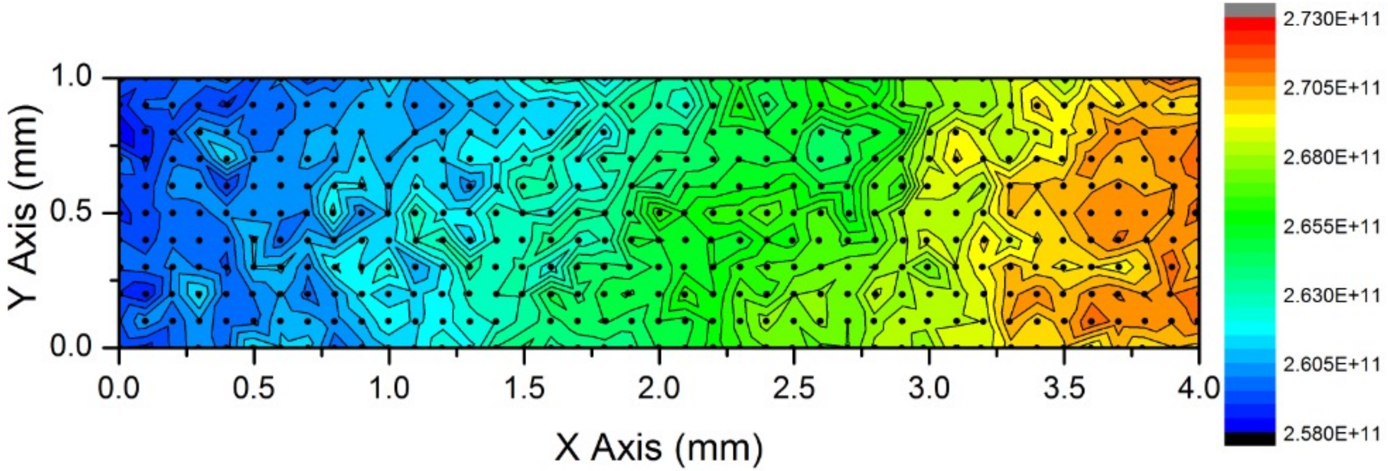
The 4.6% density change in 4 mm is about 1%/mm, as expected for the non-rotated doping-setback.

This shows our micro-PL technique can indeed measure the local 2D density in the quantum well.

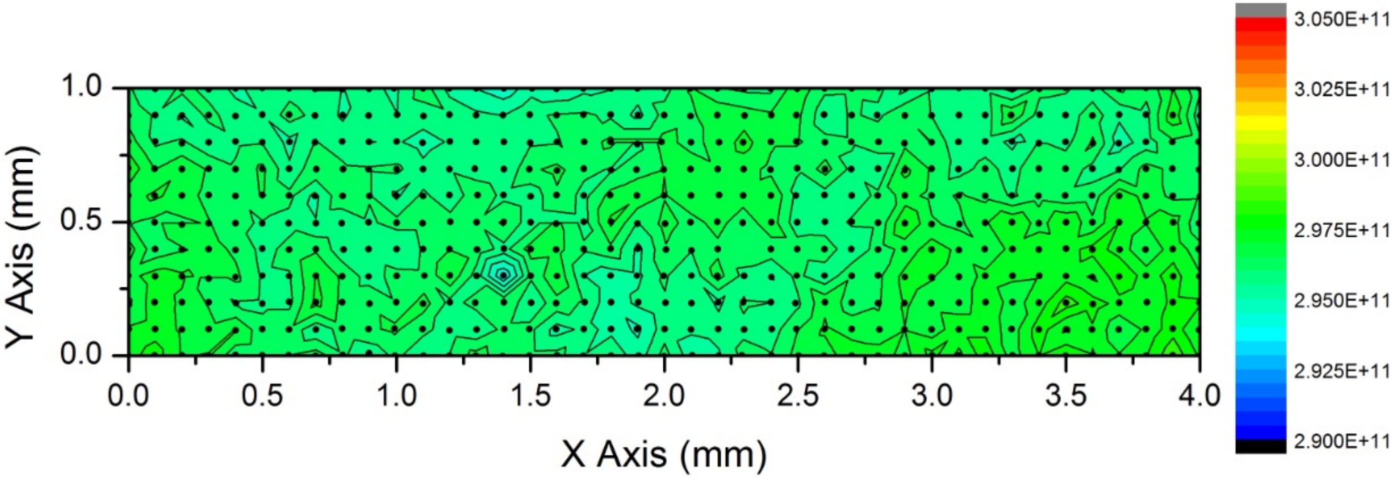
Comparing rotated and non-rotated doping-setback MBE-growth,

