



The Abdus Salam
International Centre for Theoretical Physics



2157-2

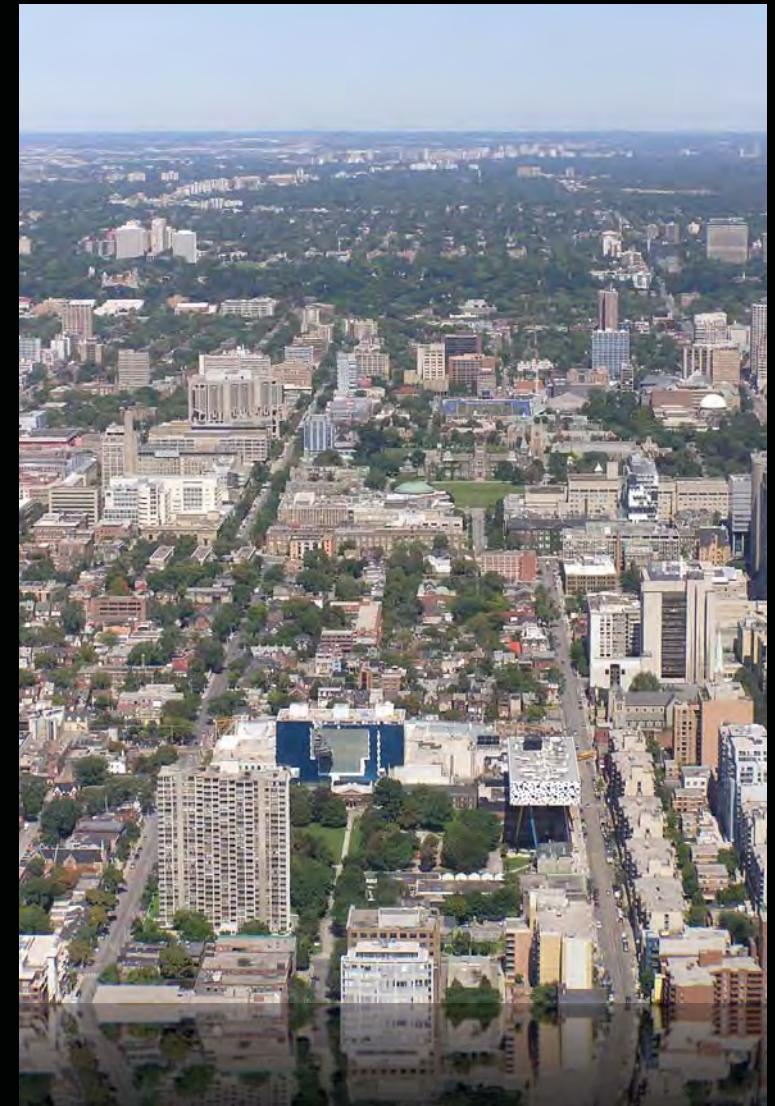
Workshop on Principles and Design of Strongly Correlated Electronic Systems

2 - 13 August 2010

Tuning Materials with Mechanical Exfoliation

Ken BURCH
*Institute for Optical Sciences
University of Toronto, 60 St. George Street
ON Toronto, M5S 1A7
CANADA*

Tuning Materials with Mechanical Exfoliation



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Tuning Materials with Mechanical Exfoliation

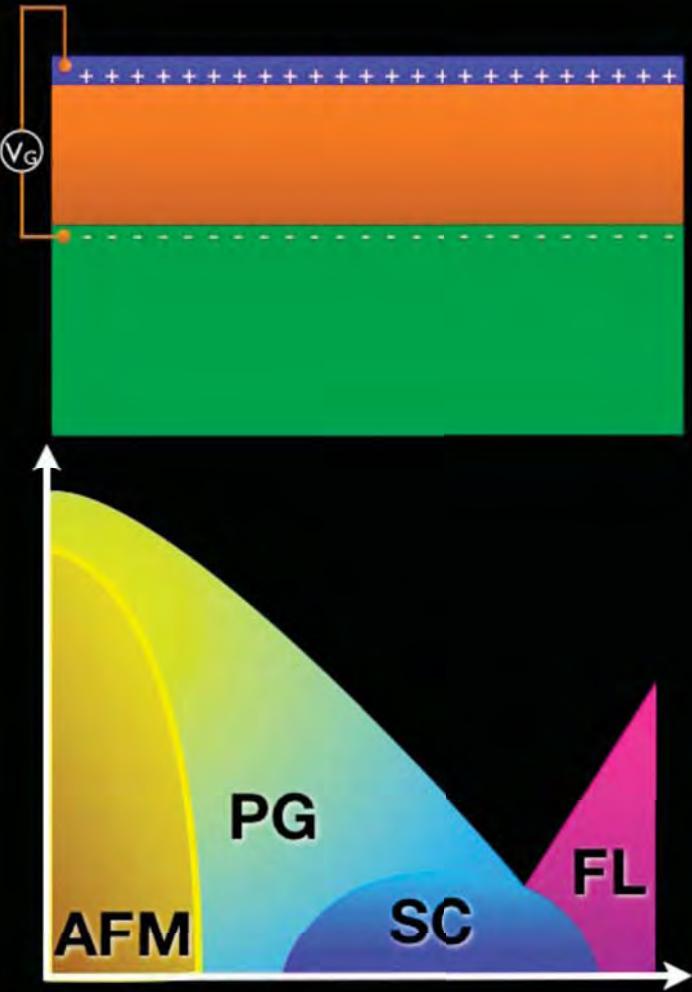


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A decorative horizontal line consisting of three wavy, colored segments: red, green, and blue.

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Tuning Materials with Mechanical Exfoliation

- Tuning
- Exfoliation
- Optics
- Summary
- Future Directions



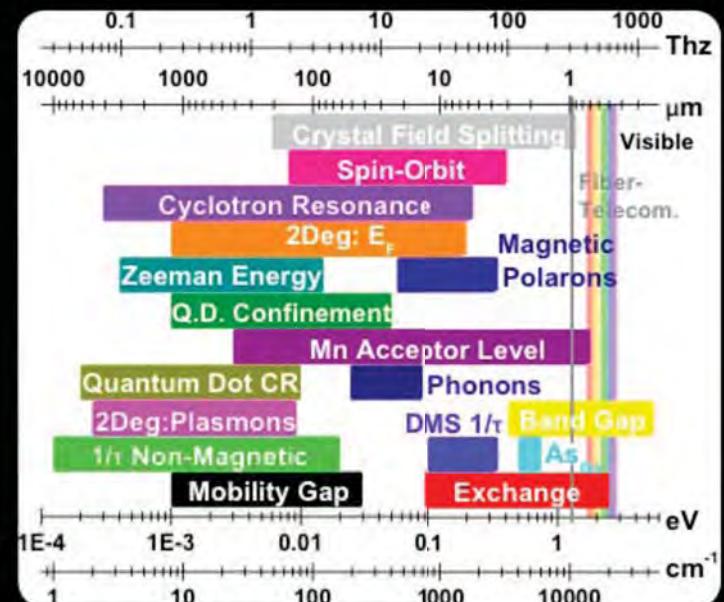
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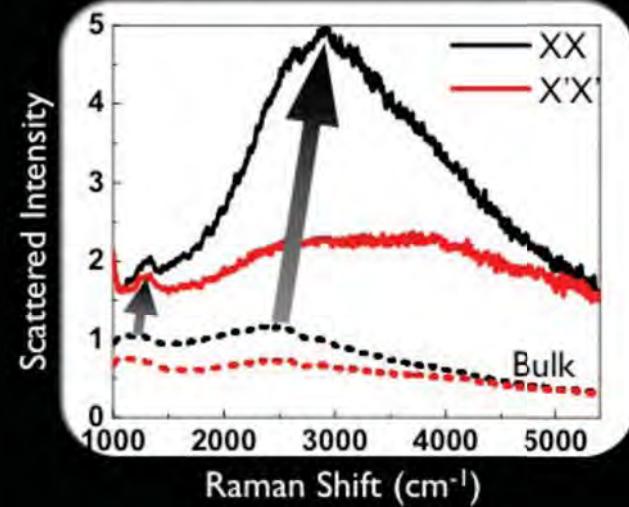
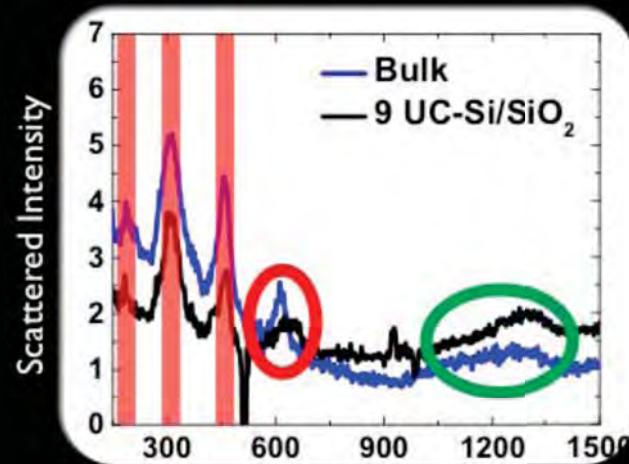
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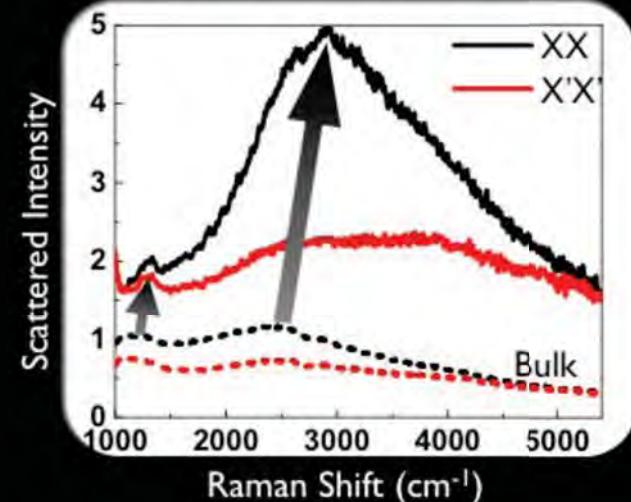
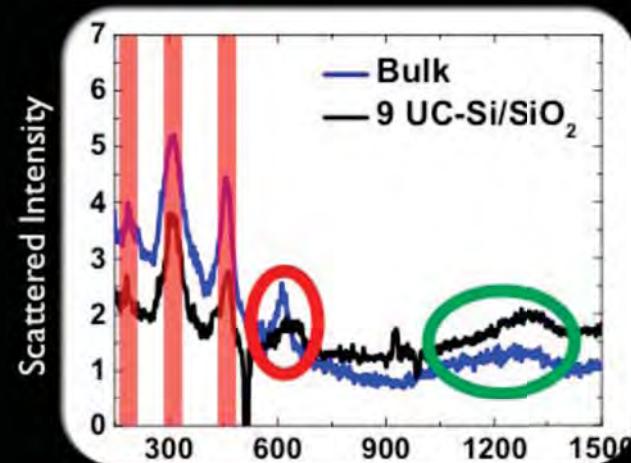
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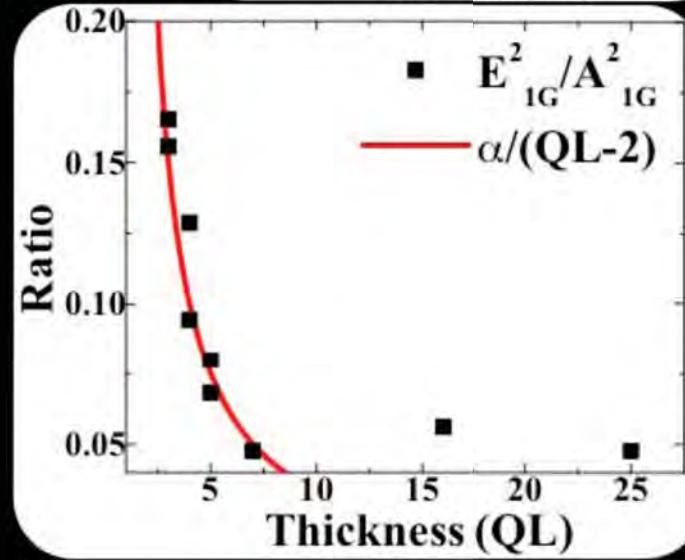
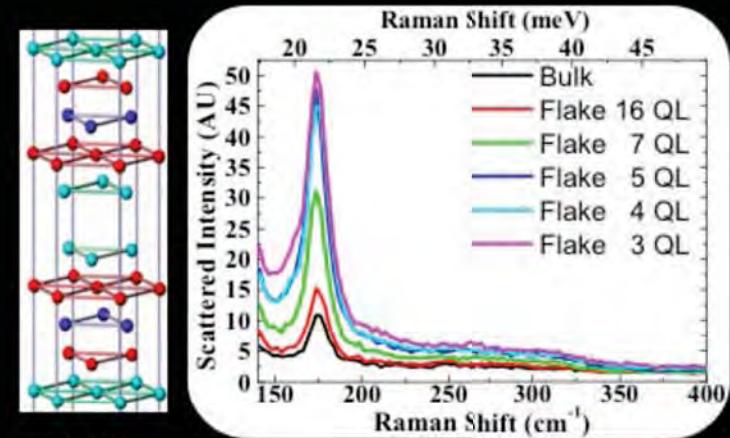
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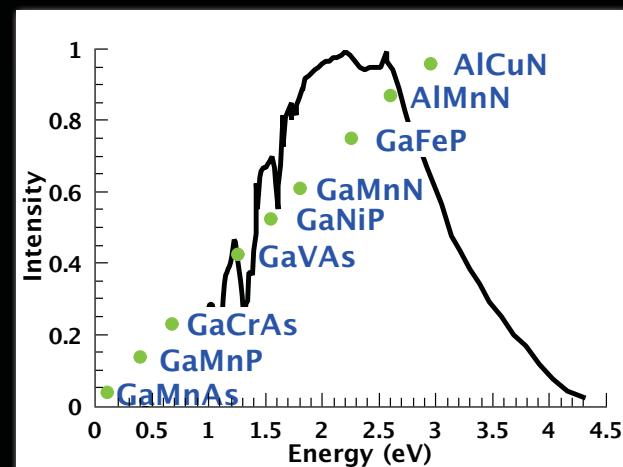
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Tuning Materials with Mechanical Exfoliation

J.X. Shen (Cornell)

G.M. Chugunov(UW)

F. Zhao

A. Mulder (Cornell)

L.J. Sandilands

A. Reijnders

C. Beekman

R. McAloney (Chem)

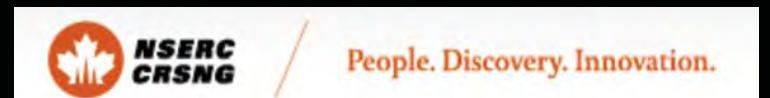
M.C. Goh (Chem)

University of Toronto

S. Ono
CREIPI

Y. Ando
Osaka University

S.W. Cheong
Rutgers University

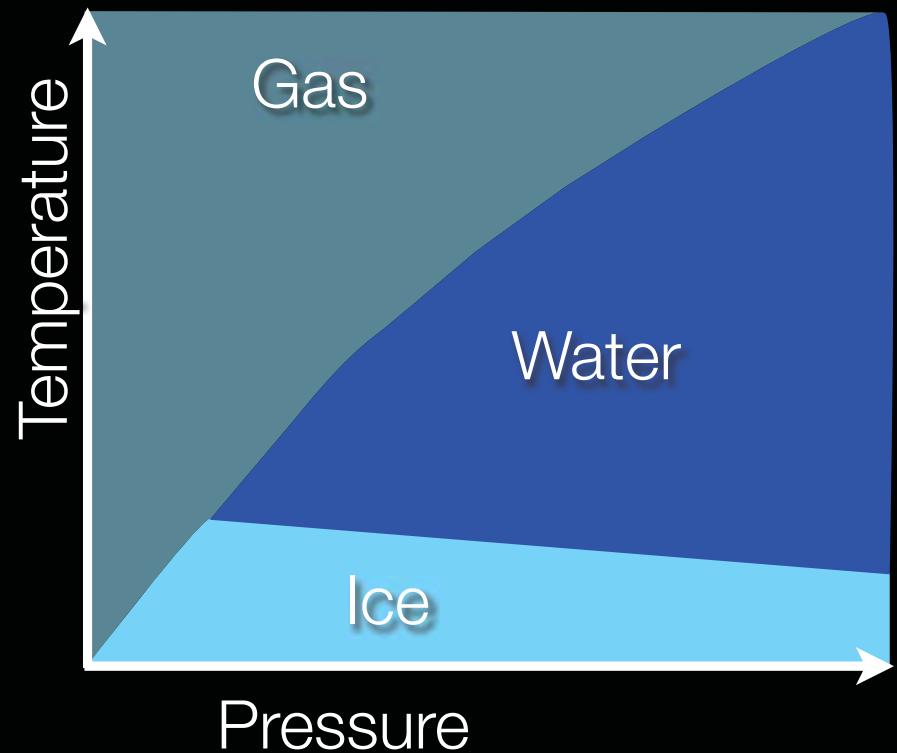


Canada Foundation
for Innovation

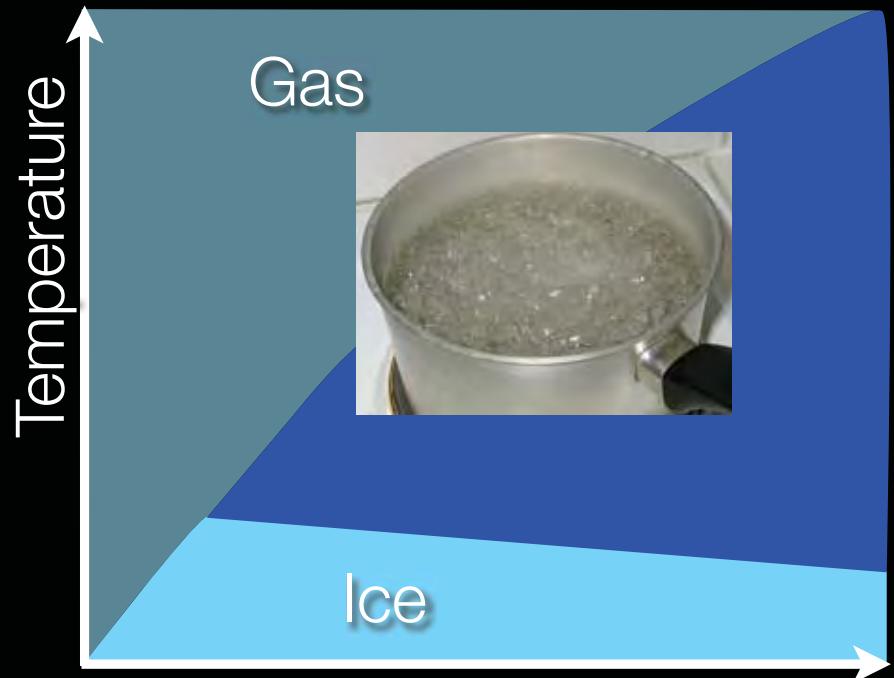
Fondation canadienne
pour l'innovation



Disorder vs Doping

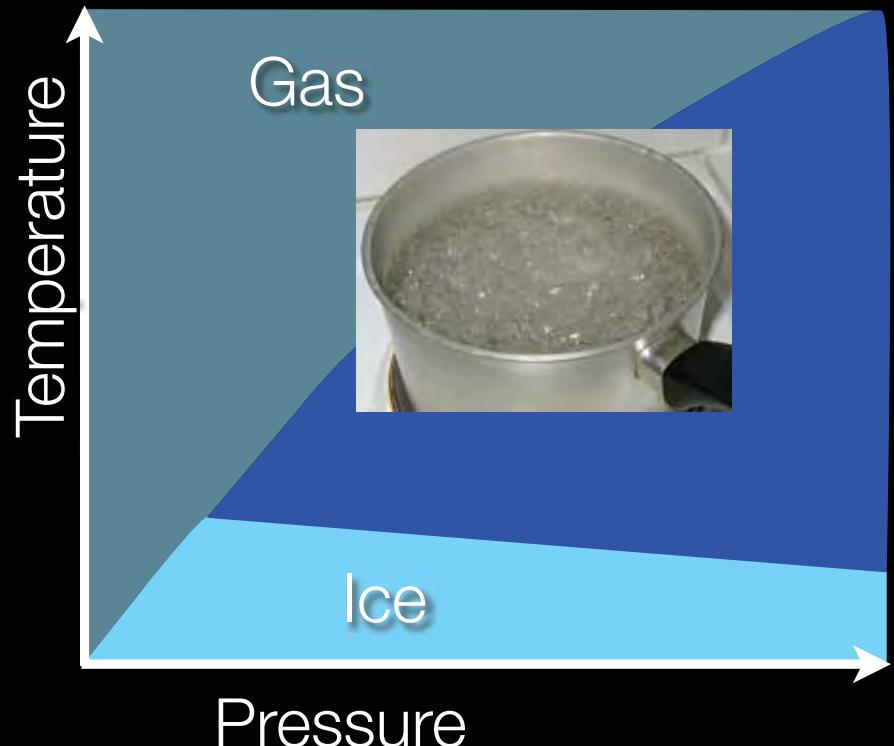


Disorder vs Doping

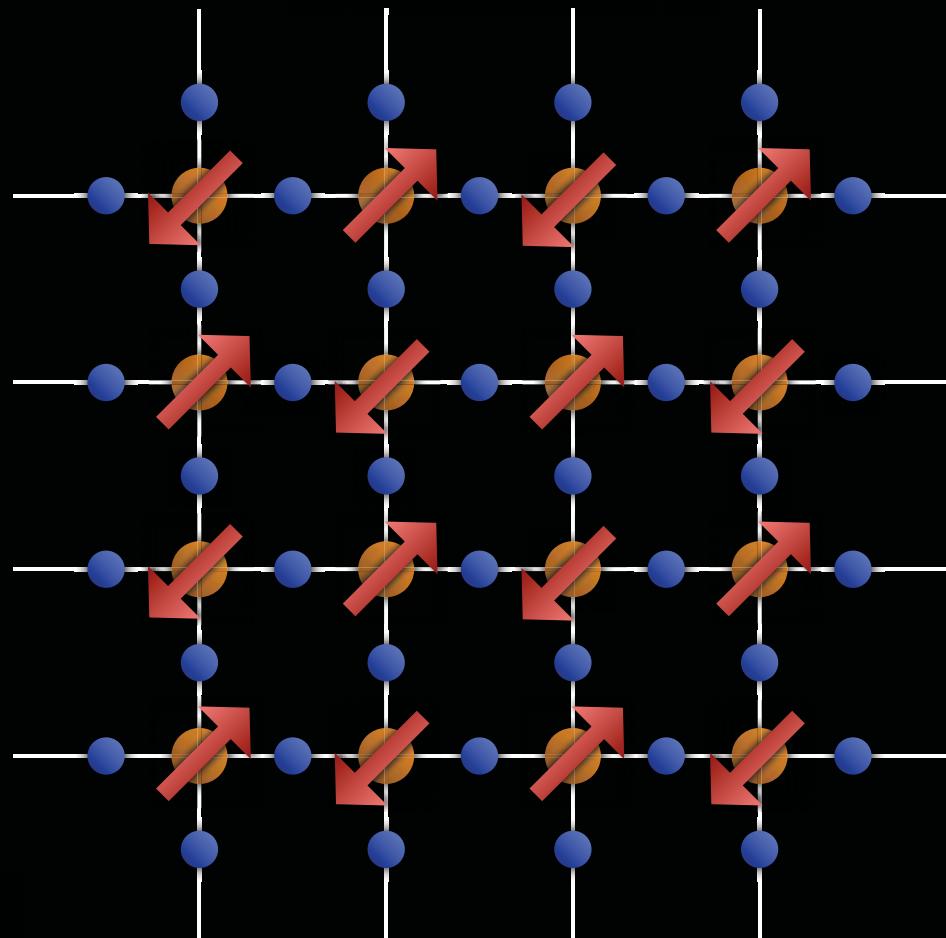


Classical Transition:
At Transition->Coexist

Disorder vs Doping



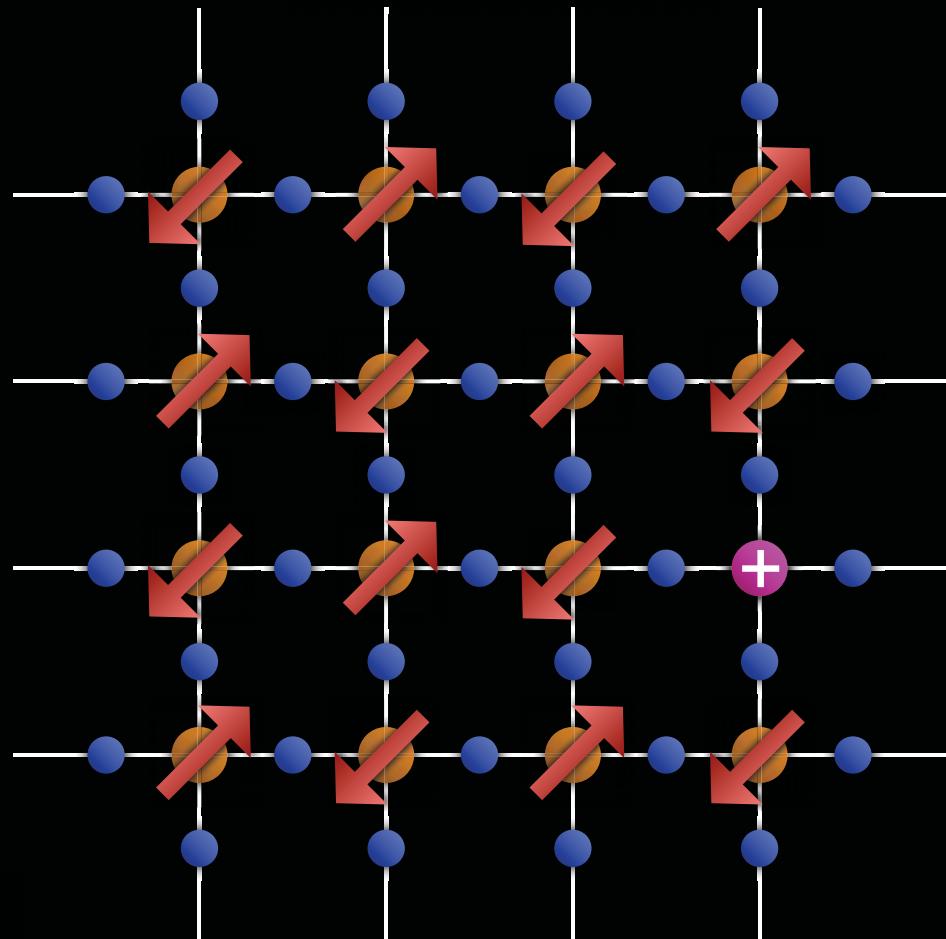
Cuprates:



Quantum Phase Transition:
New Phases?

Disorder vs Doping

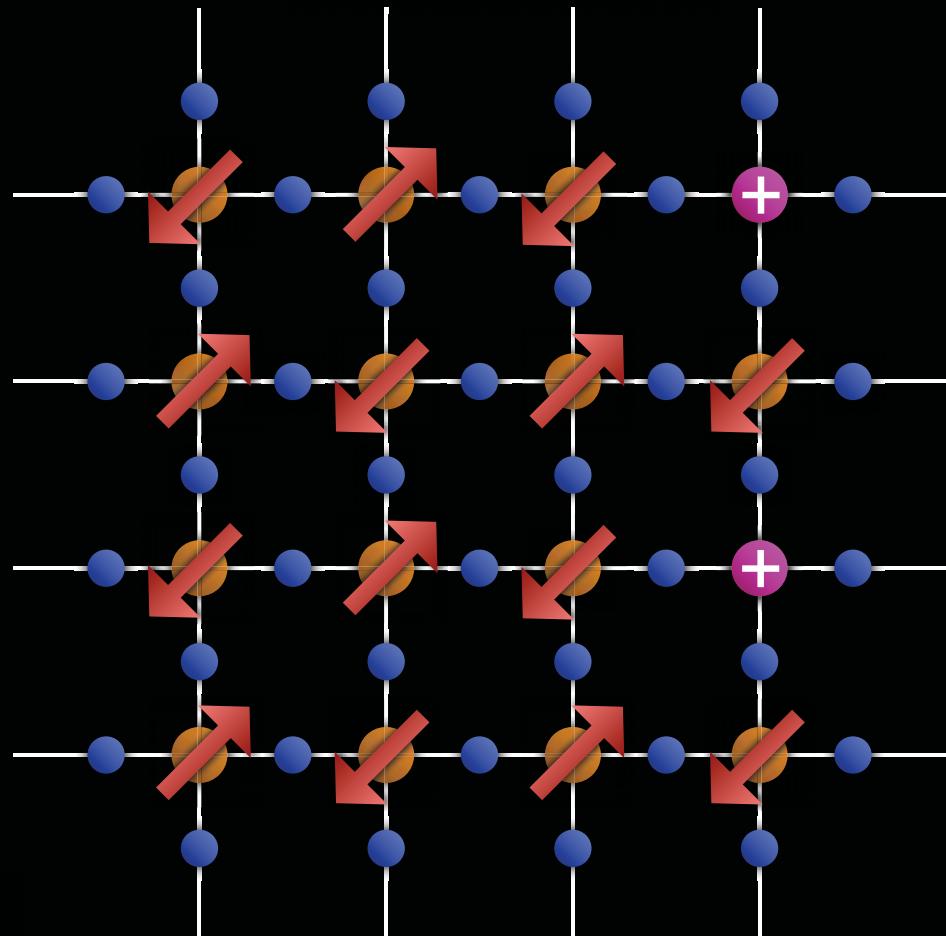
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Quantum Phase Transition:
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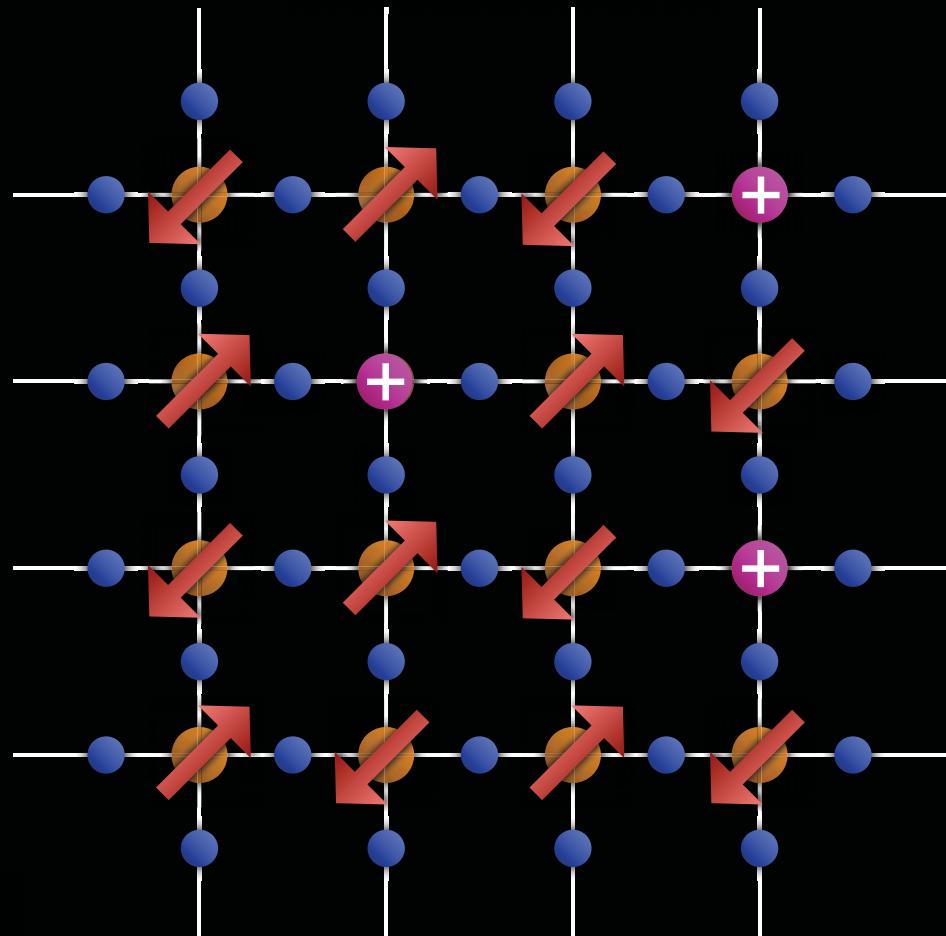
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Quantum Phase Transition:
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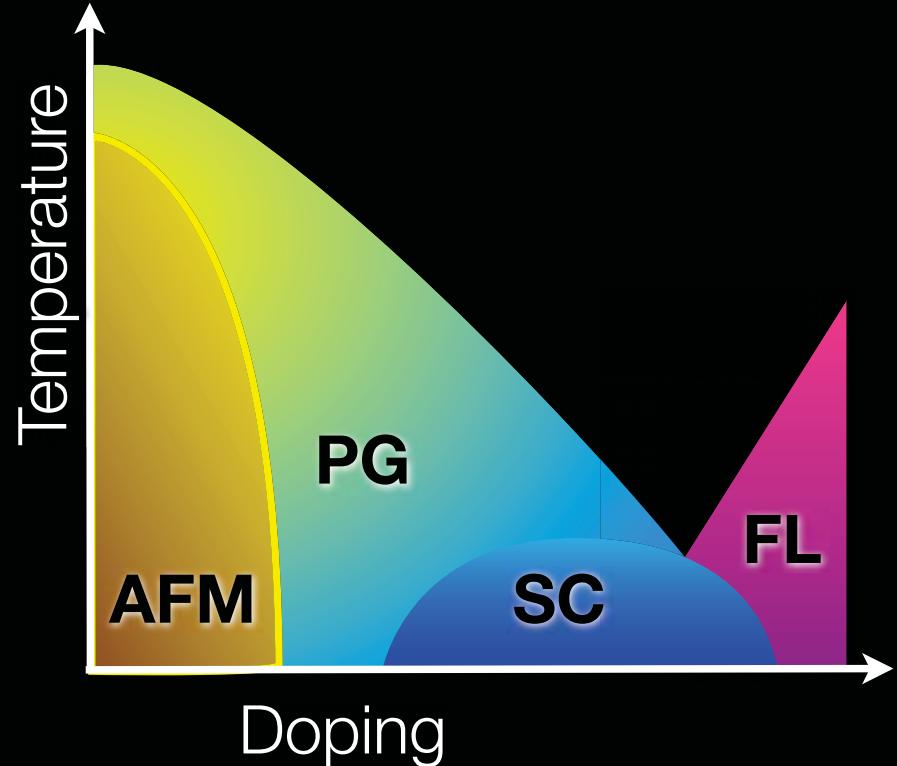
Disorder vs Doping

Cuprates:

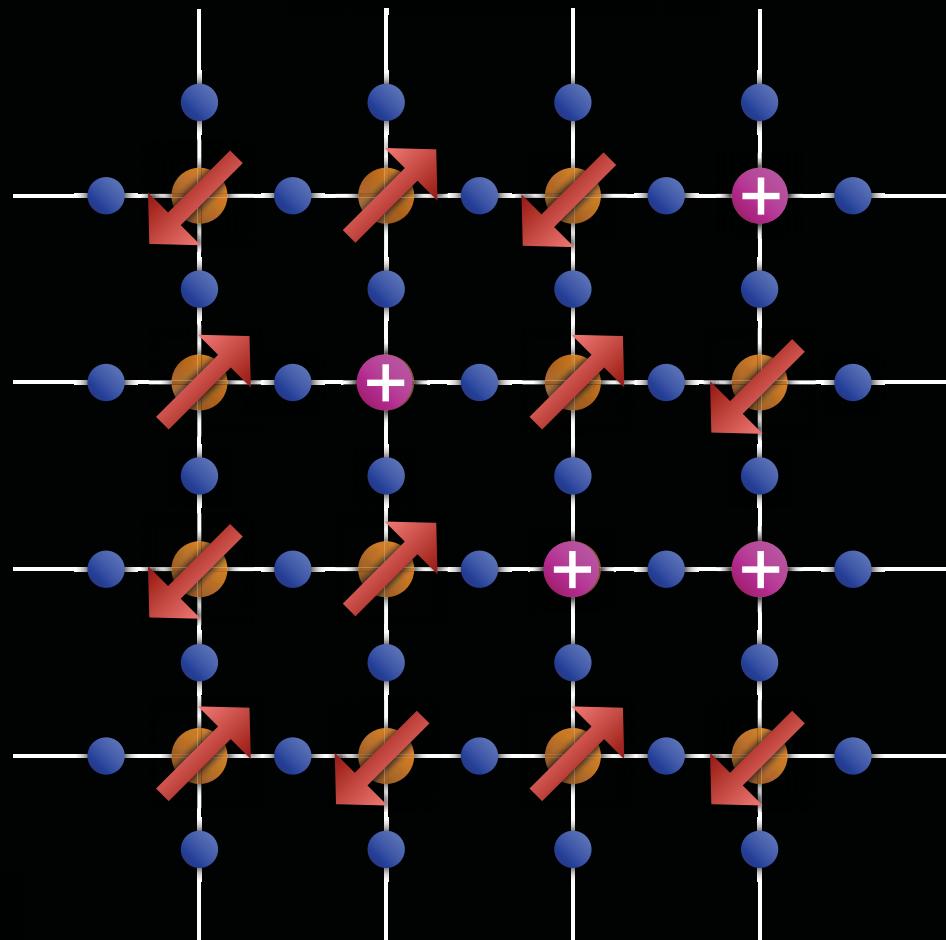


Quantum Phase Transition:
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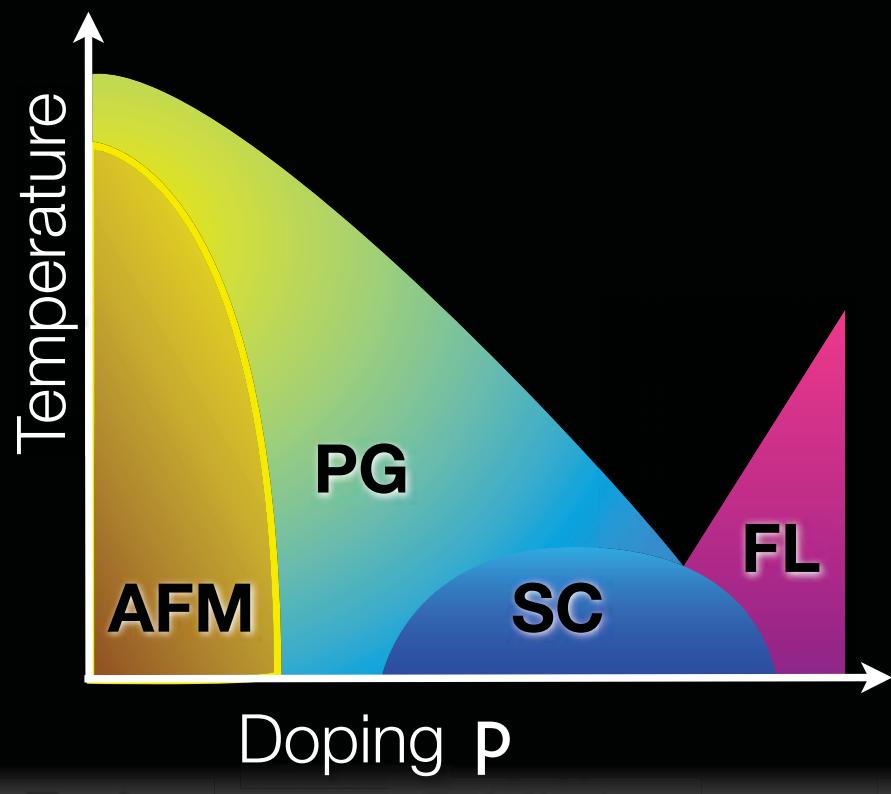
Disorder vs Doping



