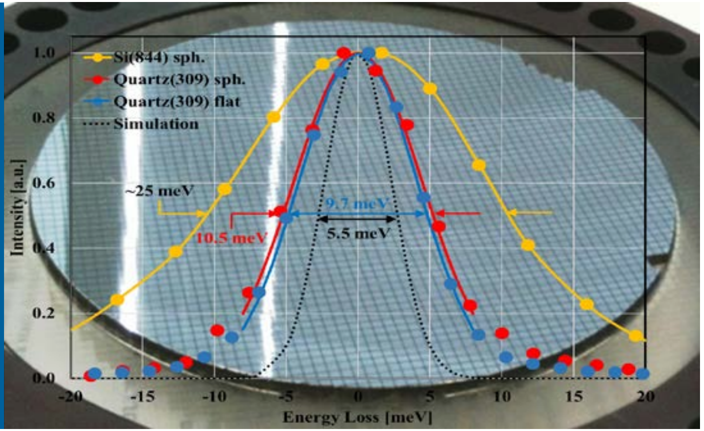
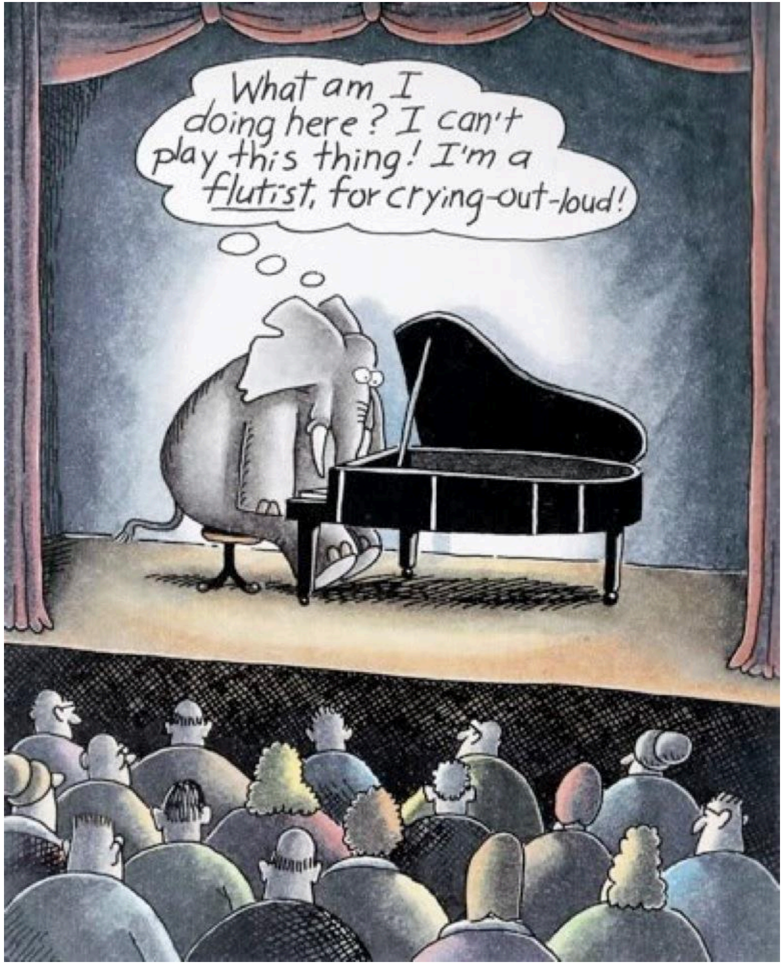
New Developments in Inelastic X-ray Scattering at the Advanced Photon Source



THOMAS GOG
On behalf of the Inelastic X-ray and Nuclear Resonant Scattering Group @ APS @ Argonne Nat'l Laboratory

IXS 2019
June 28th, 2019

The Elephant's Nightmare
(Garry Larson)



Introduction

Progress in IXS Instrumentation, Theory, …

(Spectrometers, Analyzer Systems, Detectors, Sample Environments, …)

✚

Upgrade of Synchrotron Radiation Sources

(Conversion to Low-Emittance MBA Machines)

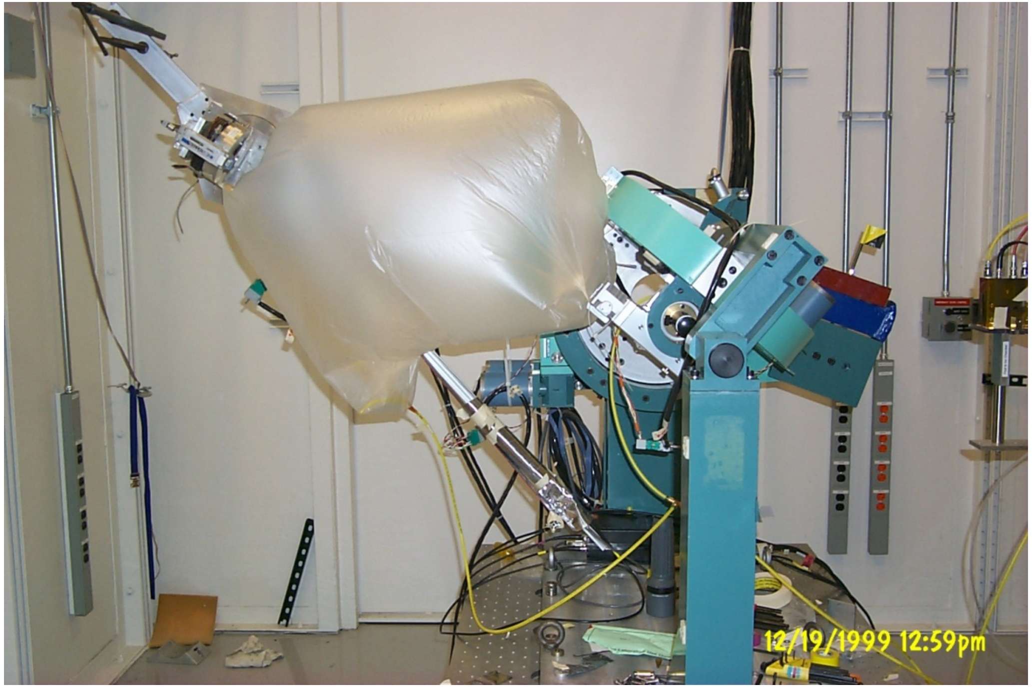
⬇

New Opportunities for IXS Experimentation, Science at Synchrotrons

RIXS at the APS

9-ID

1999



RIXS at the APS

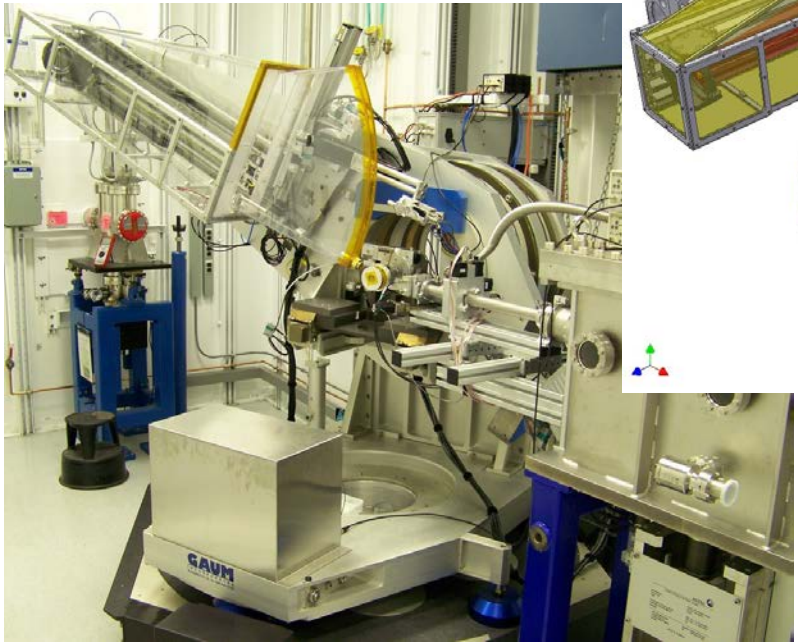
9-ID

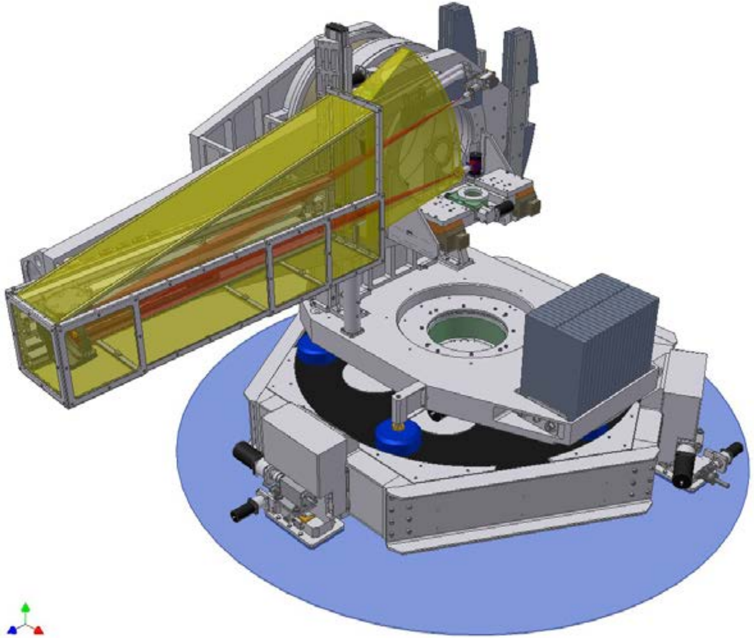
2004

RIXS at the APS

30-ID

2007
“MERIX”