using the same 5% density-color range for each data set.

Sample P9-27-17.2
205Å Q-well with
NON-Rotated
doping setback



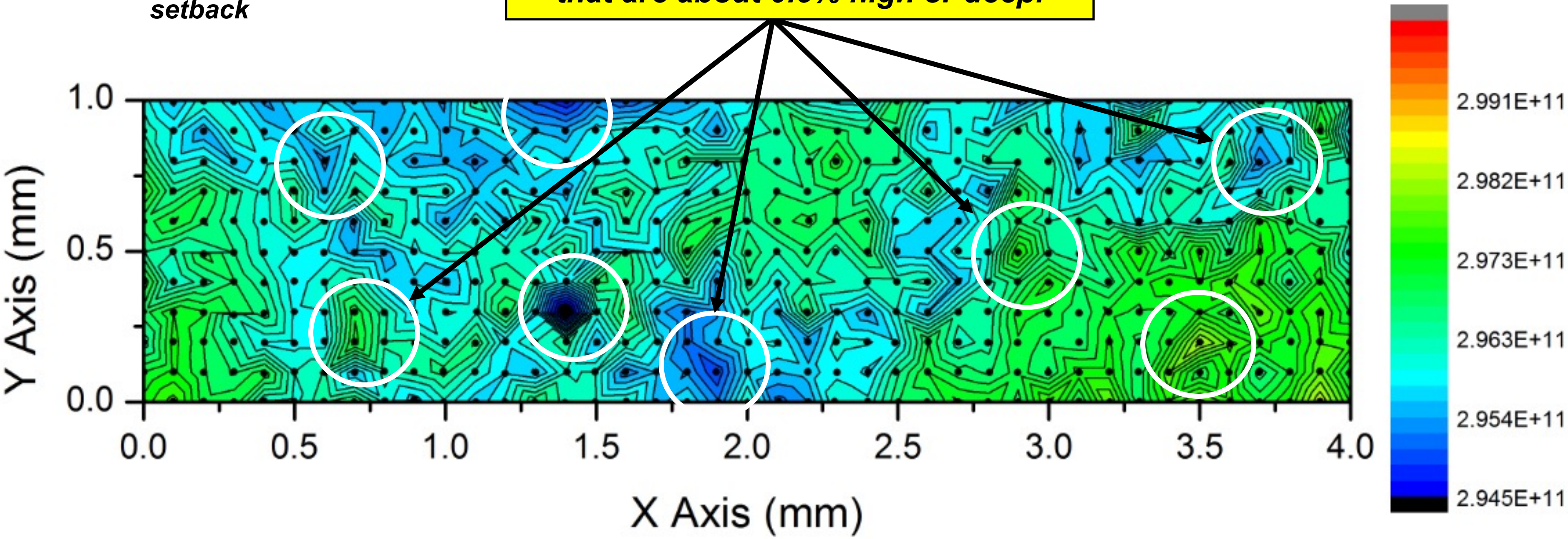
Sample P1-22-18.2
205Å Q-well with
Rotated
doping setback



Rotating the substrate during the doping-setback
eliminates the global variations in 2D electron density *as expected.*