Quantum Phase Transition:
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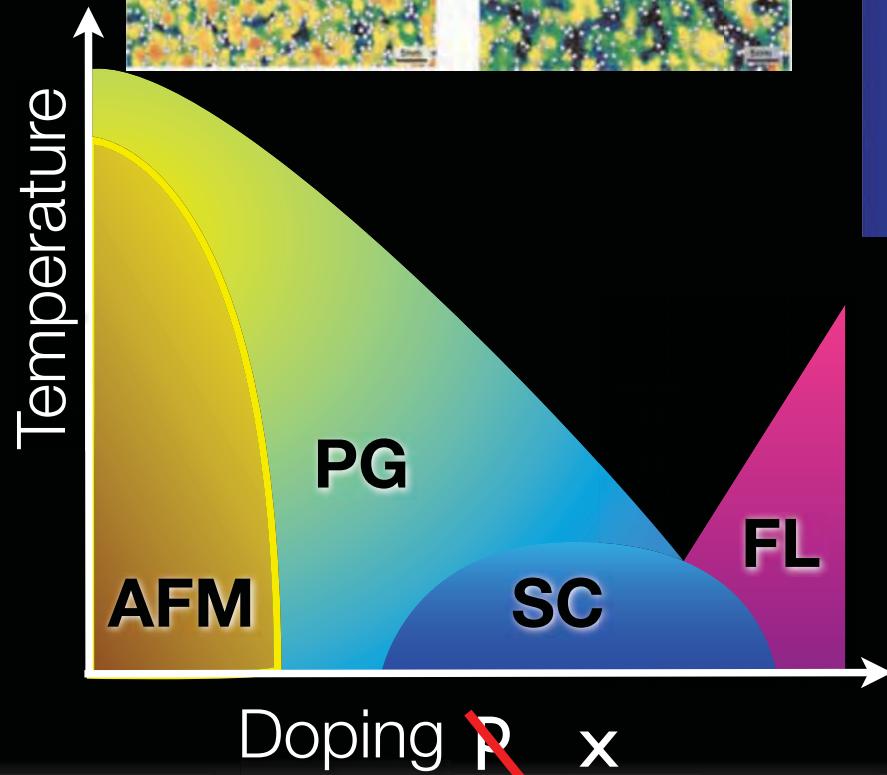
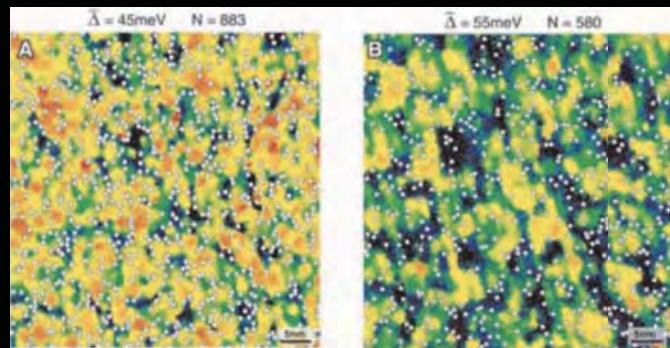
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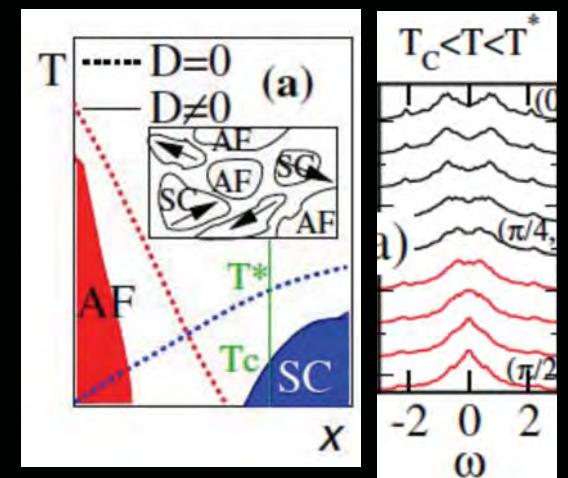
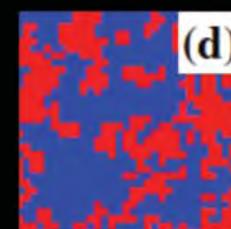
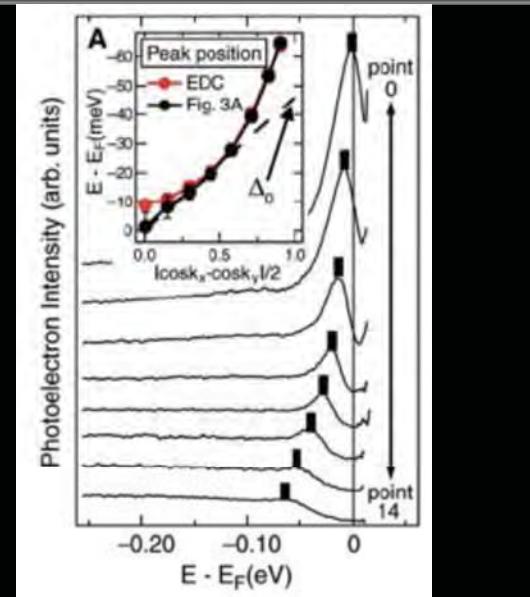
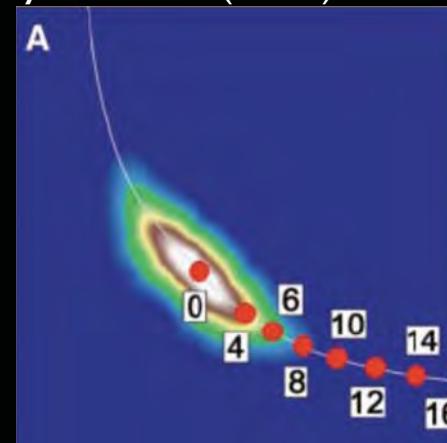
Disorder vs Doping

K. McElroy *et al.*, Science 309, 1048 (2005)

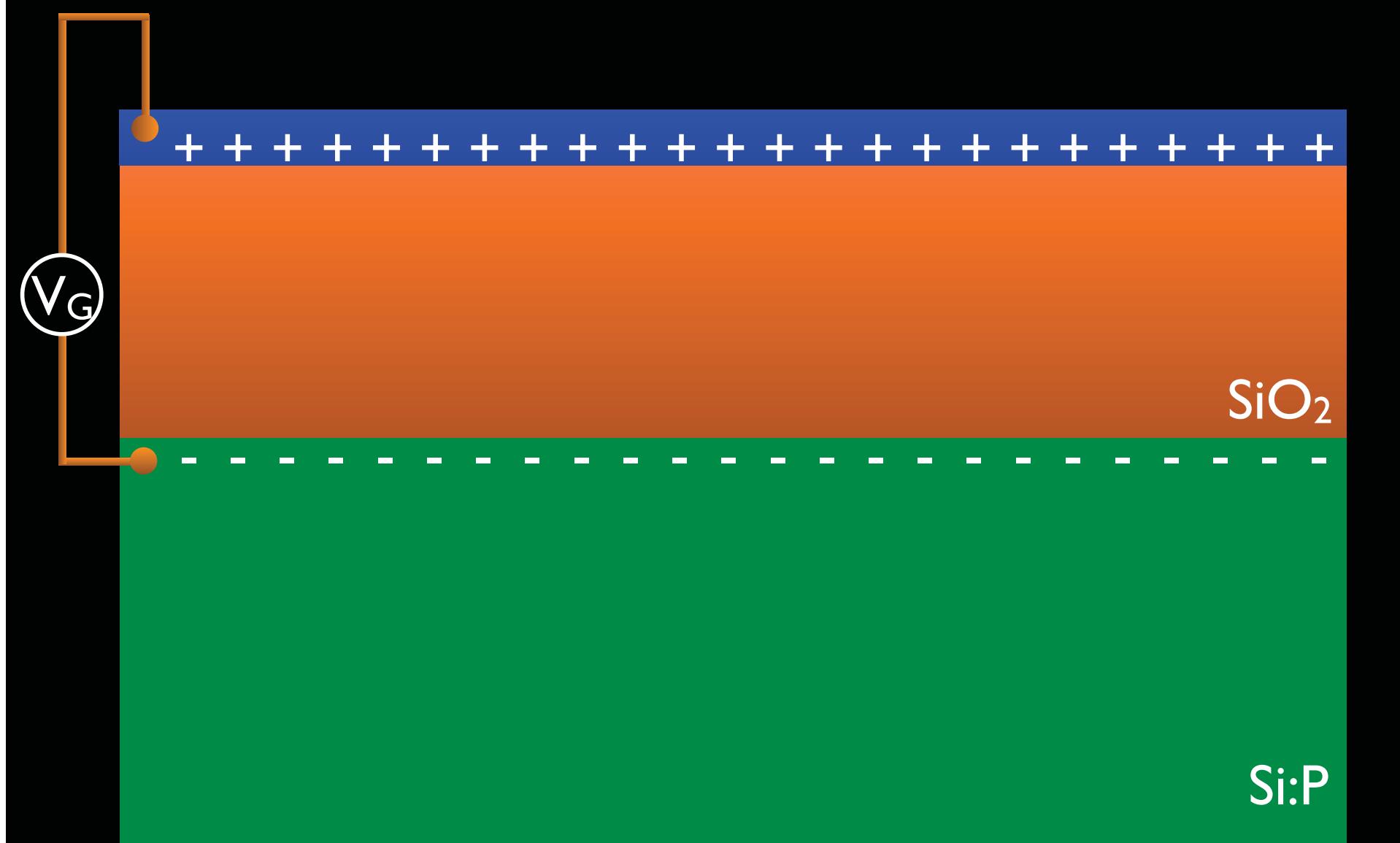
K.K. Gomes *et al.*, Nature 447, 569 (2007)



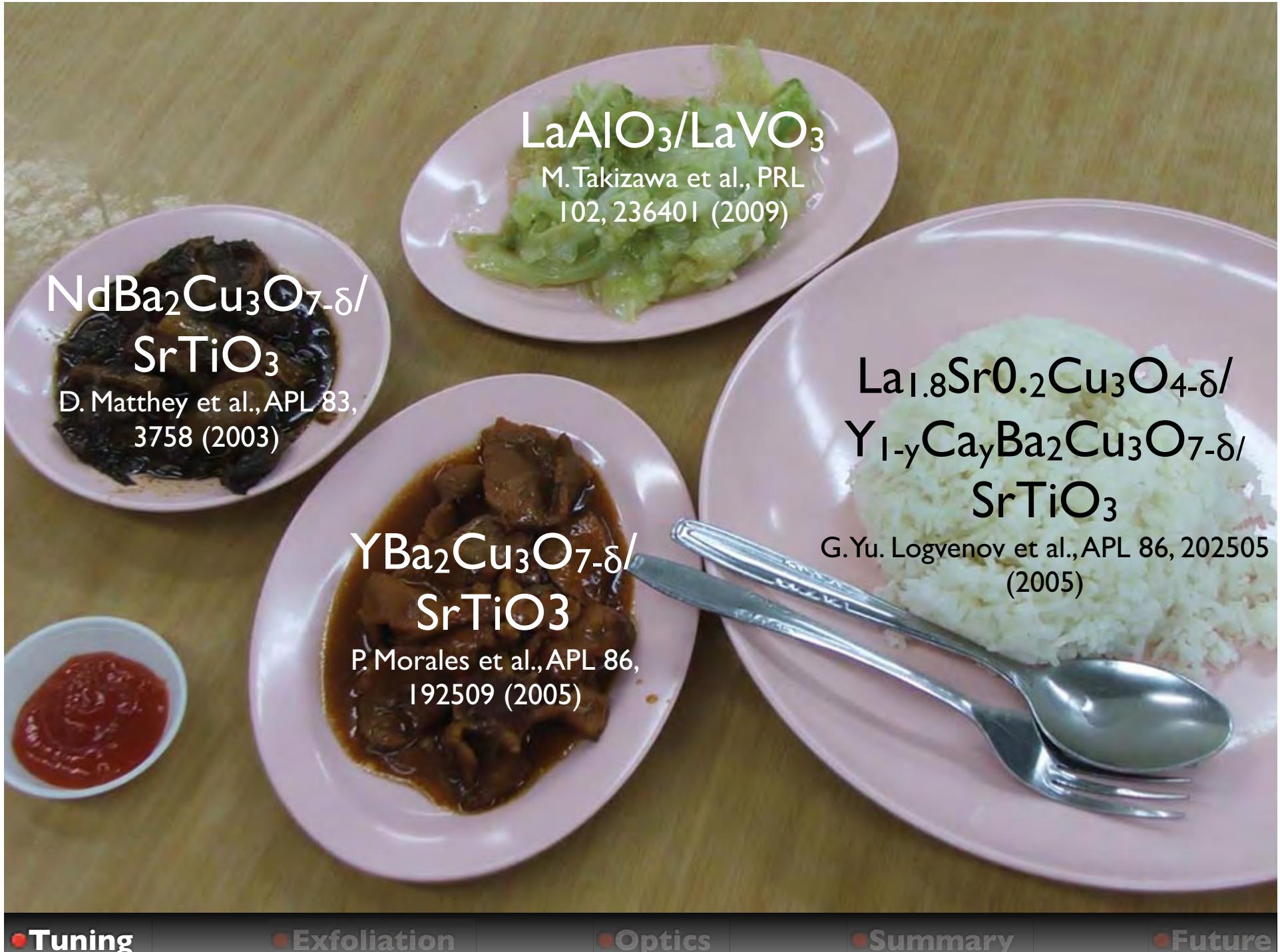
K. Tanaka, *et al.*, Science 314, 1910 (2006)
U. Chatterjee *et al.*, Nature Physics 6, 99 (2010)



Alvarez *et al.*, PRB 71 014514 (2005)









● Tuning

● Exfoliation

● Optics

● Summary

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Exfoliation

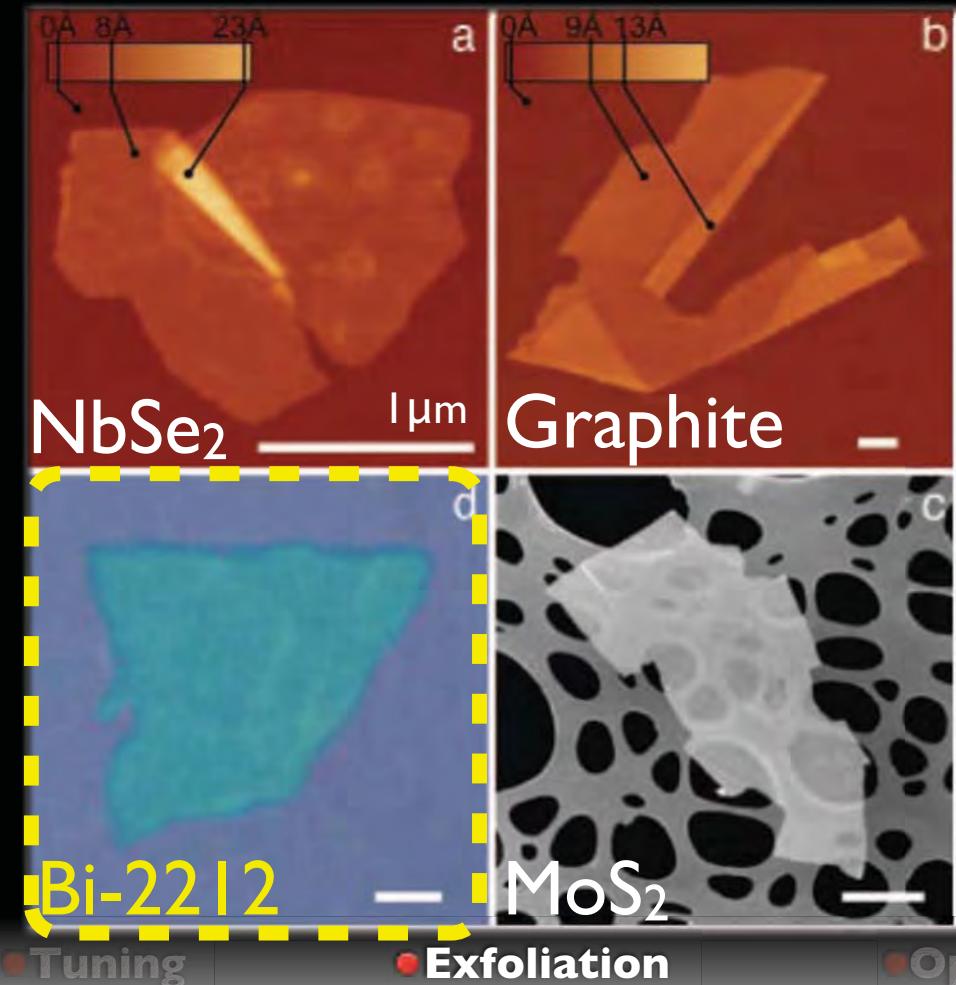
A New Way



Two-dimensional atomic crystals

K. S. Novoselov*, D. Jiang*, F. Schedin*, T. J. Booth*, V. V. Khotkevich*, S. V. Morozov†, and A. K. Geim*‡

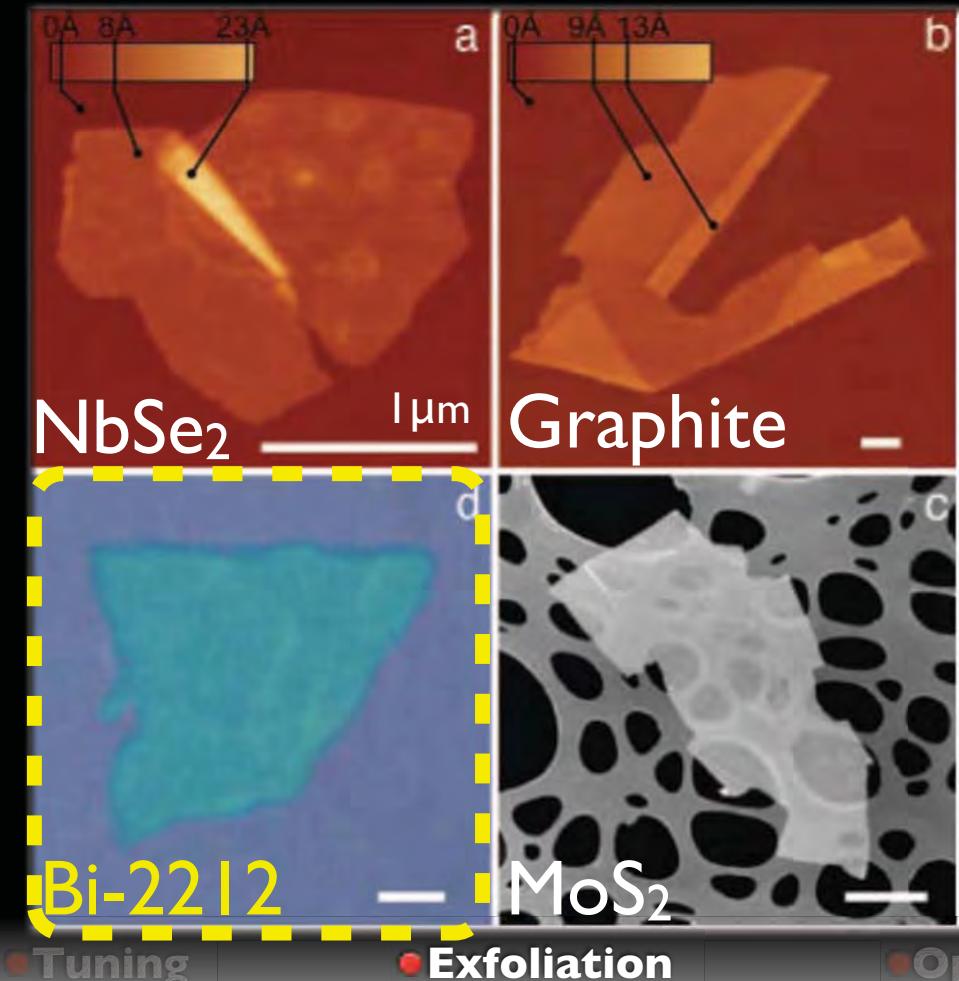
*Centre for Mesoscience and Nanotechnology and School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom;
and †Institute for Microelectronics Technology, Chernogolovka 142432, Russia



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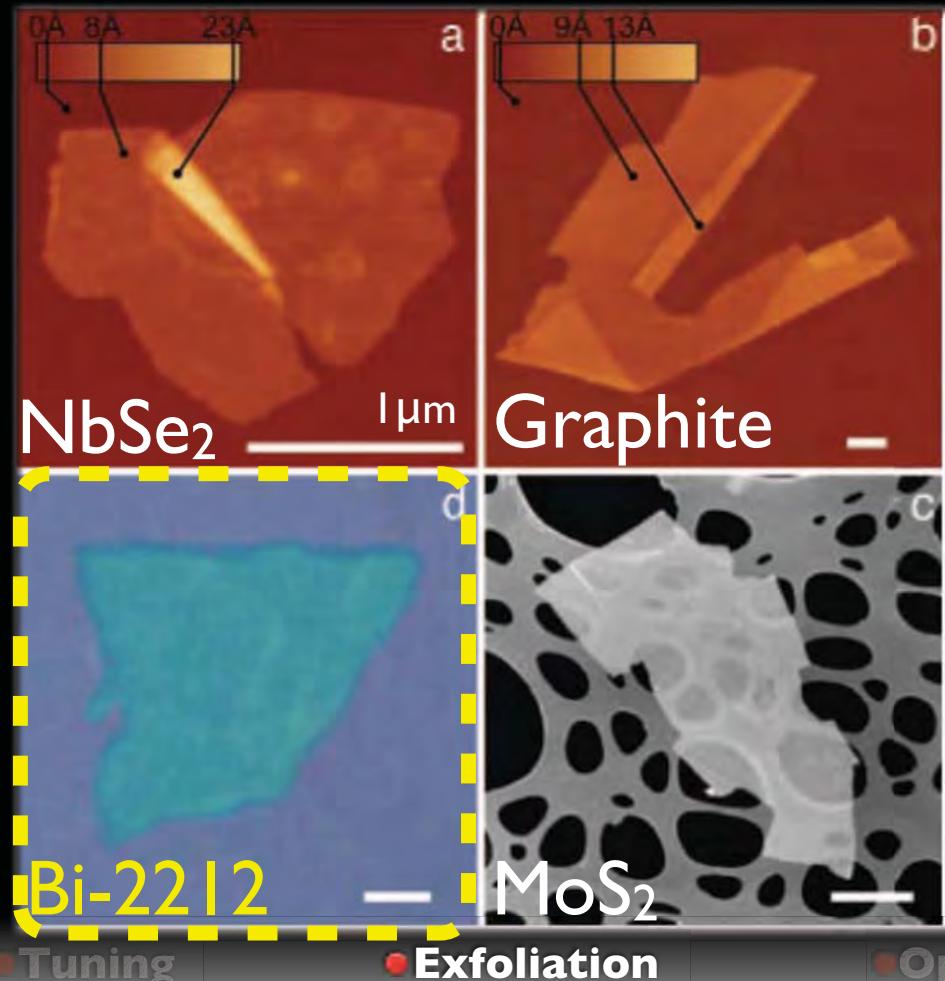
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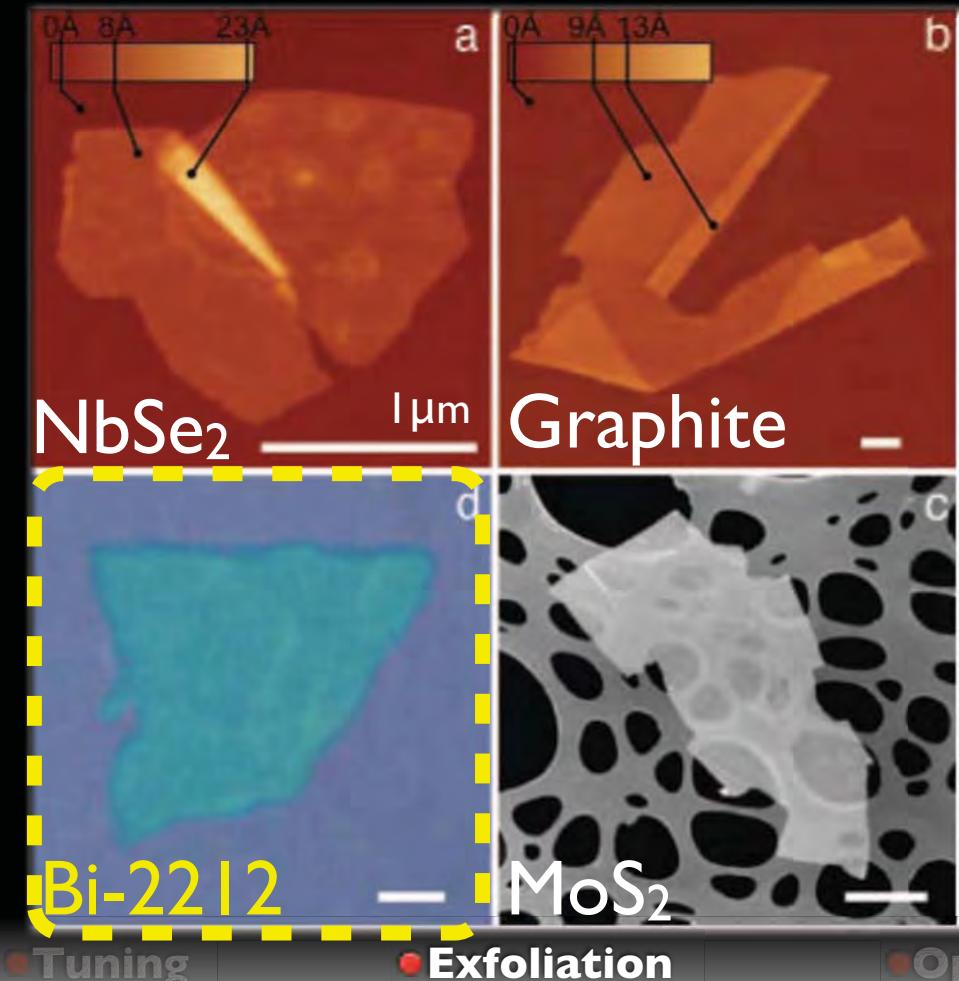
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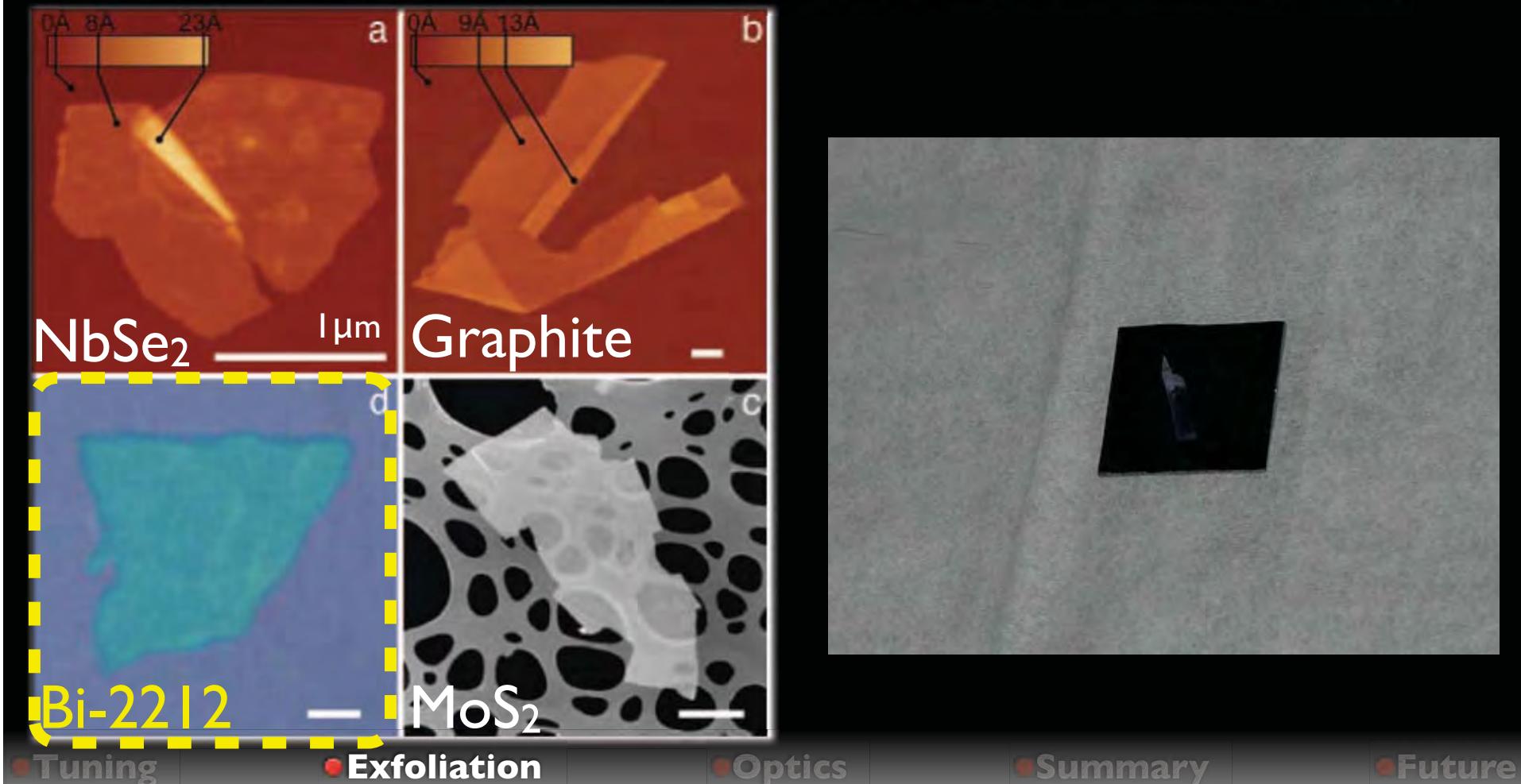
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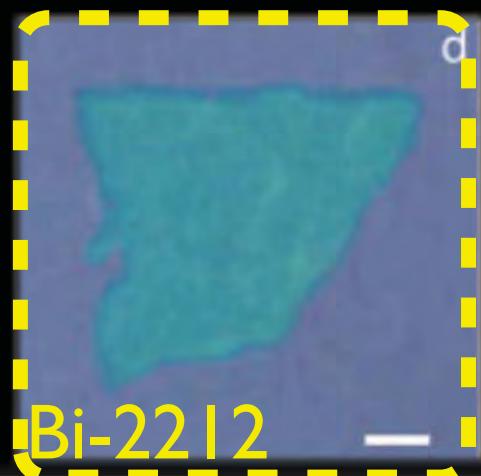
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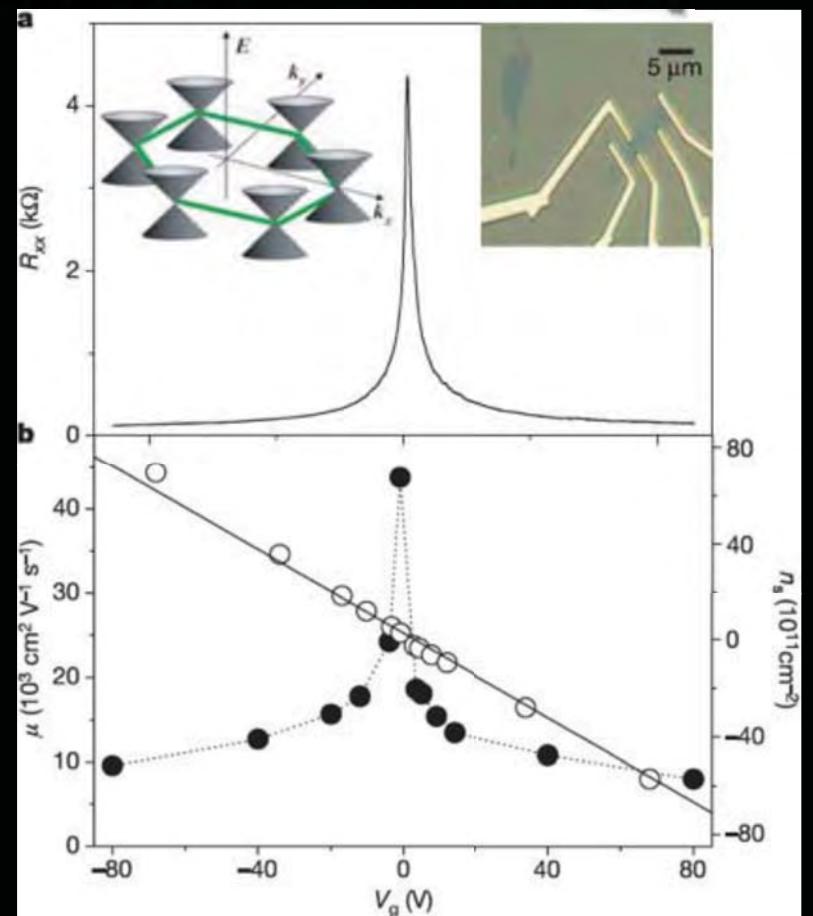
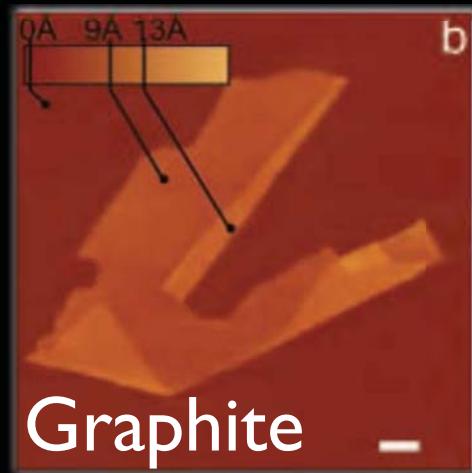
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A New Way

A collage of scientific journal covers from 2009 and 2010, including Nature Photonics, Physical Review Letters, and Nature Nanotechnology. The covers feature research on graphene photodetectors for high-speed optical communications, Dirac charge dynamics in graphene, and controlled ripple texturing of suspended graphene and ultrathin graphite membranes.