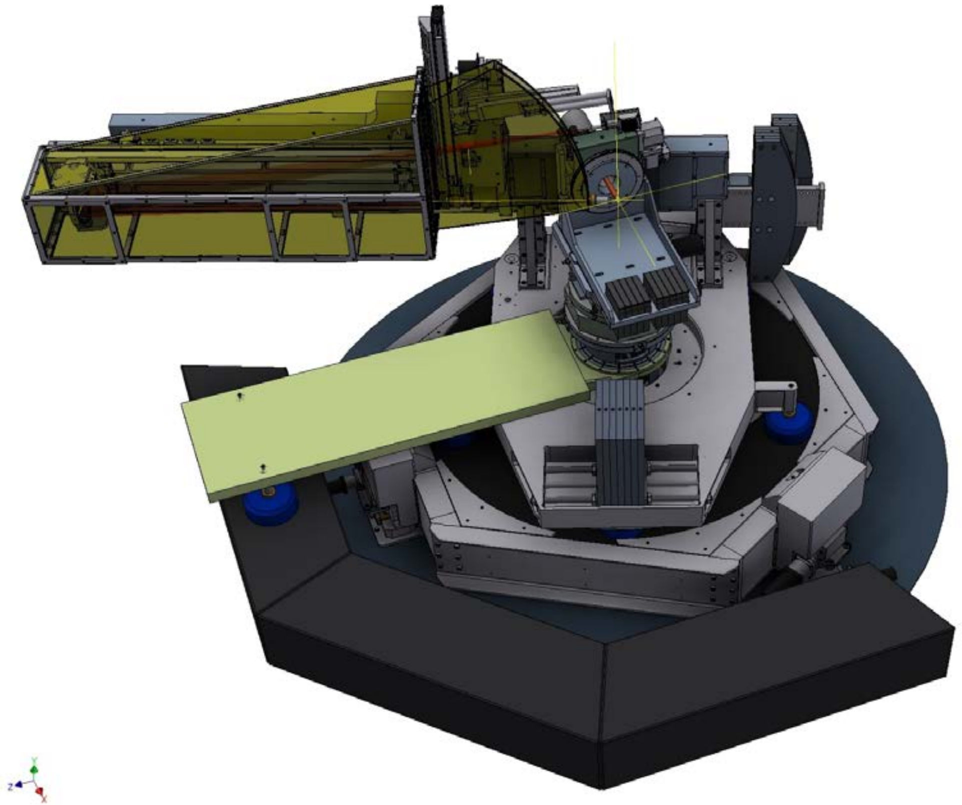




RIXS at the APS

27-ID

2020



Introduction

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Upgrade of Synchrotron Radiation Sources

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⬇

New Opportunities for IXS Experimentation, Science at Synchrotrons

New Opportunities for IXS

- Polarization Analysis
- Imaging (of heterogeneous materials)
- Time-Resolved Measurements
- Improved Energy Resolution (in Resonant Techniques)
- Novel In situ Sample Environments
- …

Introduction

Progress in IXS Instrumentation, Theory, …

(Spectrometers, Analyzer Systems, Detectors, Sample Environments, …)

+

Upgrade of Synchrotron Radiation Sources

(Conversion to Low-Emittance MBA Machines)

↓

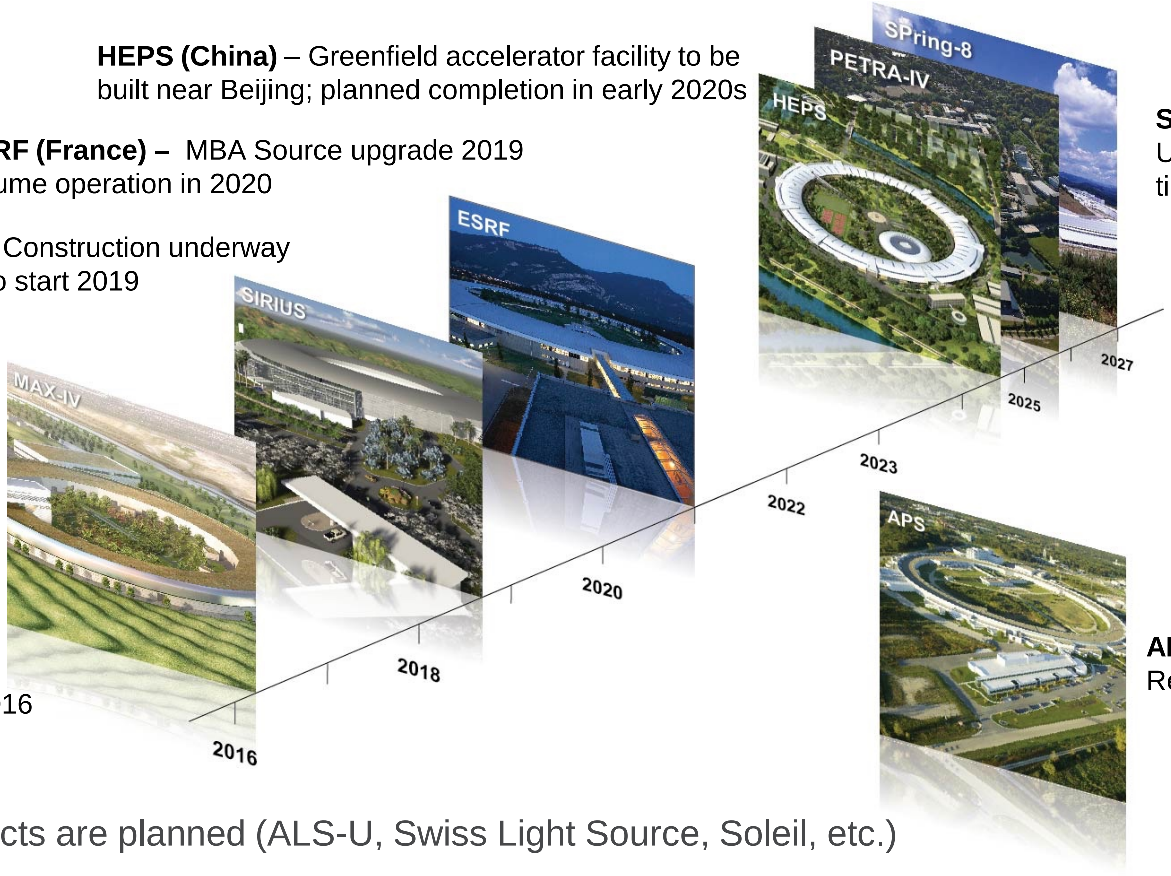
New Opportunities for IXS Experimentation, Science at Synchrotrons

World-wide MBA Low-Emittance Synchrotron Sources

HEPS (China) – Greenfield accelerator facility to be built near Beijing; planned completion in early 2020s

ESRF (France) – MBA Source upgrade 2019 resume operation in 2020

SIRIUS (Brazil) – Construction underway Commissioning to start 2019



SPring-8 (Japan) – Upgrading in 2027 timeframe

MAX-IV (Sweden)
Inauguration June 2016
in operation

APS-U – Upgrade 2022
Resume operation in 2023

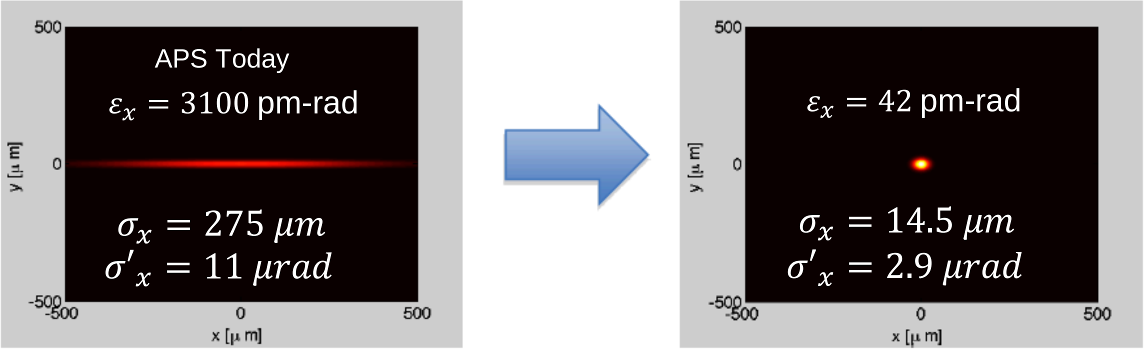
Many other projects are planned (ALS-U, Swiss Light Source, Soleil, etc.)

APS - Upgrade

- Dramatically improved Brilliance (Flux / (Area × Solid Angle))

  (… mostly through reduction of horizontal emittance)

Electron Beam at APS

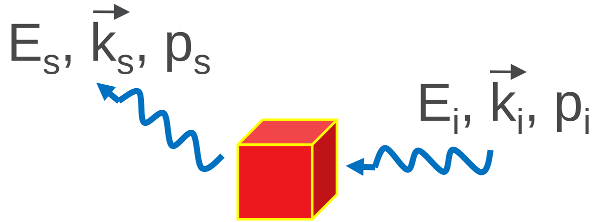


- Double the Ring Current to 200 mA
- Improved Focusing, Smaller (sub-μm-, nm-) beams
- Improved Coherence (IXS?)