The fully rotated MBE sample again, **but with a finer density-color scale**

Sample P1-22-18.2
205Å Q-well with
<u>rotated</u> doping
setback

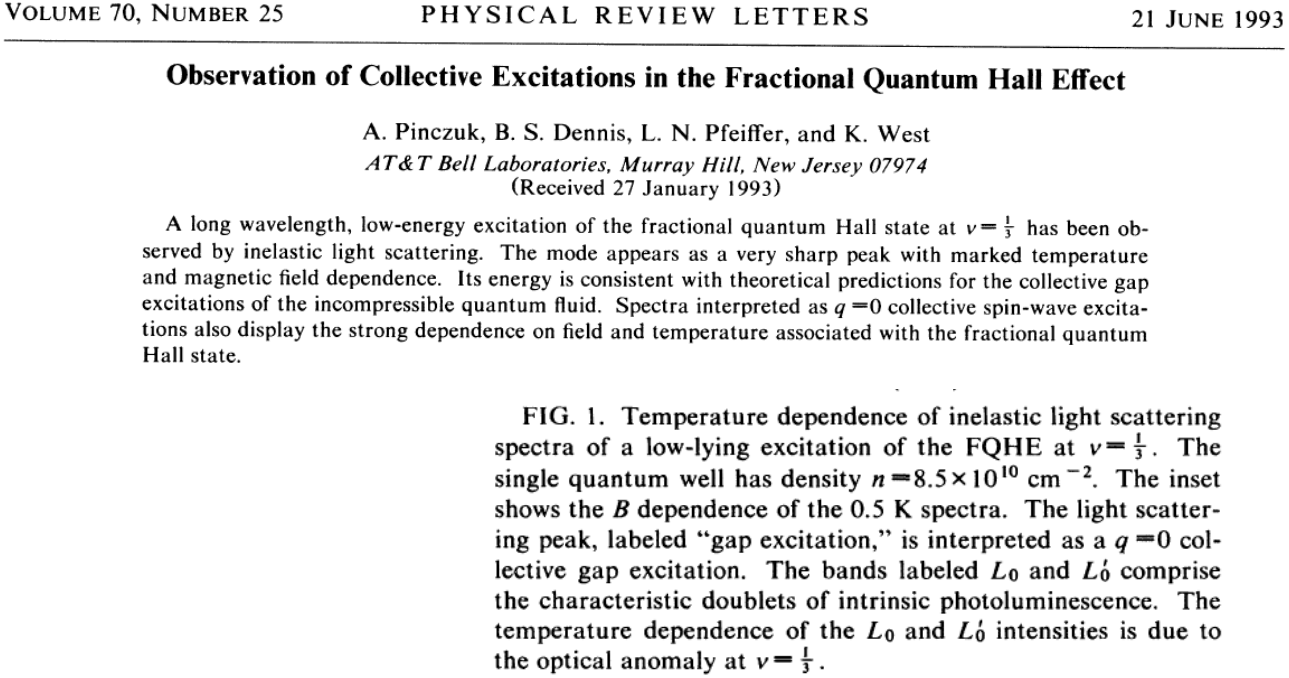


We see local density variations
that are about 0.5% high or deep.

These 0.5% density variations seem to occur in <u>all</u> of our quantum wells.
Thus the μ-PL scanning technique that Aron inspired has revealed <u>ubiquitous</u> density variations in our quantum wells.
This is a new category of disorder we hadn't considered.

Perhaps the most significant paper in Aron's long career was this one:

Ken West and I grew the quantum well sample; Brian Dennis ran some of the experiments;
*but **the new-physics ideas were all Aron's**.*