Tuning

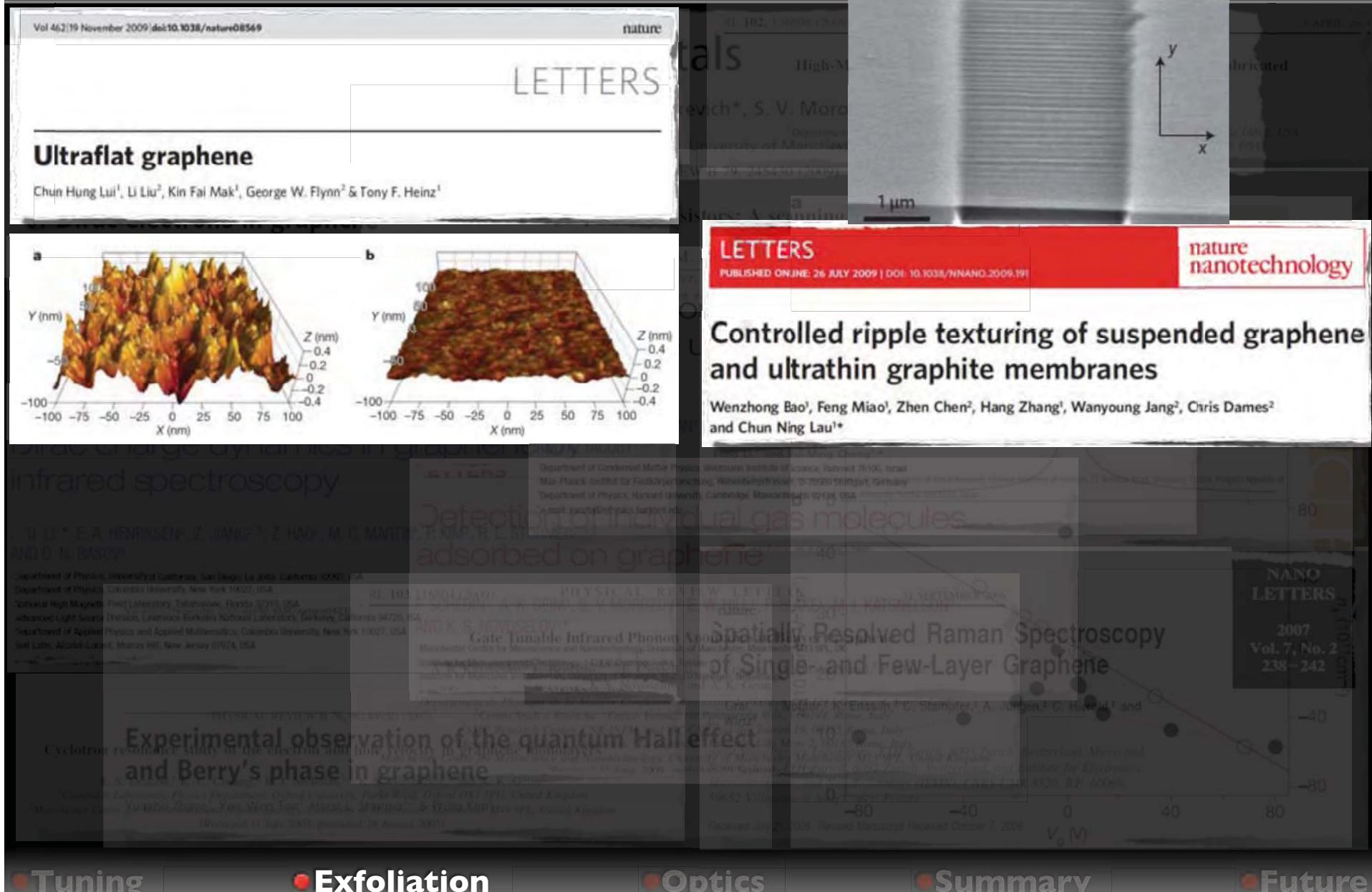
Exfoliation

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Tuning

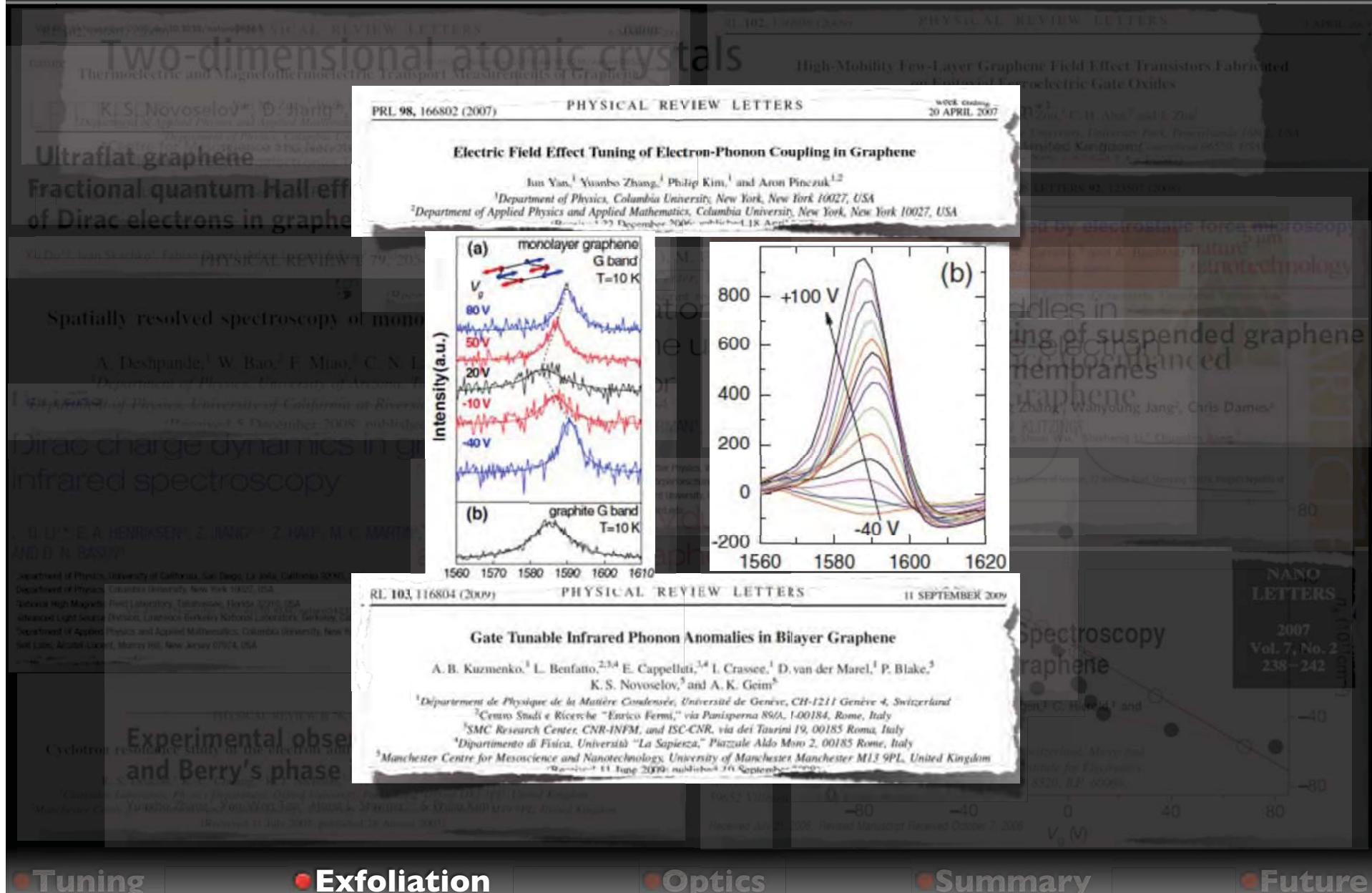
● Exfoliation

Optics

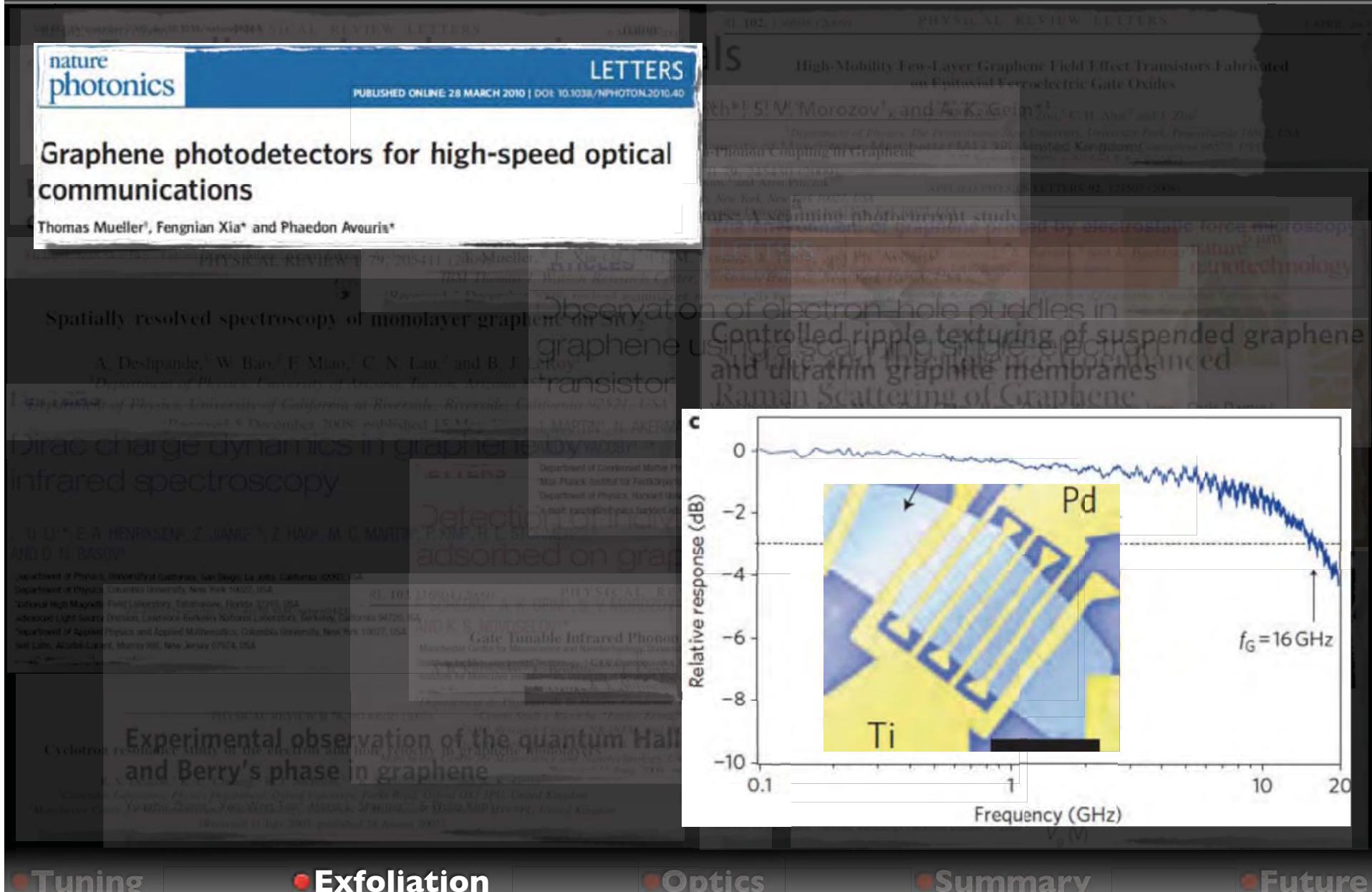
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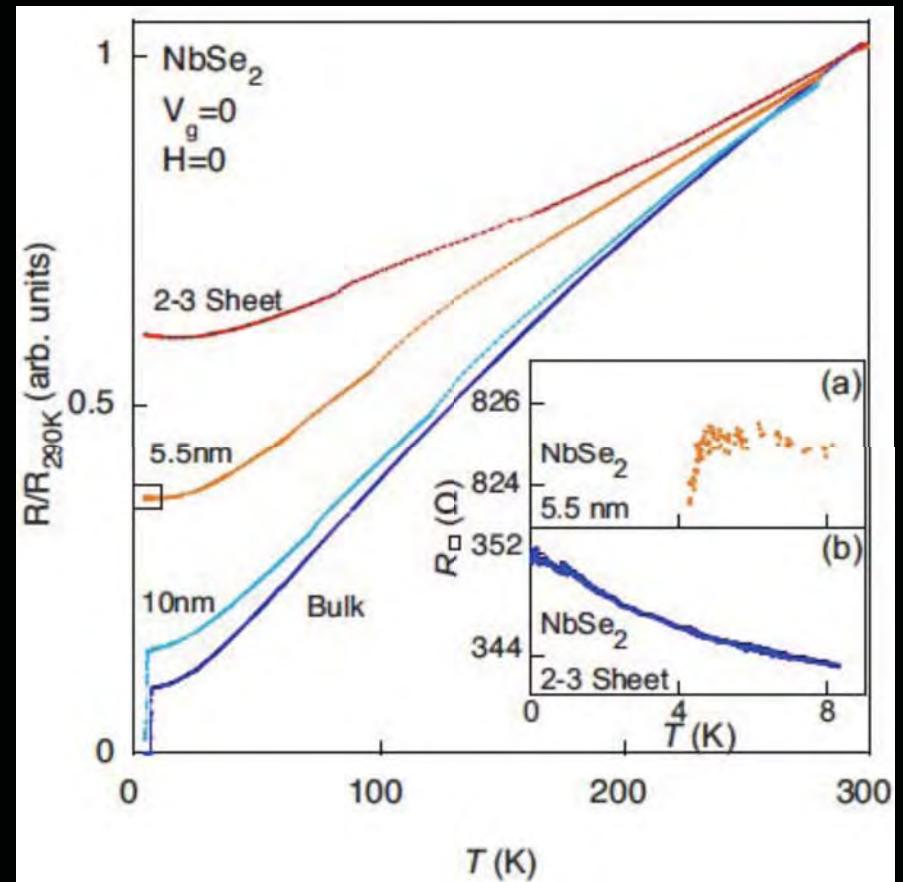
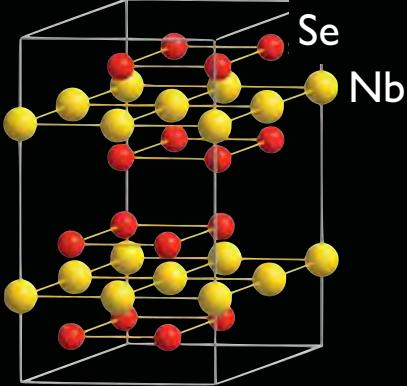
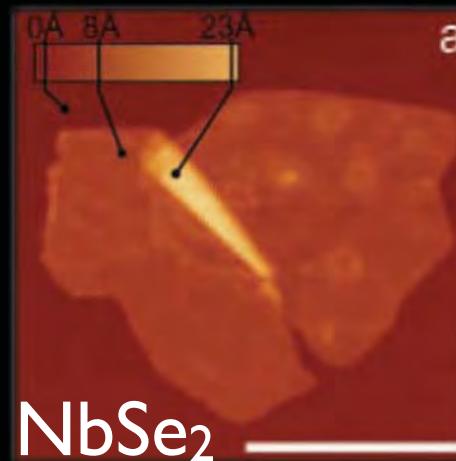
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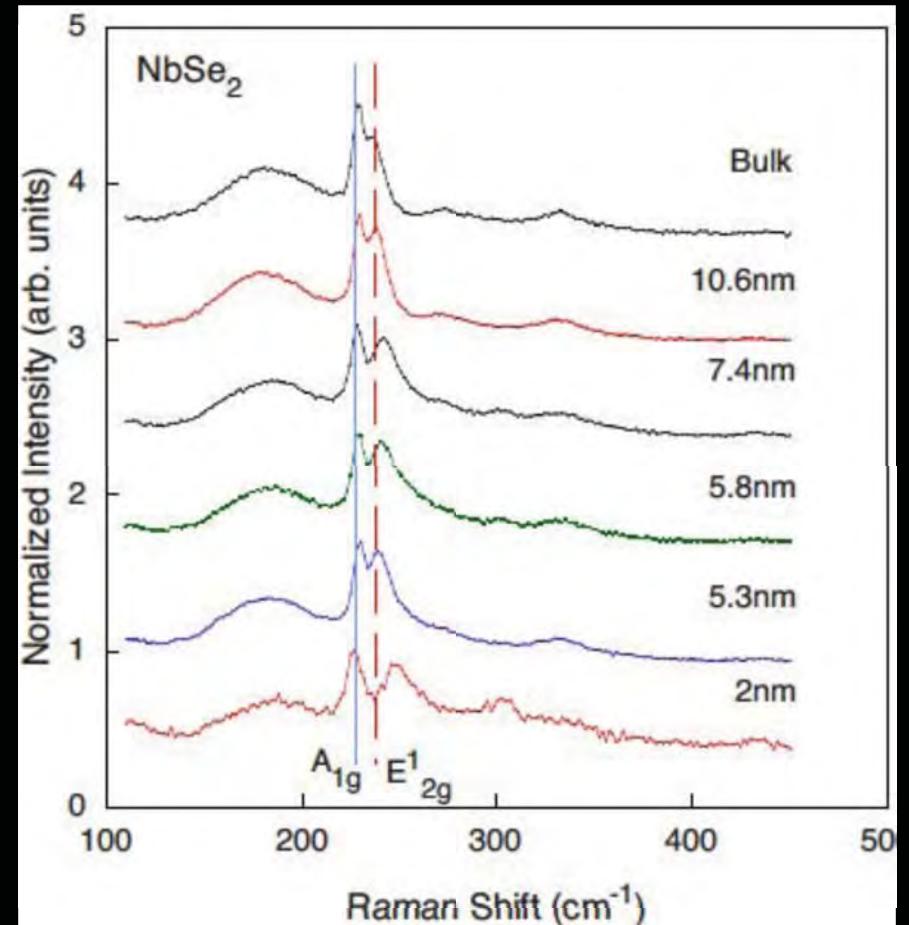
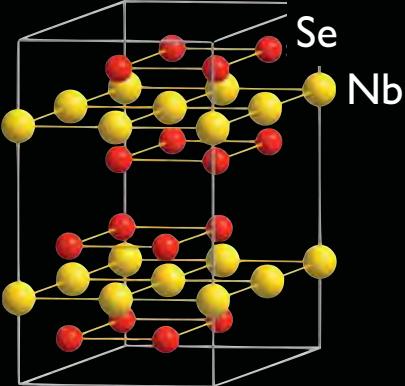
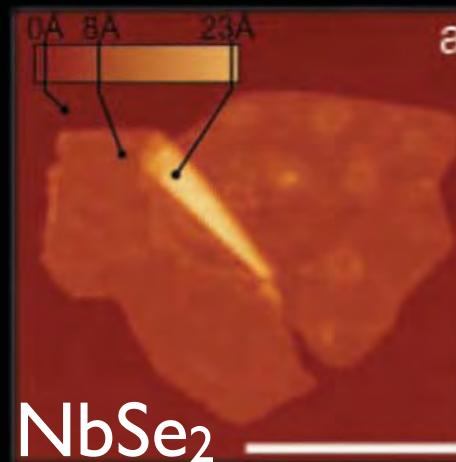


A New Way



N.E. Staley et. al, PRB 80, 184505 (2009)

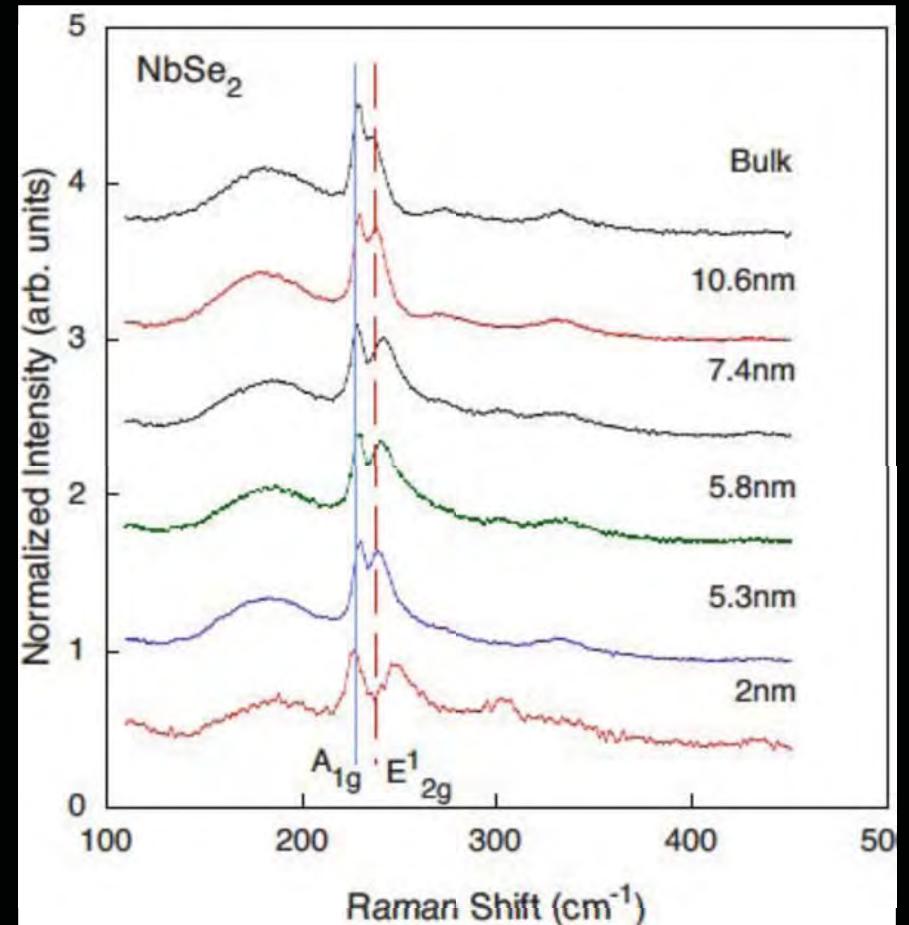
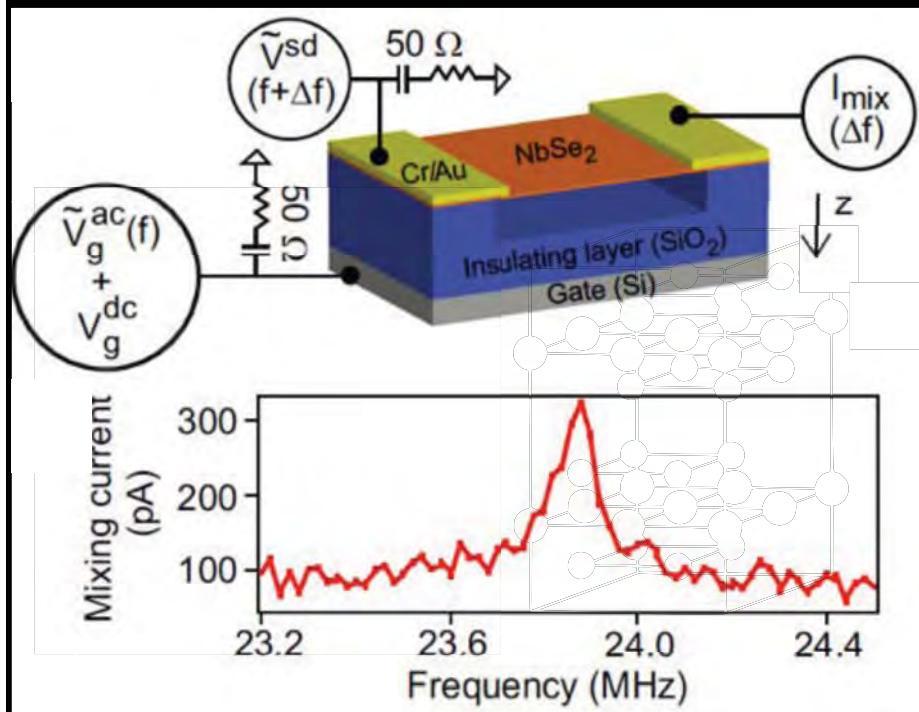
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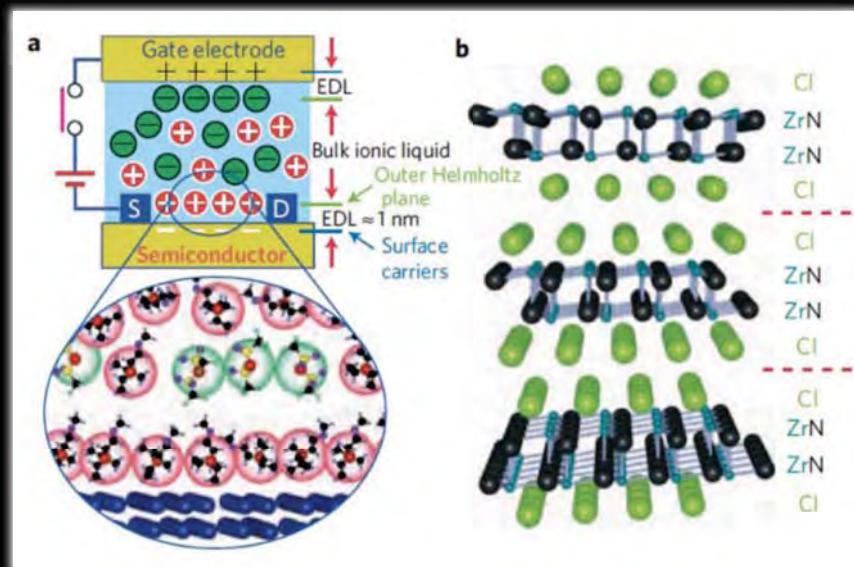
S. Sengupta et. al, arXiv:1004.3453



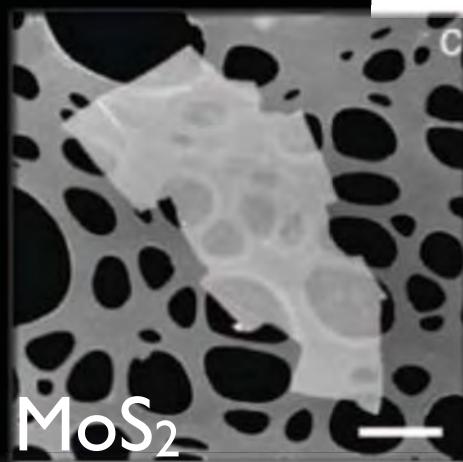
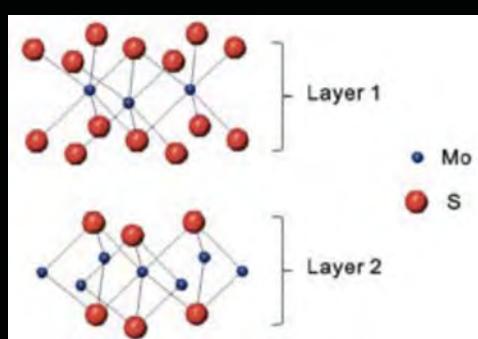
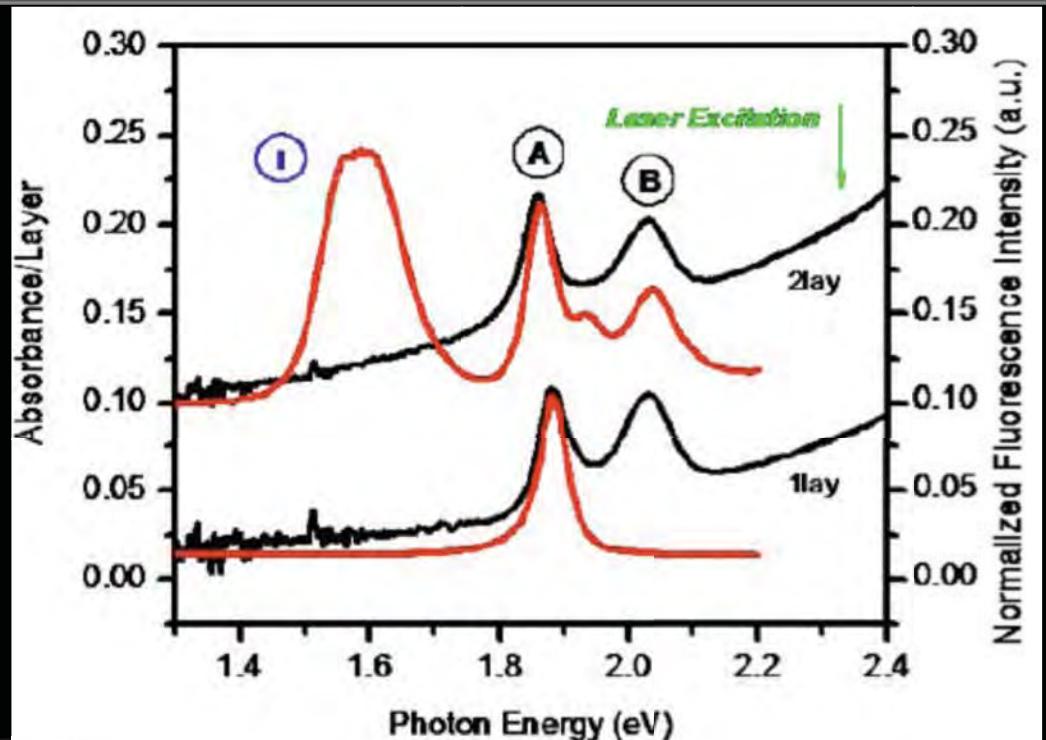
N.E. Staley et. al, PRB 80, 184505 (2009)

Liquid-gated interface superconductivity on an atomically flat film

J. T. Ye^{1,2*}, S. Inoue¹, K. Kobayashi¹, Y. Kasahara¹, H. T. Yuan^{1,3}, H. Shimotani^{1,3} and Y. Iwasa^{1,3*}



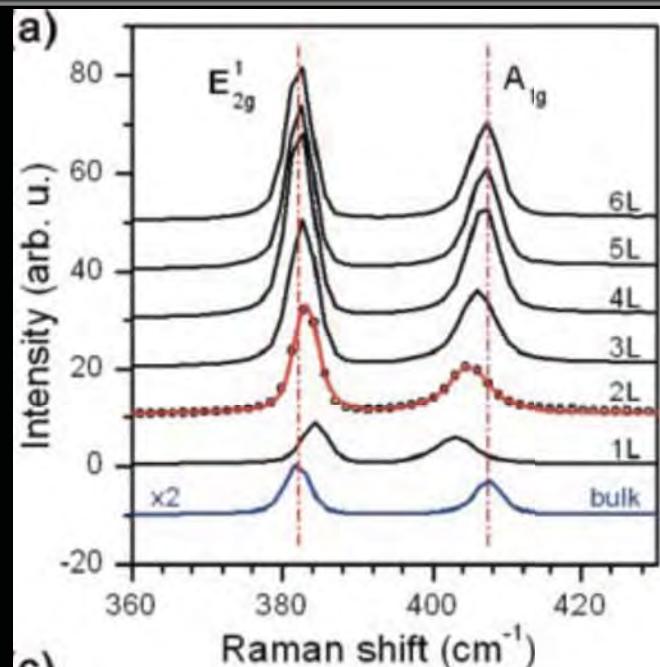
A New Way



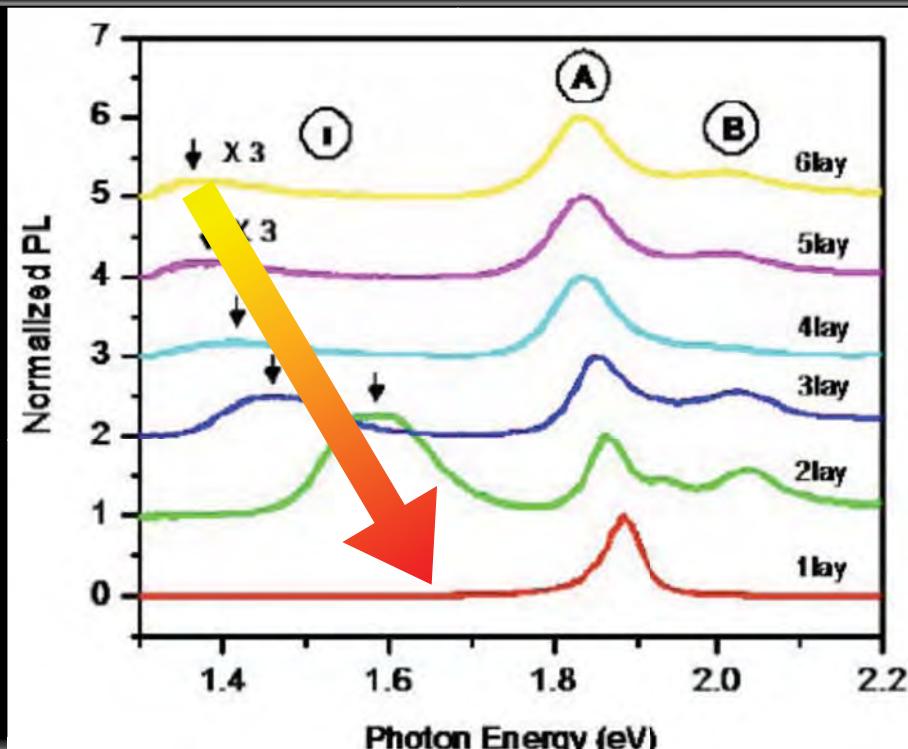
K.F. Mak et. al, arxiv 1004.0546

A. Splendiani et. al, Nano. Lett. 4, 1271 (2010)

A New Way

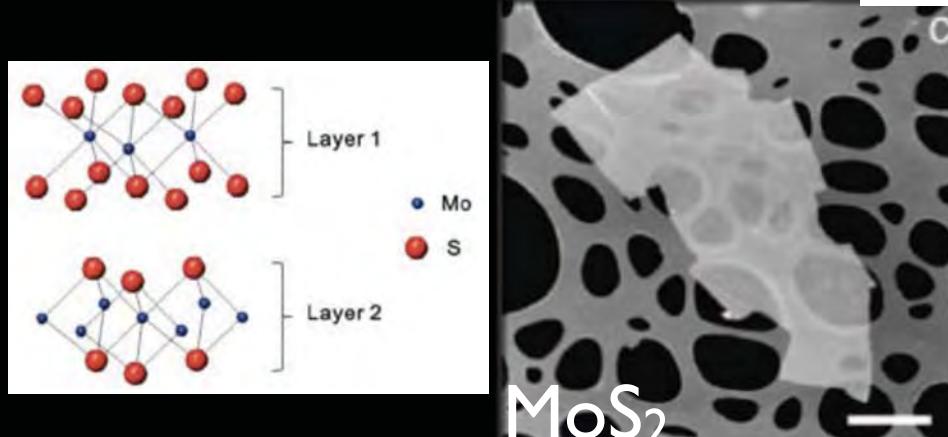


C. Lee et al, ACS Nano. 4, 2695 (2010)

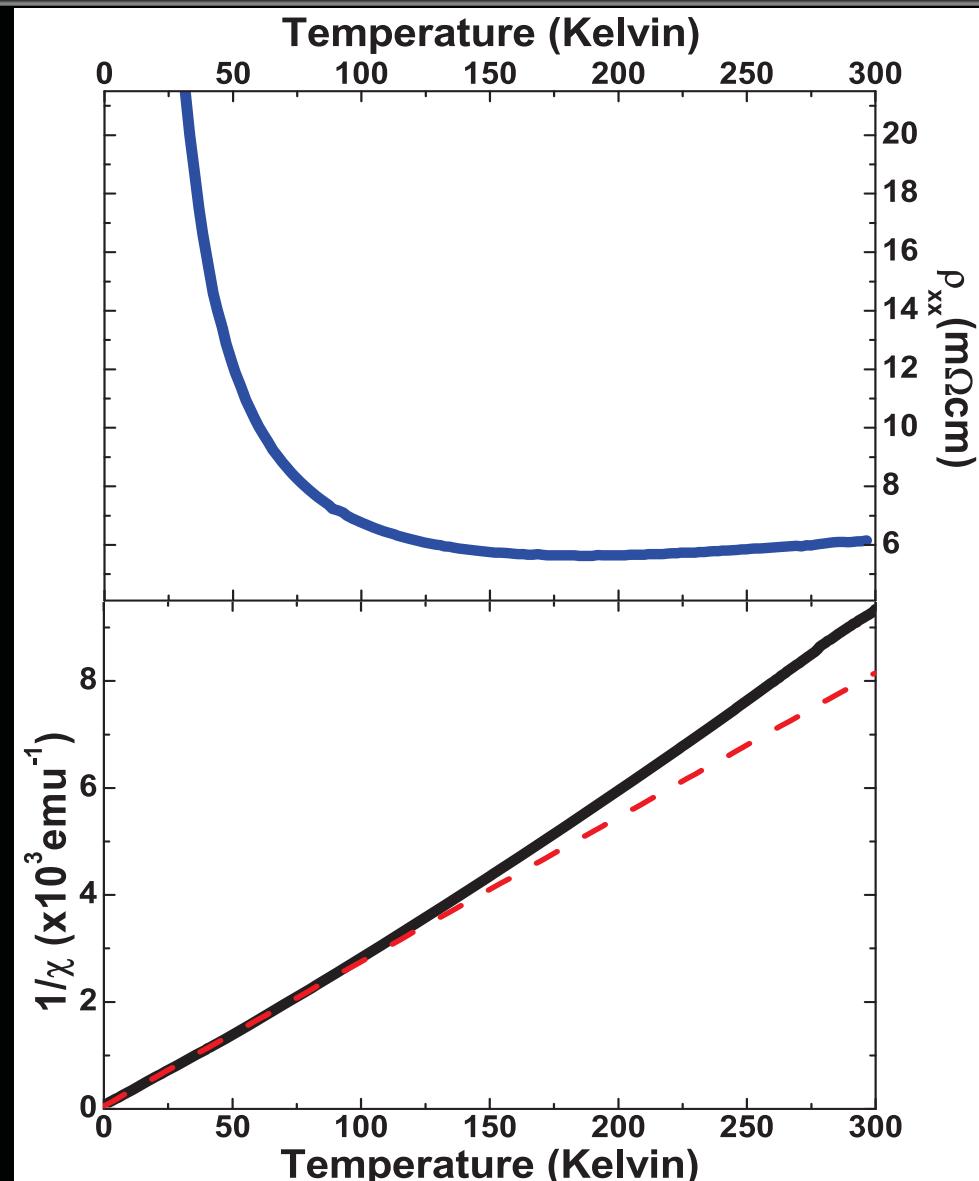


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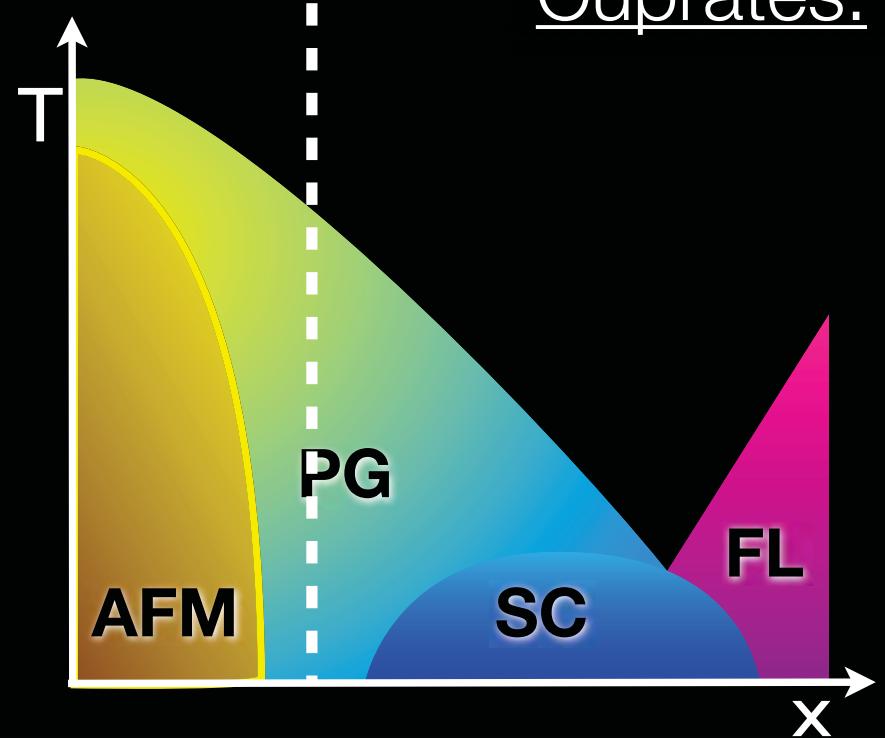


Bulk Properties

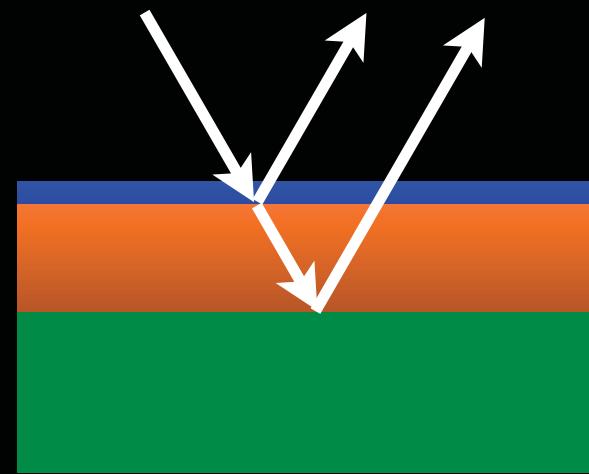
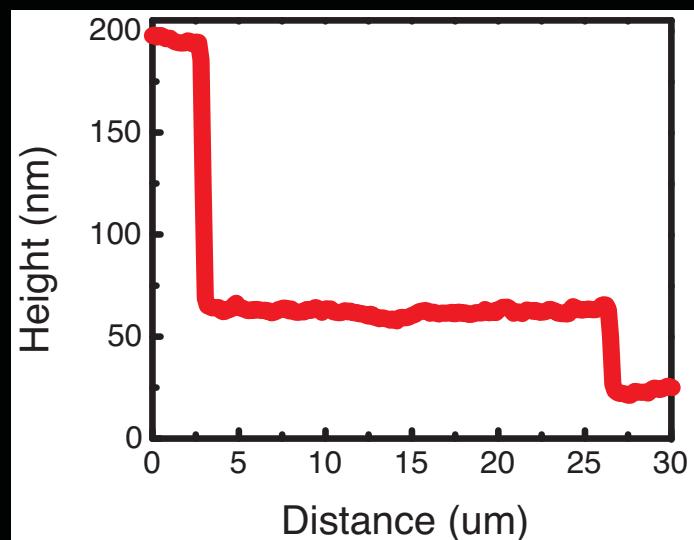
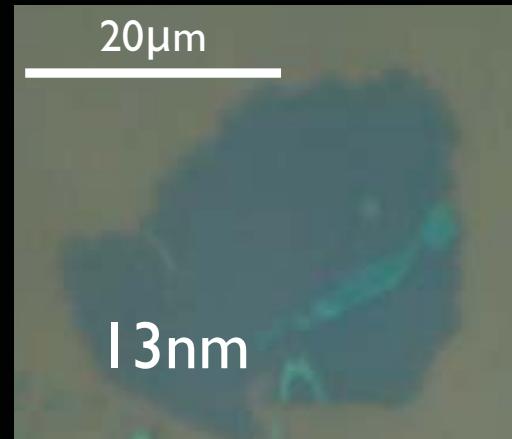
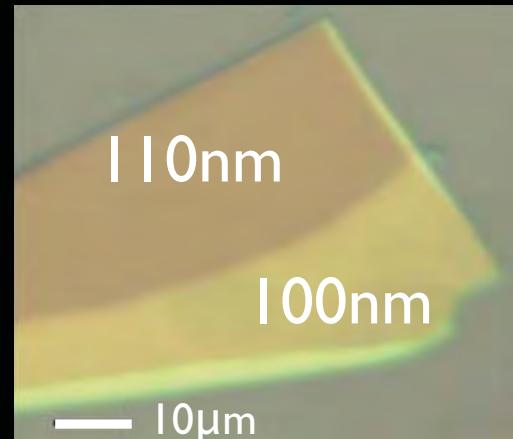
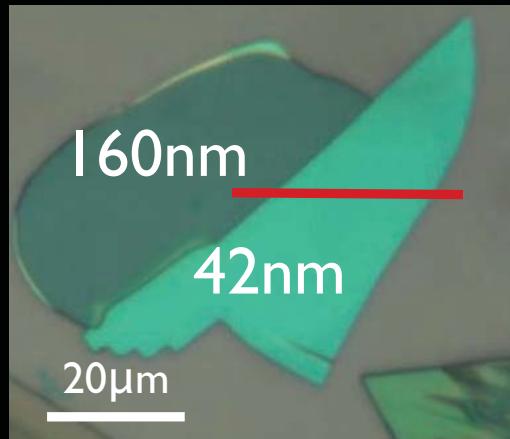


$\text{Bi}_2\text{Sr}_2\text{Ca}_{1-x}\text{Dy}_x\text{Cu}_2\text{O}_{8+\delta}$
 $x=0.3, 0.4$

Cuprates:

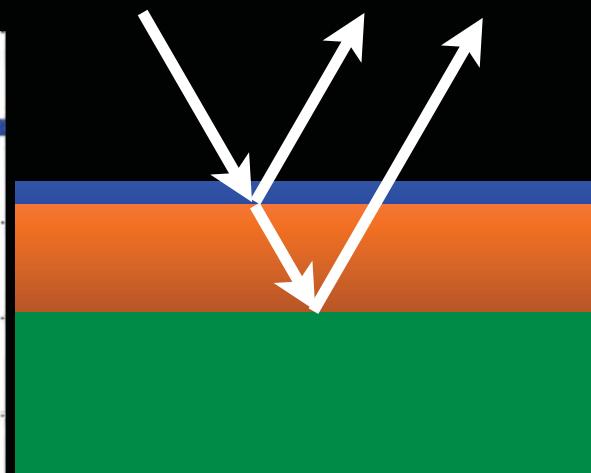
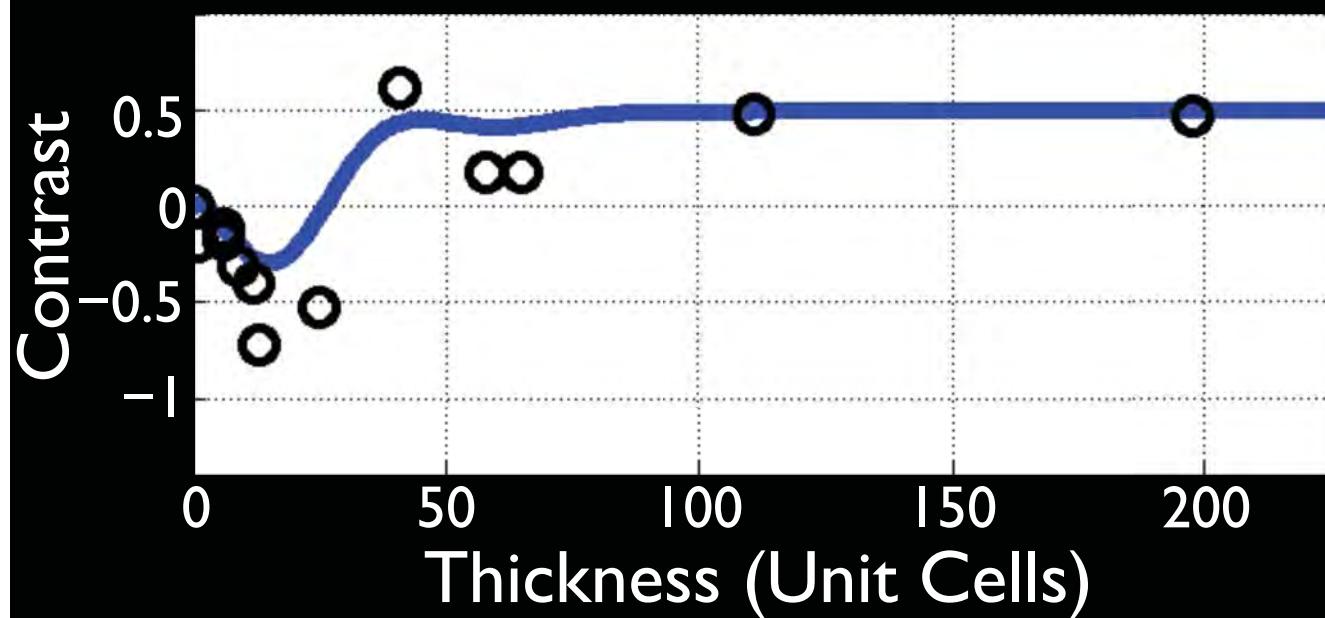
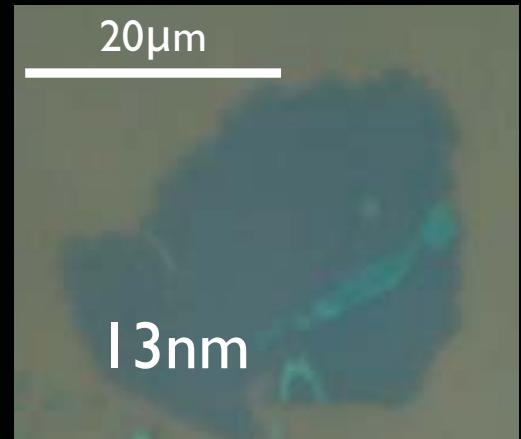
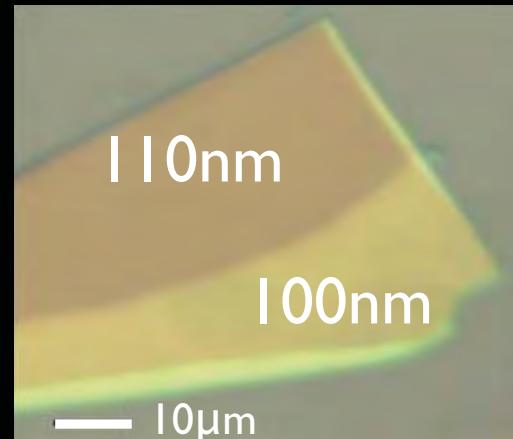
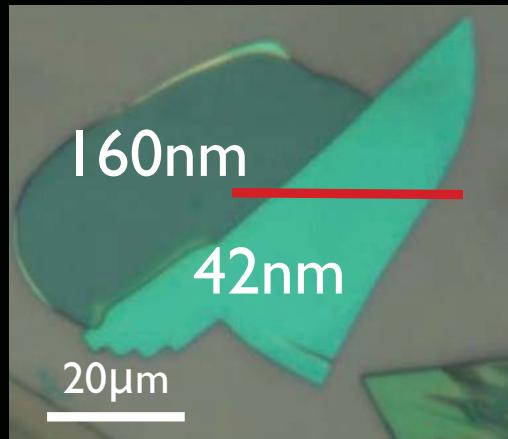