New Opportunities for IXS

- Polarization Analysis
- Imaging (of
- Time-Resolved Me
- Improved Energy
- Novel In situ

IXS:



polarization largely ignored in the past

(… hard to do experimentally)

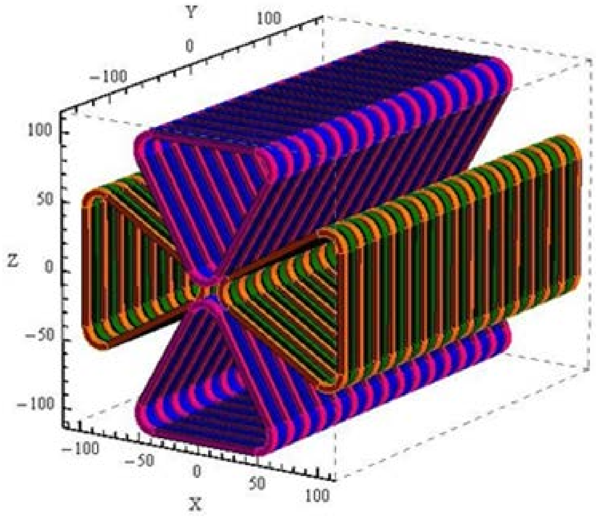
Sources of (variable) Polarization

- Phase Plates (low efficiency, low polarization purity)
- Special Insertion Devices (availability)

New Undulator Concepts: SCAPE (Yuri Ivanyushenkov, APS)
(Superconducting Arbitrarily Polarizing Emitter)

- Would like Undulator capable of generating linear and circular polarized photons
- Electromagnetic, superconducting undulator with four planar, magnetic cores, assembled around a cylindrical beam vacuum chamber
- APS Upgrade MBA-lattice enables cylindrical vacuum chambers with

  6 mm ID
- Prototype successfully tested

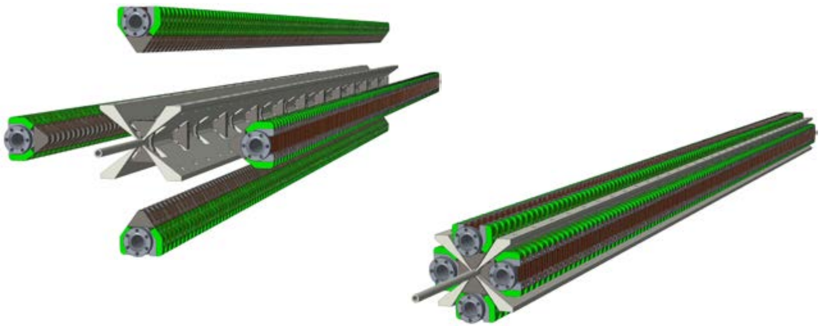


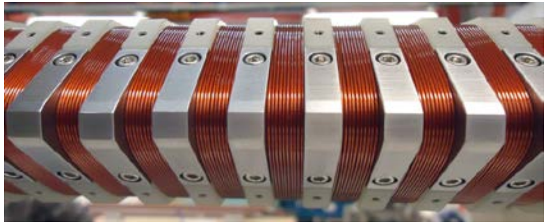
Concept of SCAPE: a universal SCU with four planar superconducting coil structures. A beam chamber is not shown.

SCAPE PROTOTYPE TEST

- SCAPE 0.5-m long prototype magnet is built:
  - period length – 30 mm
  - magnetic gap – 10 mm
- The prototype has been successfully tested in a LHe bath cryostat equipped with a movable Hall probe.

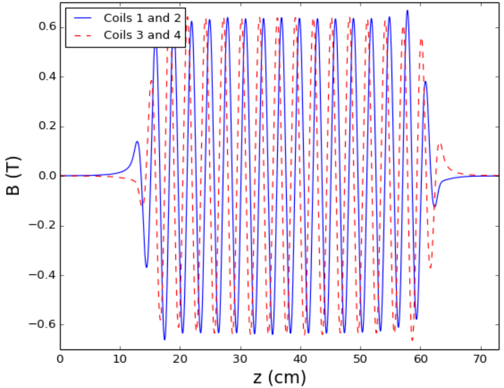
SCAPE design model

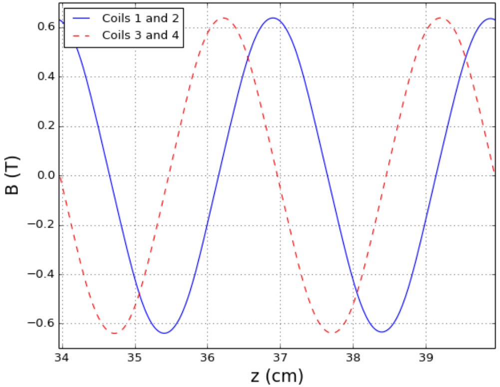




SCAPE prototype mechanical structure and a single core

Measured field profiles





Why Polarization ?

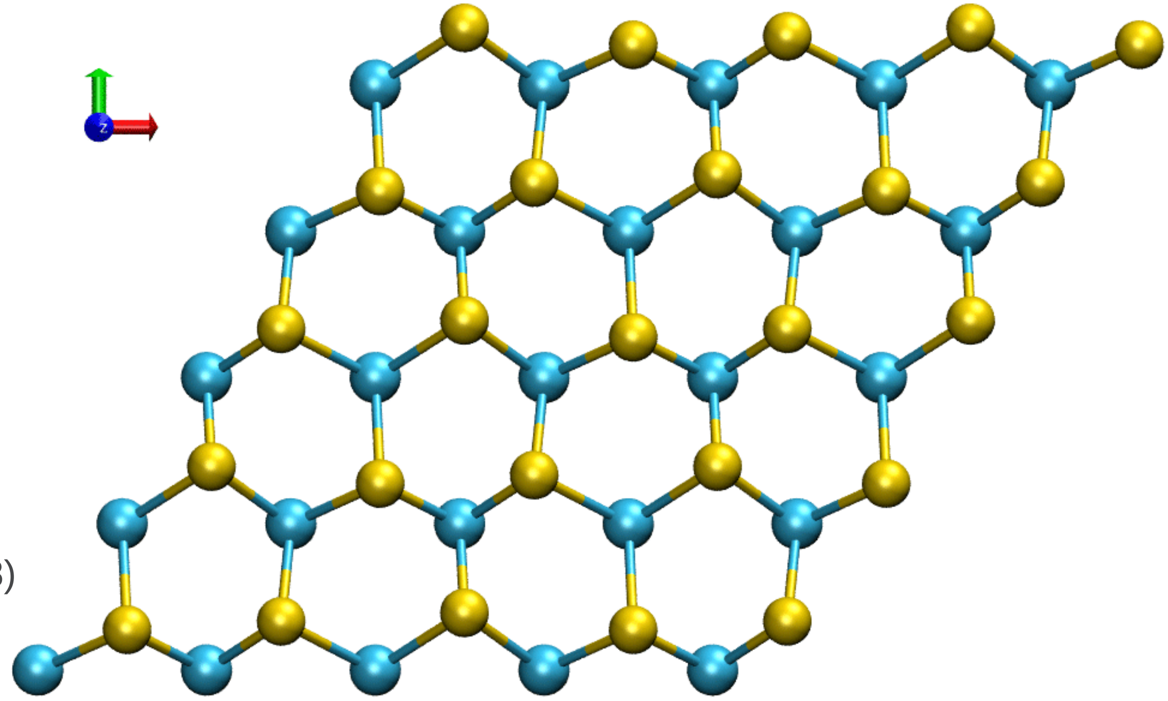
Phonons can carry angular momentum:

CHIRAL PHONONS

(in materials with

broken inversion

Symmetry)



Chiral Phonon in
Mono-layer of WSe_2
From: Hanyu Zhu et al.,
Science **359**, 579 (2018)

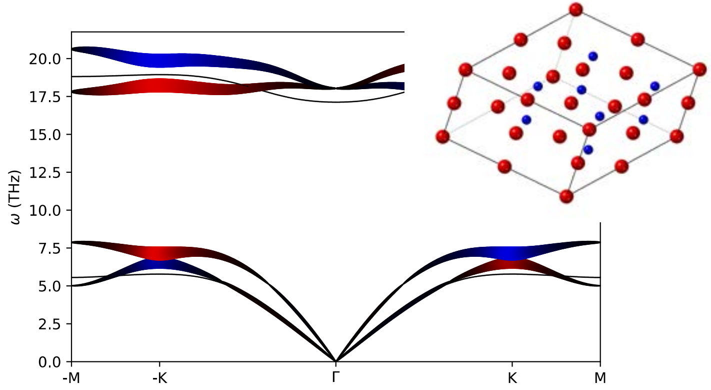
PROBING PHONONS WITH ANGULAR MOMENTUM BY IXS (HERIX@30-ID, Chen Li, UCR)

- WC lacks space inversion symmetry

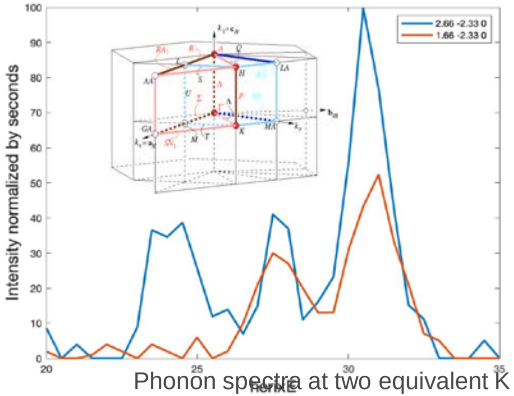
  ➡ may exhibit chiral phonons

Scientific questions:

- Is it possible to identify chiral phonons by meV-IXS, using circular- or linear-polarized X-ray?
- Are the rules governing the scattering different?
- How do such chiral phonons contribute to the thermal and transport properties in materials with broken inversion symmetry?
  - Phonon-phonon scattering and phonon lifetime
  - Spin-phonon and electron-phonon interactions