VOLUME 70, NUMBER 25 PHYSICAL REVIEW LETTERS 21 JUNE 1993

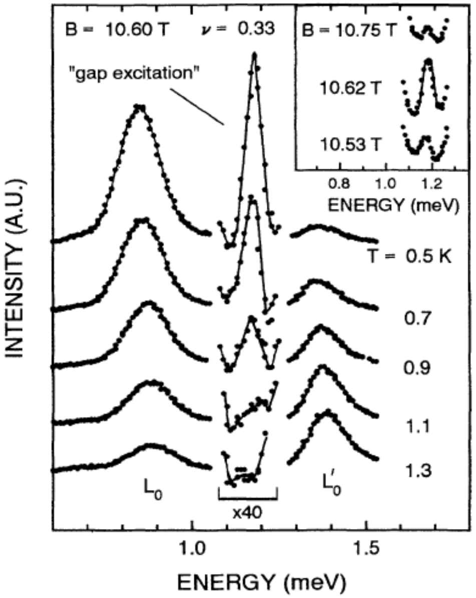
Observation of Collective Excitations in the Fractional Quantum Hall Effect

A. Pinczuk, B. S. Dennis, L. N. Pfeiffer, and K. West
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

(Received 27 January 1993)

A long wavelength, low-energy excitation of the fractional quantum Hall state at $\nu = \frac{1}{3}$ has been observed by inelastic light scattering. The mode appears as a very sharp peak with marked temperature and magnetic field dependence. Its energy is consistent with theoretical predictions for the collective gap excitations of the incompressible quantum fluid. Spectra interpreted as $q = 0$ collective spin-wave excitations also display the strong dependence on field and temperature associated with the fractional quantum Hall state.

FIG. 1. Temperature dependence of inelastic light scattering spectra of a low-lying excitation of the FQHE at $\nu = \frac{1}{3}$. The single quantum well has density $n = 8.5 \times 10^{10}$ cm^{-2}. The inset shows the B dependence of the 0.5 K spectra. The light scattering peak, labeled "gap excitation," is interpreted as a $q = 0$ collective gap excitation. The bands labeled L_0 and L_0' comprise the characteristic doublets of intrinsic photoluminescence. The temperature dependence of the L_0 and L_0' intensities is due to the optical anomaly at $\nu = \frac{1}{3}$.



Six months after this paper appeared,

Aron was awarded the 1994 Buckley Prize,

the most prestigious Prize in Condensed Matter Physics!

The citation reads:

"To Aron Pinczuk for pioneering light-scattering studies of low- dimensional electron systems"

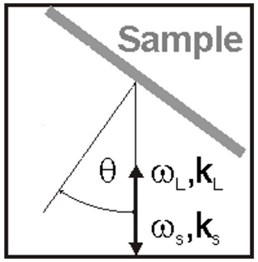
VOLUME 70, NUMBER 25 PHYSICAL REVIEW LETTERS 21 JUNE 1993

Observation of Collective Excitations in the Fractional Quantum Hall Effect

A. Pinczuk, B. S. Dennis, L. N. Pfeiffer, and K. West

Aron used Raman light-scattering to excite a super-sharp (50 μeV) long-wavelength gap excitation of the 2D electron liquid in the well.

Consider the precise parameter-tuning that Aron needed to find this 50 μeV FWHM resonance!