Visibility



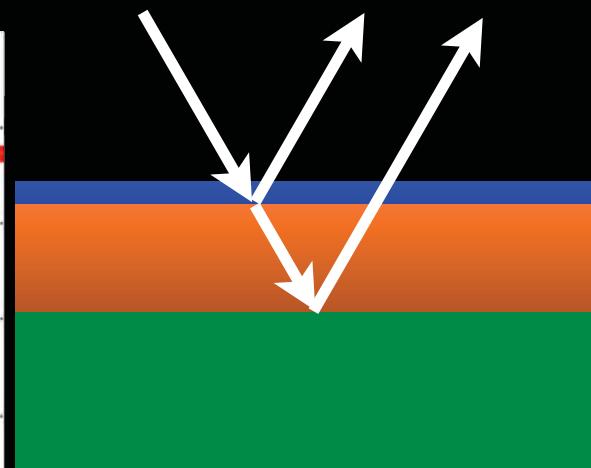
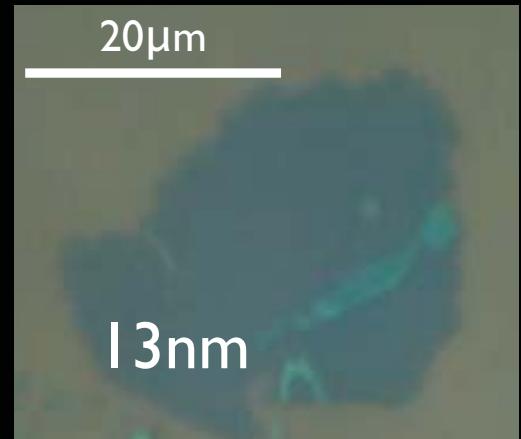
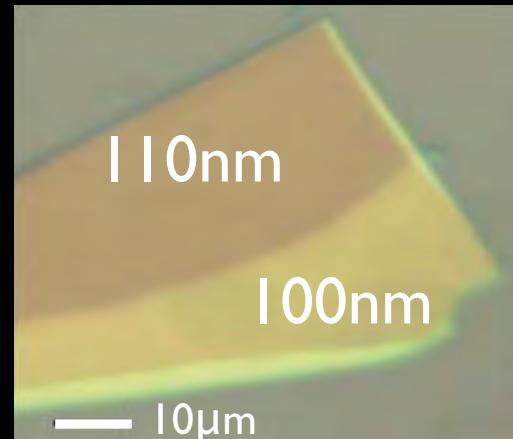
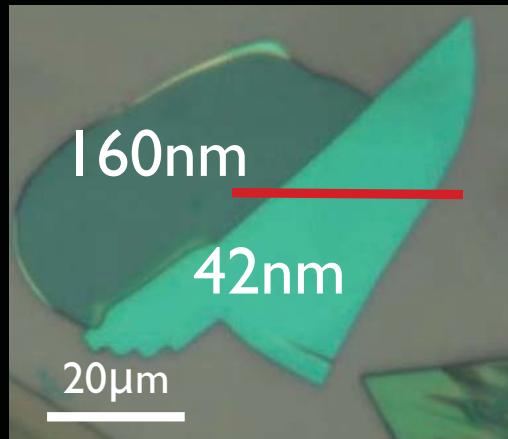
Theory:
A.H. Castro Neto et al.,
APL 91, 063124 (2007)

Visibility



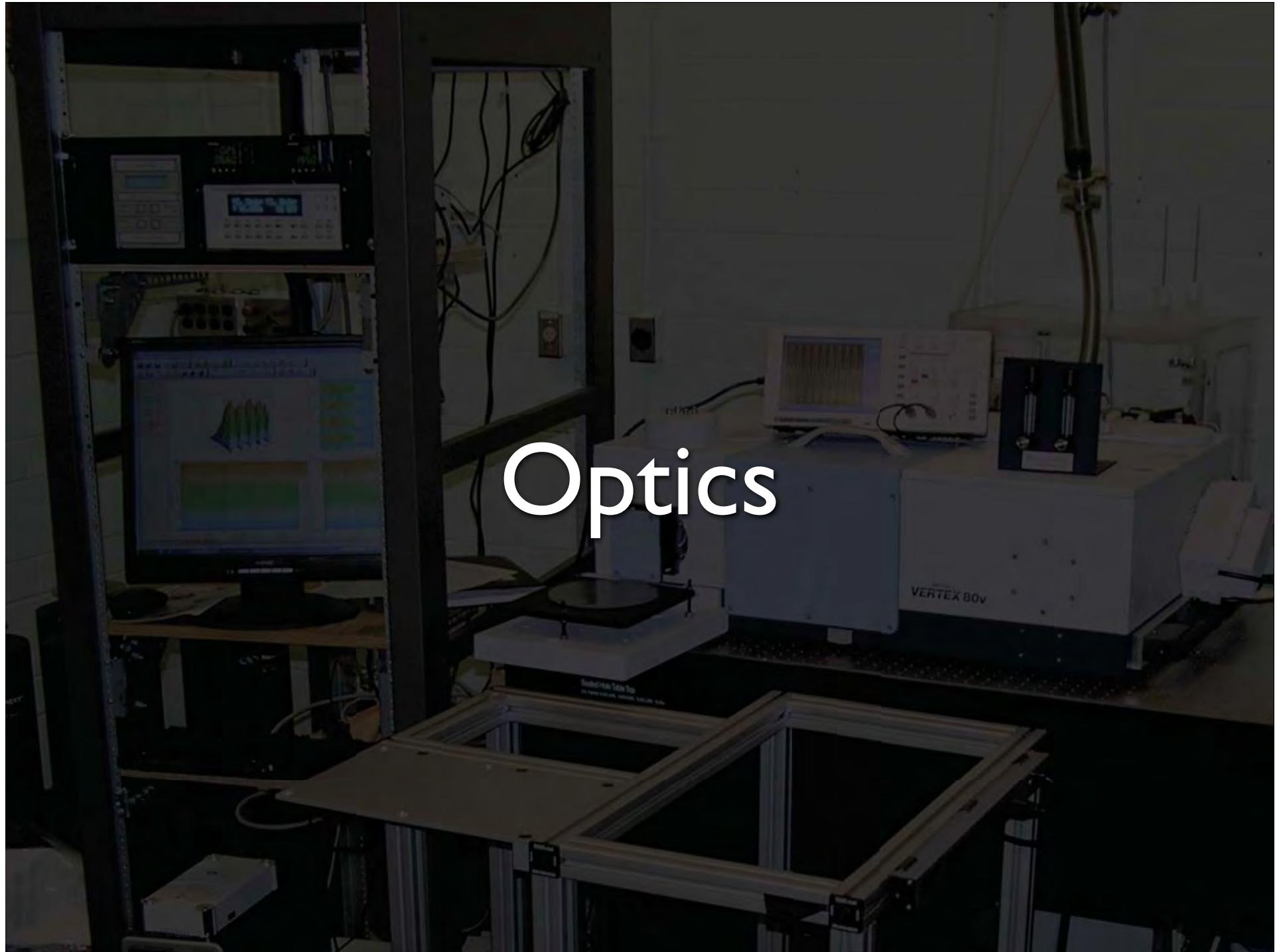
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APL 91, 063124 (2007)

Visibility

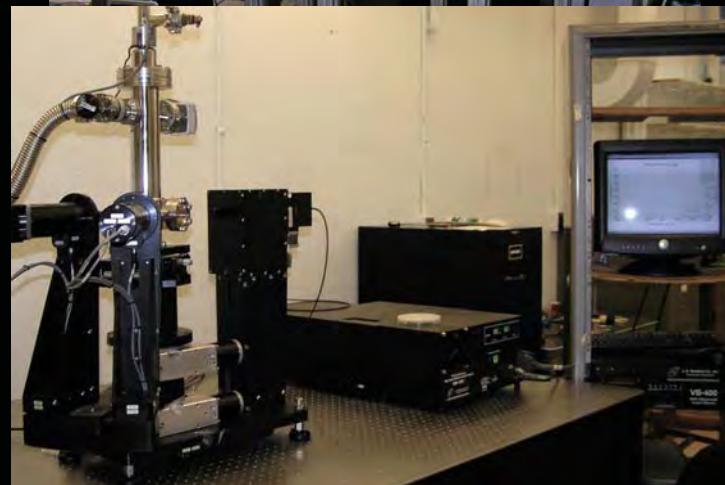
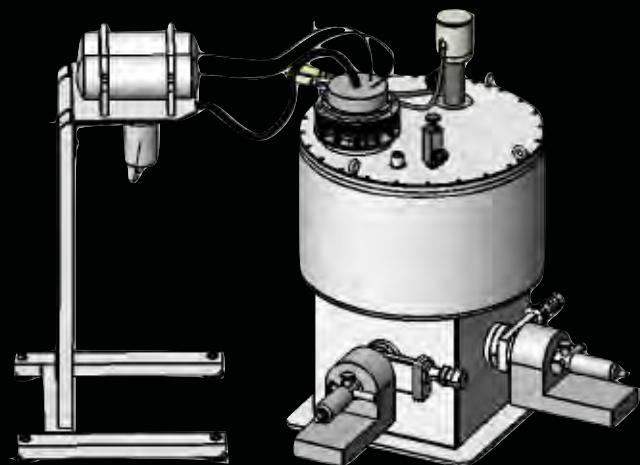
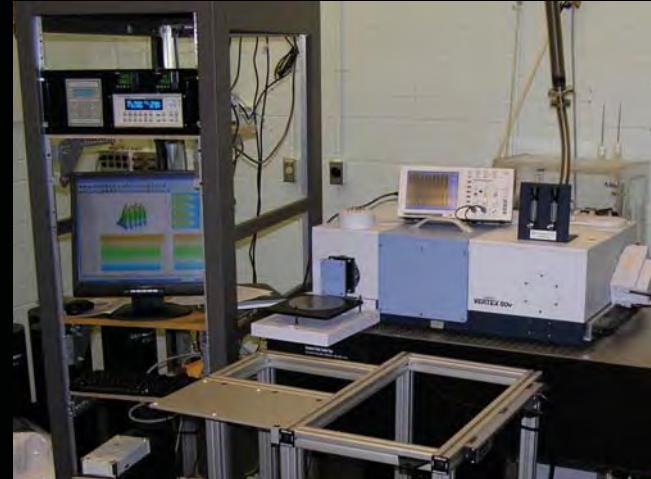
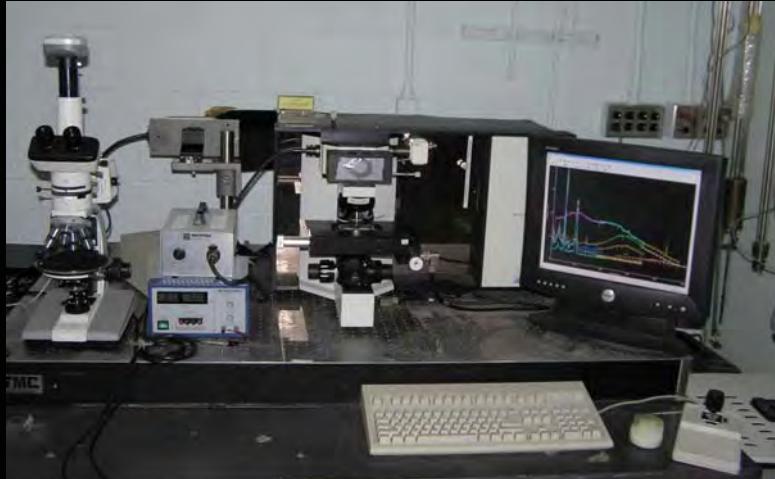


Theory:
A.H. Castro Neto et al.,
APL 91, 063124 (2007)

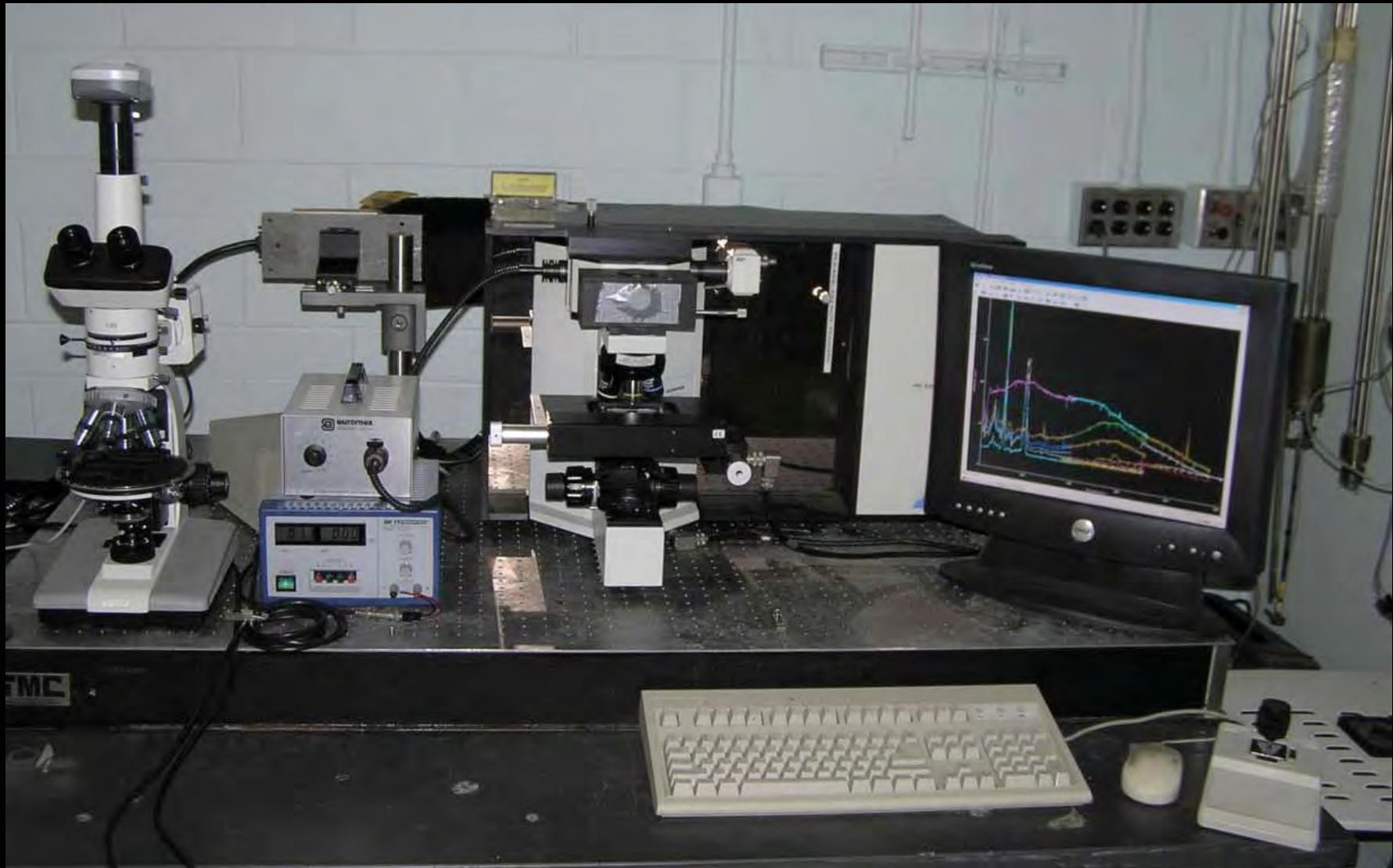
Optics



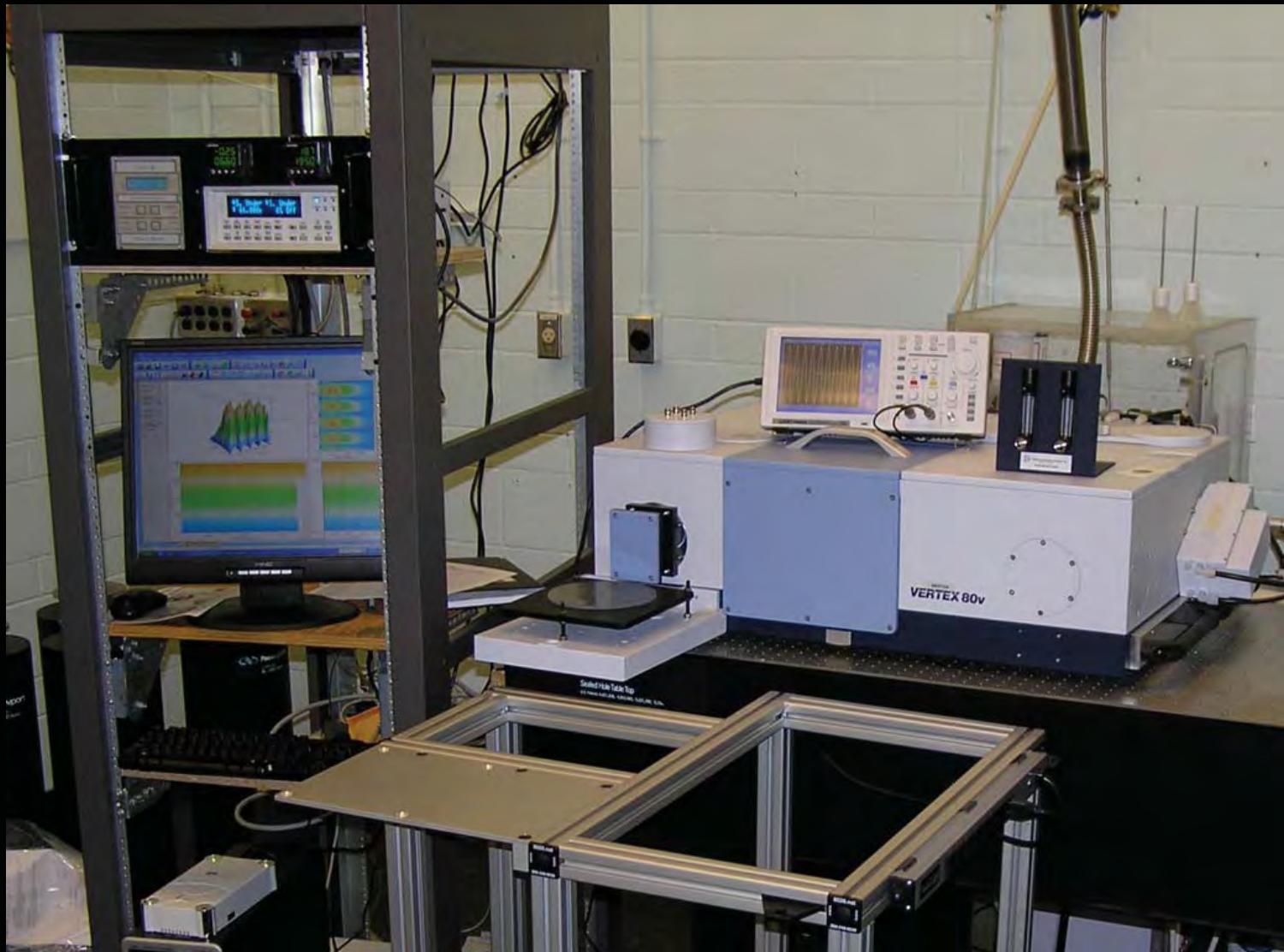
Lab Tour



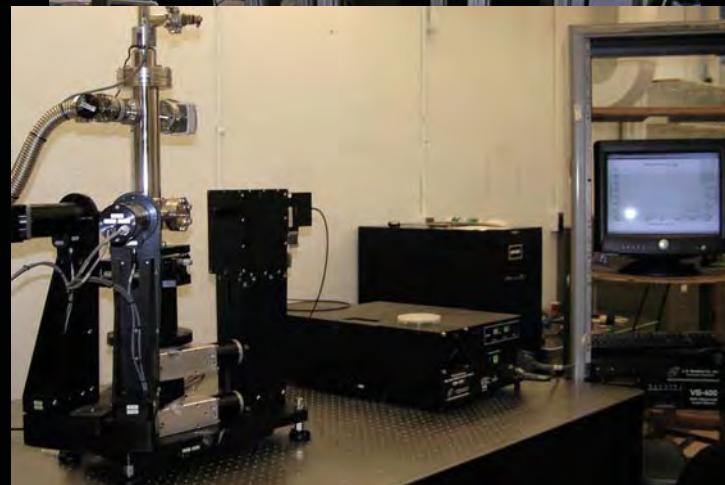
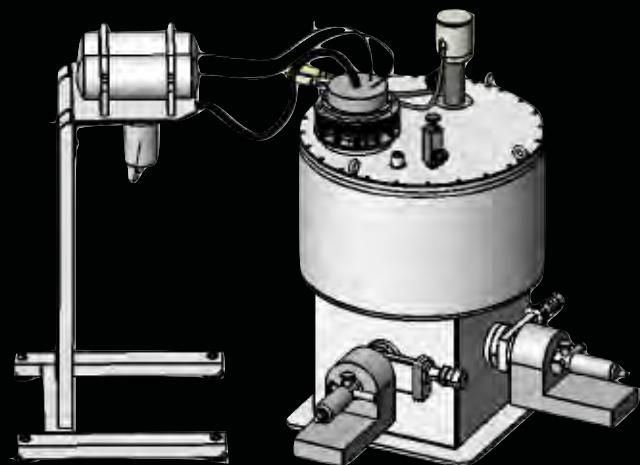
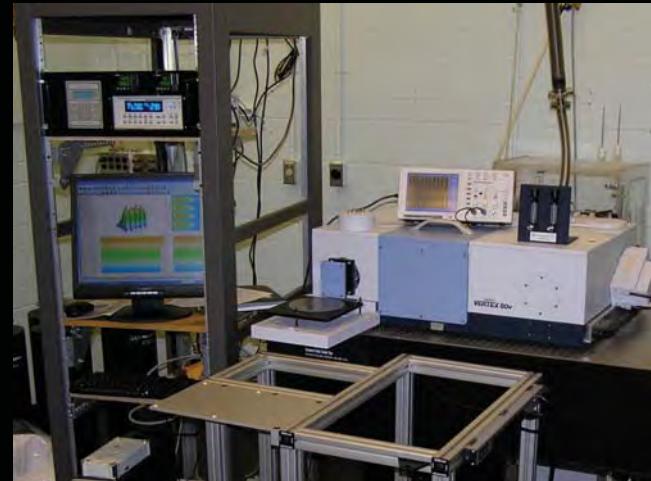
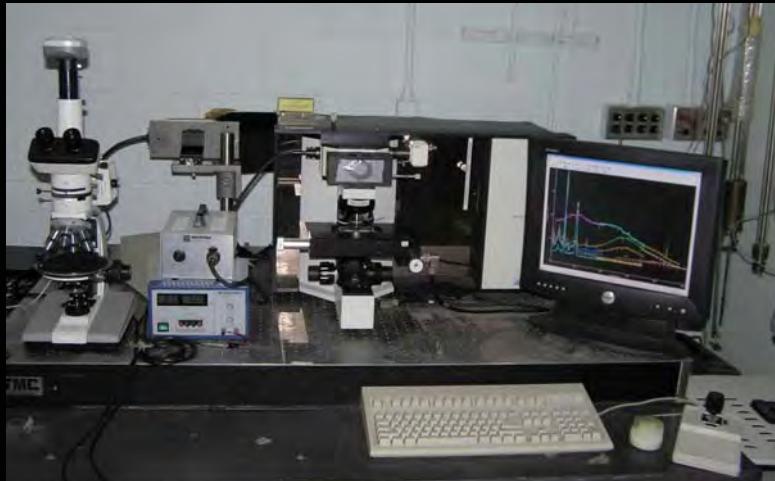
Lab Tour



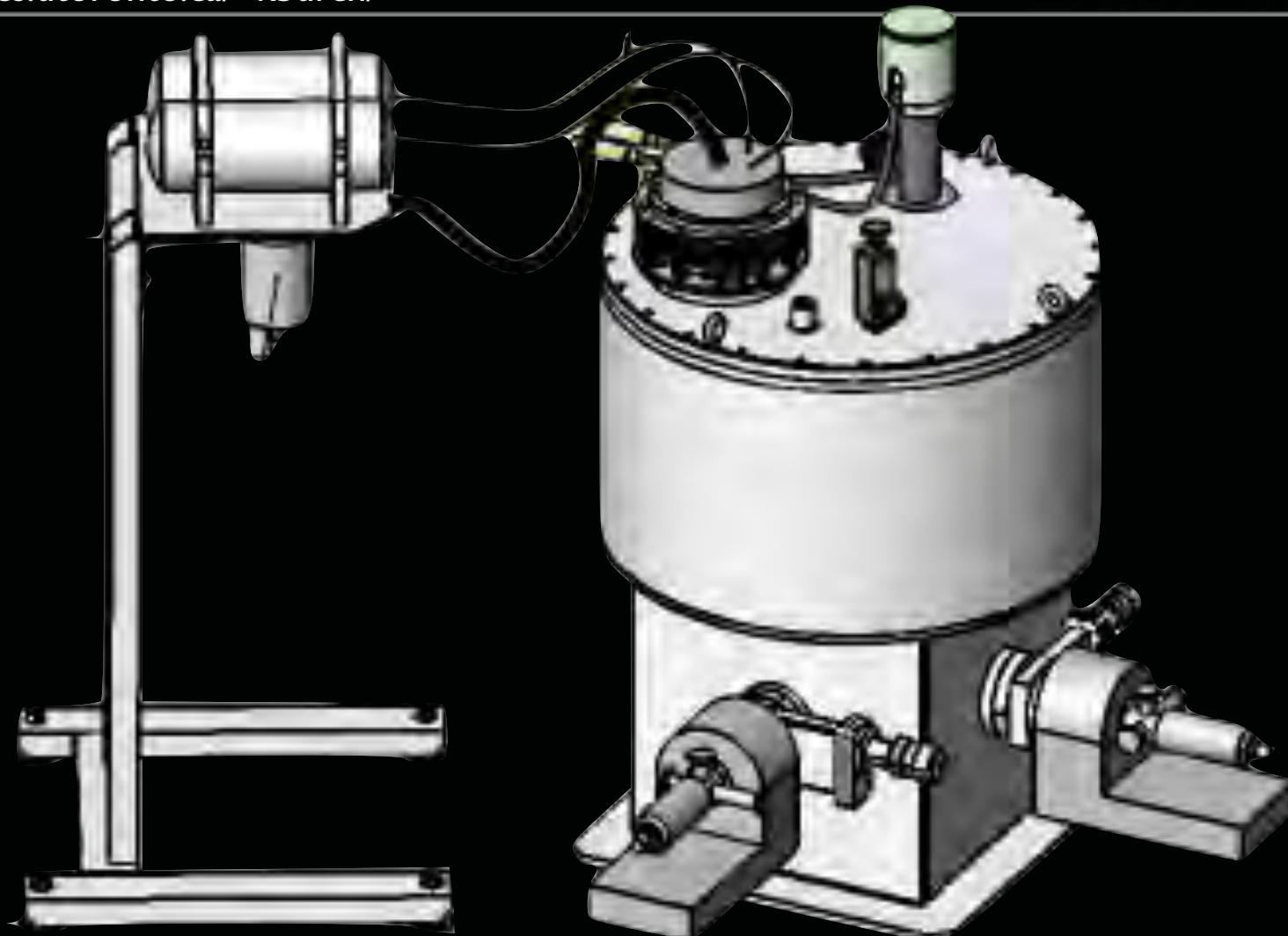
Lab Tour



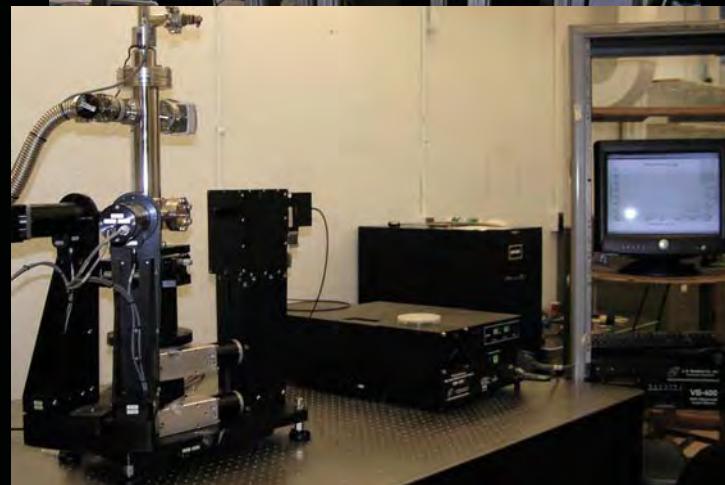
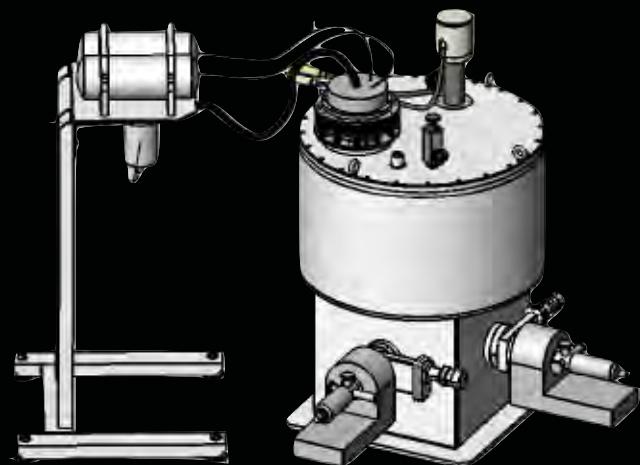
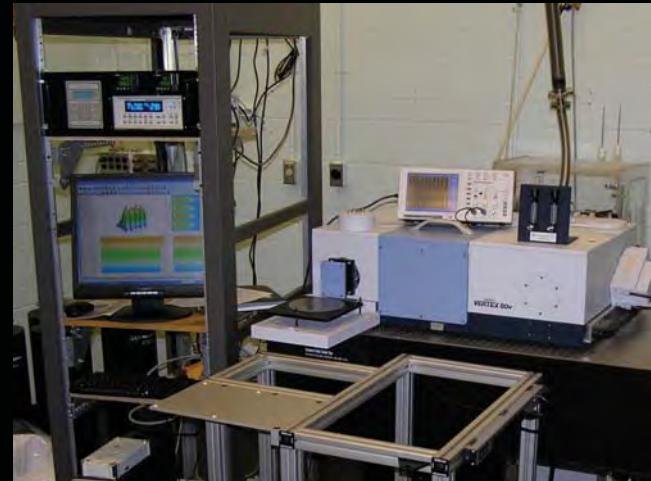
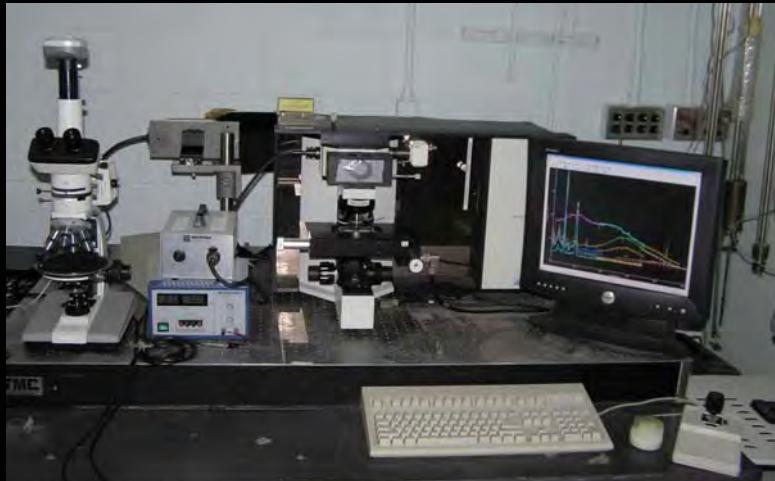
Lab Tour



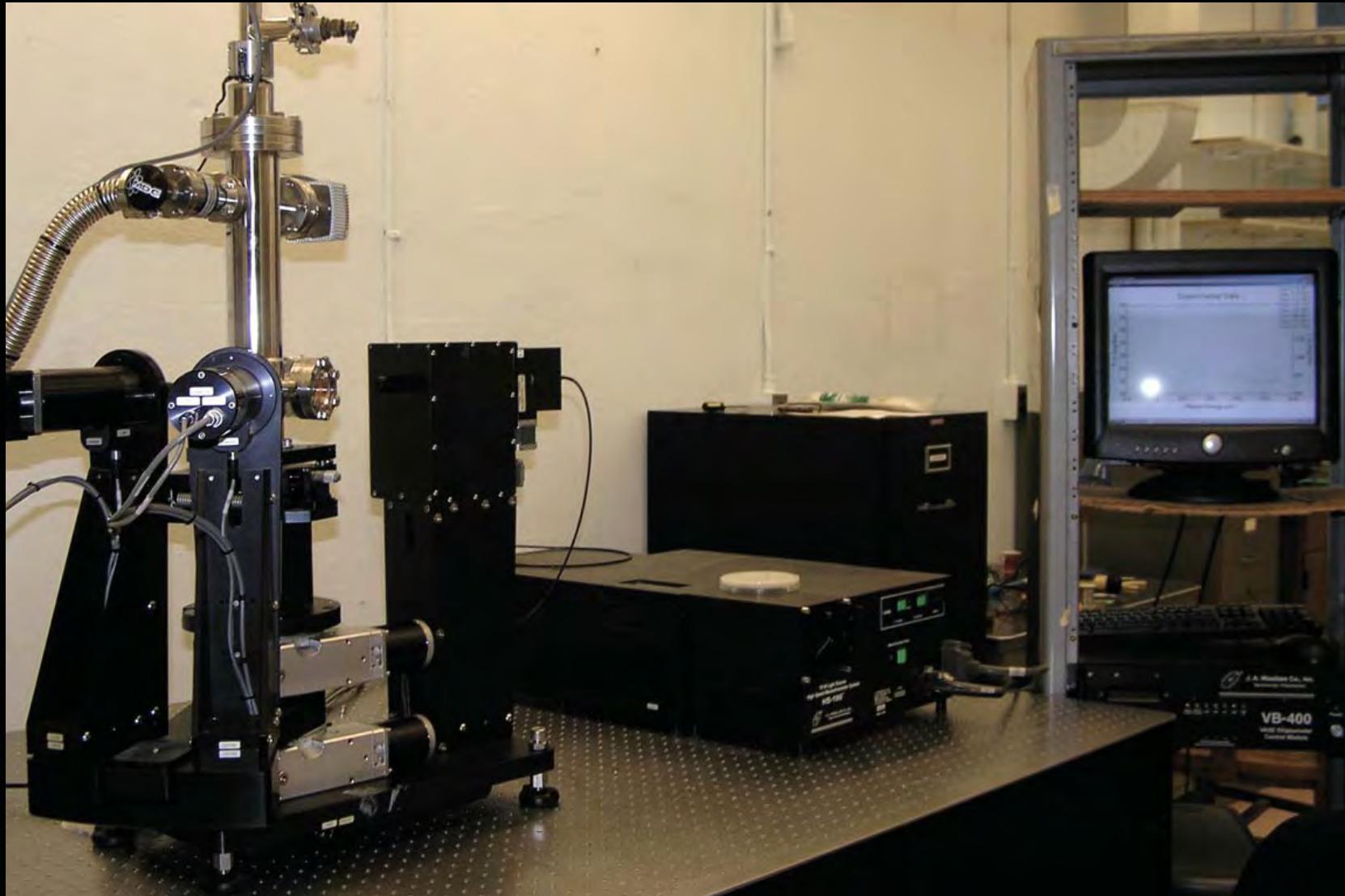
Lab Tour

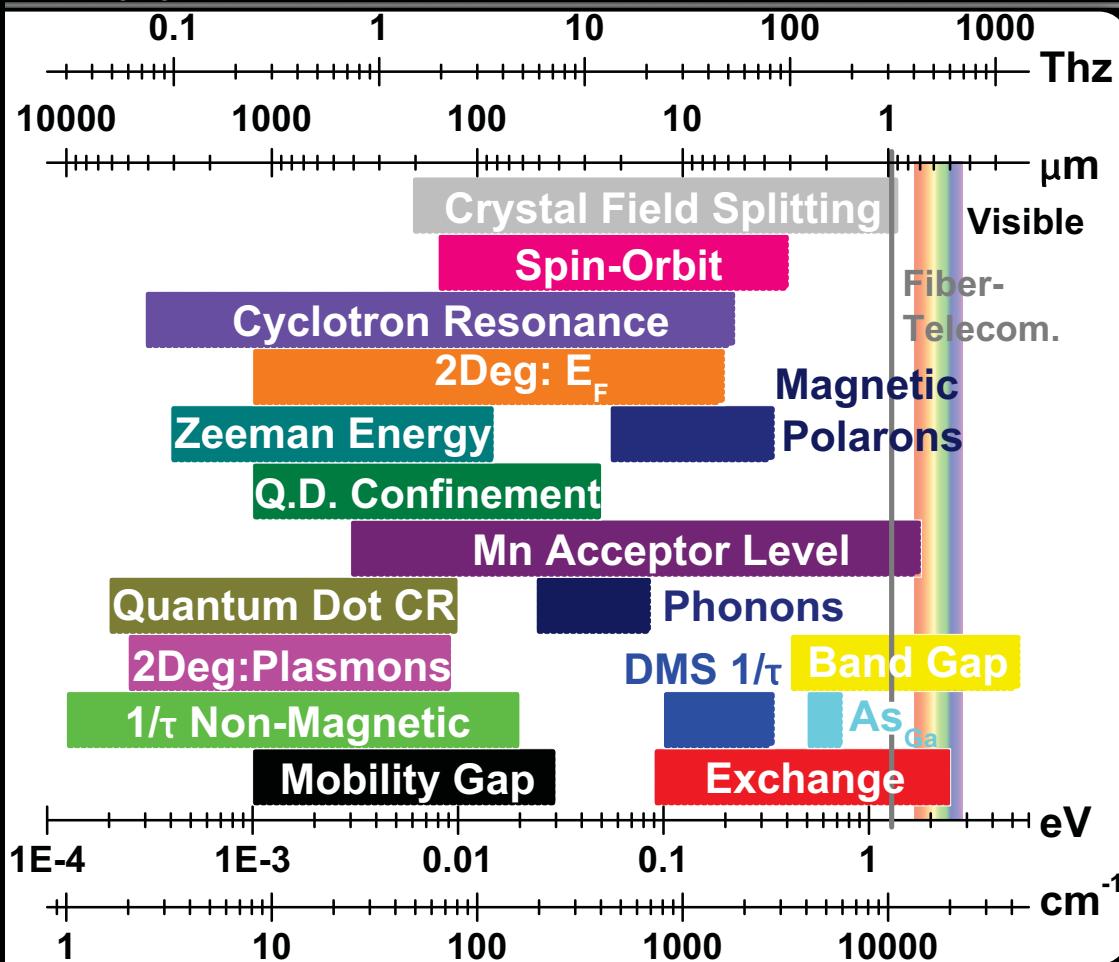


Lab Tour



Lab Tour



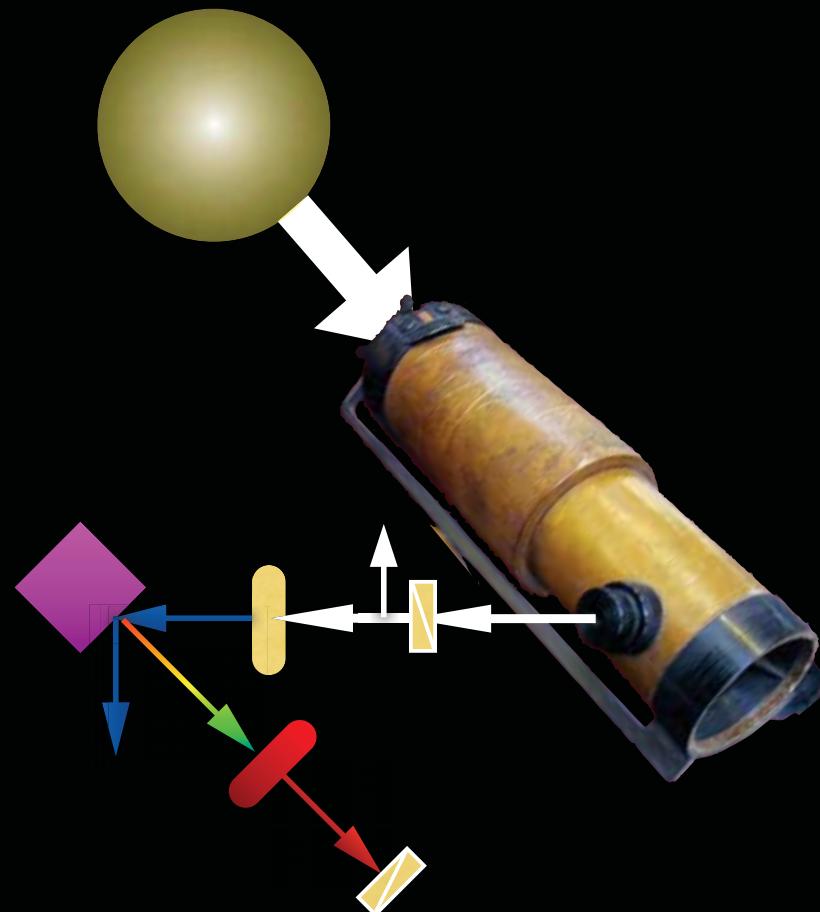


- Surface Quality
- Interface Quality
- Layer Thickness
- Contact Free Probe

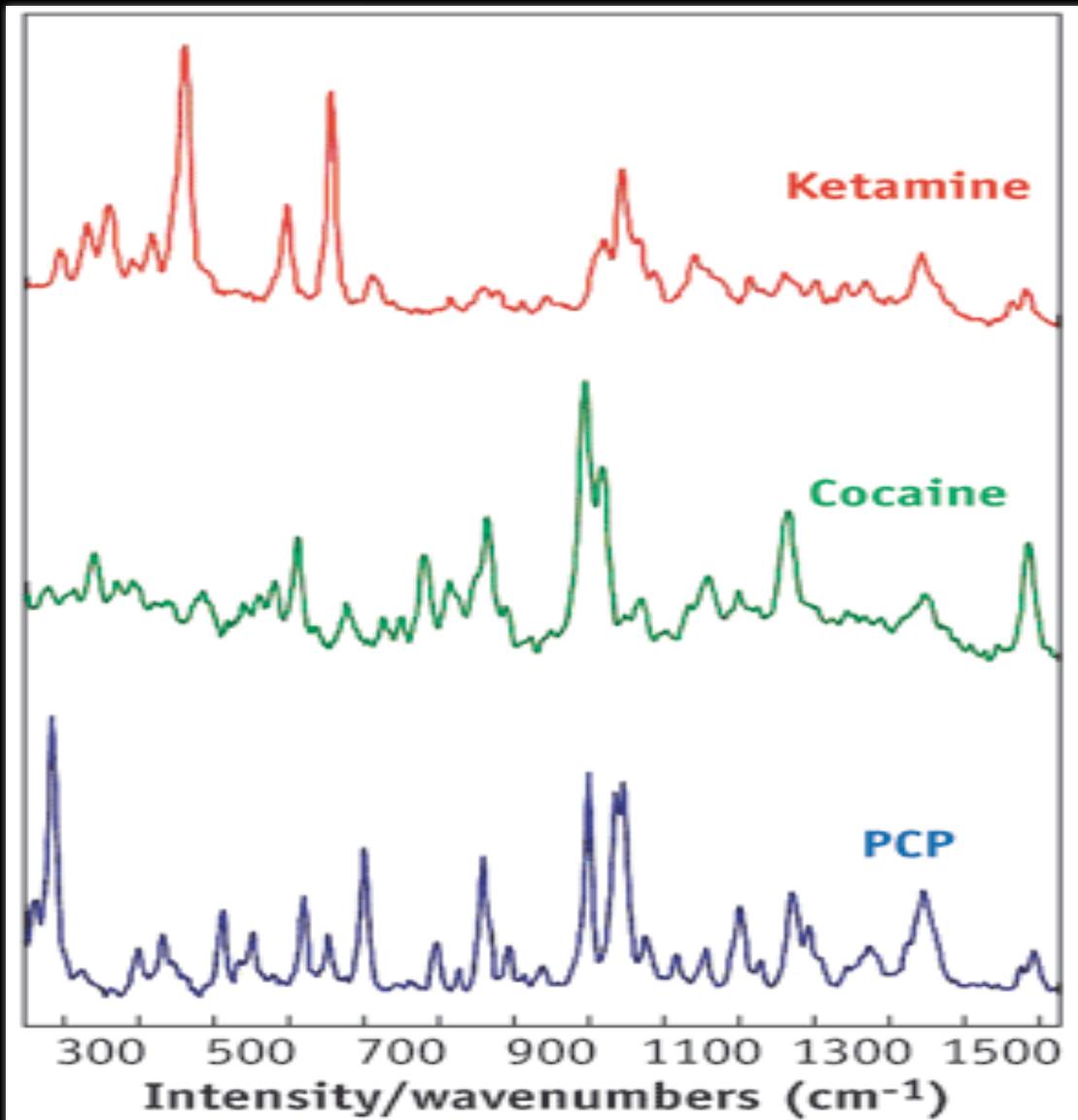
GOOD RULES OF THUMB:
 $8000 \text{ cm}^{-1} \sim 1 \text{ eV}$ ($1.5 \text{ eV} \sim 800 \text{ nm}$)