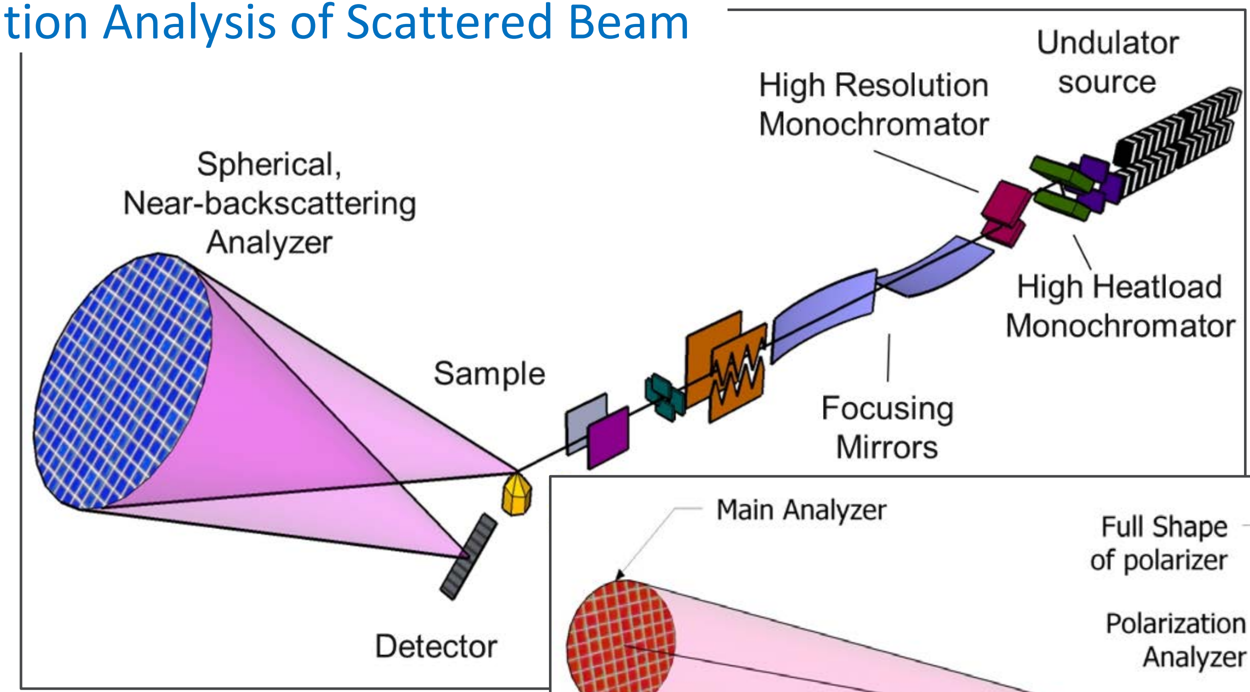


First-principle phonon dispersion calculation of WC (structure in insert). The linewidth indicates the angular momentum of phonons. Blue: right-handed; red: left-handed.

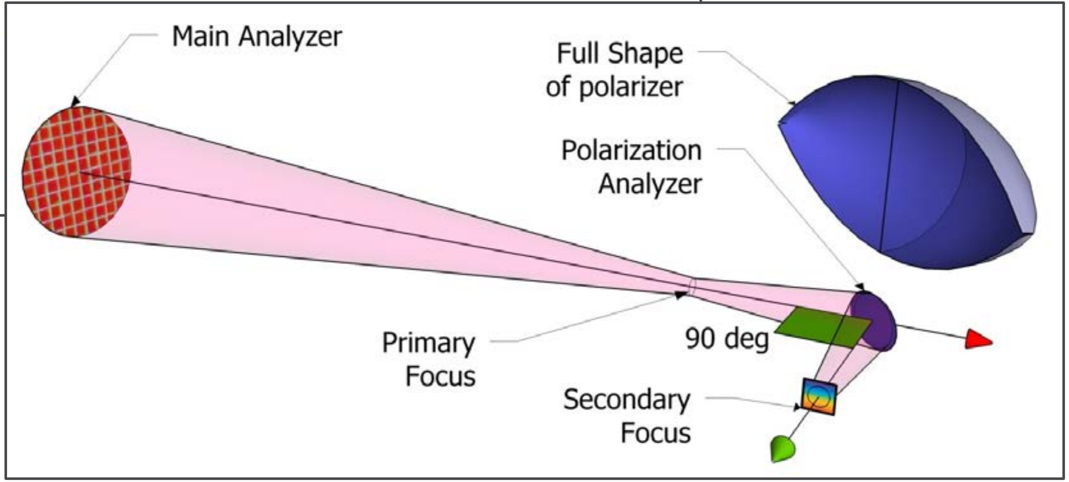


Phonon spectra at two equivalent K points

Polarization Analysis of Scattered Beam



Typical IXS Set-up



Polarizer Set-up

Polarization Analysis of Scattered Beam

PHYSICAL REVIEW B **83**, 241101(R) (2011)

Polarization-analyzed resonant inelastic x-ray scattering of the orbital excitations in $KCuF_3$

K. Ishii,[1] S. Ishihara,[2,3] Y. Murakami,[1,2,4] K. Ikeuchi,[1,4] K. Kuzushita,[1] T. Inami,[1] K. Ohwada,[1] M. Yoshida,[1] I. Jarrige,[1] N. Tatami,[2] S. Niioka,[2] D. Bizen,[2] Y. Ando,[2] J. Mizuki,[1] S. Maekawa,[3,5] and Y. Endoh[1,6]

[1]*SPring-8, Japan Atomic Energy Agency, Hyogo 679-5148, Japan*
[2]*Department of Physics, Tohoku University, Sendai 980-8578, Japan*
[3]*CREST, Japan Science and Technology Agency (JST), Tokyo 102-0075, Japan*
[4]*Photon Factory / Condensed Matter Research Center, Institute of Materials Structure Science, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*
[5]*Advanced Science Research Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan*
[6]*International Institute for Advanced Studies, Kizu, Kyoto 619-0025, Japan*
(Received 18 May 2011; published 16 June 2011)

Spherical Analyzer + Flat HOPG crystal

HOPG reflectivity ~ 2%

Energy Resolution: 400…600 meV

Could distinguish orbital excitations between

$\mathbf{e_g} \Rightarrow \mathbf{e_g}$ and $\mathbf{t2_g} \Rightarrow \mathbf{e_g}$

Spherical Analyzer + Sculptured HOPG crystal

HOPG reflectivity ~ 6%

Energy Resolution: ~200 meV

Preliminary measurements on $CuGeO_3$

Development of a graphite polarization analyzer for resonant inelastic x-ray scattering

Cite as: Rev. Sci. Instrum. **82**, 113108 (2011); https://doi.org/10.1063/1.3662472
Submitted: 07 September 2011 . Accepted: 30 October 2011 . Published Online: 23 November 2011

Xuan Gao, Clement Burns, Diego Casa, Mary Upton, Thomas Gog, Jungho Kim, and Chengyang Li

Polarization Analysis of Scattered Beam (soft x-ray)

The simultaneous measurement of energy and linear polarization of the scattered radiation in resonant inelastic soft x-ray scattering

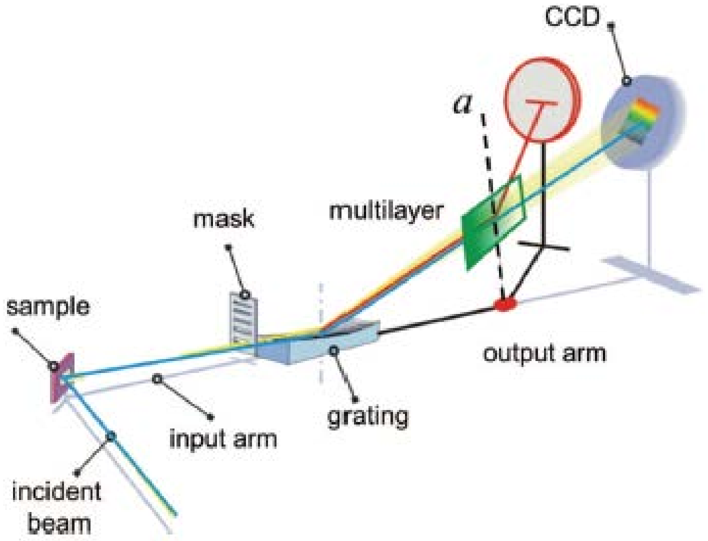
Cite as: Rev. Sci. Instrum. **85**, 115104 (2014); https://doi.org/10.1063/1.4900959
Submitted: 09 September 2014 . Accepted: 22 October 2014 . Published Online: 11 November 2014

L. Braicovich, M. Minola, G. Dellea, M. Le Tacon, M. Moretti Sala, C. Morawe, J.-Ch. Peffen, R. Supruangnet, F. Yakhou, G. Ghiringhelli, and N. B. Brookes

Graded, parabolic W/B_4C multilayer mirror as polarizer

underdoped $YBa_2Cu_3O_{6.6}$

Energy Resolution: ~200 meV



Interlude: Flat Crystal Optics

- Striving for greatly improved energy resolution ($\approx<$ 5meV)
- Flat crystal optics:
  - Additional variable: crystal asymmetry, no figure errors
  - Opportunity for polarization analysis

BUT: **Very little** Solid-Angle Acceptance

Ø25mm Sph. Analyzer at 2m: $\Omega \approx 100\ \mu$srad

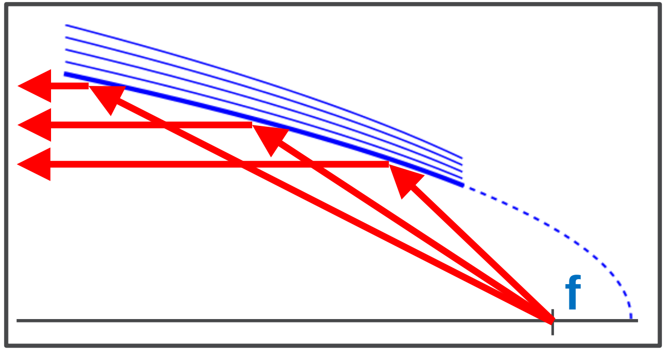
Flat X-tal 20 ×100 μrad^2: $\Omega \approx 0.002\ \mu$srad

⇨ **Need Collimator to bridge the gap**

Interlude: Flat Crystal Optics

Honnicke et al., J. Synchr. Rad. **18**, 862 (2011)
Mundboth et al., J. Synchr. Rad. **21**, 16 (2014)

Parabolic, laterally graded multi-layer mirror

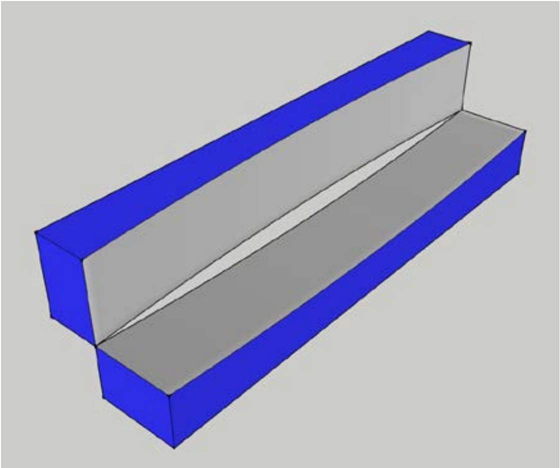


Angular Acceptance: 10×10 $mrad^2$

$\Rightarrow$ W ≈ 100 μsrad

Angular Emittance: 100×100 μrad^2

Manufacturer: Incoatec GmbH



Multi-layer: Ruthenium / Carbon

Substrate: Si(100)