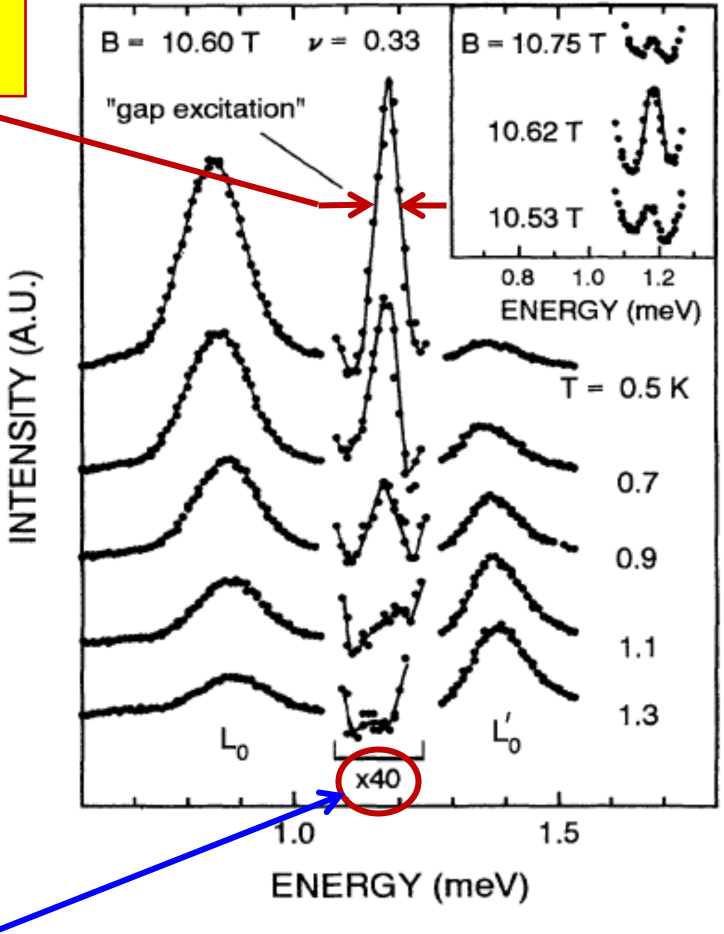
Conservation of energy:

$$\omega = \omega_L - \omega_S$$

Conservation of wave-vector:

$$q = k_L - k_S = (2\omega_L/c)\sin\theta$$

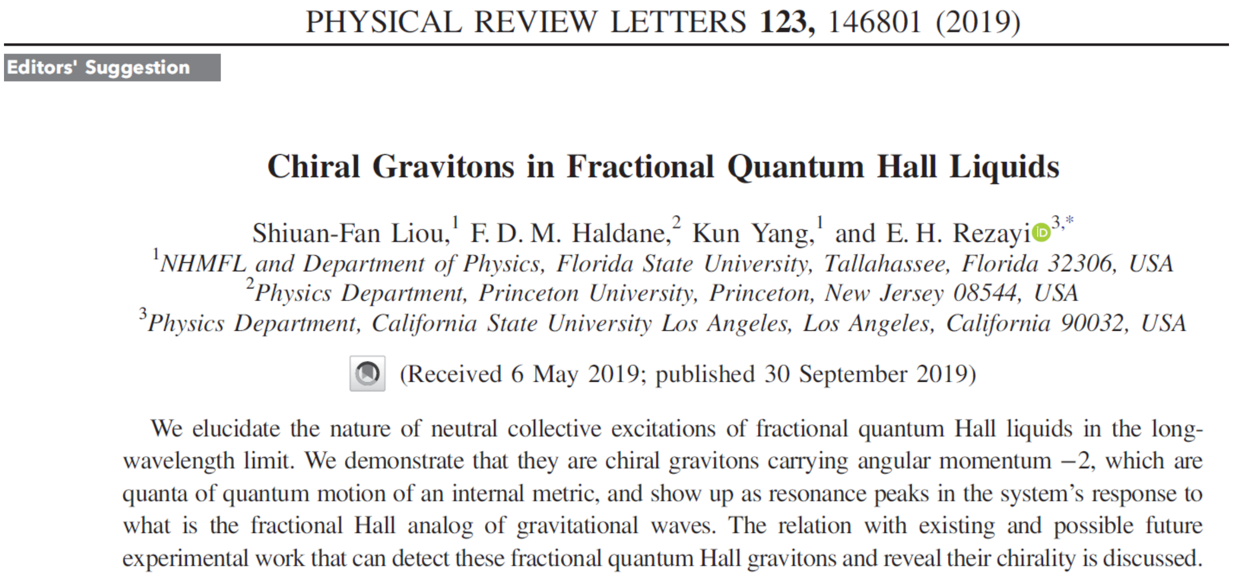
- ***The scattering angle Θ must be set to zero to minimize the transferred momentum and excite only the long-wavelength excitation.***
- ***The temperature must be 0.5K or lower.***
- ***The B-field must be set to precisely 10.6 Tesla to couple to the ν = 1/3 Quantum Hall state where the resonant enhancement occurs.* *(See figure inset.)***
- ***The resonant gap excitation is super-narrow, and has a tiny amplitude, which must be dug out of the large L_0 and L'_0 intrinsic PL background.***