D.N. Basov & T. Timusk, RMP 77, 721 (2005)
 K.S. Burch et al., JMMM 320, 3207(2008)

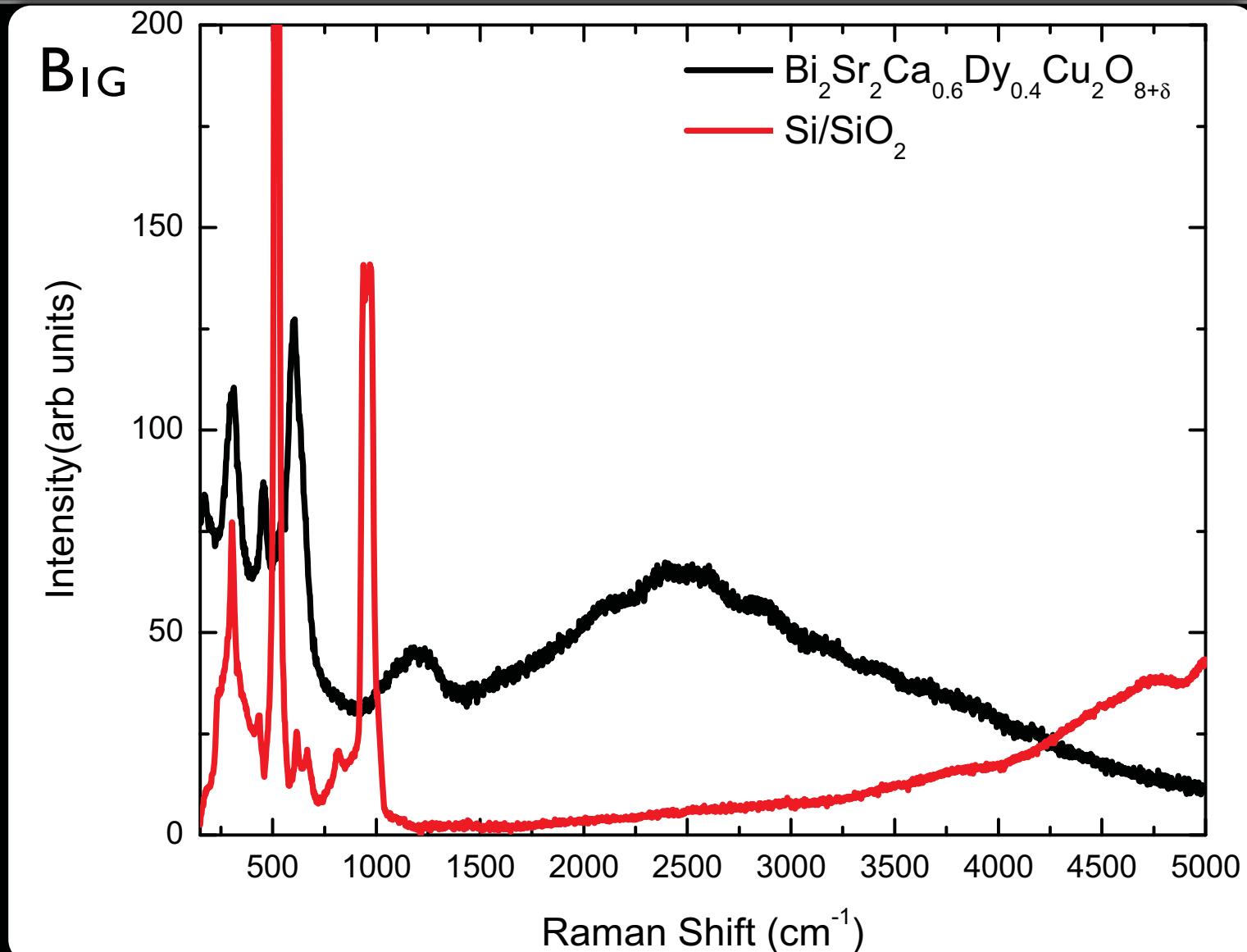
Raman Scattering



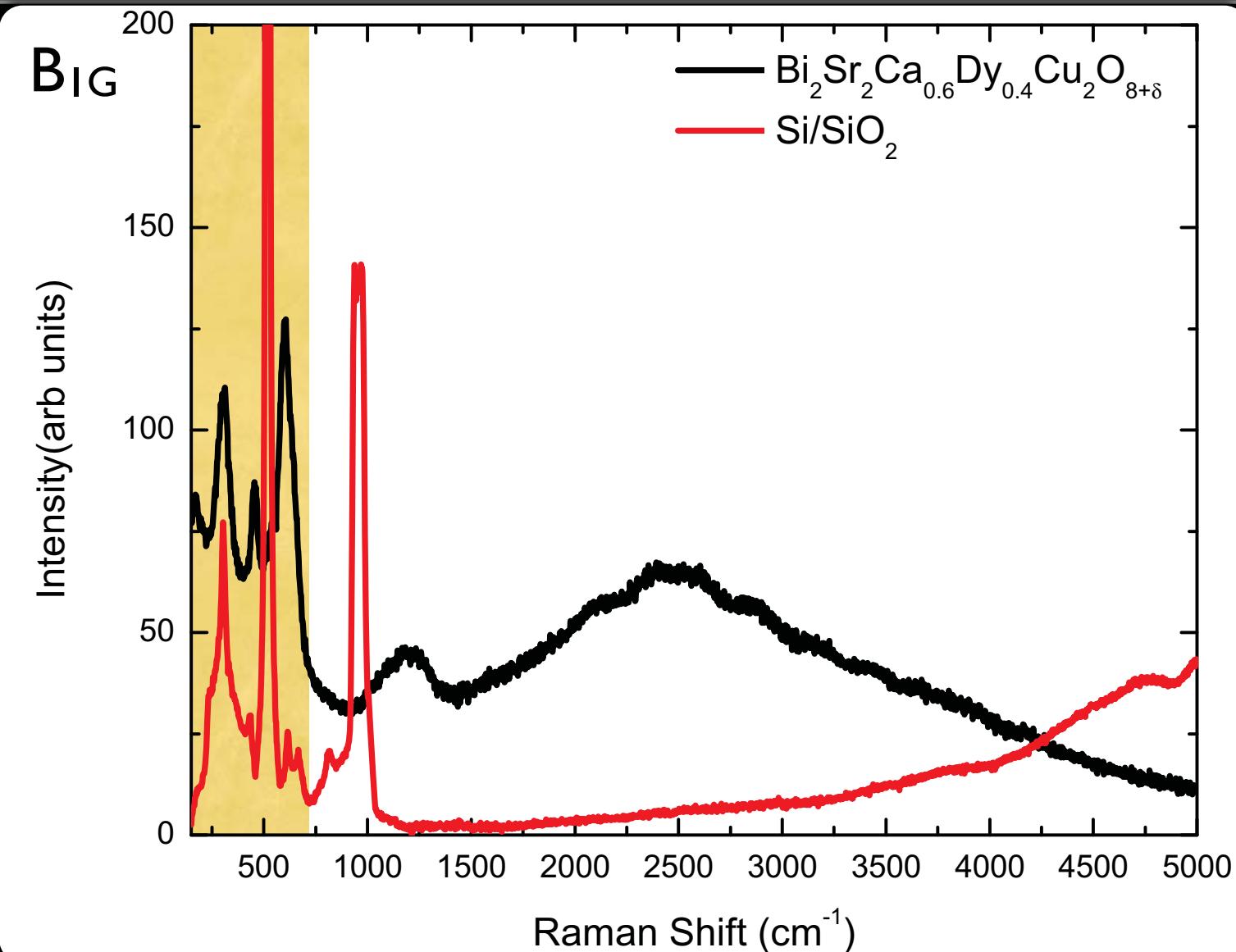
Raman Scattering



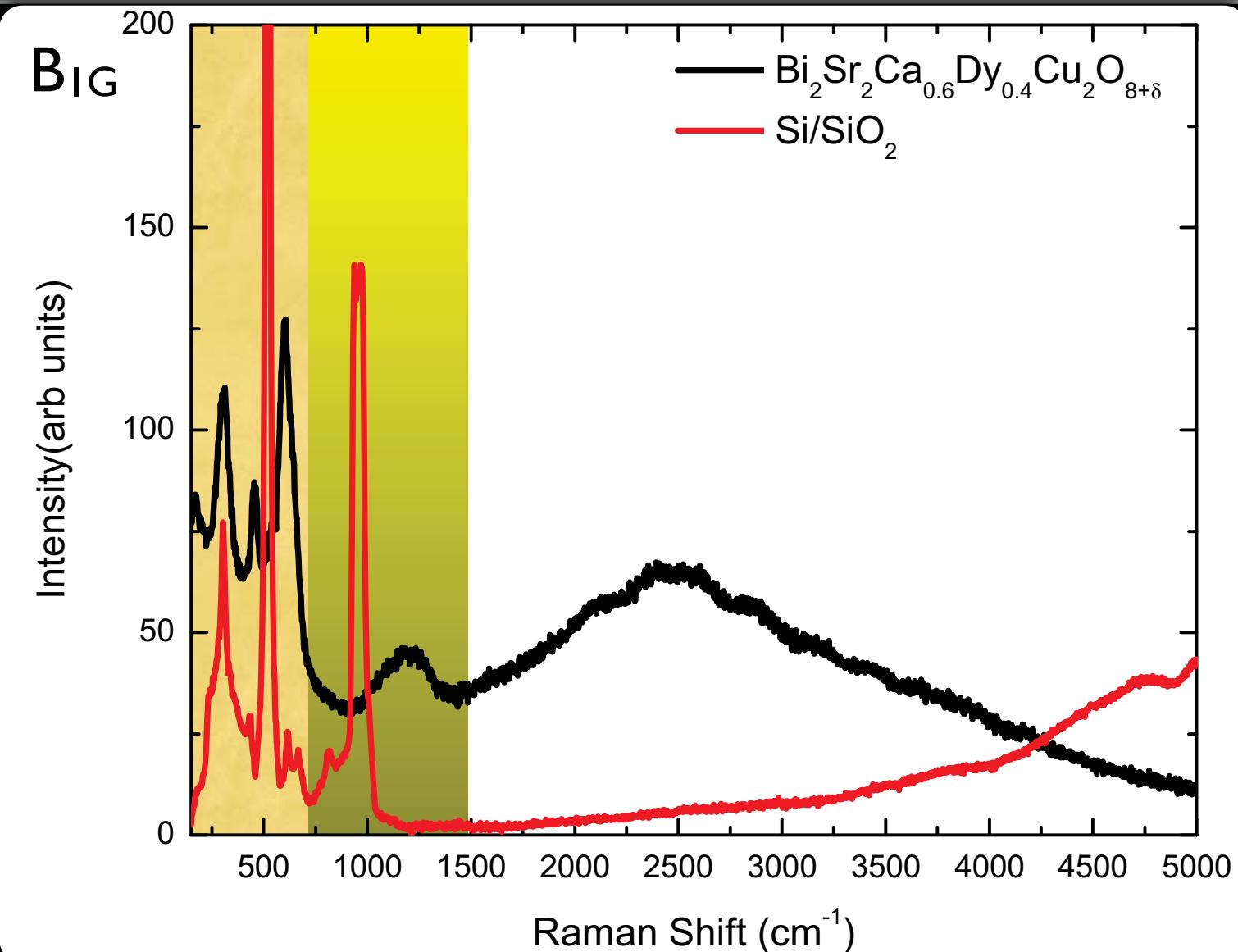
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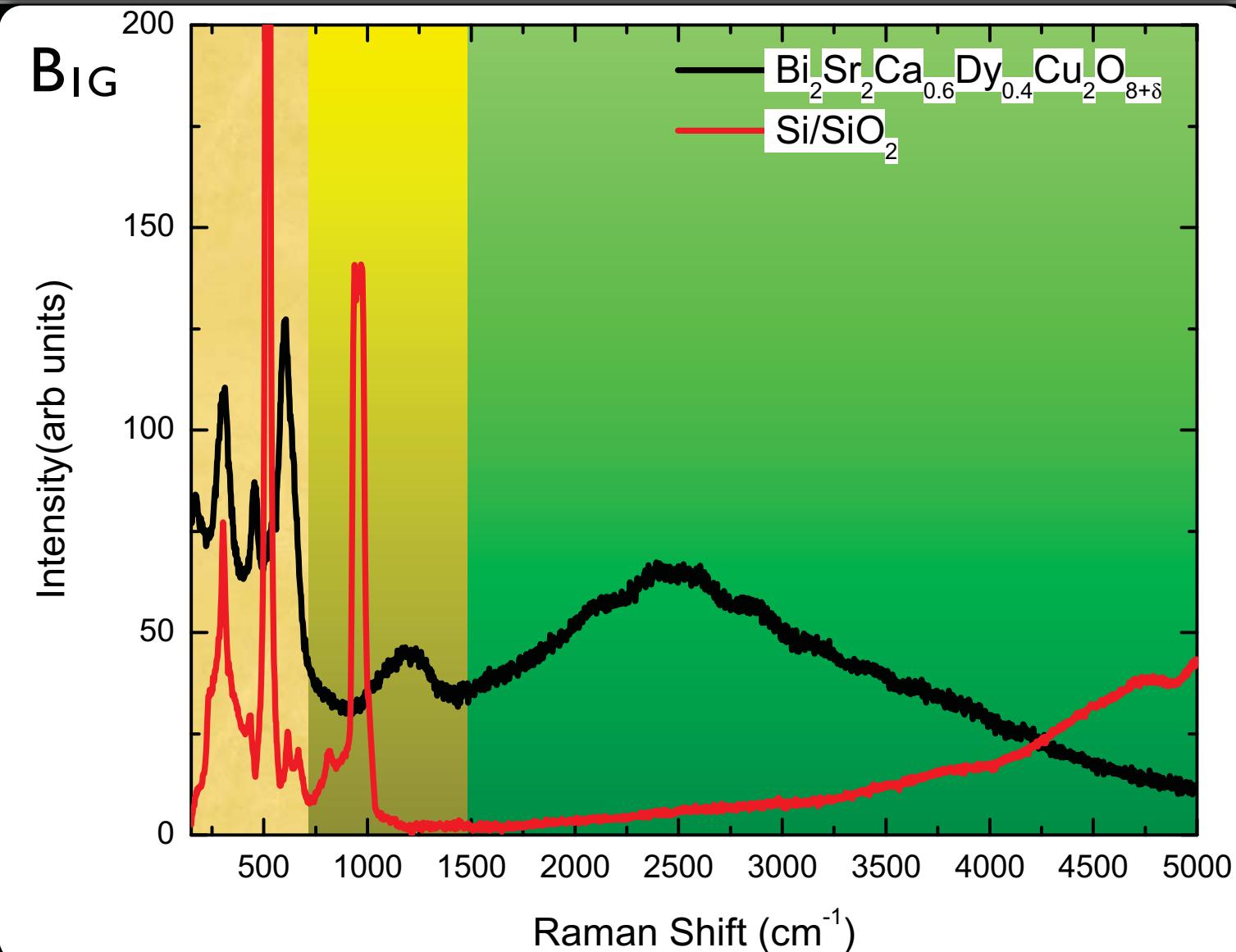
Raman Scattering



Raman Scattering



Raman Scattering



Two Magnon

Review:

T.P. Devereaux and R. Hackl RMP
79, 175 (2007)

W. Weber and R. Merlin *Raman Scattering in Materials Science* (2000)

Experiment:

S. Sugai et. al, Phys. Rev. B 68, 184504 (2003)

G. Blumberg, et. al, Science 278, 1427 (1997)

R.R.P. Singh et. al, PRL 62, 2736 (1989)

Theory:

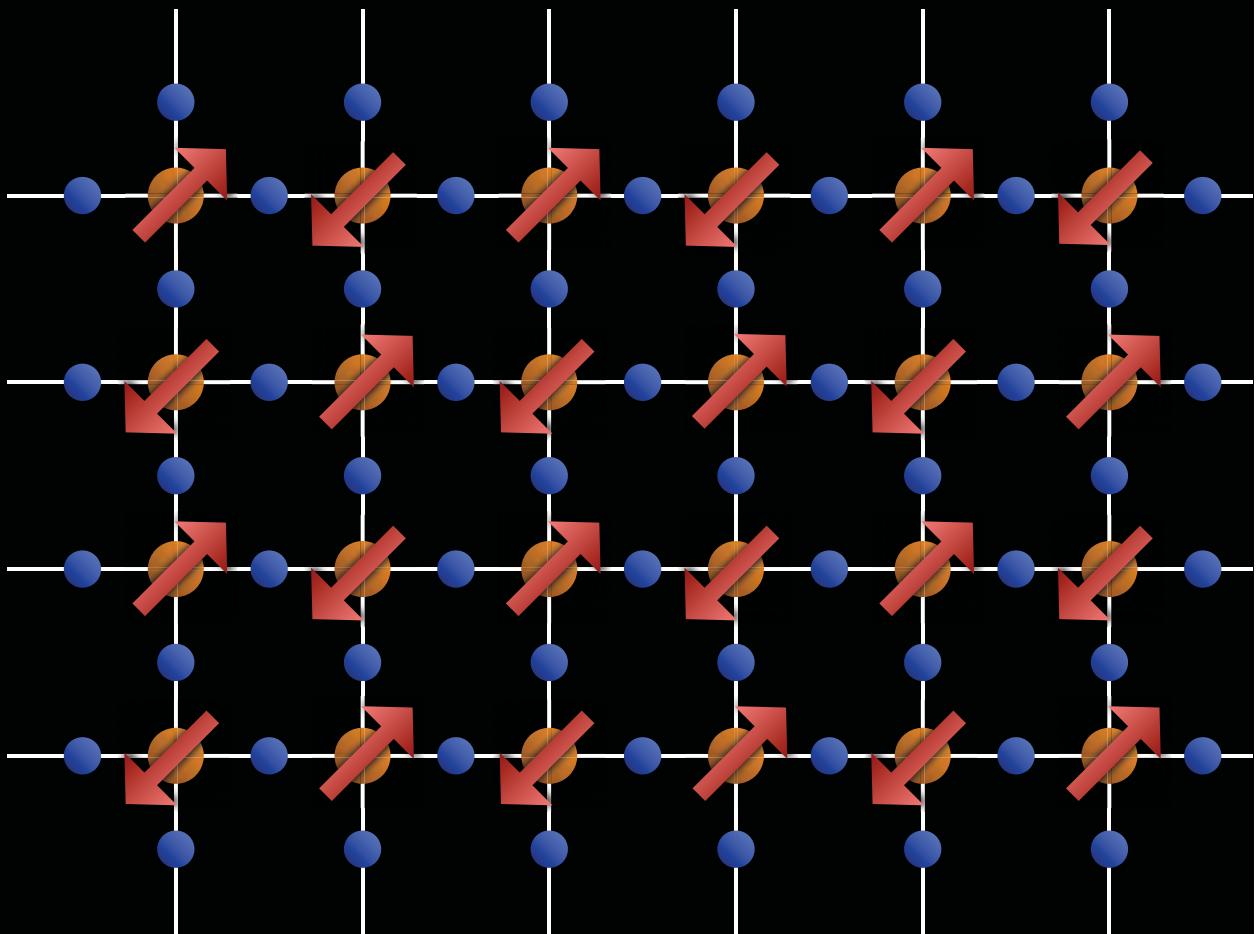
B.S. Shastry and B.I. Shraiman
PRL 65, 1068 (1990)

A.V. Chubukov and D.M. Frenkel
PRB 52, 9760 (1995)

F. Nori et. al, PRL 75, 553 (1995)

$$H = J \sum_{ij} S_i S_j$$

$$\Delta E = J(S^2 - S(S-1)) = \frac{J}{2}$$



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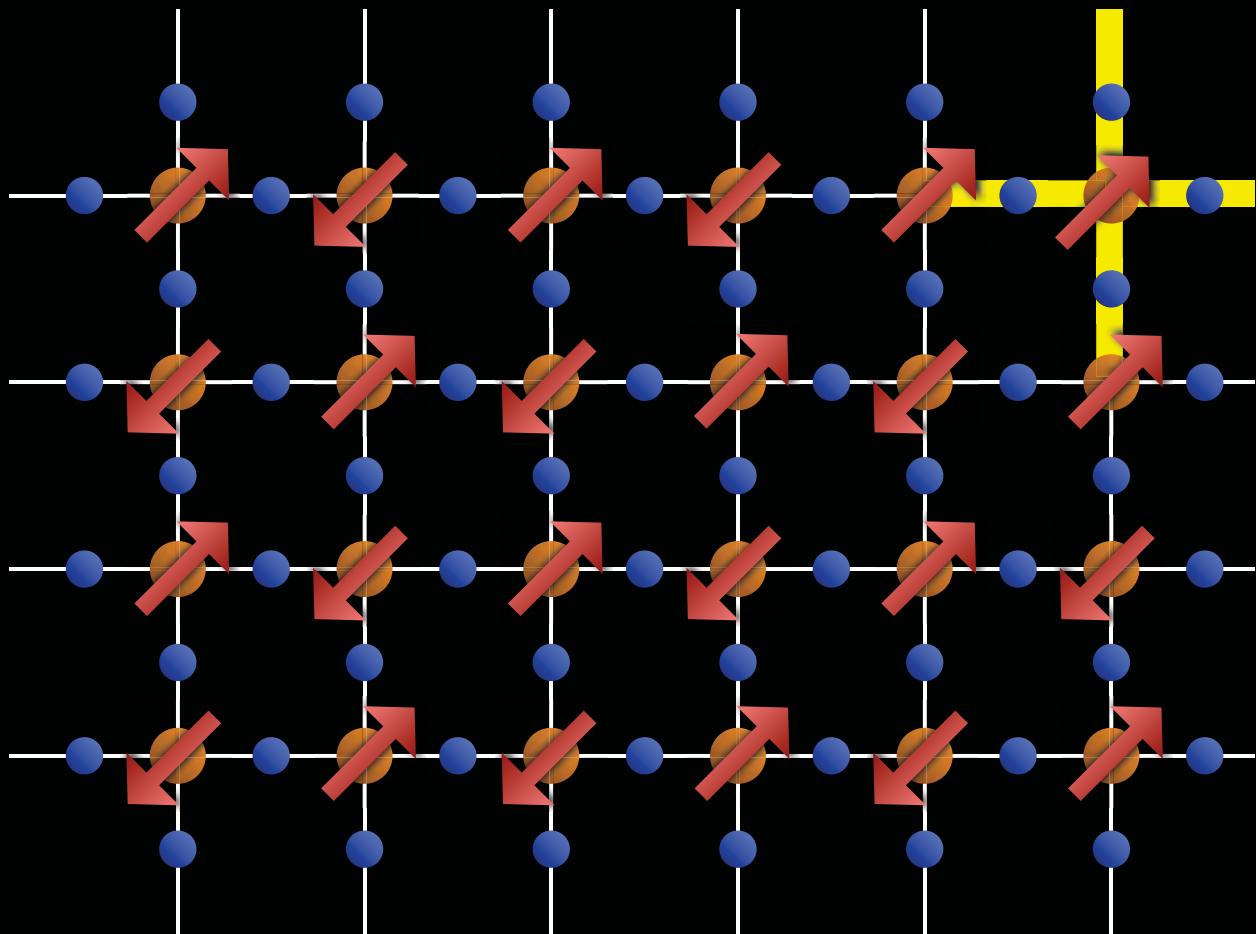
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$$\Delta E_{\text{magnon}} = 2J$$

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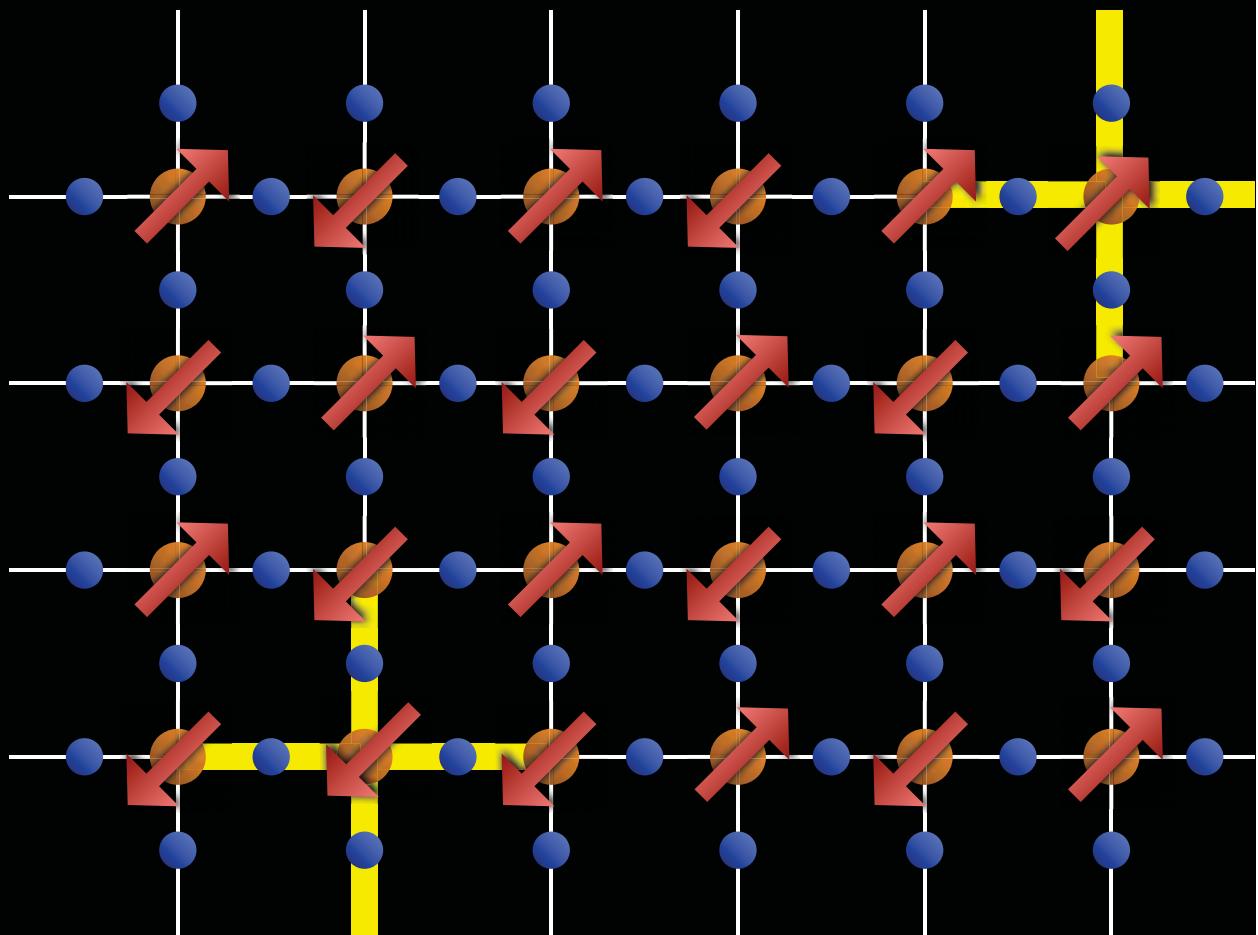
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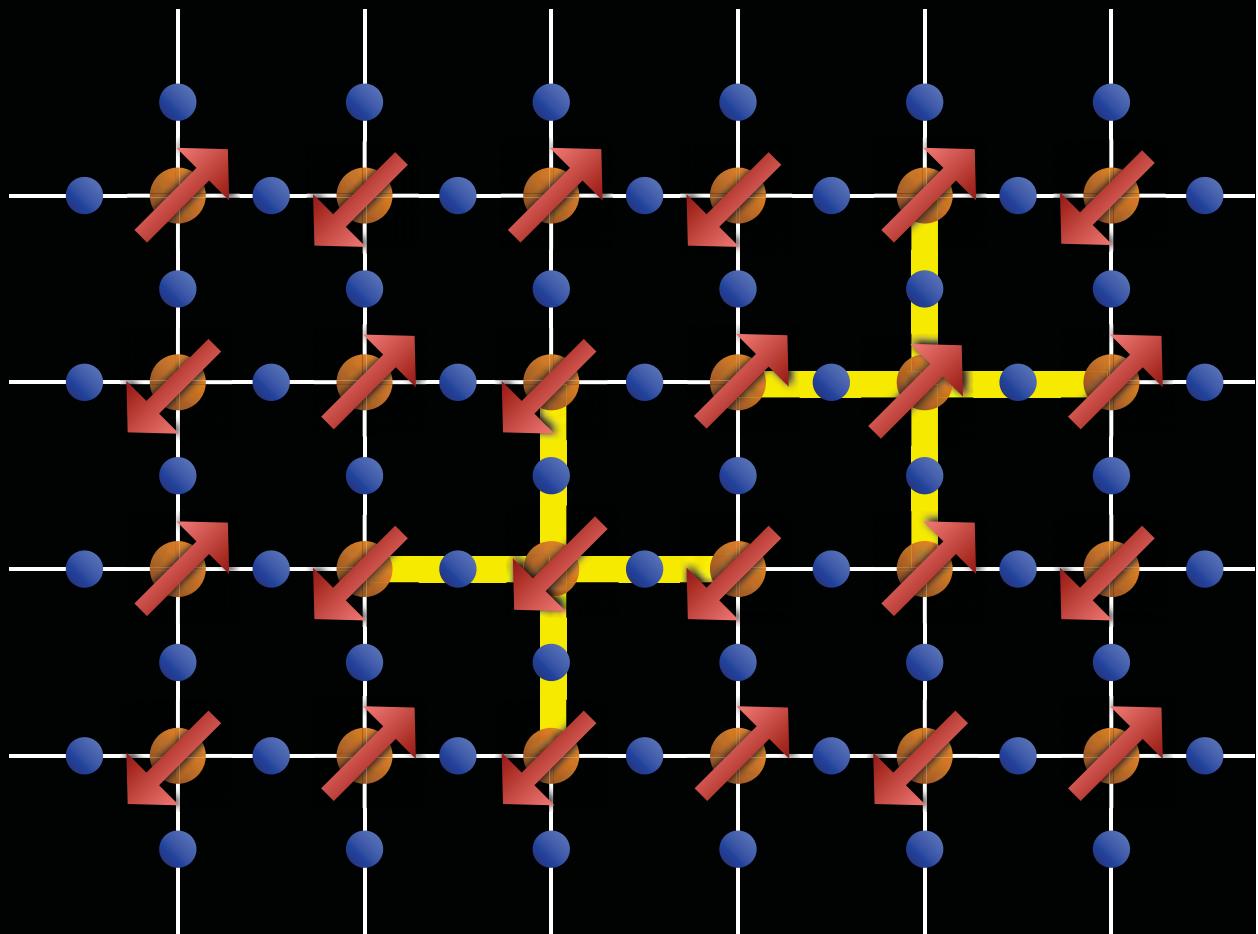
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$$\Delta E_{1\text{magnon}} = 2J$$

$$\Delta E_{2\text{mag}} = 4J$$



Two Magnon

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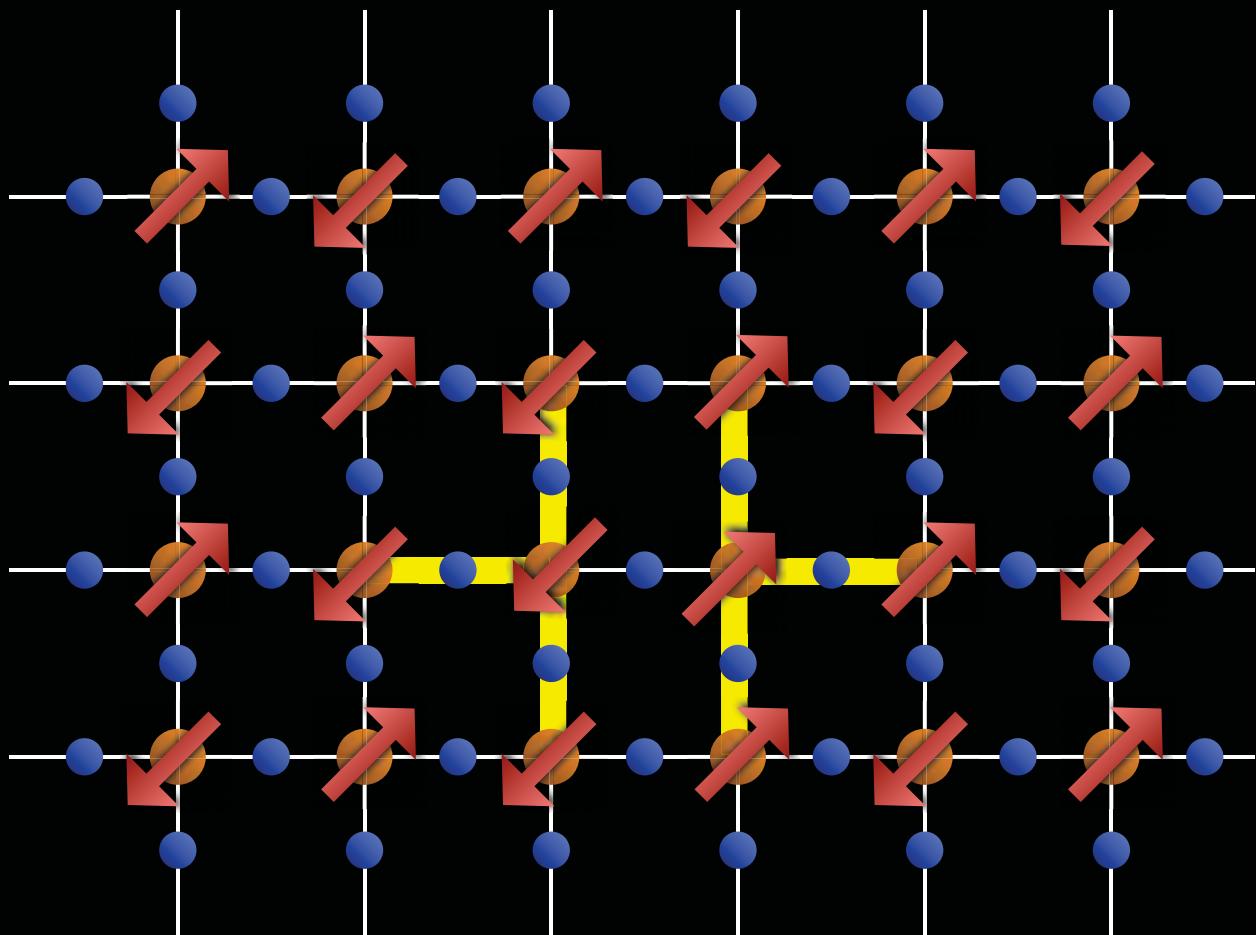
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$$\Delta E_{2\text{mag}}^* = 3J$$