Dimension 150×7×7 mm^3

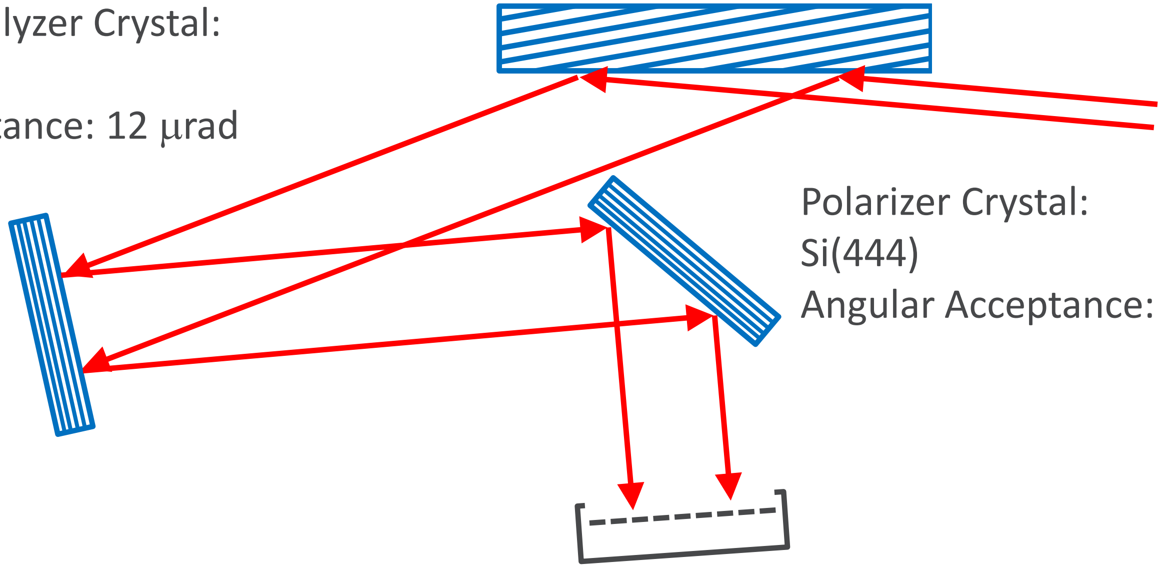
Focal distance: 200 mm

Reflectivity: > 80 %

Flat Crystal Analyzer with Polarizer

Asymmetric Collimator Crystal:
Si(111), b=-0.064
Angular Acceptance: 95 μrad
Angular Emission: 6 μrad

Symmetric Analyzer Crystal:
Quartz(309)
Angular Acceptance: 12 μrad



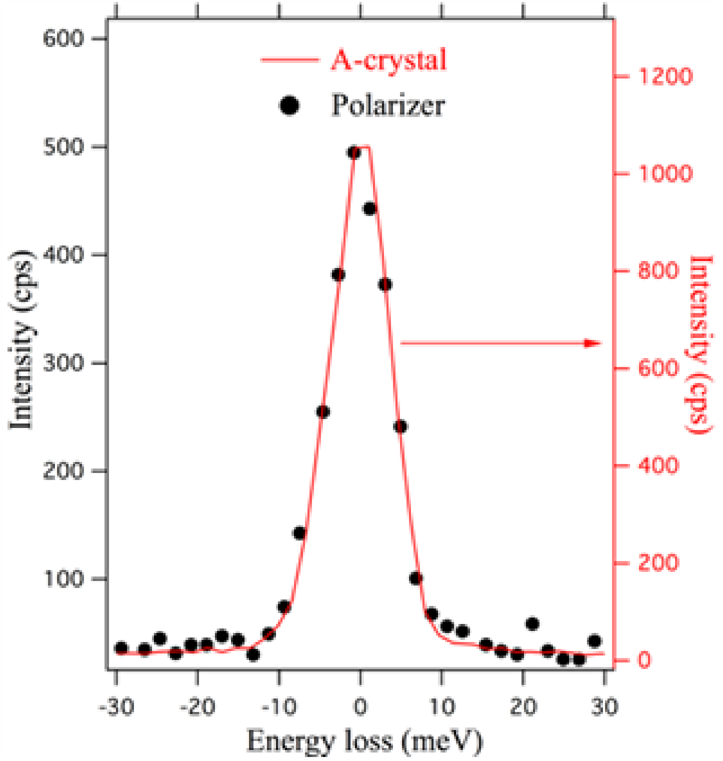
Polarizer Crystal:
Si(444)
Angular Acceptance: 6 μrad

Strip Detector
(Mythen)

Flat Crystal Analyzer with Polarizer

Elastic spectra w/ and w/o polarizer:

- No loss in resolution
- ~50 % throughput
- ~80 % w/ asymmetric polarizer crystal



Polarization Analysis of Scattered Beam

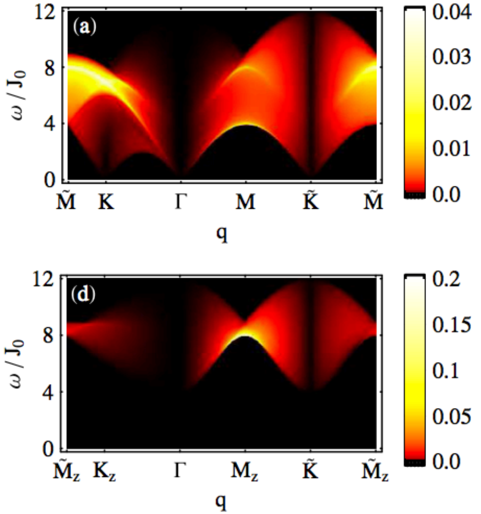
PRL 117, 127203 (2016) PHYSICAL REVIEW LETTERS week ending 16 SEPTEMBER 2016

Resonant Inelastic X-Ray Scattering Response of the Kitaev Honeycomb Model

Gábor B. Halász,[1] Natalia B. Perkins,[2] and Jeroen van den Brink[3,4]
[1]*Kavli Institute for Theoretical Physics, University of California, Santa Barbara, California 93106, USA*
[2]*School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55116, USA*
[3]*IFW Dresden, Helmholtzstrasse 20, 01069 Dresden, Germany*
[4]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
(Received 10 May 2016; published 16 September 2016)

We calculate the resonant inelastic x-ray scattering (RIXS) response of the Kitaev honeycomb model, an exactly solvable quantum-spin-liquid model with fractionalized Majorana and flux excitations. We find that the fundamental RIXS channels, the spin-conserving (SC) and the non-spin-conserving (NSC) ones, do not interfere and give completely different responses. SC RIXS picks up exclusively the Majorana sector with a pronounced momentum dispersion, whereas NSC RIXS also creates immobile fluxes, thereby rendering the response only weakly momentum dependent, as in the spin structure factor measured by inelastic neutron scattering. RIXS can, therefore, pick up the fractionalized excitations of the Kitaev spin liquid separately, making it a sensitive probe to detect spin-liquid character in potential material incarnations of the Kitaev honeycomb model.

DOI: 10.1103/PhysRevLett.117.127203



Probing the elusive fractionalized Majorana excitations
→ Polarization analysis is required to distinguish the SC from the NSC (magnon).

New Opportunities for IXS

- Polarization Analysis
- Imaging (of heterogeneous materials)
- Time-Resol
- Improved E
- Novel In sit
- …

- … for hard x-rays, now possible
- efficiently and without loss of resolution, using
- new insertion devices
- flat crystal optics

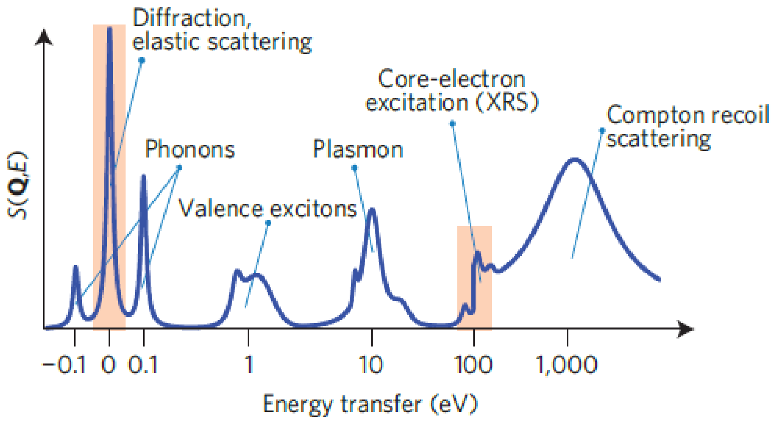
New Opportunities for IXS

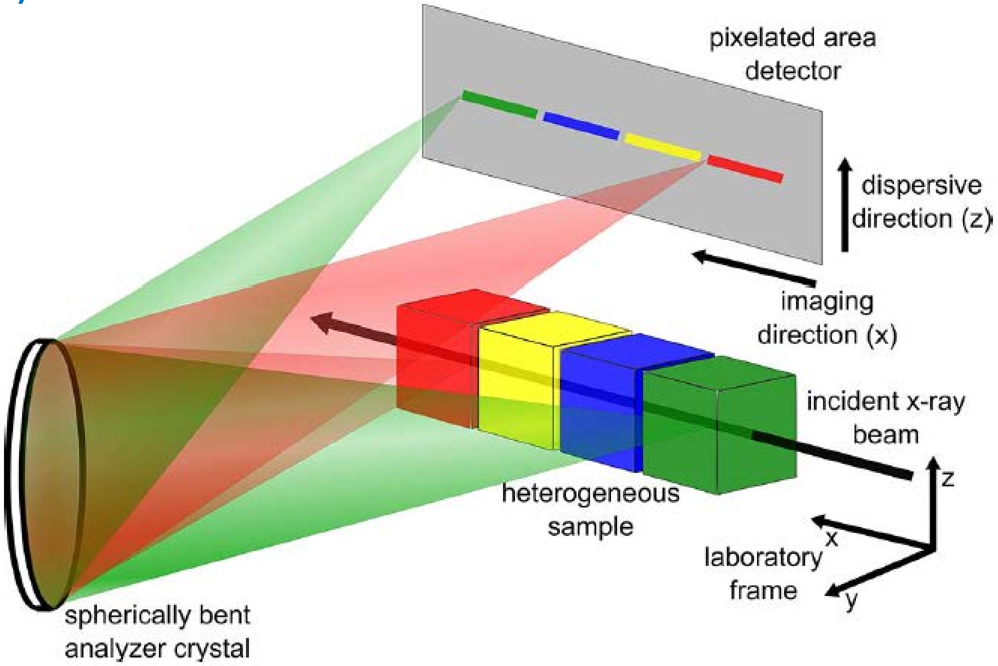
- Polarization Analysis
- Imaging (of heterogeneous materials)
- Time-Resolved Measurements
- Improved Energy Resolution (in Resonant Techniques)
- Novel In situ Sample Environments
- …