26 years after Aron's 1993 paper, it was cited by Haldane et. al. as ***direct evidence for a chiral graviton mode at the Quantum Hall ground state of the Coulomb interaction at v = 1/3.***

The resonance peak that Aron observed in 1993 ***is due to neutral collective excitations that are the 2D-system's response to what is the fractional Hall analog of gravitational waves.***

In September 2021, when I last saw Aron, he was planning experiments to pursue these ideas.



PHYSICAL REVIEW LETTERS **123,** 146801 (2019)

Editors' Suggestion

Chiral Gravitons in Fractional Quantum Hall Liquids

Shiuan-Fan Liou,[1] F. D. M. Haldane,[2] Kun Yang,[1] and E. H. Rezayi[3,*]

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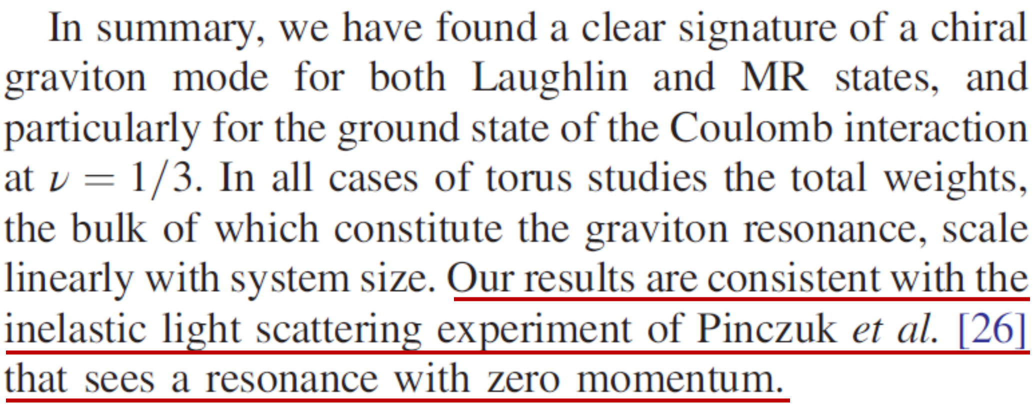
(Received 6 May 2019; published 30 September 2019)

We elucidate the nature of neutral collective excitations of fractional quantum Hall liquids in the long-wavelength limit. We demonstrate that they are chiral gravitons carrying angular momentum -2, which are quanta of quantum motion of an internal metric, and show up as resonance peaks in the system's response to what is the fractional Hall analog of gravitational waves. The relation with existing and possible future experimental work that can detect these fractional quantum Hall gravitons and reveal their chirality is discussed.

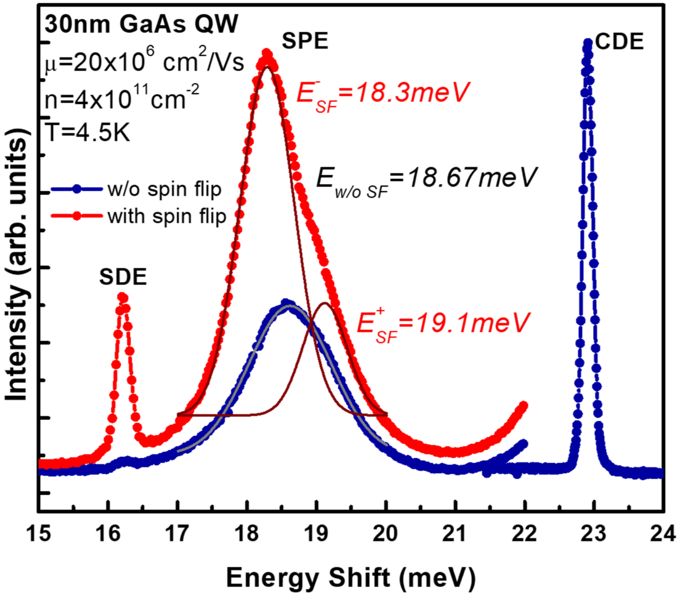
The paper concludes:



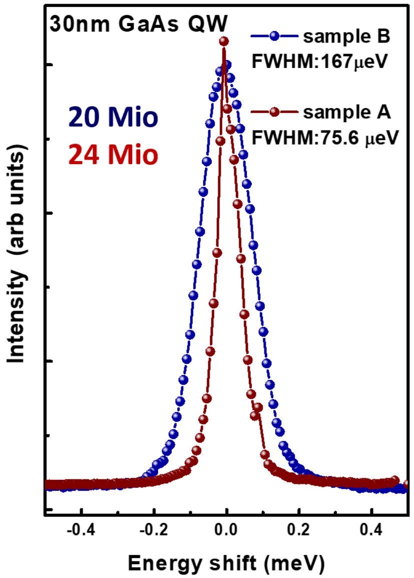
In summary, we have found a clear signature of a chiral graviton mode for both Laughlin and MR states, and particularly for the ground state of the Coulomb interaction at $\nu = 1/3$. In all cases of torus studies the total weights, the bulk of which constitute the graviton resonance, scale linearly with system size. Our results are consistent with the inelastic light scattering experiment of Pinczuk *et al.* [26] that sees a resonance with zero momentum.

Now we consider the possibility of using these ultra-sharp Raman resonances of collective 2DES-excitations to inform our MBE growth program.

*Relevant here is the work of **Pinczuk and Wurstbauer** who showed **the sharpness of the Raman Charge Density Excitation** correlates directly with the **magneto-transport mobility** of the structure.*



line width CDE



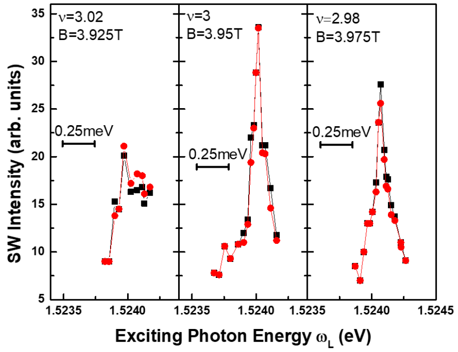
Here Wurstbauer compares two high mobility samples.
and shows the
24 Million
*mobility sample has a CDE-width twice as sharp as the CDE-width of the **20 Million** mobility sample.*

*In this 2013 March APS talk Ursula Wurstbauer suggested that the sharpness of the CDE linewidth **could be an alternative figure of merit when comparing the quality of quantum well samples.***
No magnetic field is required to see the CDE linewidth.

*If we cool the samples to 40mK, turn on a B-field, and tune to v = 3, we get the **Quantum Hall enhanced resonant profile** of the two samples.*

Sample A

Mobility =24 M



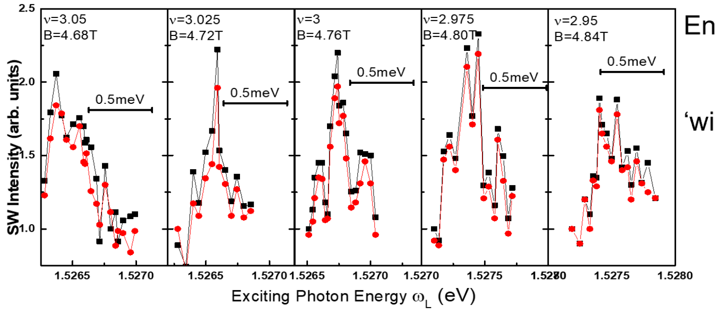
Enhancement profile:
$\Delta\omega_L \approx 0.25$meV

'width' of ν=3: $|\Delta\nu| < 0.02$

FWHM = 12 μeV

Sample B

Mobility =20 M



Enhancement profile:
$\Delta\omega_L \approx 0.5$meV

'width' of ν=3: $|\Delta\nu| < 0.05$

FWHM < 50 μeV

The 24 M mobility sample looks to be ultra-sharp and homogenous.
The 20 M mobility sample looks to be inhomogenously broadened
with what several adjacent resonance peaks.