Two Magnon

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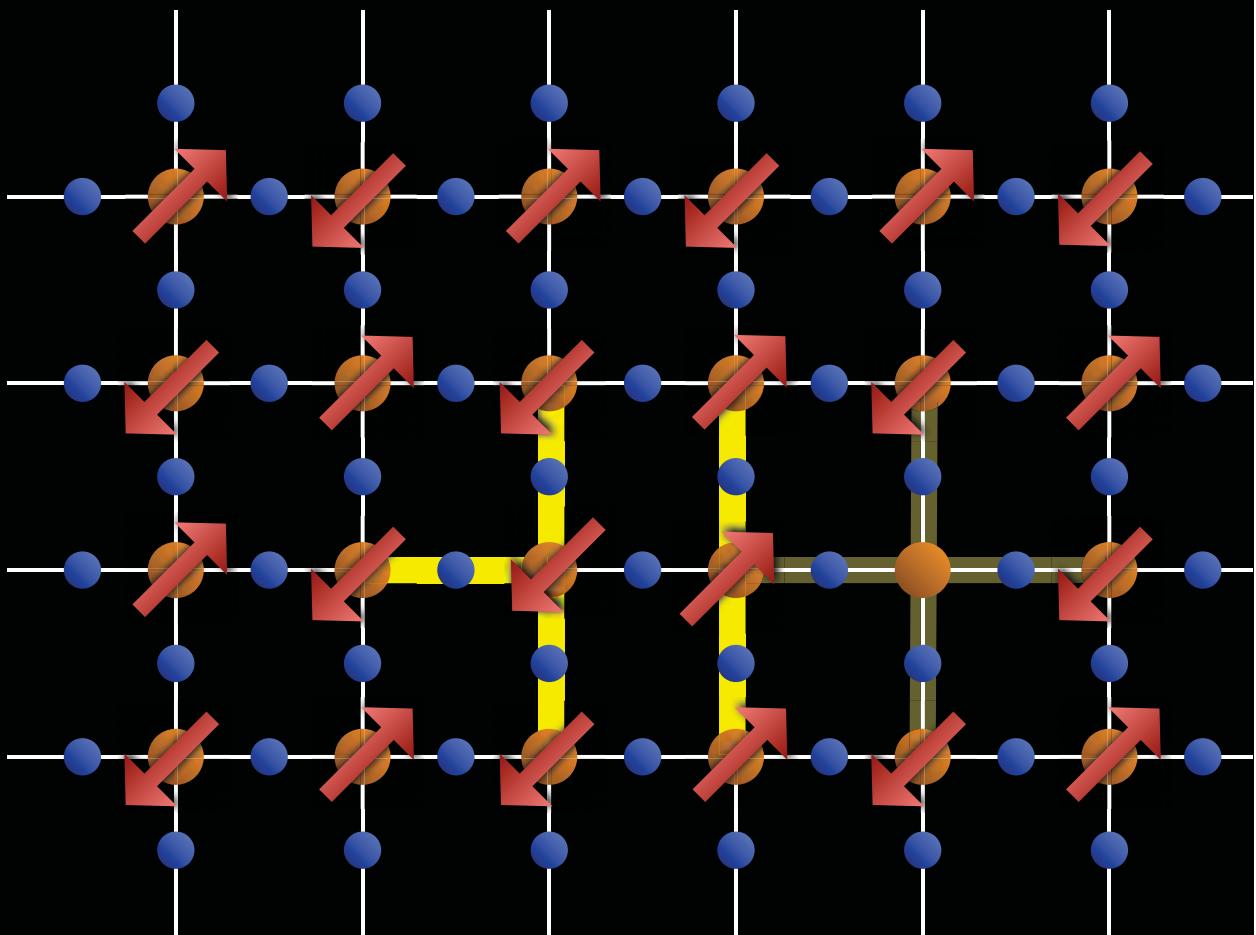
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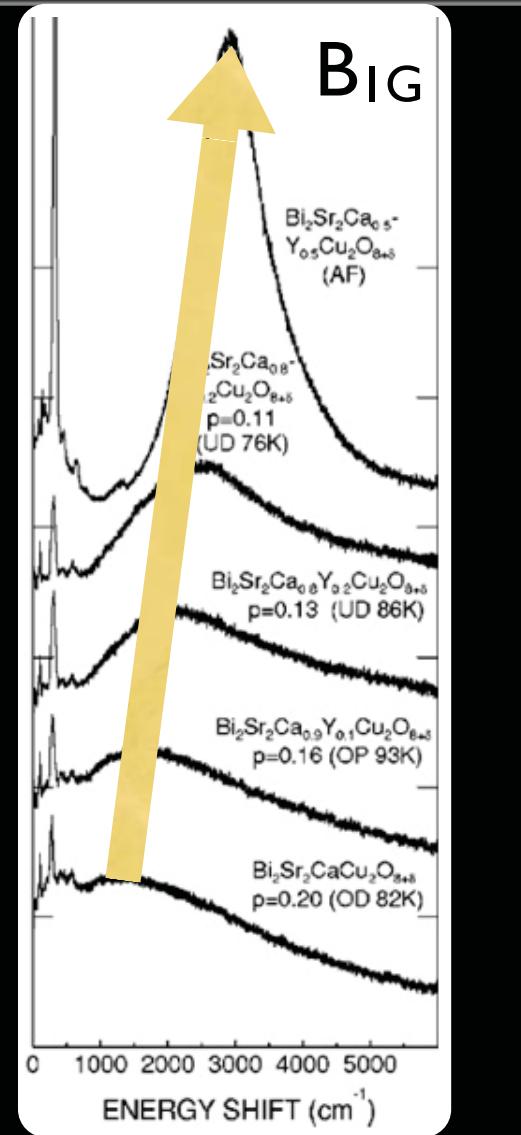
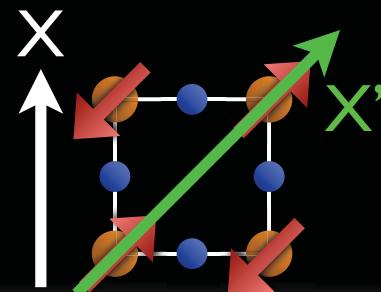


$$\Delta E_{1\text{magnon}} = 2J$$

$$\Delta E_{2\text{mag}} = 4J$$

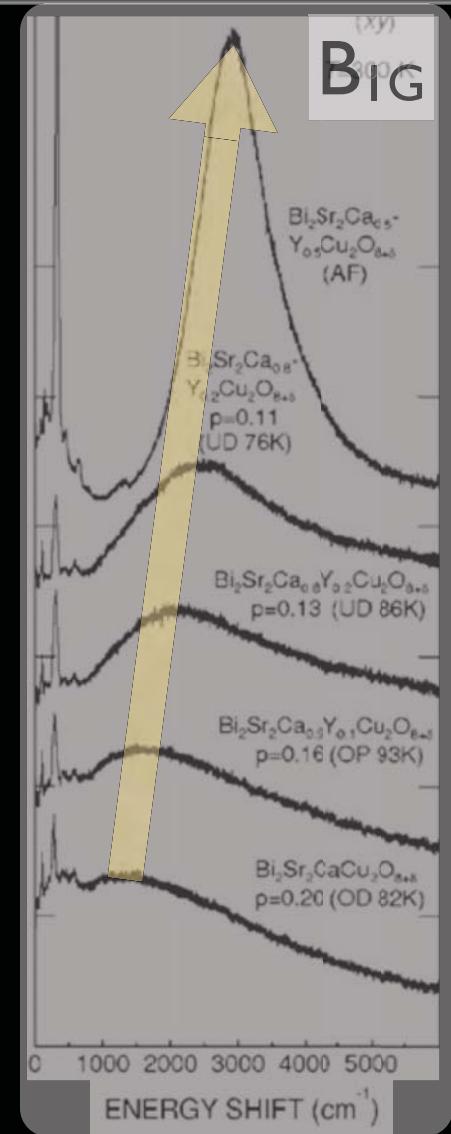
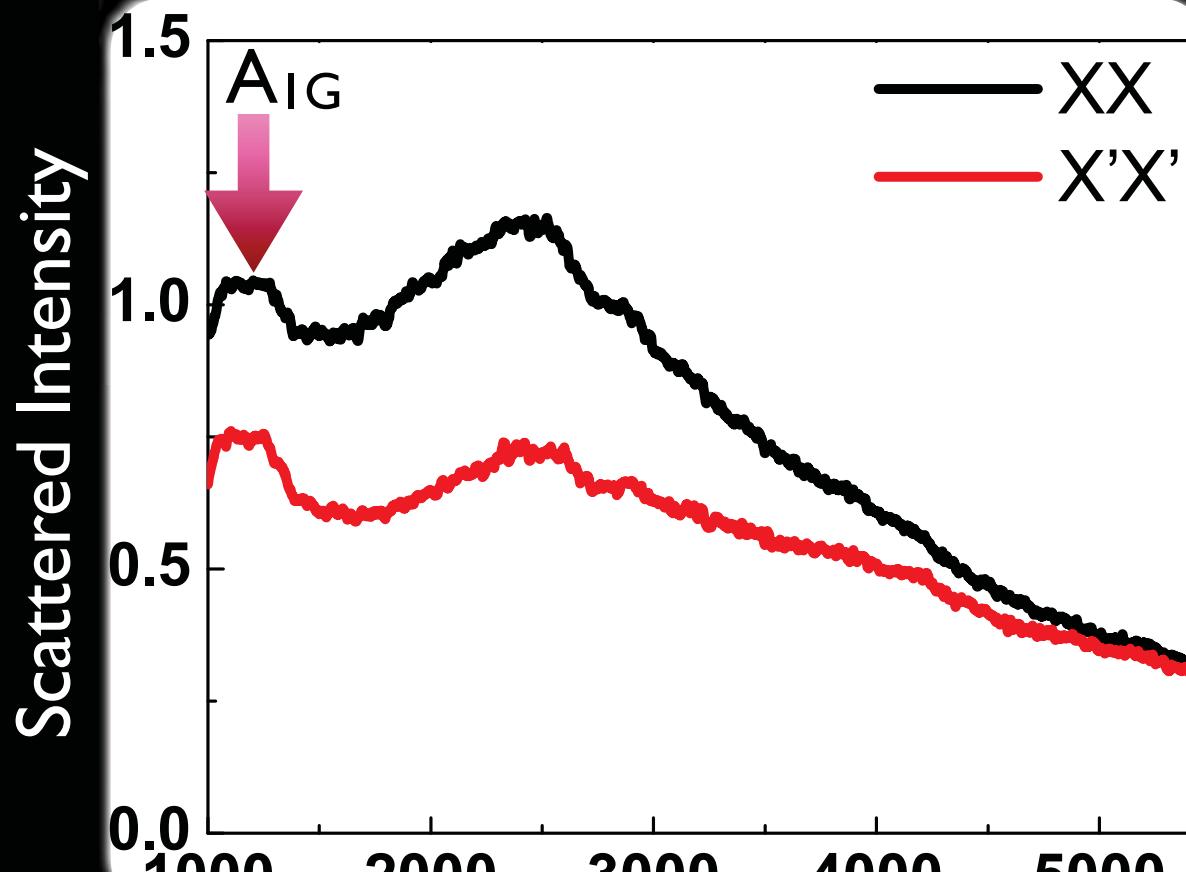
$$\Delta E_{2\text{mag}}^* = 3J$$

Two Magnon



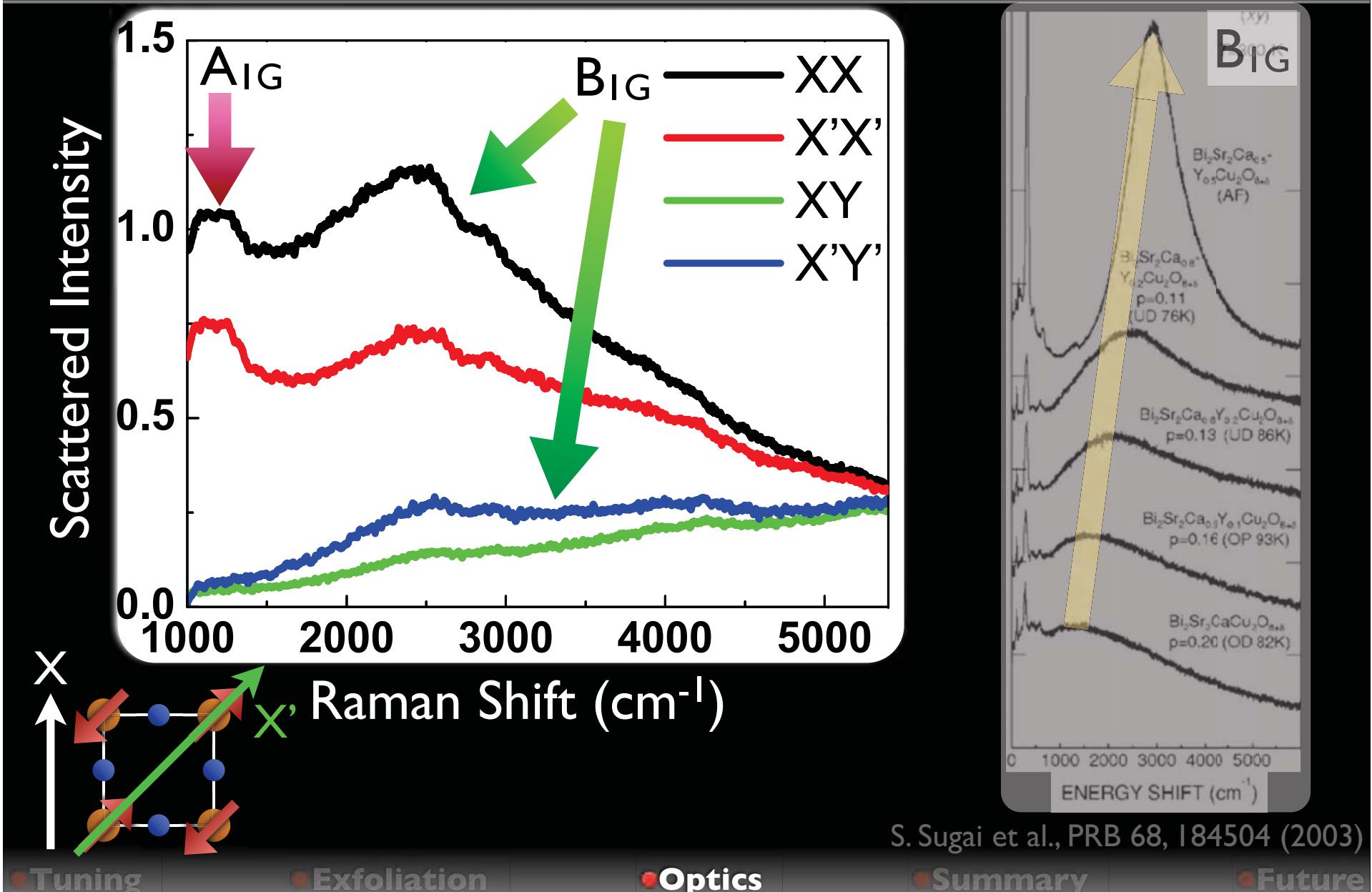
S. Sugai et al., PRB 68, 184504 (2003)

Two Magnon

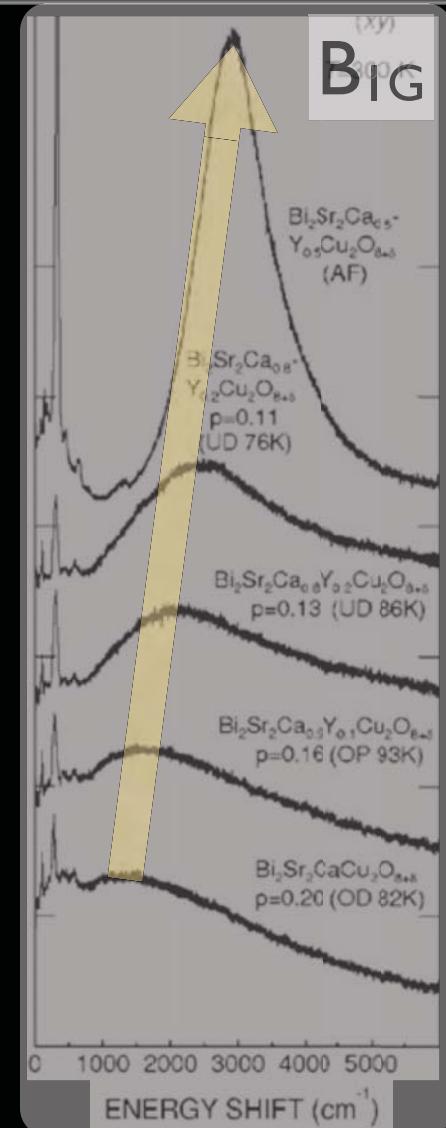
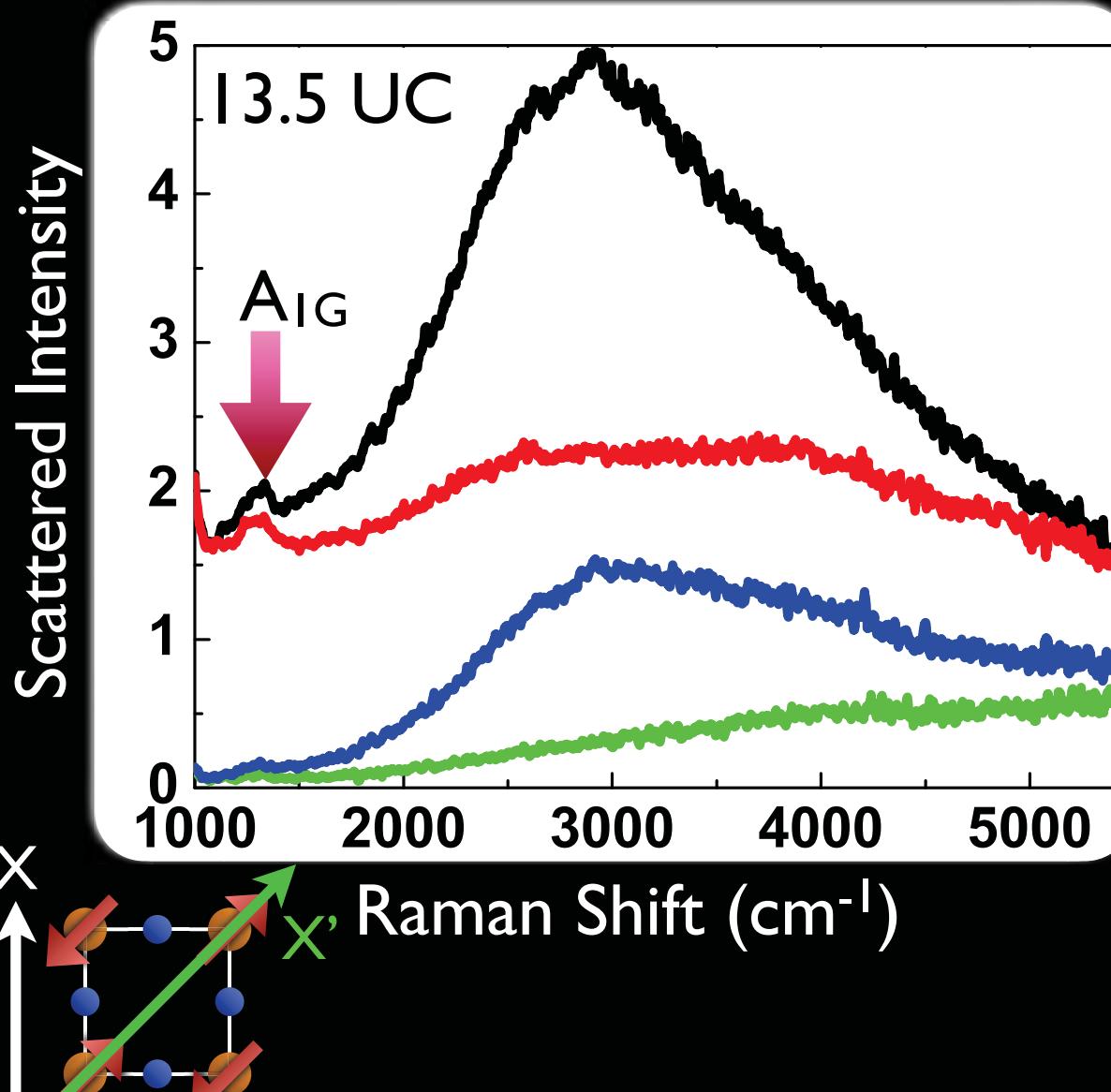


S. Sugai et al., PRB 68, 184504 (2003)

Two Magnon

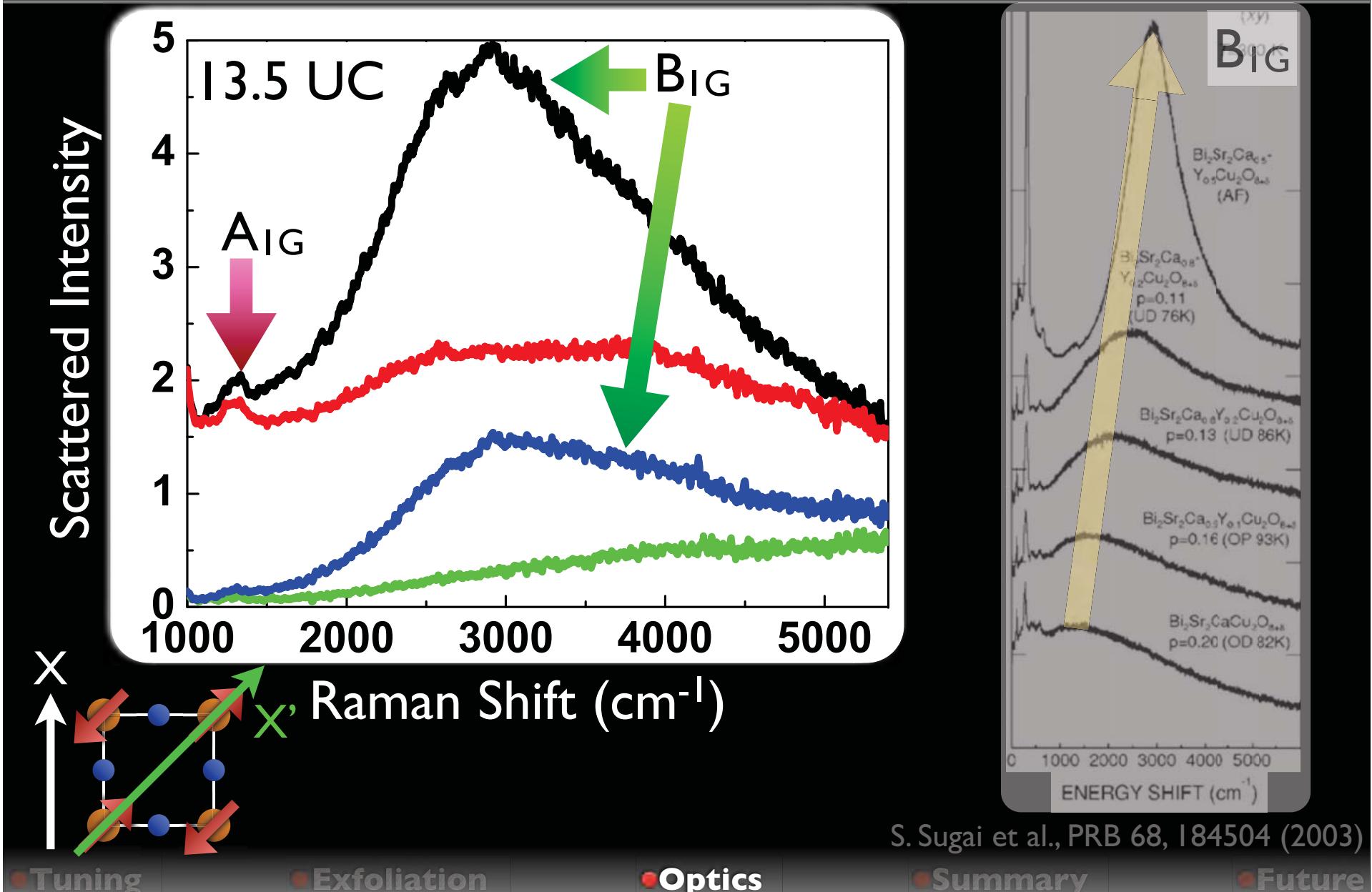


Two Magnon

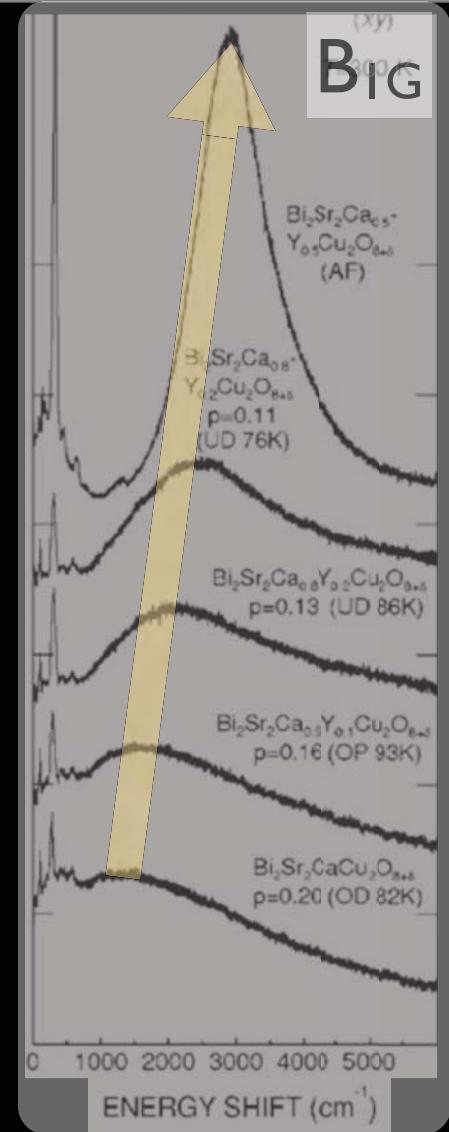
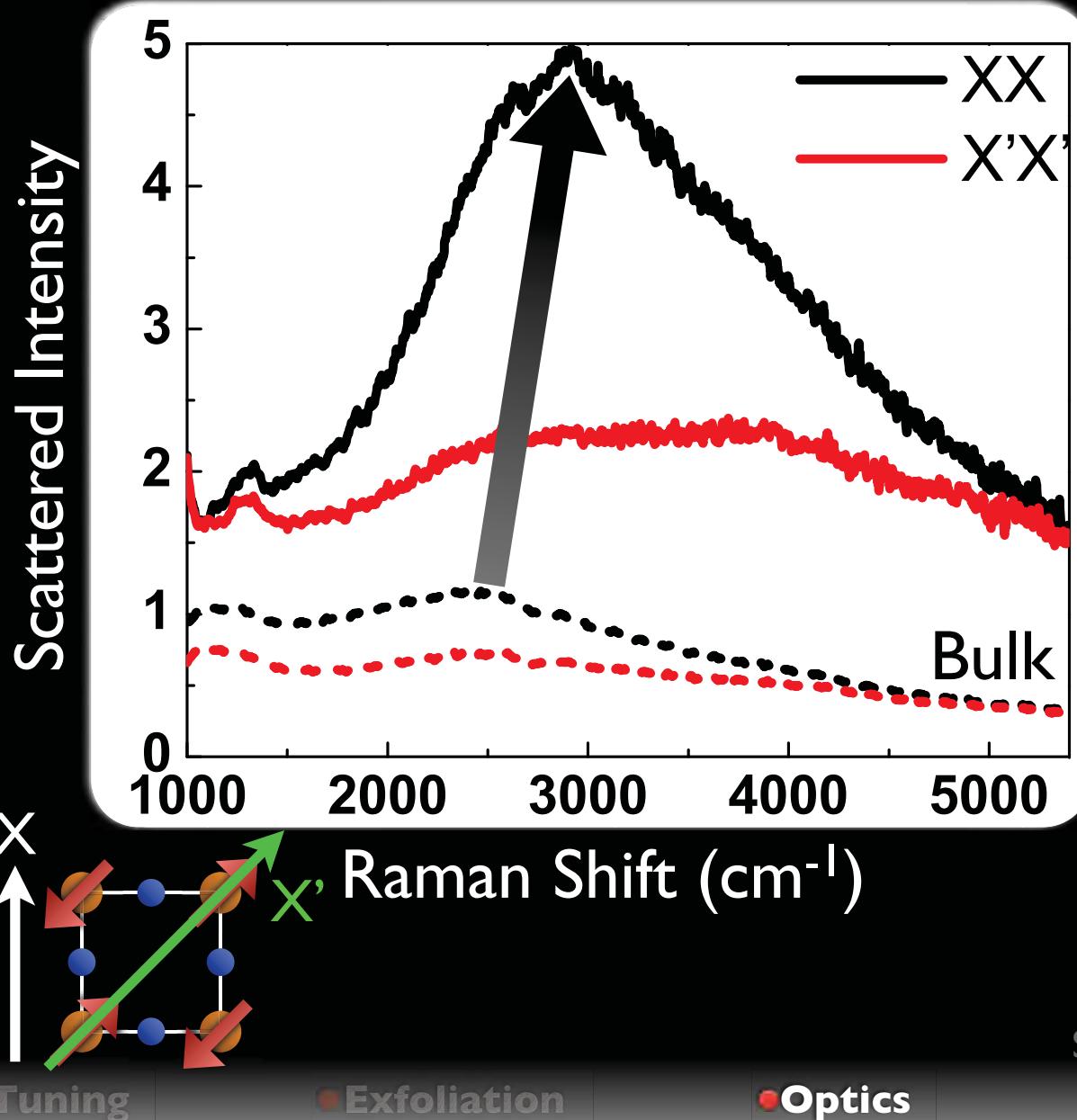


S. Sugai et al., PRB 68, 184504 (2003)

Two Magnon



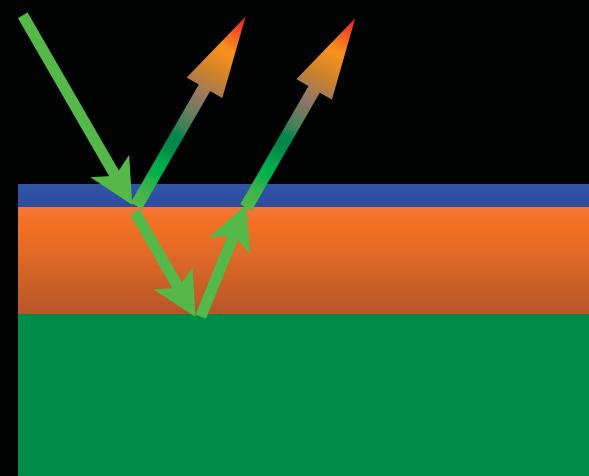
Two Magnon



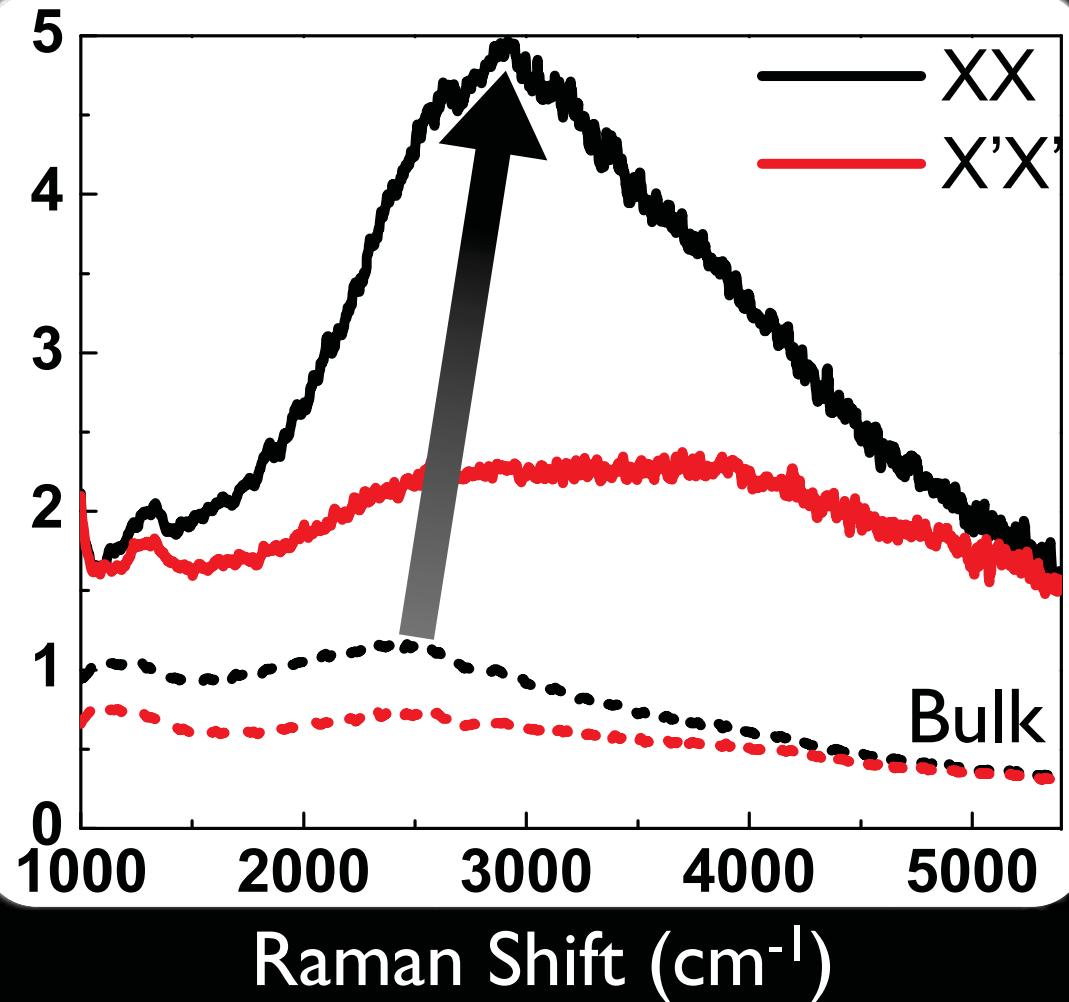
S. Sugai et al., PRB 68, 184504 (2003)

Two Magnon

- Interference?



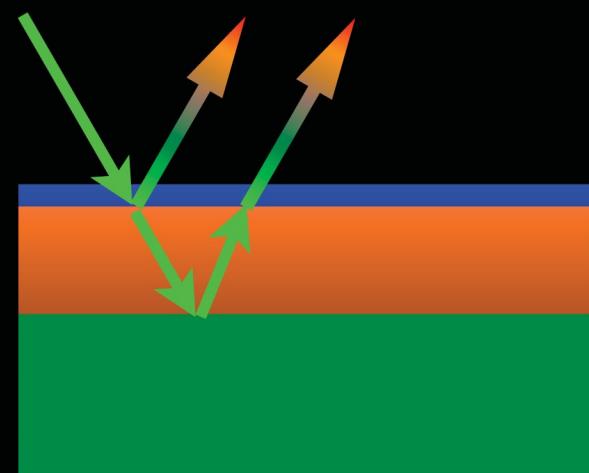
Scattered Intensity



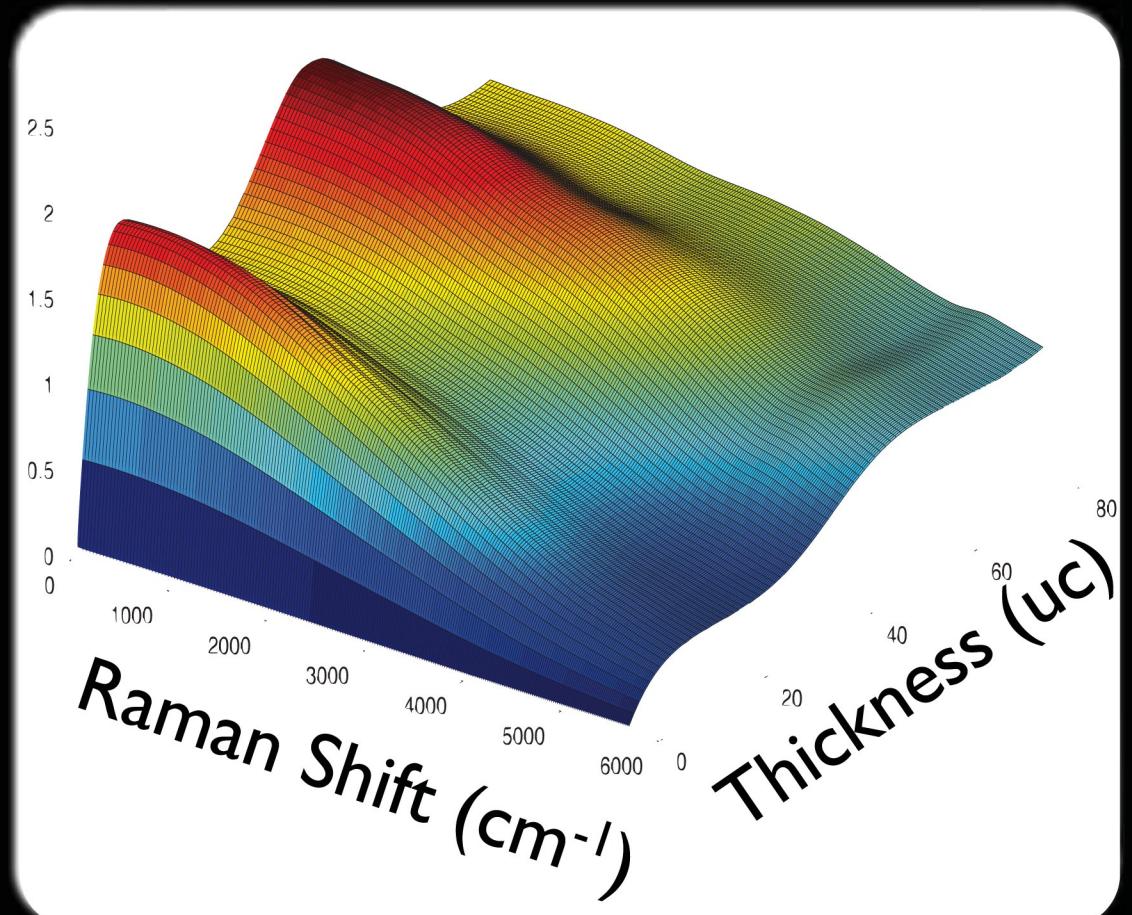
Interference Correction:
Y.Y. Wang et al., APL 92, 043121 (2008)

Two Magnon

- Interference?
- Structural Change



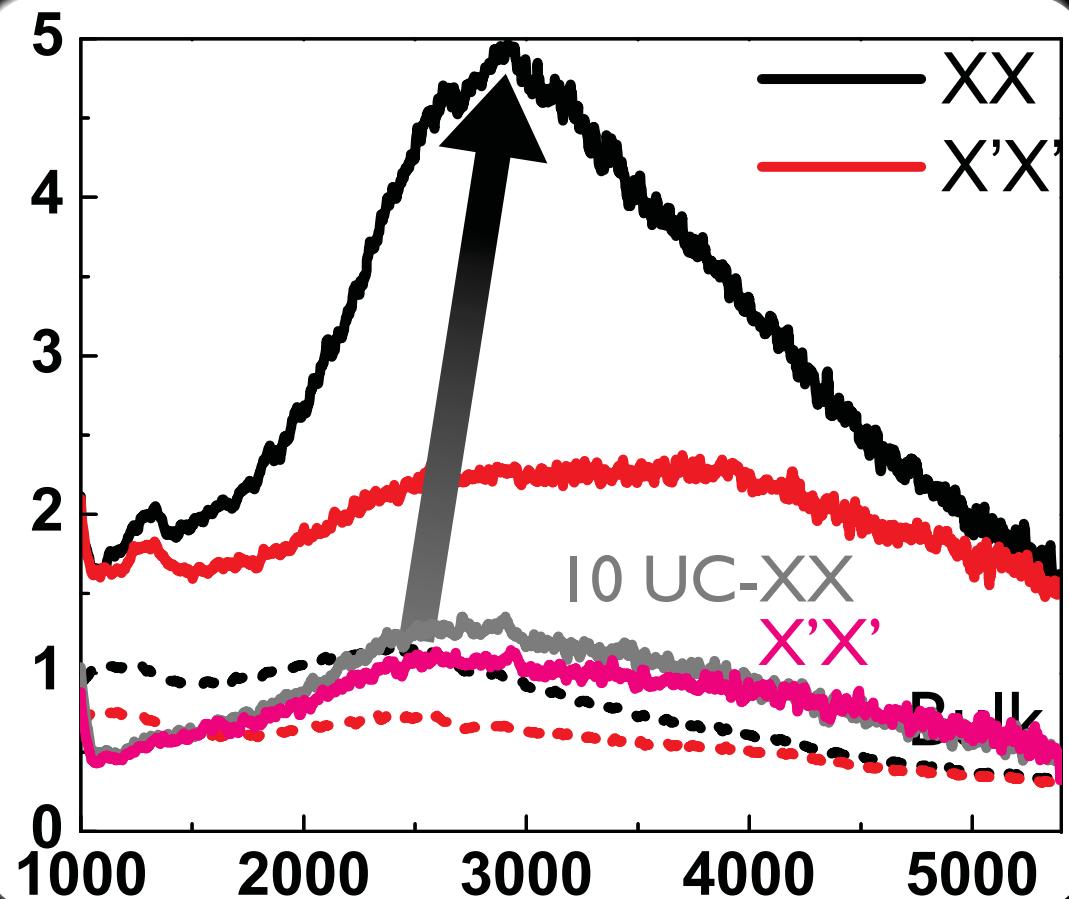
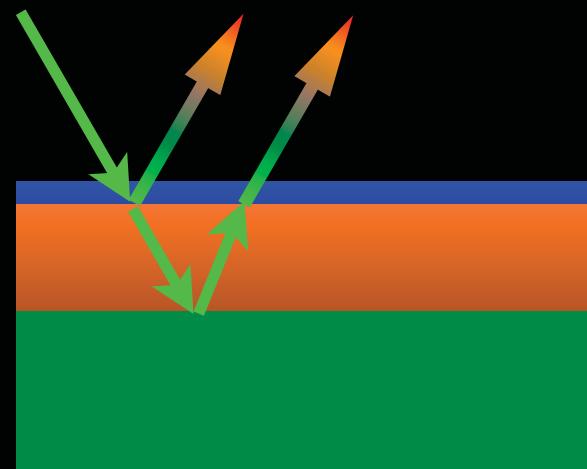
Enhancement