Imaging (of heterogeneous materials)

- XRS-based Direct Tomography
- Energy / Spatial Resolution:

  1 to 3 eV / 50 to 150 μm





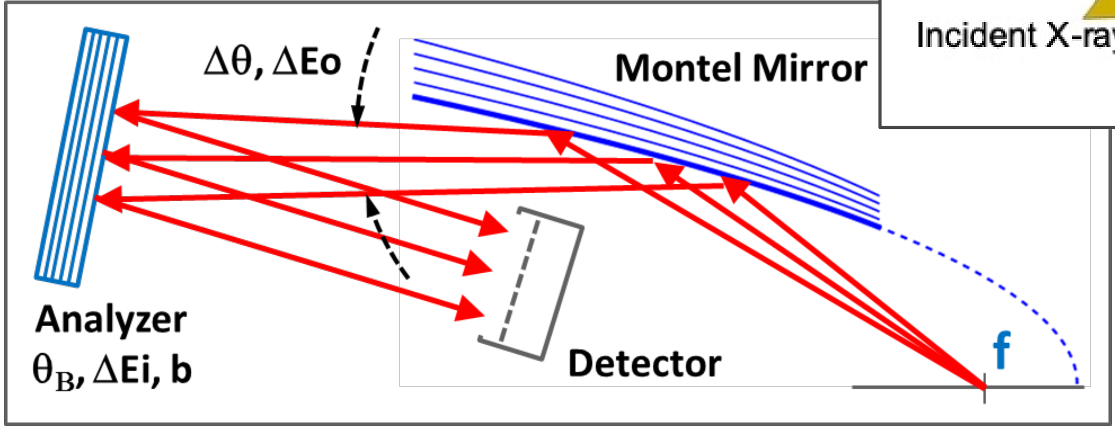
Direct Tomography with Chemical-bond Contrast
Simo Houtari et al., Nature Mat **10**, 489 (2011)
Sahle et al., J. Synchrotron Rad **24**, 476 (2017)

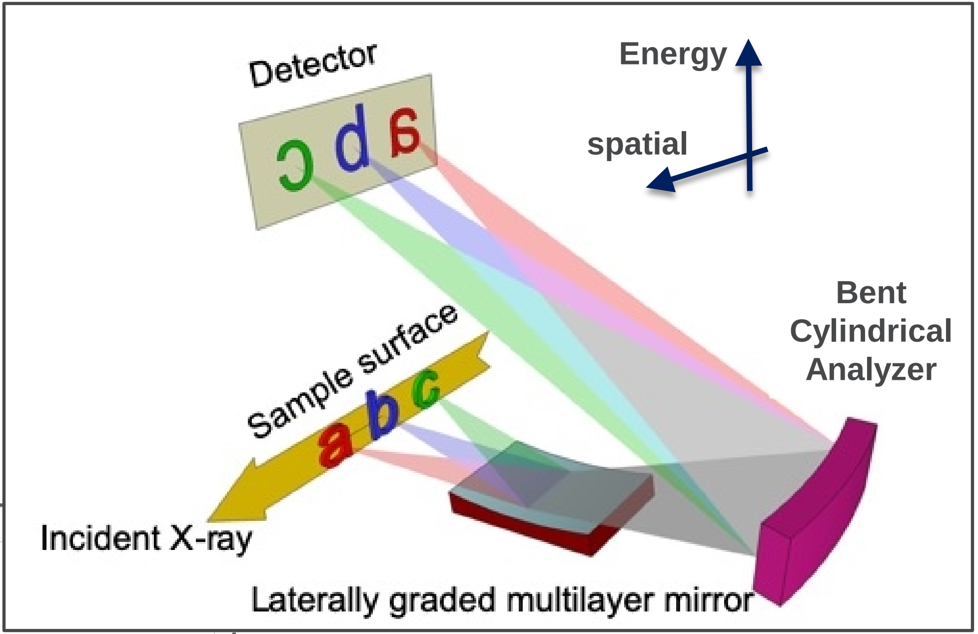
Imaging (of heterogeneous materials)

- RIXS
- Improved Energy Resolution using multi-layer collimator

$$\Delta E \approx \sqrt{\Delta E_o^2 + \Delta E_i^2 + (E_o \cot(\theta_B)\,\Delta\theta)^2}$$

E_o=11.215 keV, Si(844): ΔE≈125 meV



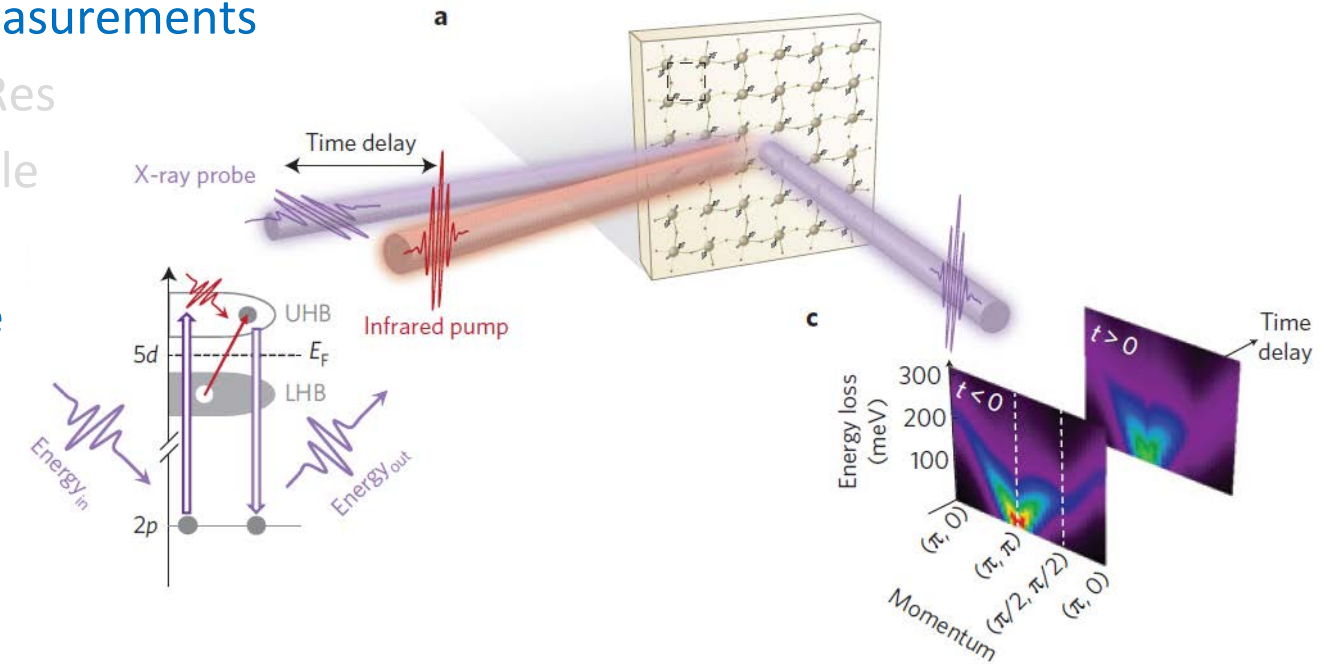


- Mapping electronic / magnetic excitations
- Batteries, Catalysts

New Opportunities for IXS

- Polarization Analysis
- Imaging (of heterogeneous materials)
- Time-Resolved Measurements
- Improved Energy Res
- Novel In situ Sample

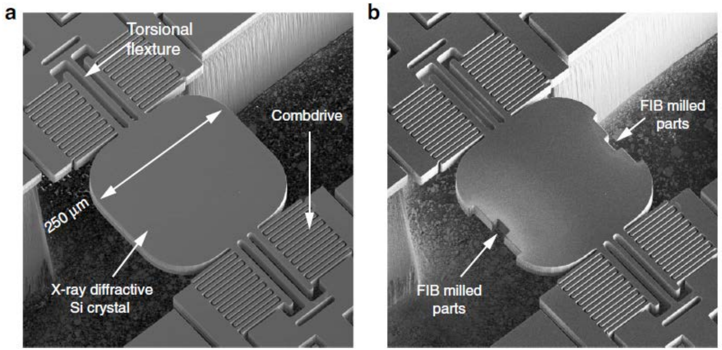
Ultrafast energy- and momentum-resolved dynamics of magnetic correlations in the photo-doped Mott insulator Sr_2IrO_4
Dean et al., Nature Mat **15**, 601 (2016)