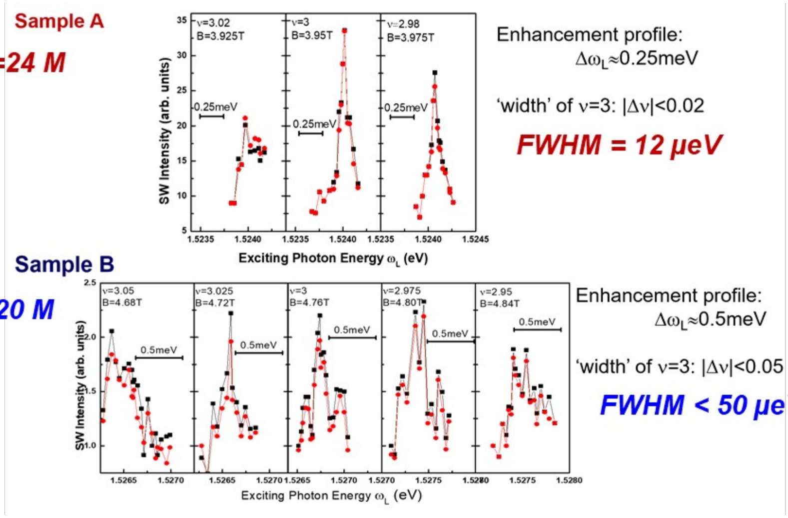
Assuming the 12 μeV resonance linewidth from the 24 M sample is due to ***homogenous lifetime broadening,***

we can use the uncertainly relation to estimate the <u>resonance-lifetime</u> of the zero-momentum excited state of the 2D electron puddle <u>as 27 psec</u>.

This number agrees with the range of values one gets for the ***quantum lifetime*** *in the best quantum wells.*

Mobility =24 M

Mobility =20 M



Enhancement profile: $\Delta\omega_L \approx 0.25$meV

'width' of ν=3: $|\Delta\nu| < 0.02$

FWHM = 12 μeV

Enhancement profile: $\Delta\omega_L \approx 0.5$meV

'width' of ν=3: $|\Delta\nu| < 0.05$

FWHM < 50 μeV

Idea for future work:

Measure the <u>local quantum lifetime</u> under the Raman laser spot.
By reducing the size of that spot, and raster-scanning it across regions of the sample,
we could perhaps produce spatial-maps of <u>quantum lifetime variations</u>.

The 20 M mobility sample shows signs of <u>inhomogenous</u> broadening,
suggesting the presence of domains in the 2D-system.
Such domain textures were reported by Aron and his collaborators in January 2022.

Physical Review Letters 138, 017401 (2022)

In June of 2021 we celebrated a new high mobility milestone for our MBE Group with small party at a Princeton restaurant.

Aron Pinczuk was there! *Here are some pictures!*

Horst Stormer chats with Dan Tsui


Levi's

In September 2021 Aron again came to Princeton
'just to keep in-touch' *and talk about new experiments.*

Here is a guy who has passed his 83rd birthday,
planning <u>new</u> experiments that would test Haldane's and Kang's ideas about the analogy between graviton physics and fractional quantum Hall physics.

Planning new physics at 83! ***That was Aron!***

Congratulations to Loren N. Pfeiffer
and his team at Princeton

New benchmark in Molecular Beam Epitaxy
of Gallium Arsenide

Aron and Gladys Pinczuk
June 2021

At the end of that visit Aron presented me with a <u>gift</u> commemorating the June Dinner and our group's MBE Milestone.

Caring about a friend,
and making him a thoughtful
commemoration gift!

That was Aron!

What a sweet guy!