Interference Correction:
Y.Y. Wang et al., APL 92, 043121 (2008)

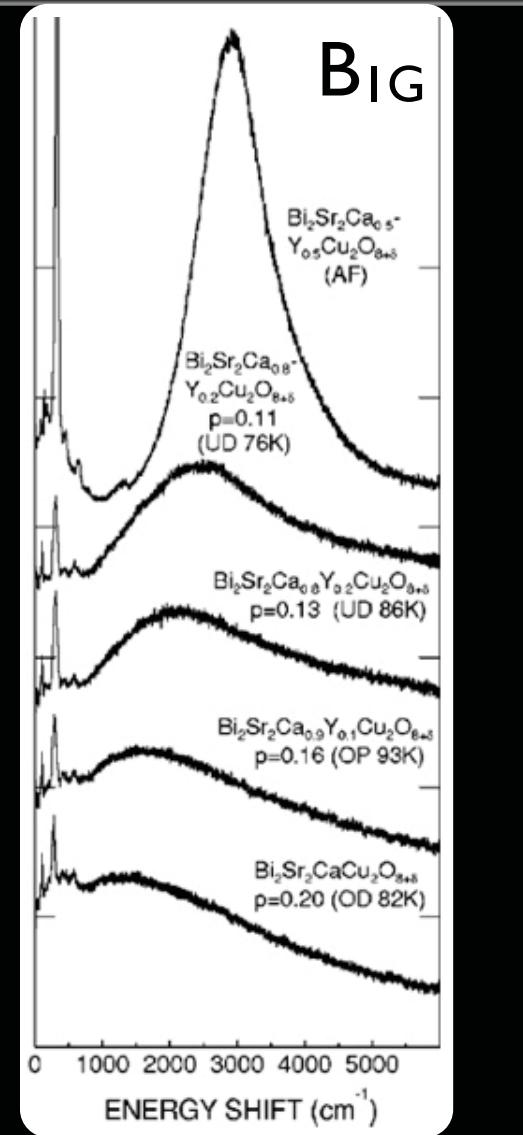
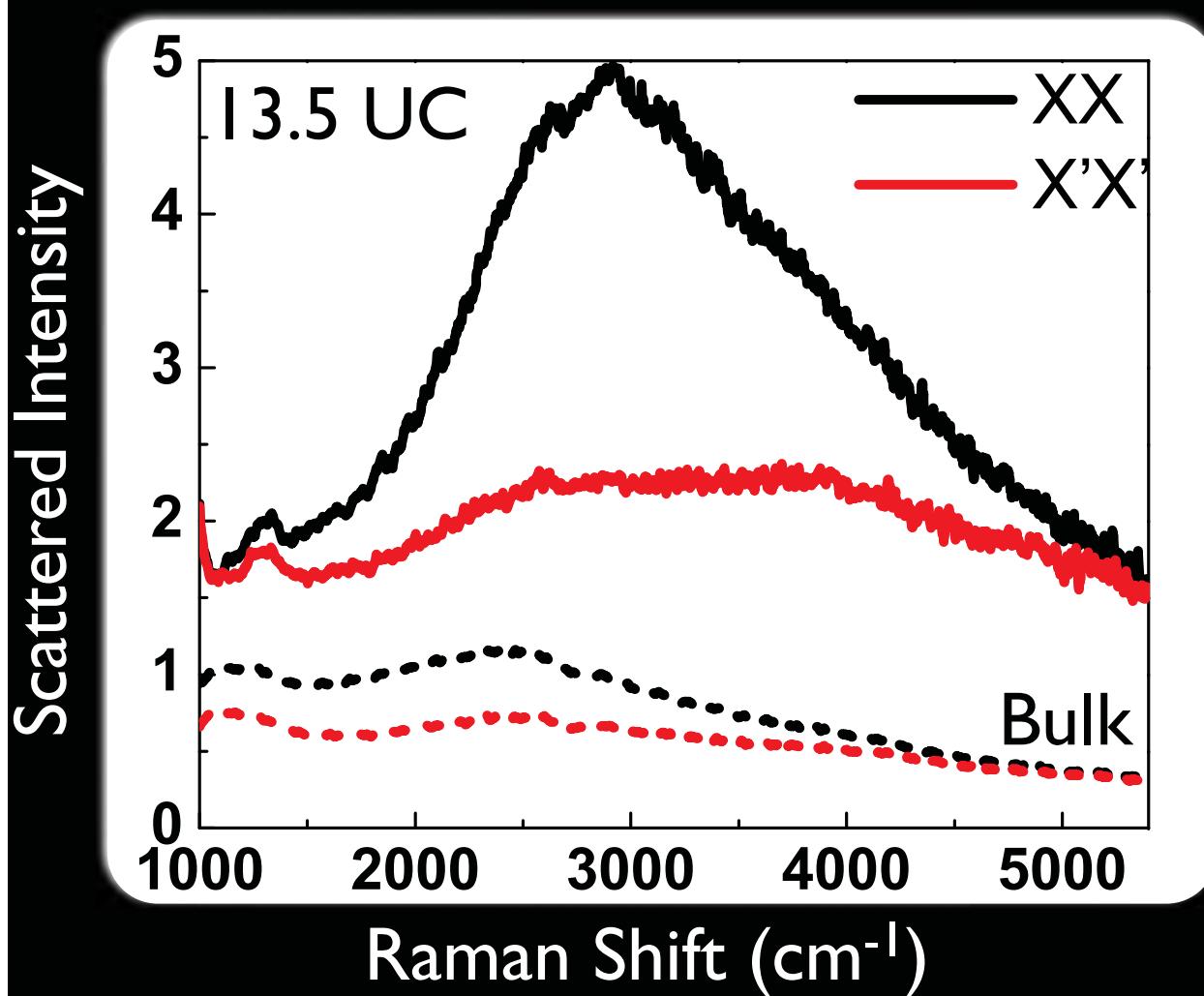
Two Magnon

- Interference?
- Structural Change
- Doping



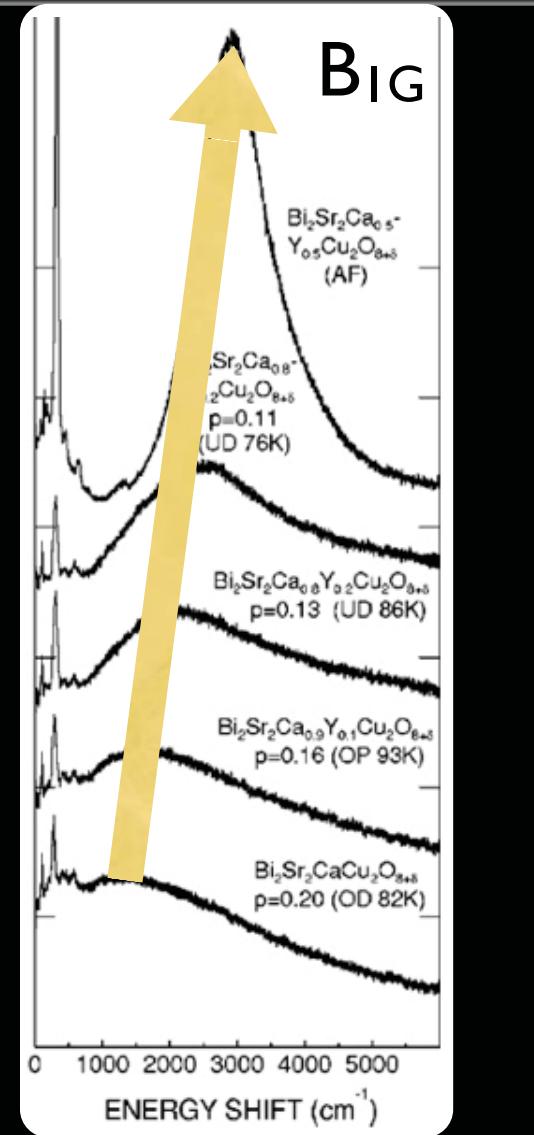
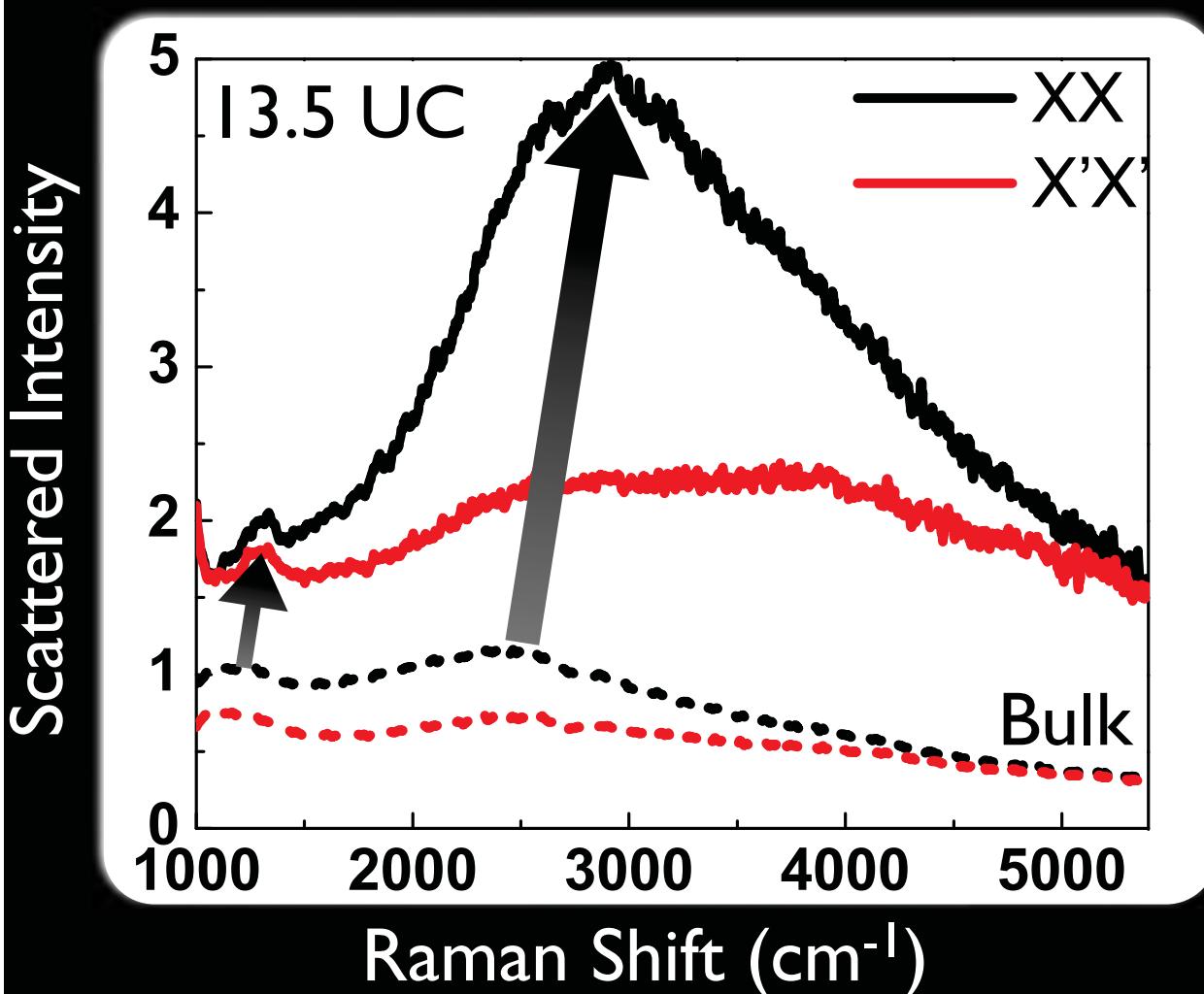
Interference Correction:
Y.Y. Wang et al., APL 92, 043121 (2008)

Doping



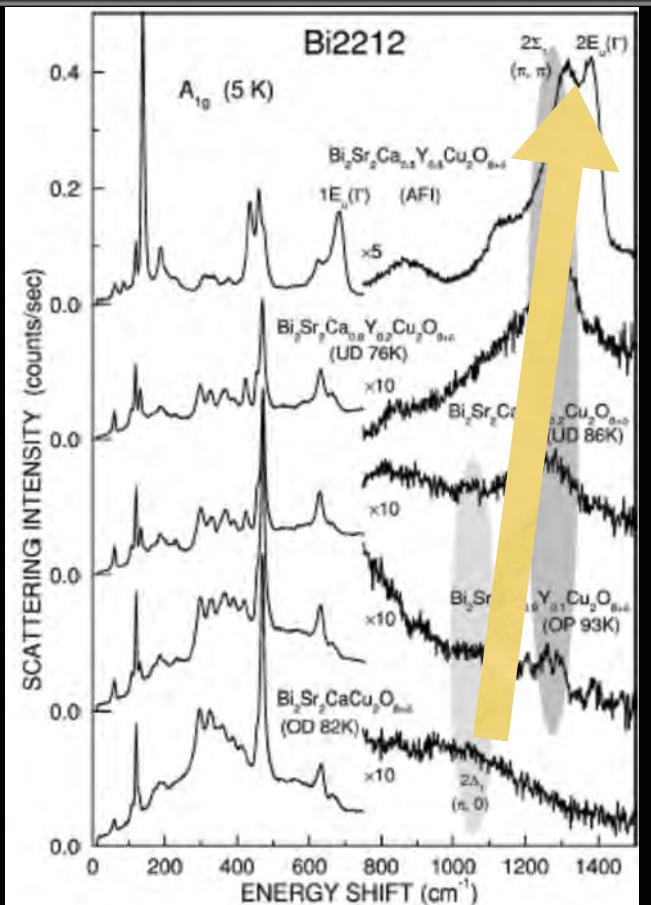
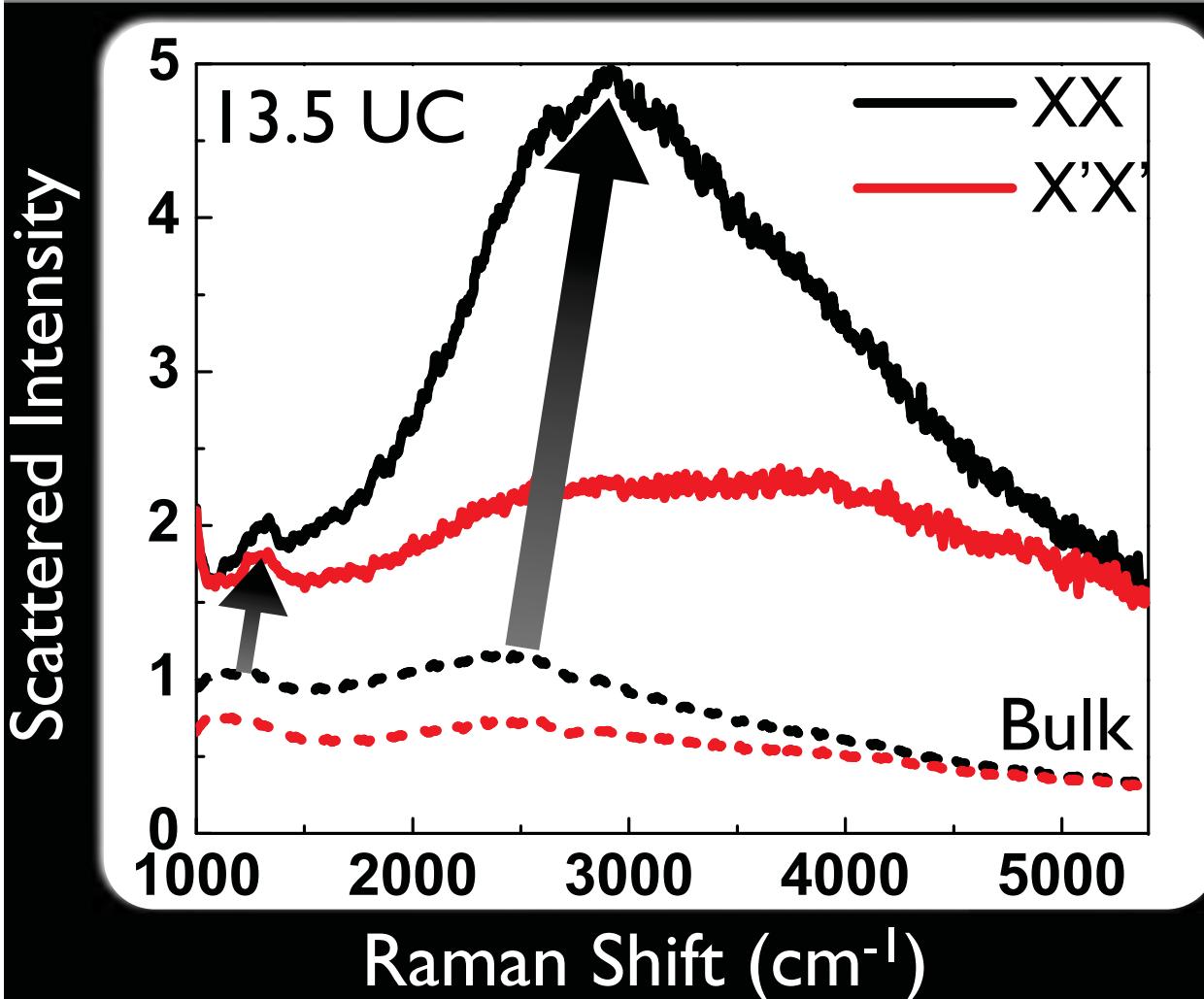
S. Sugai et al., PRB 68, 184504 (2003)

Doping



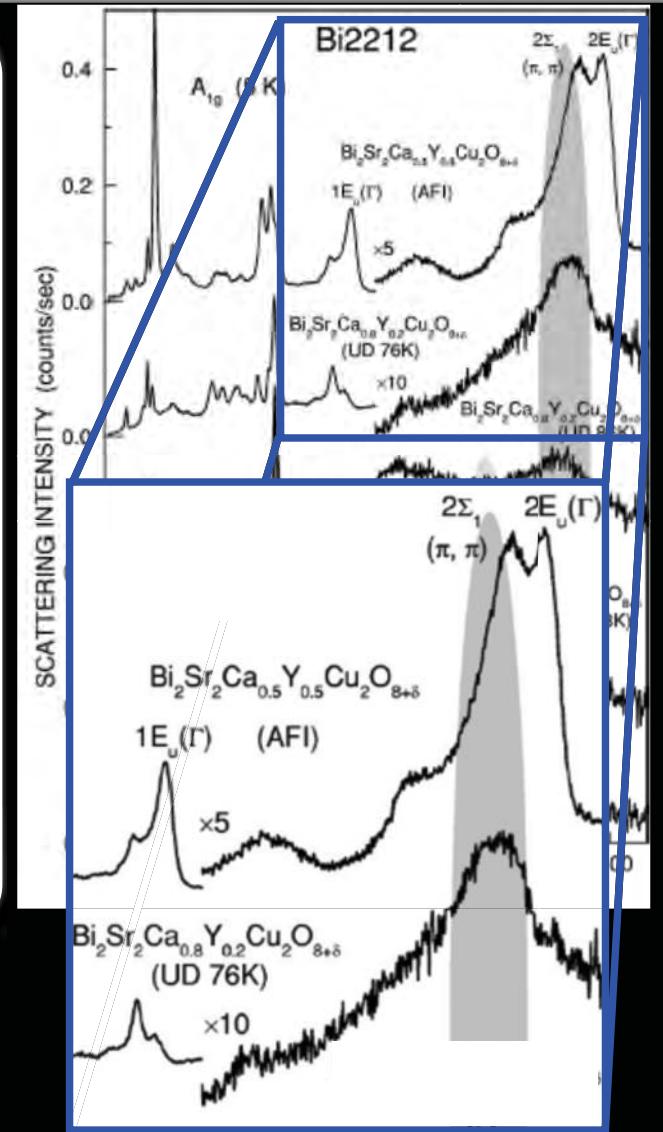
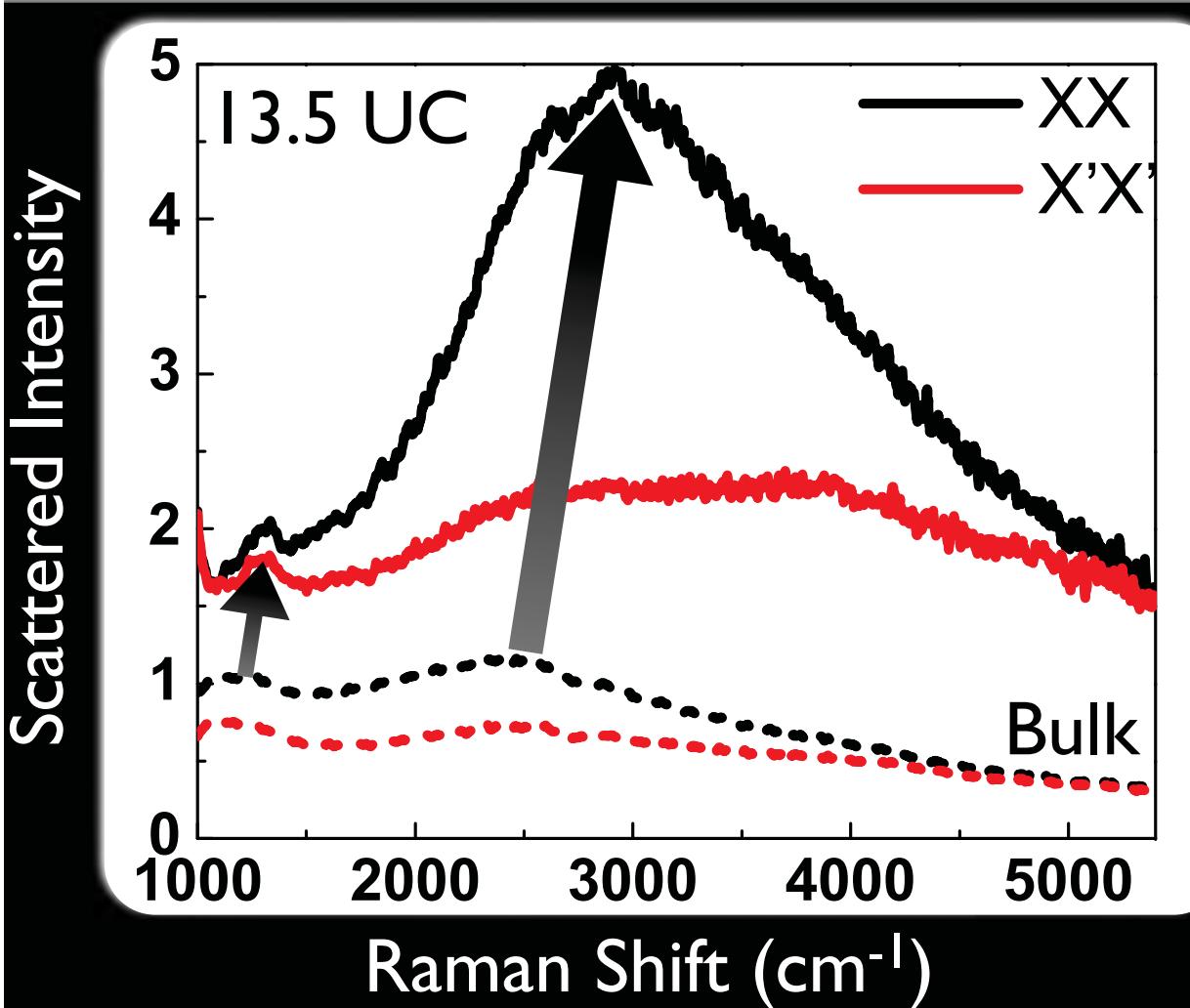
S. Sugai et al., PRB 68, 184504 (2003)

Doping



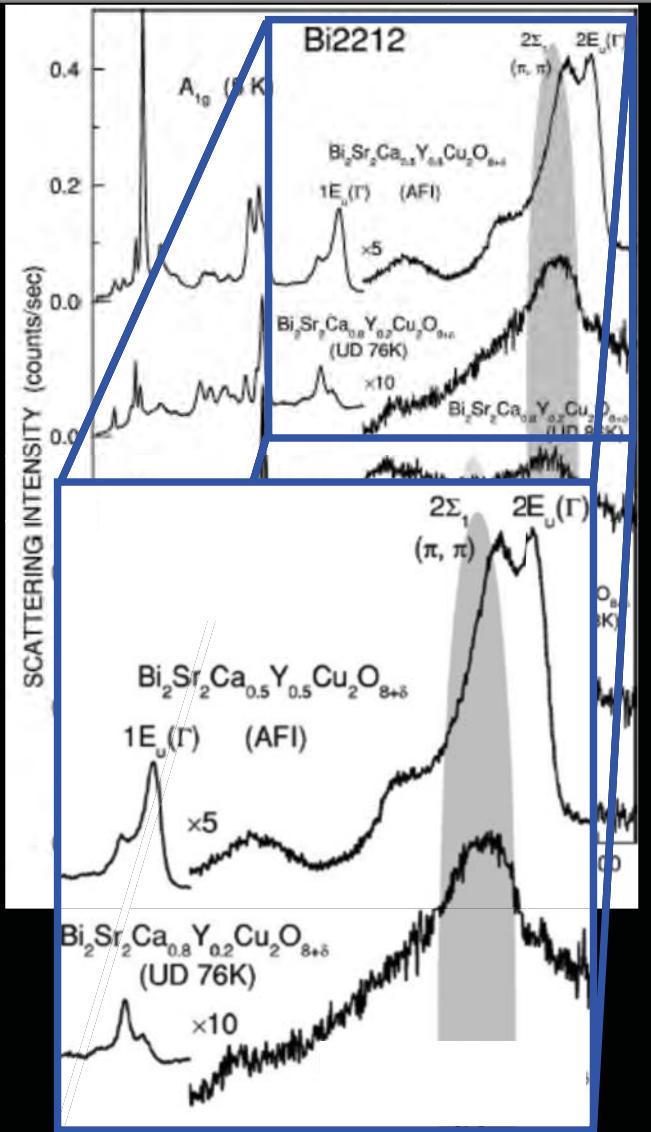
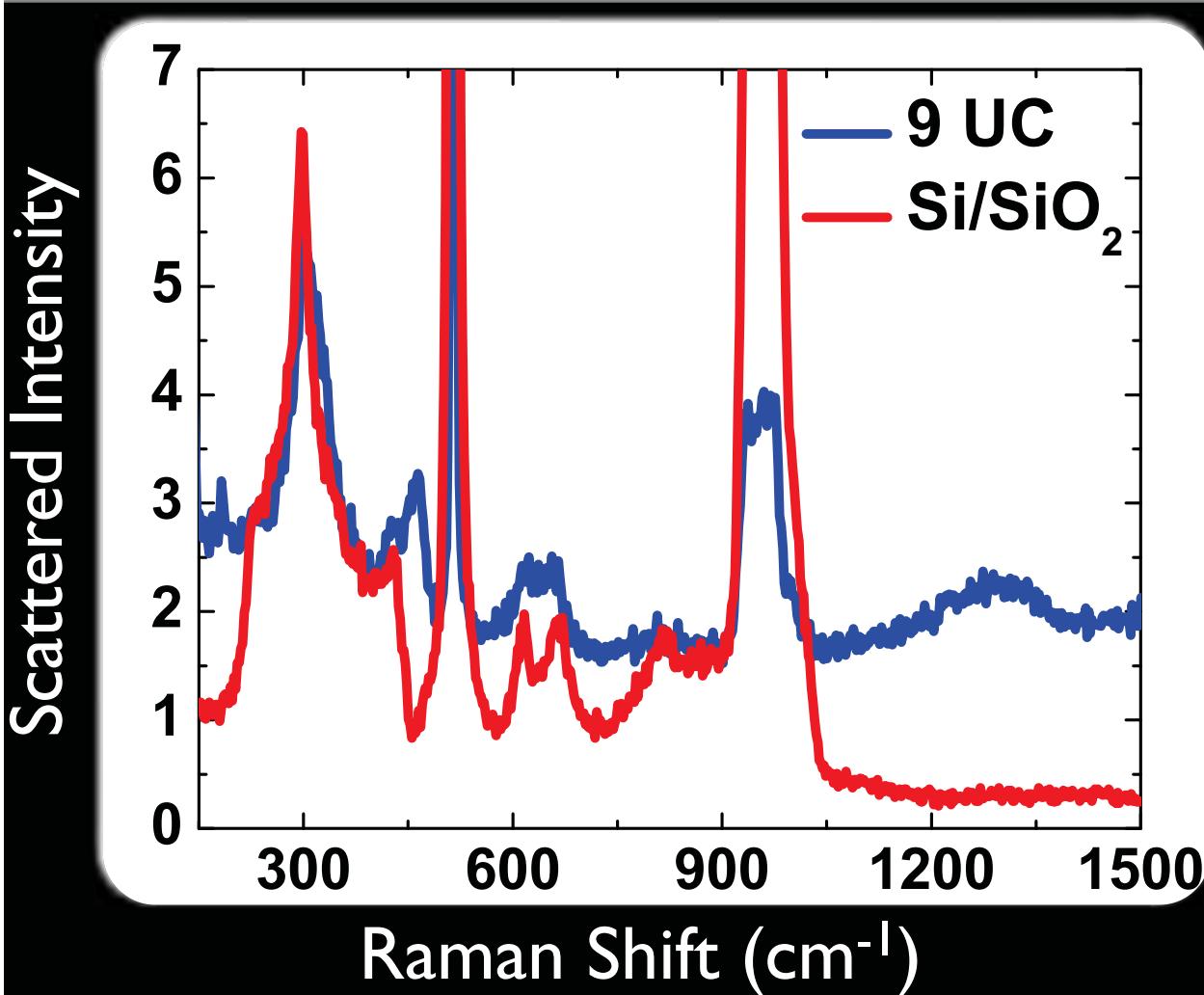
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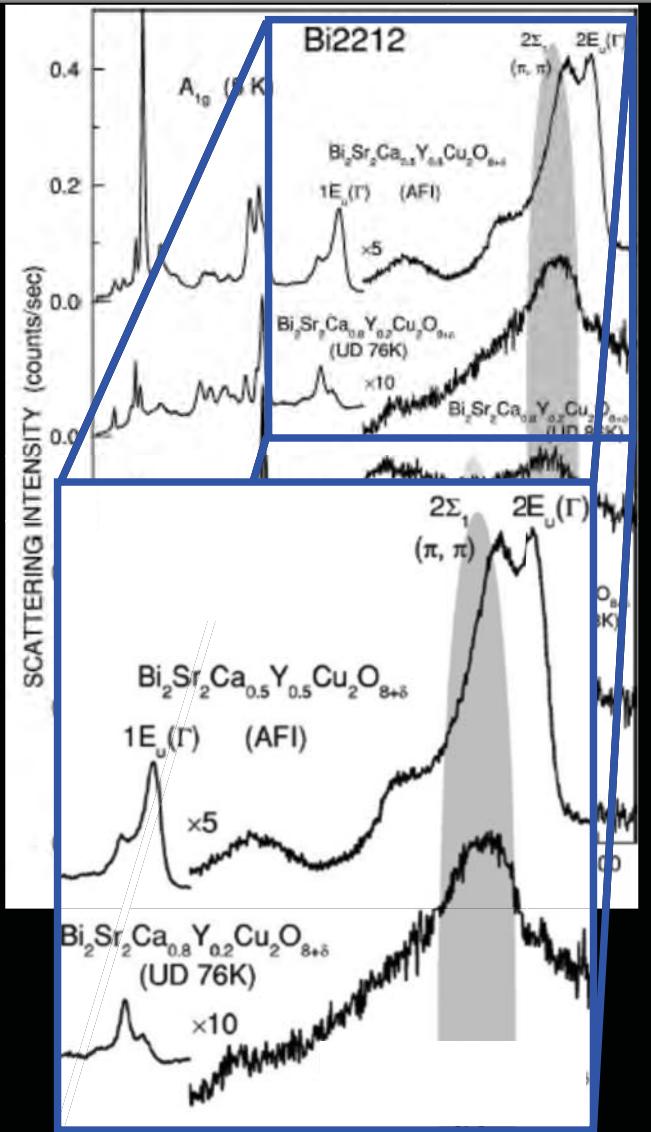
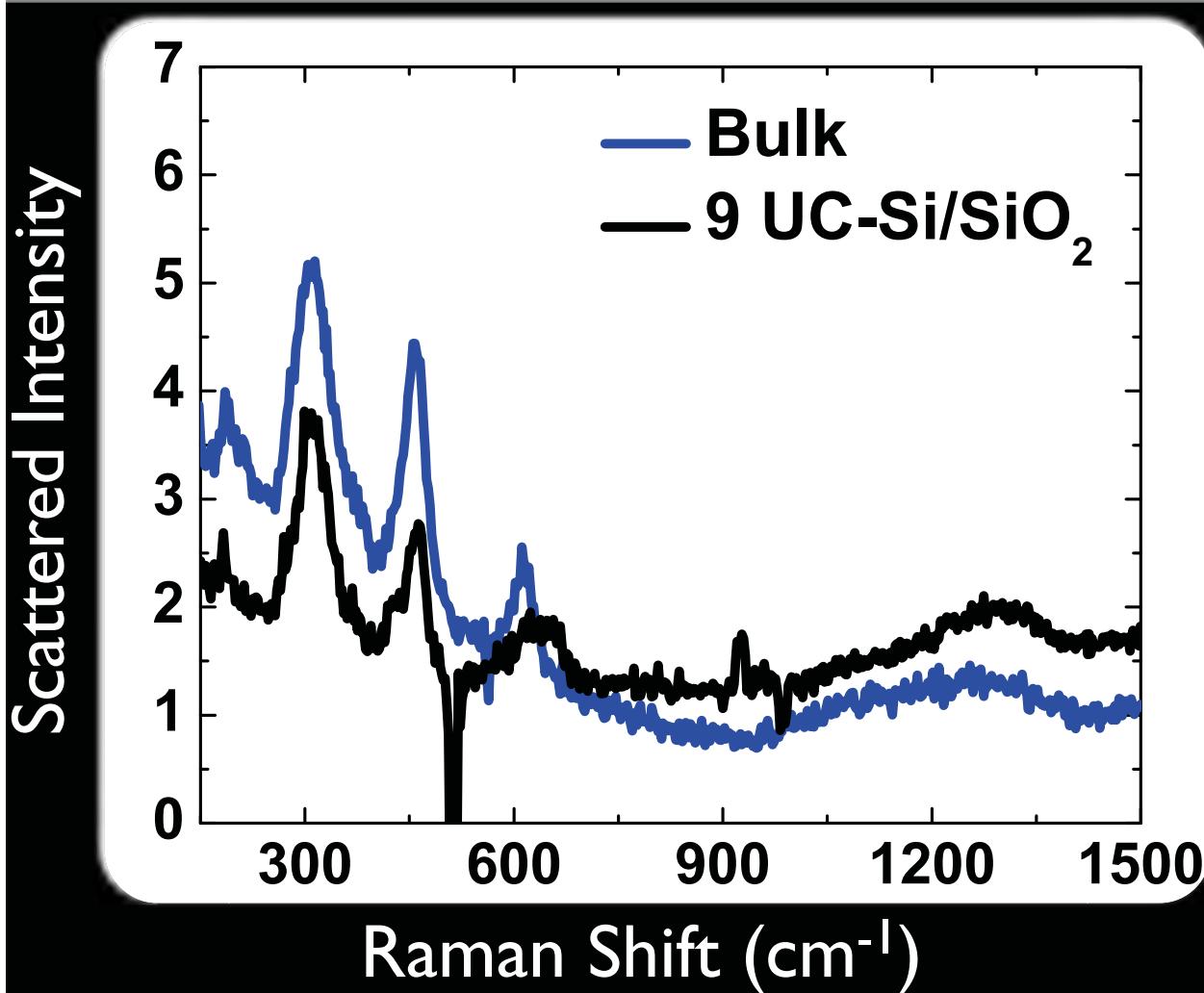


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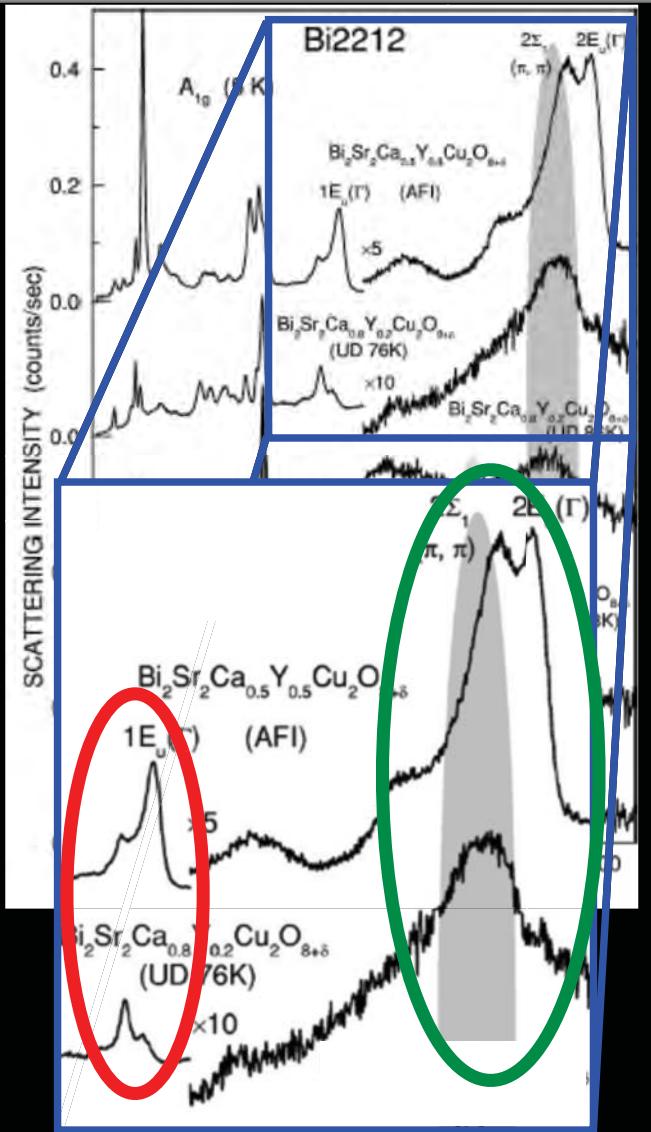
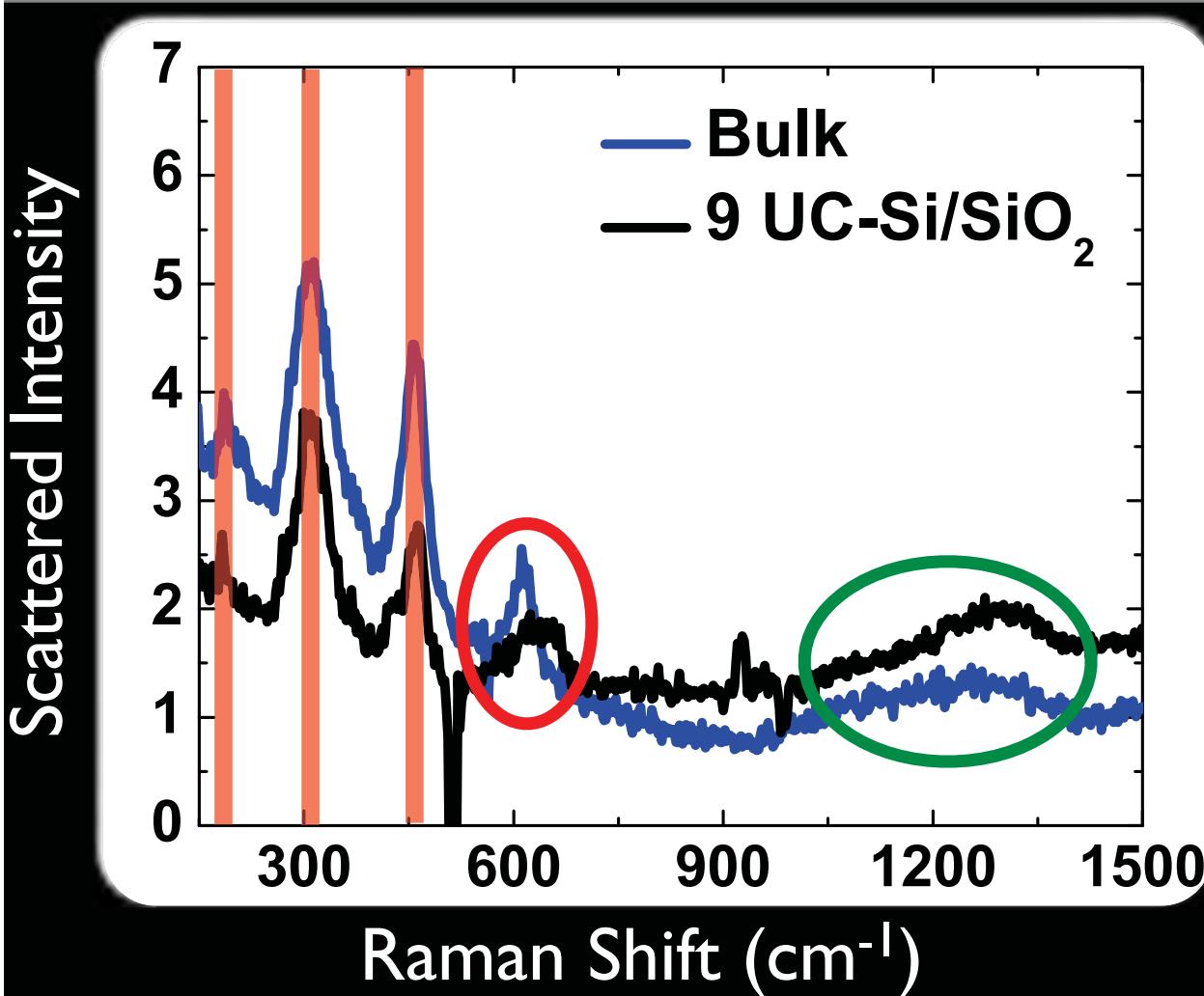