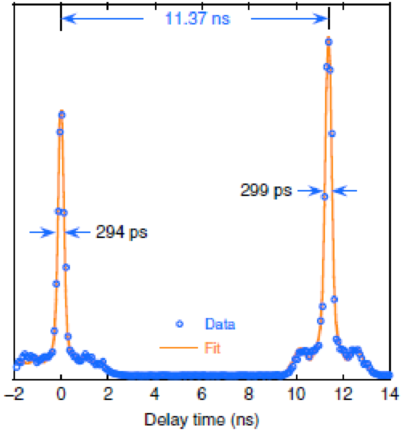
First RIXS study to probe the dynamic response of magnetic and orbital excitations

Time-Resolved Measurements

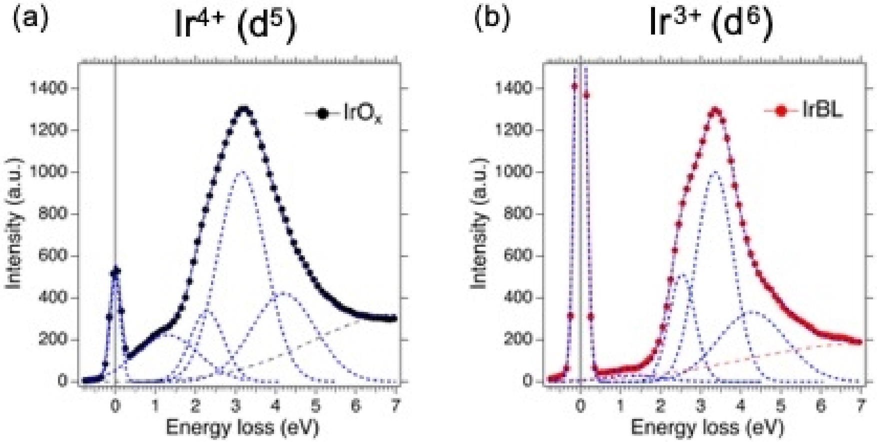
- Exploit unique time structure at APS (152 ns)
- MEMS (micro-electro-mechanical-system)



Chen et al., Nature Comm **10:1158** (2019)



Study the electron-hole recombination dynamics response of two Iridium oxide catalysts, IrO_x and IrBL, by time- and energy resolved RIXS imaging

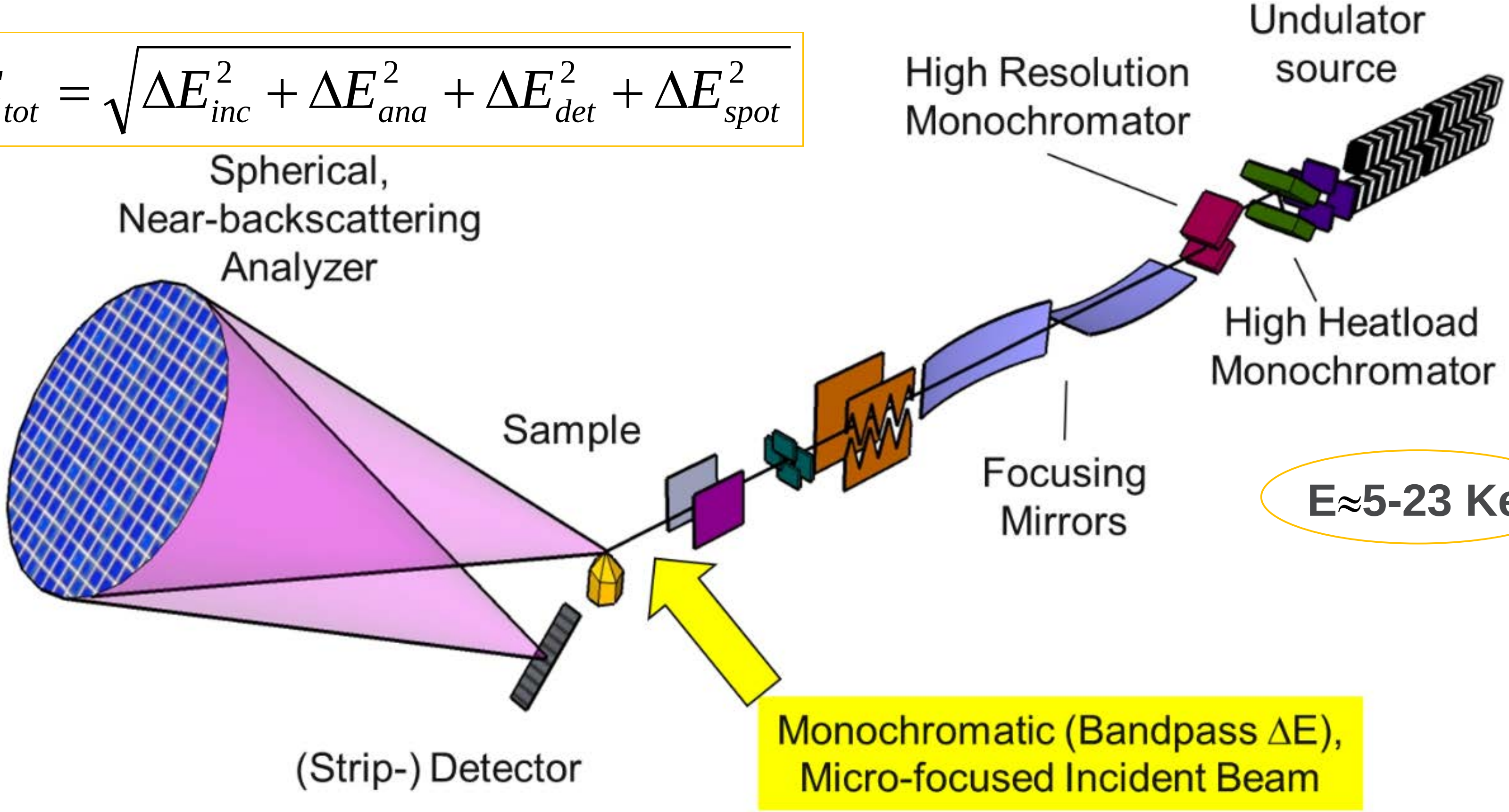


New Opportunities for IXS

- Polarization Analysis
- Imaging (of heterogeneous materials)
- Time-Resolved Measurements
- Improved Energy Resolution (in Resonant Techniques)
- Novel In situ Sample Environments
- …

Improved Energy Resolution

$$\Delta E_{tot} = \sqrt{\Delta E_{inc}^2 + \Delta E_{ana}^2 + \Delta E_{det}^2 + \Delta E_{spot}^2}$$



E≈5-23 KeV

Improved Energy Resolution

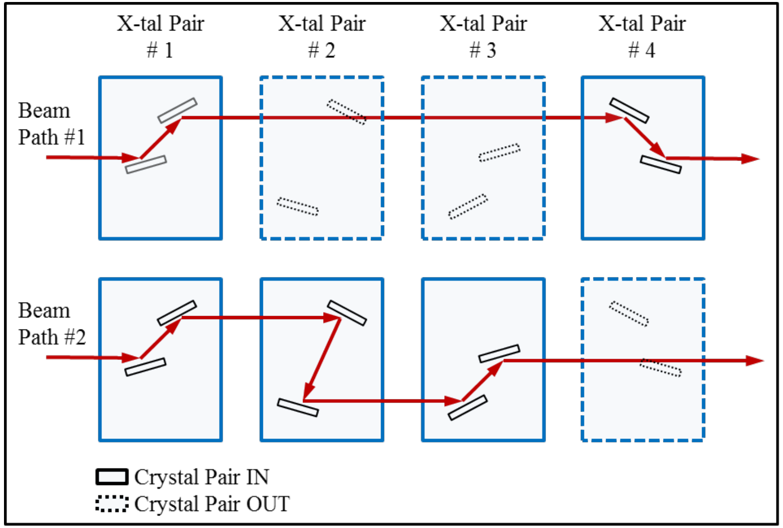
$$\Delta E_{tot} = \sqrt{\Delta E_{inc}^2 + \Delta E_{ana}^2 + \Delta E_{det}^2 + \Delta E_{spot}^2}$$