Doping



S. Sugai et al., PRB 68, 184504 (2003)

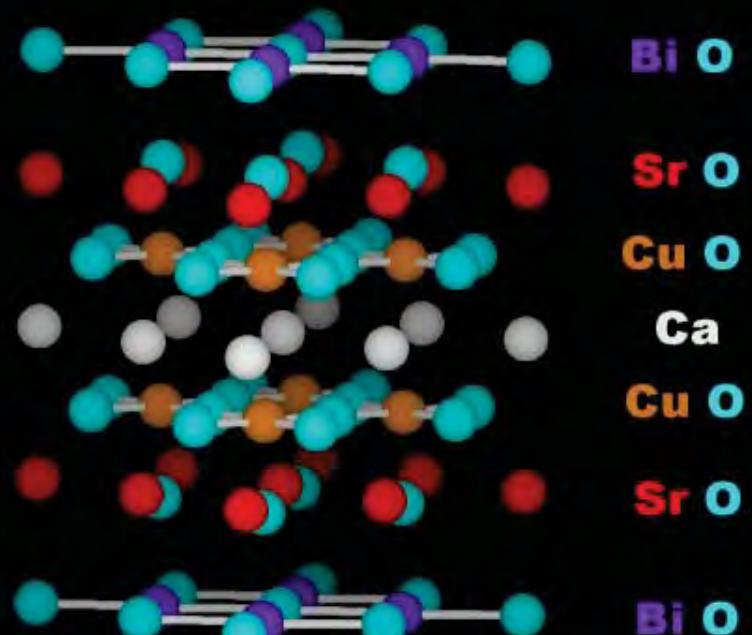
Doping



S. Sugai et al., PRB 68, 184504 (2003)

Doping

$\text{Bi}_2\text{Sr}_2\text{Ca}_{1-x}\text{Dy}_x\text{Cu}_2\text{O}_{8+\delta}$
 $x=0.3, 0.4$

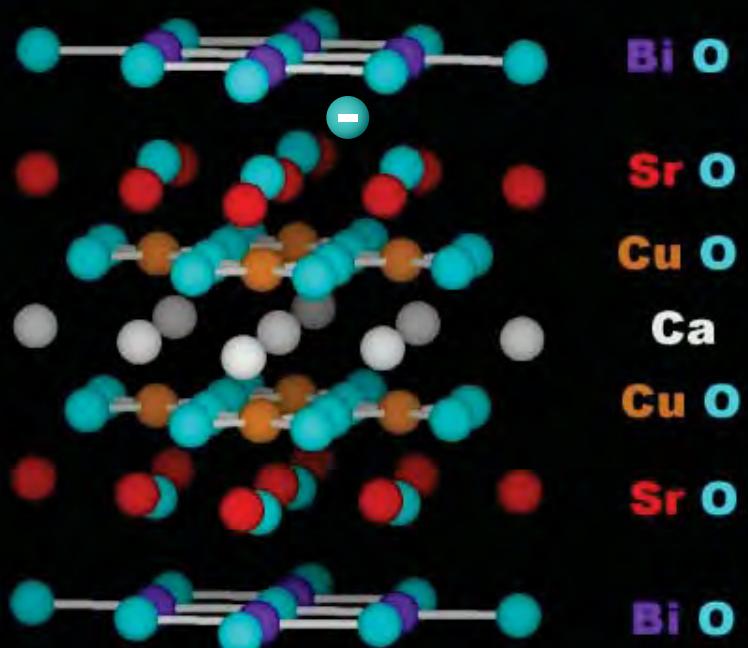


W. Que, M. B. Walker, Phys. Rev. B 46, 14772 (1992)
D. Grebille et al., Acta Crystallogr. B52, 628 (1996)

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Oxygen Interstitial

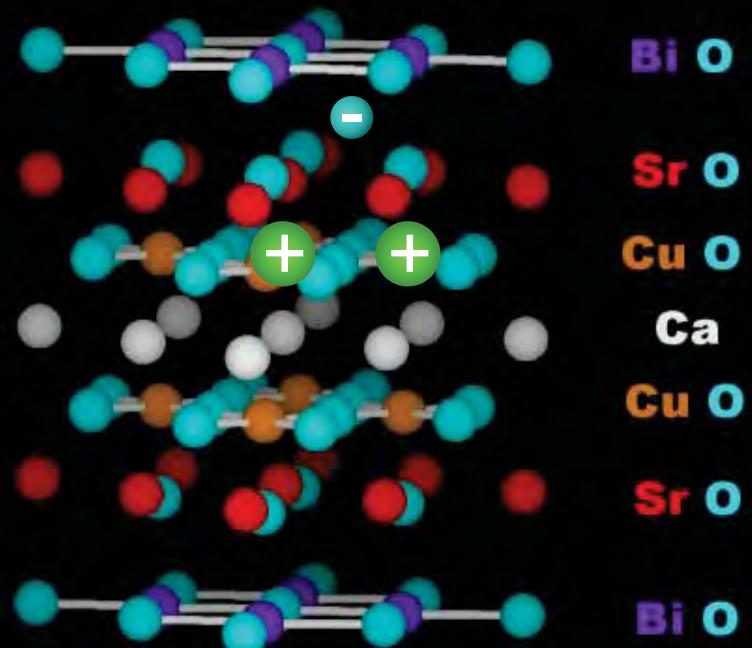


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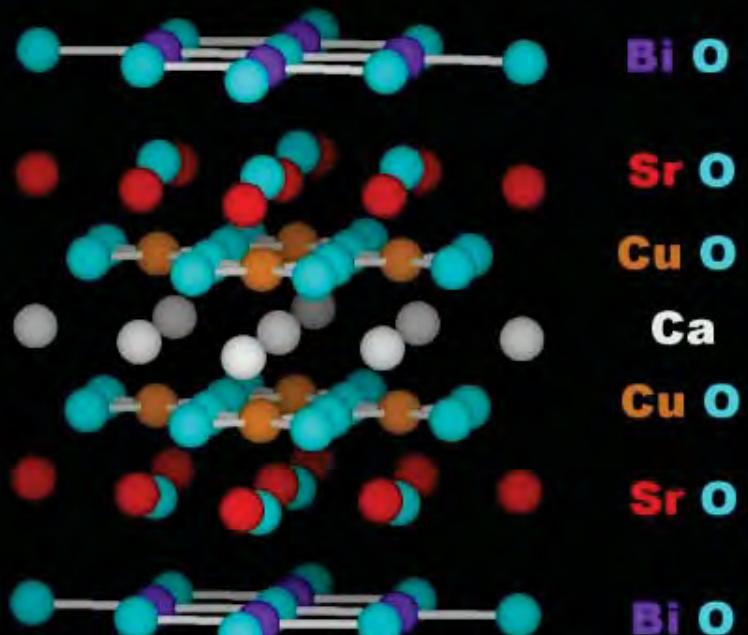
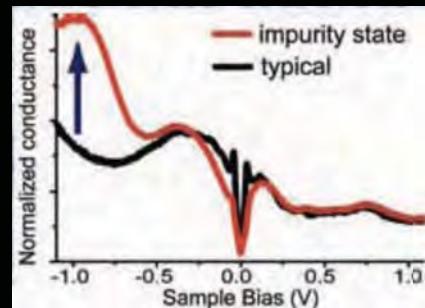
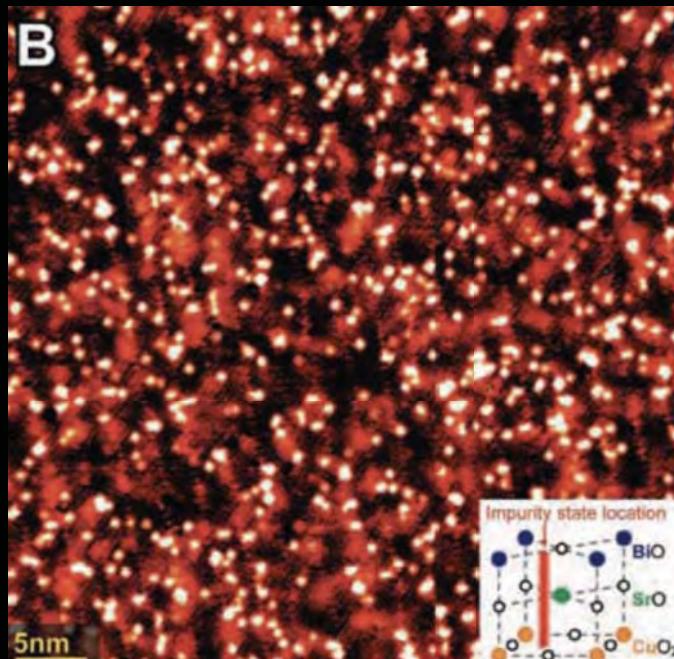


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 $x=0.3, 0.4$

Oxygen Interstitial



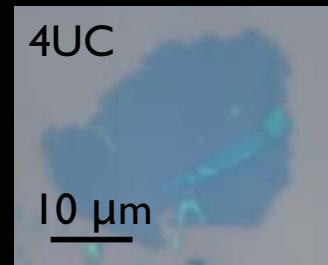
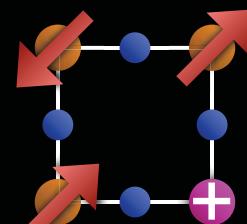
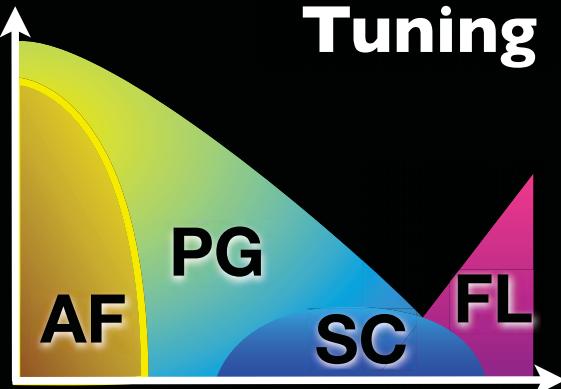
K. McElroy *et al.*, Science 309 1048 (2005)

W. Que, M. B. Walker, Phys. Rev. B 46, 14772 (1992)

D. Grebille *et al.*, Acta Crystallogr. B52, 628 (1996)

Summary

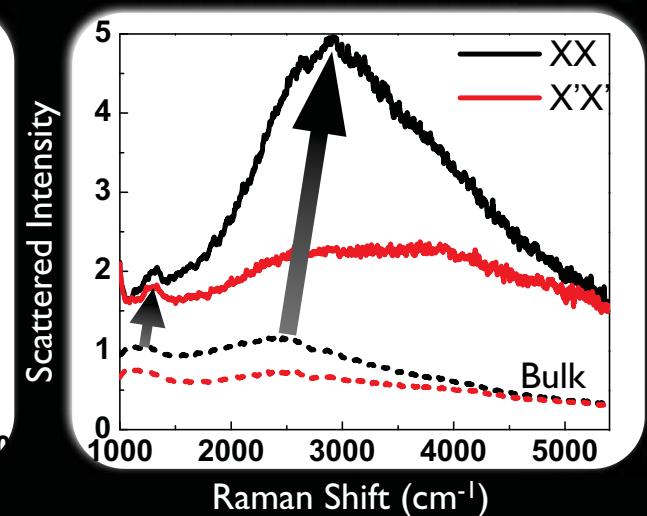
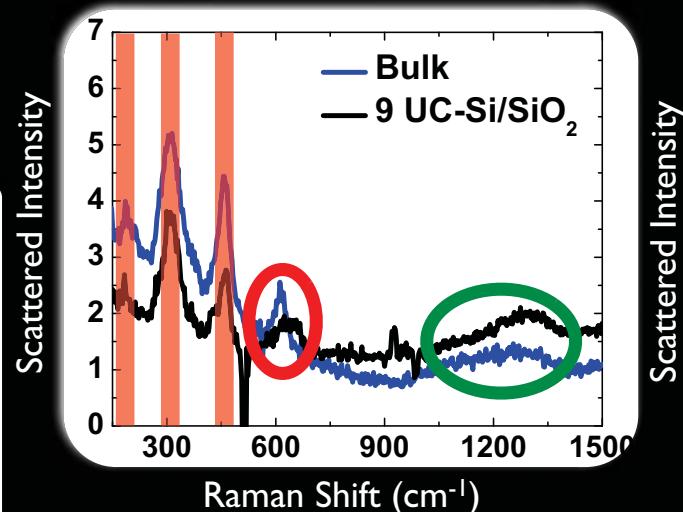
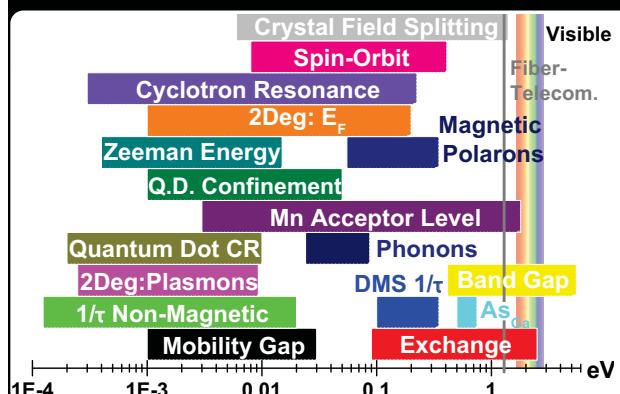
Tuning Materials



Exfoliation



Optics



Flakes Available Upon Request

● Tuning

● Exfoliation

● Optics

● Summary

● Future

Tuning Materials

4UC

Exfoliation

PG

AF

SC

10 μm

Thanks
Go Blue



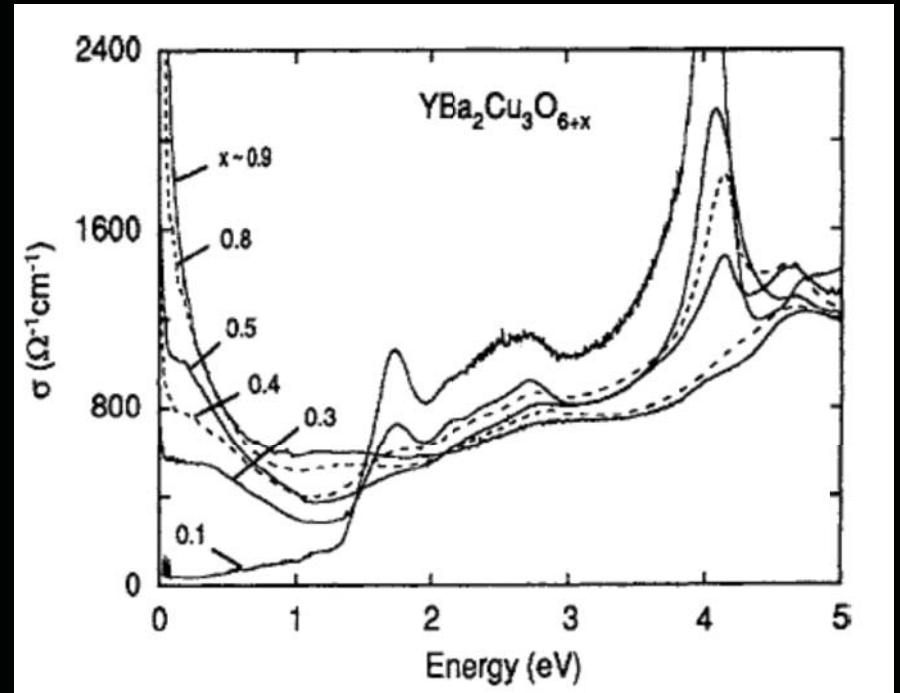
Optics



Flakes Available Upon Request
• Summary

Exfoliation

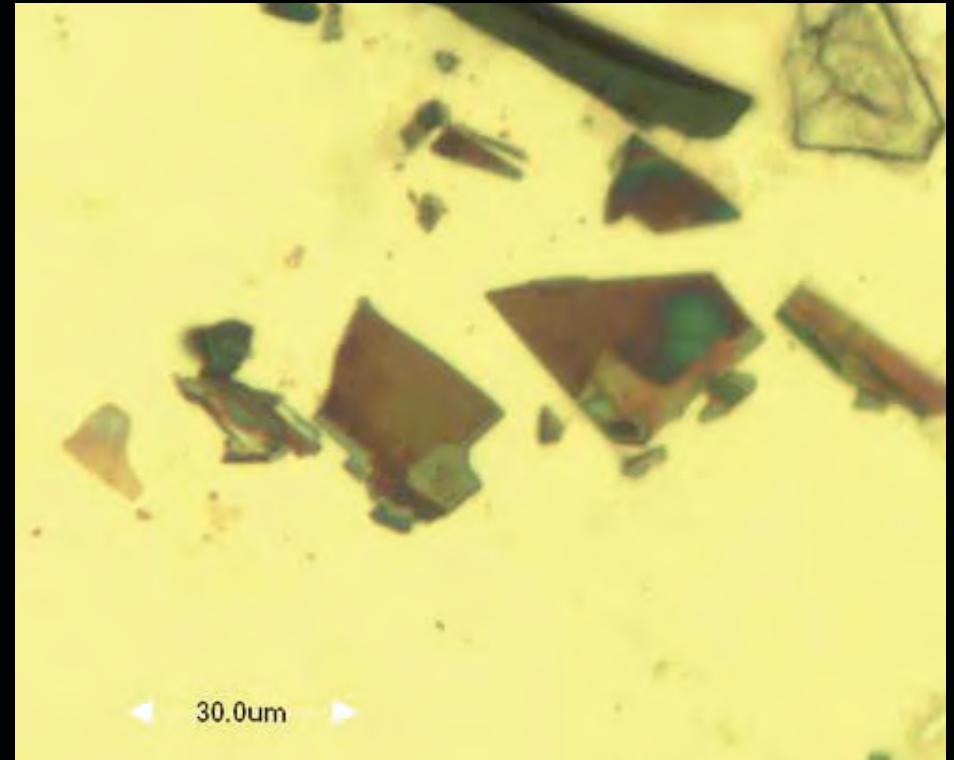
- X-Ray
- Infrared & Visible Microscopy



S.L. Cooper et al., PRB 47, 8233 (1993)

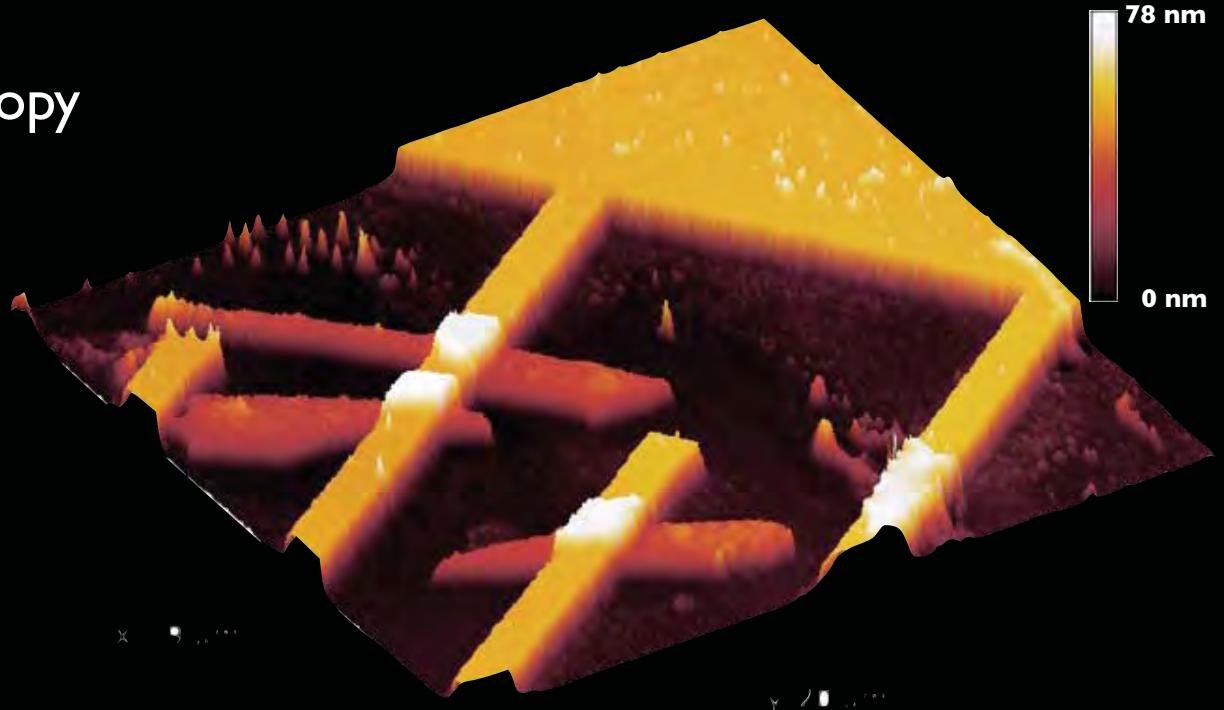
Exfoliation

- X-Ray
- Infrared & Visible Microscopy
- New substrates



- X-Ray
- Infrared & Visible Microscopy
- New substrates
- Devices

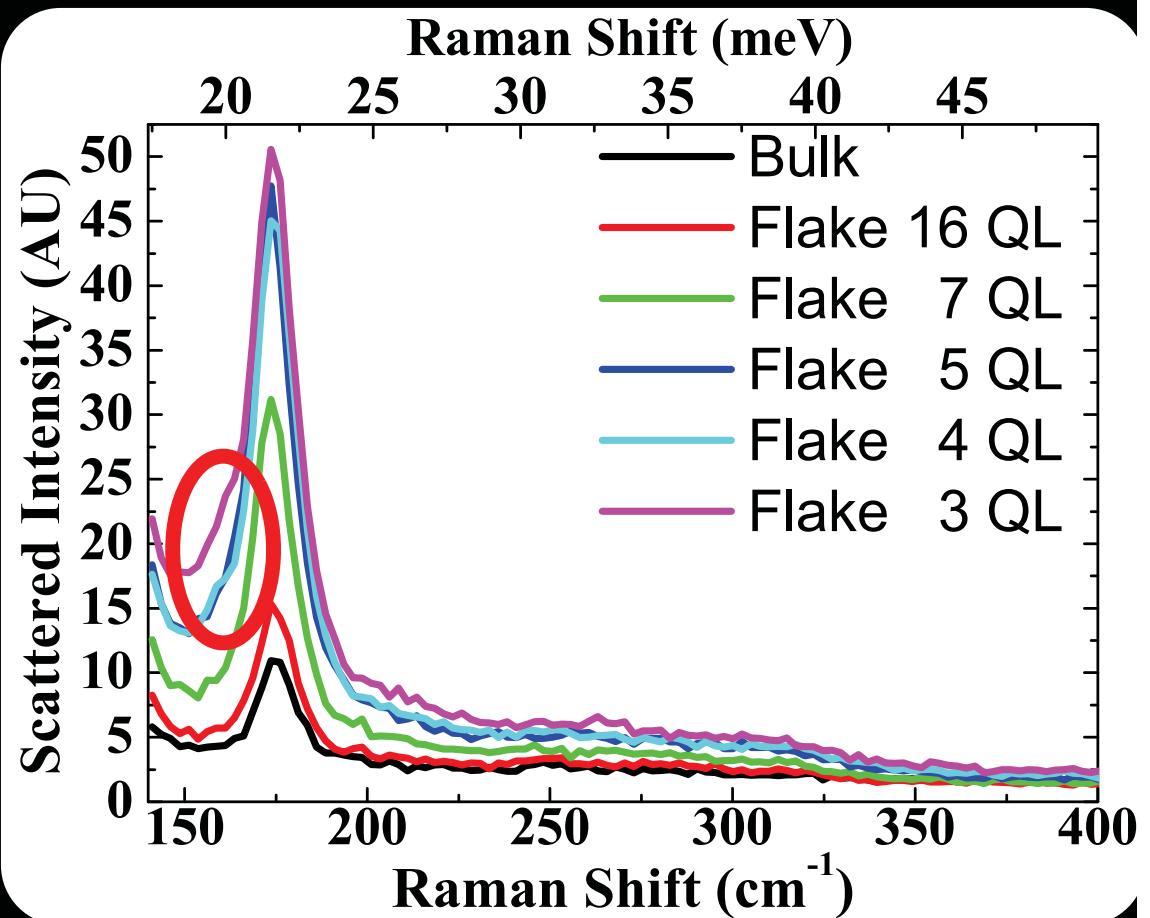
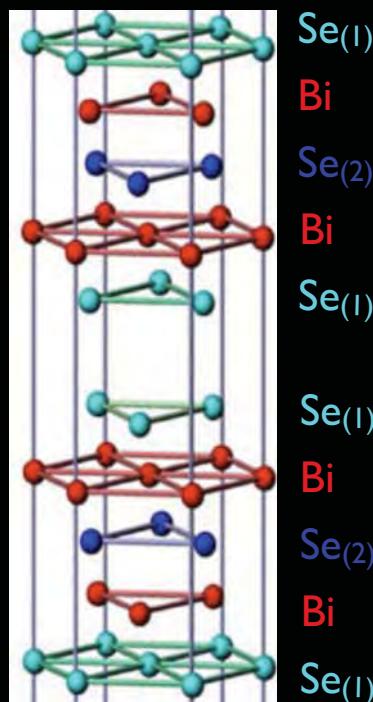
Exfoliation



Exfoliation

- X-Ray
- Infrared & Visible Microscopy
- New substrates
- Devices
- Other Materials

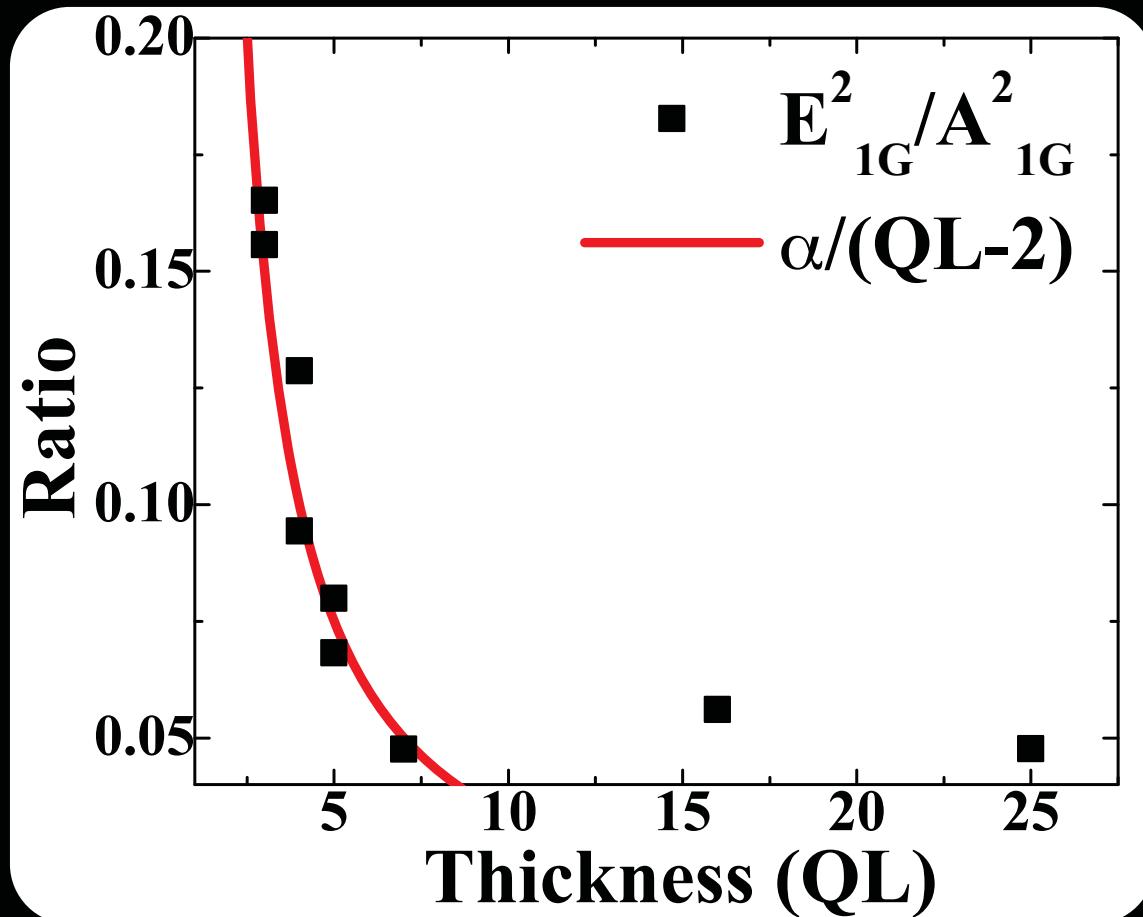
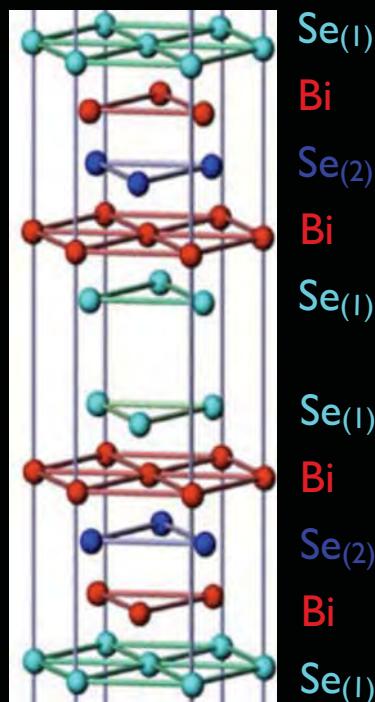
Bi_2Se_3

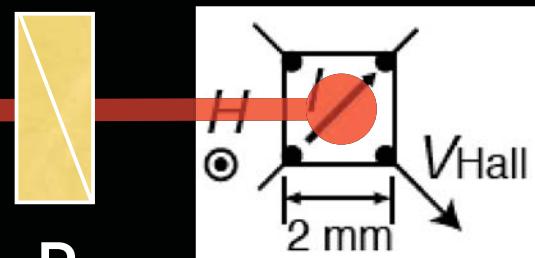


Exfoliation

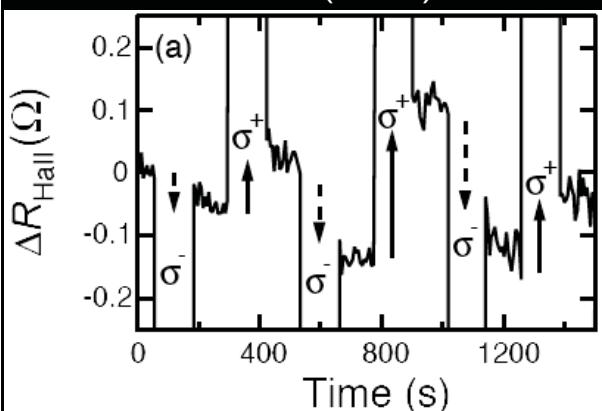
- X-Ray
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- New substrates
- Devices
- Other Materials

Bi_2Se_3

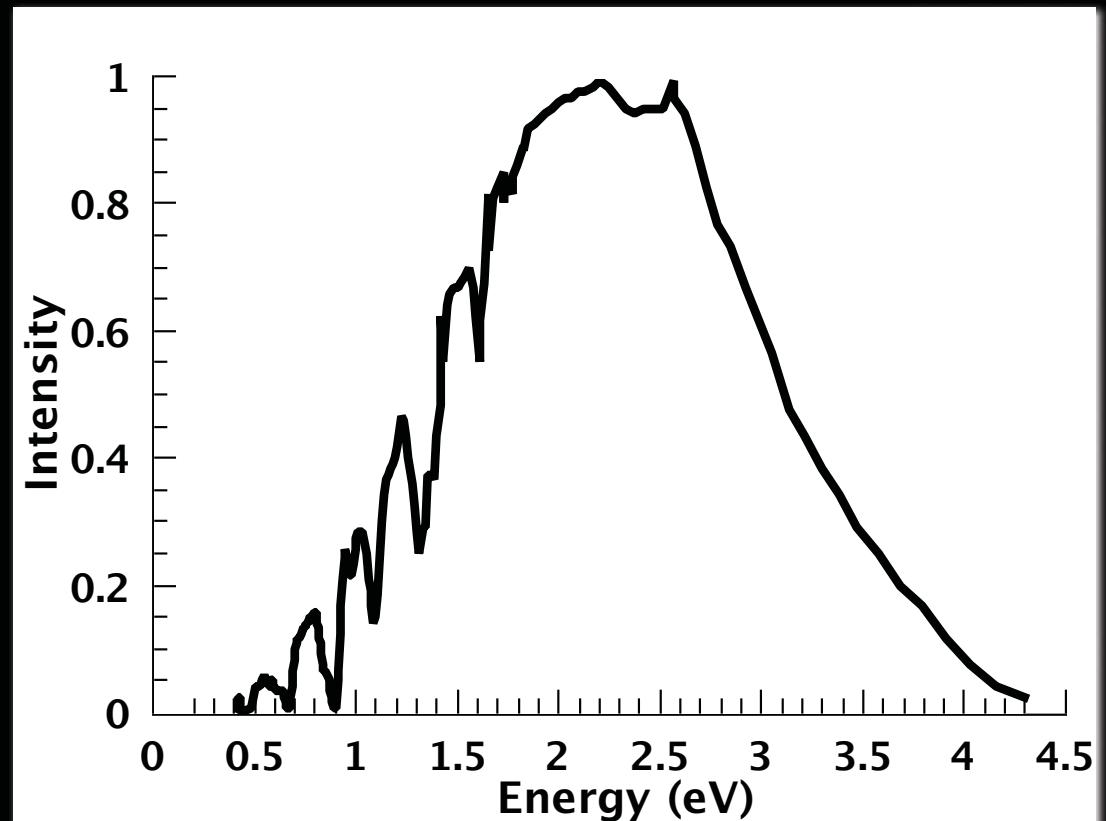


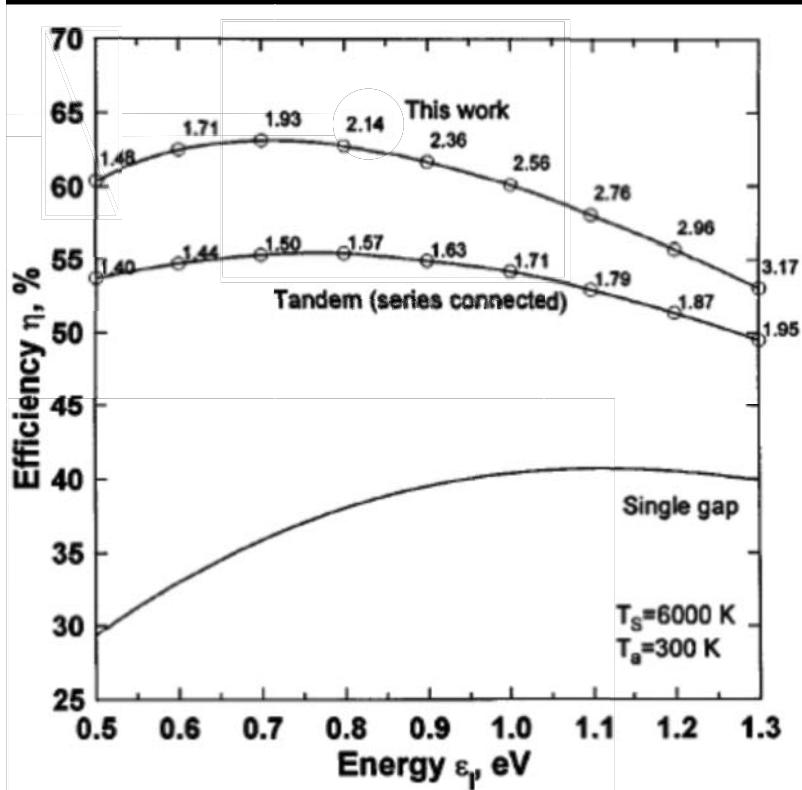


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A. Oiwa, et. al. PRL 88,
137202 (2002)

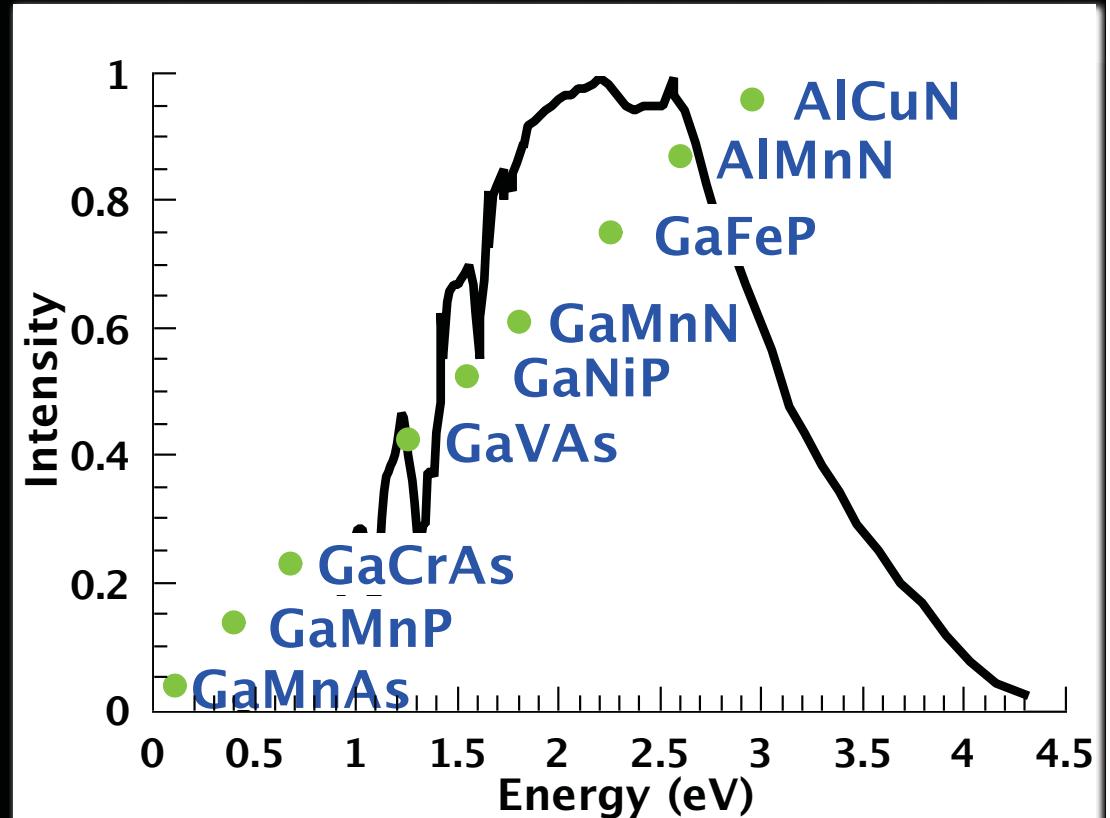


A. Luque et al., PRL 78, 5014 (1997)





A. Luque et al., PRL 78, 5014 (1997)



K.S. Burch et al., JMMM 320, 3207 (2008)