ΔE_{inc} : Bandpass determined by High-Resolution Monochromator

suitable $\Delta E_{inc} < 5$ meV achievable

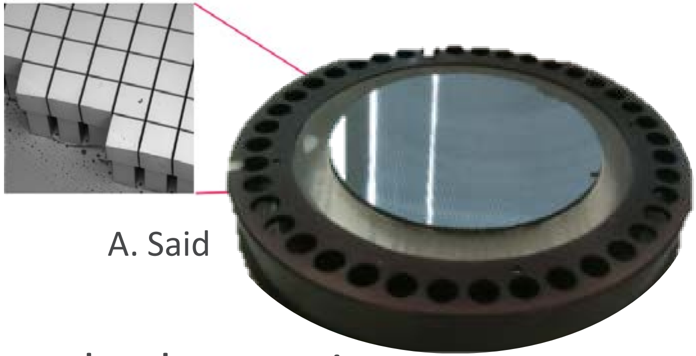
ΔE_{det} : Detector Pitch < 50 μm

ΔE_{spot} : Micro-focusing < 10 μm



T. Toellner

Improved Energy Resolution

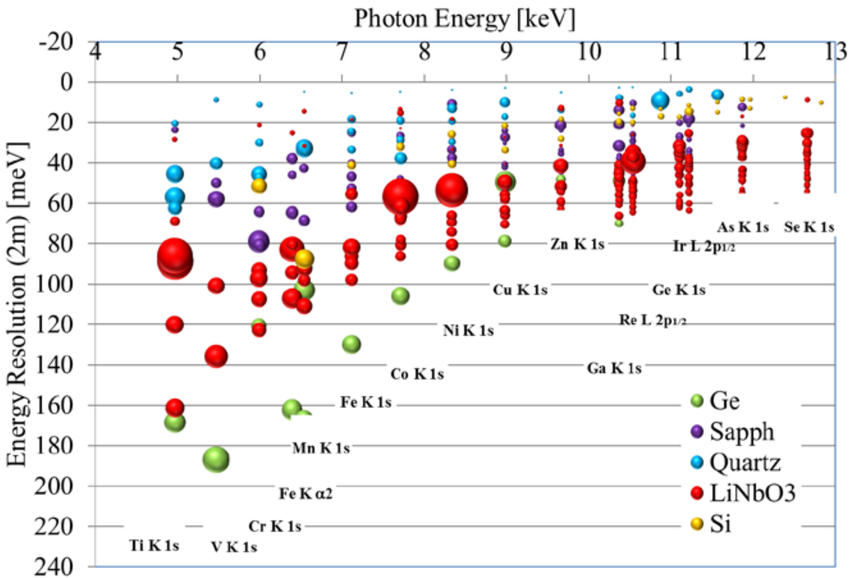


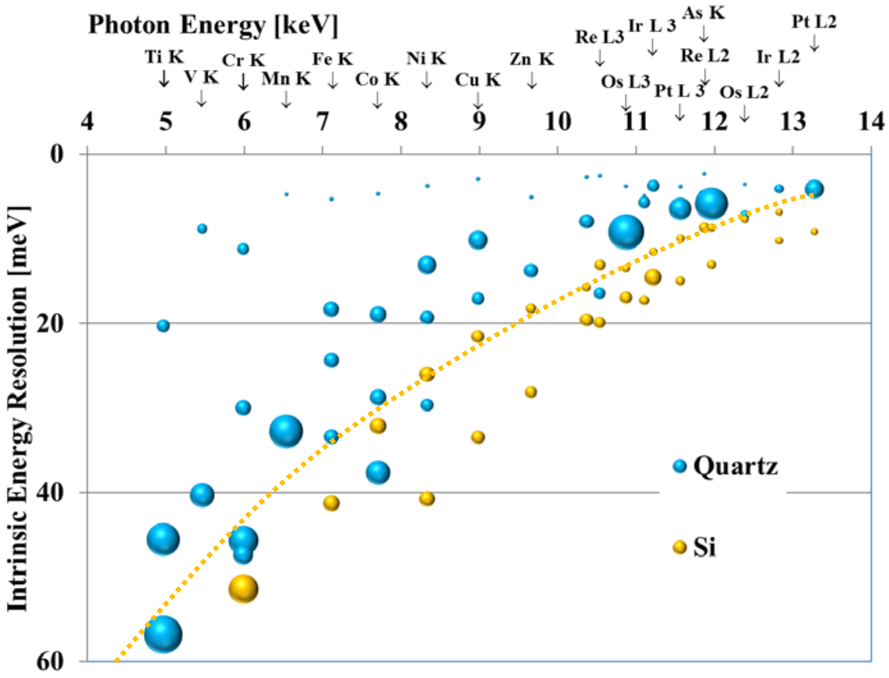
A. Said

ΔE_{ana} : **Diced, spherical analyzers**

- large solid angle coverage
- energy resolution: **$\Delta E = E \cot \theta_B \Delta\theta$** => need near-backscattering
- resonant character of RIXS => need to find suitable material/reflection for E
- material: typically Si or Ge (large, perfect crystals)
- but: lower symmetry materials offer more choices of reflections
- Quartz, Sapphire, Lithium Niobate, … available as near perfect crystals
- compiled "Analyzer Atlas" to aid choice of analyzer
- recently, using Q(309) => ΔE_{tot} = 10.5 meV **New Record !**

Improved Energy Resolution

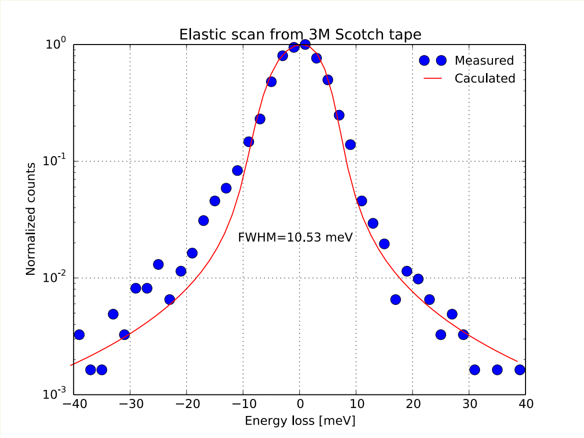


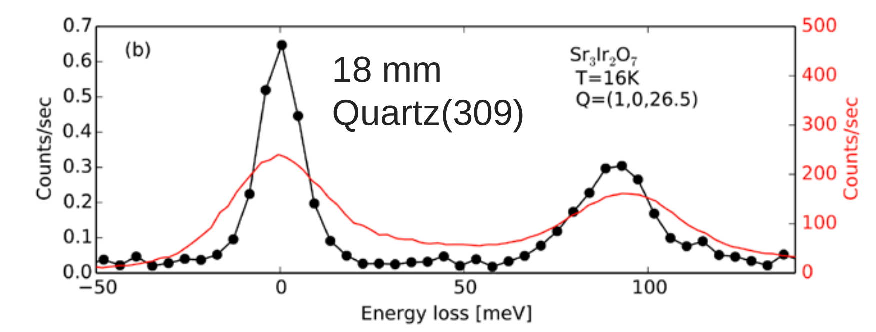


Spherical Quartz Analyzers

- A prototype spherical quartz (309) analyzer has been made and tested at 27-ID at the APS.
- A record energy resolution was achieved (10.5 meV)
- Joel Bertinshaw talk on Sr_2IrO_4 / $Sr_3Ir_2O_7$ super lattices .

Mask,
D=18mm



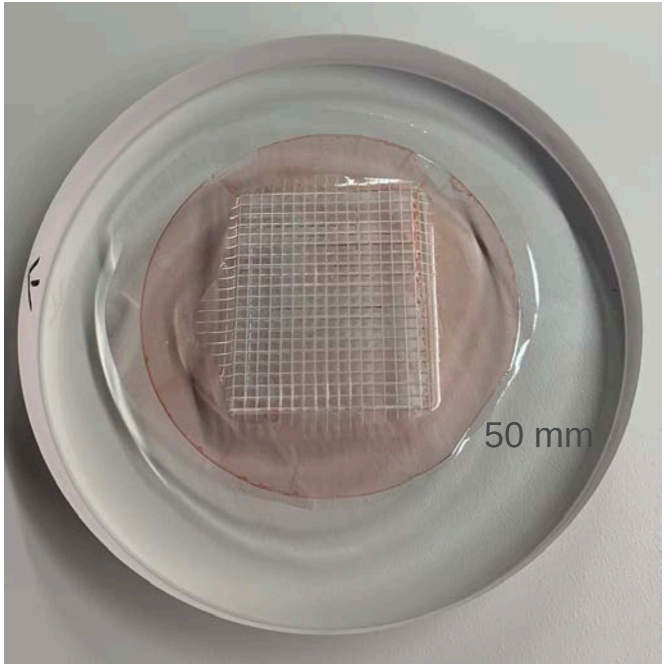


100 mm
Si(844)

Issues:
-Small area (lower efficiency)
-We saw degradation of the glue used to hold the quartz pixels.

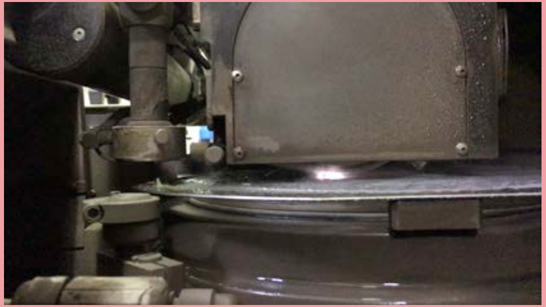
J. Synchrotron Rad. (2018). **25**, 373-377

Spherical Quartz Analyzers

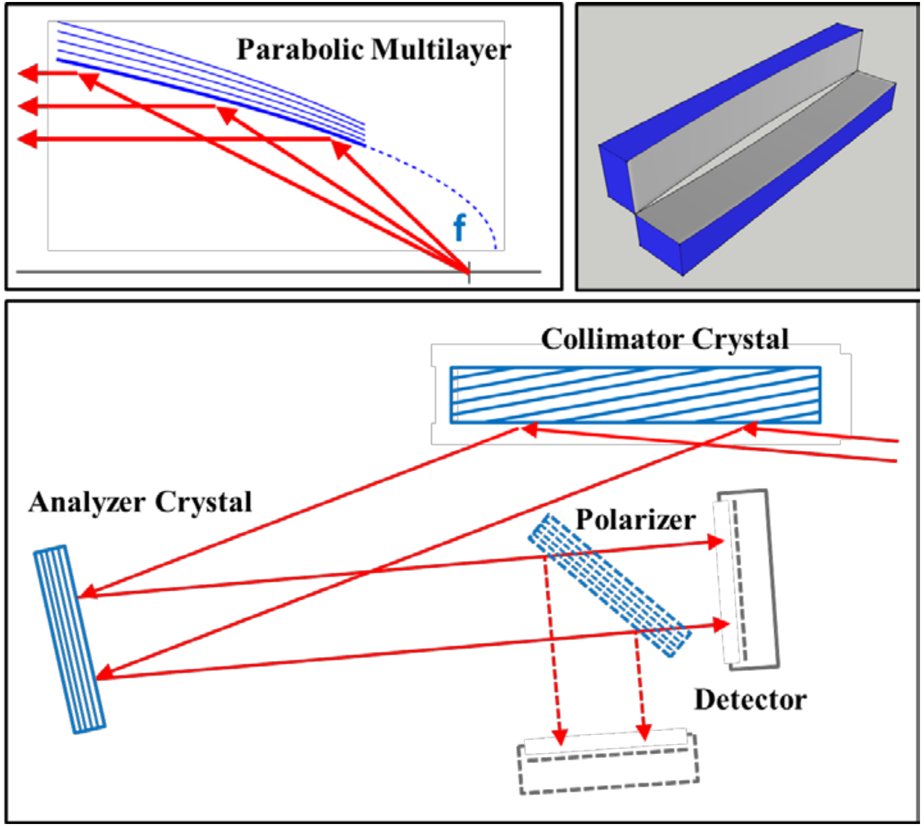


Current Challenge
Finding a glue or other bonding method which can survive more than 10 hours of HF etching and keep its integrity over time .

Overcame Challenge
Dicing (cracking during dicing)

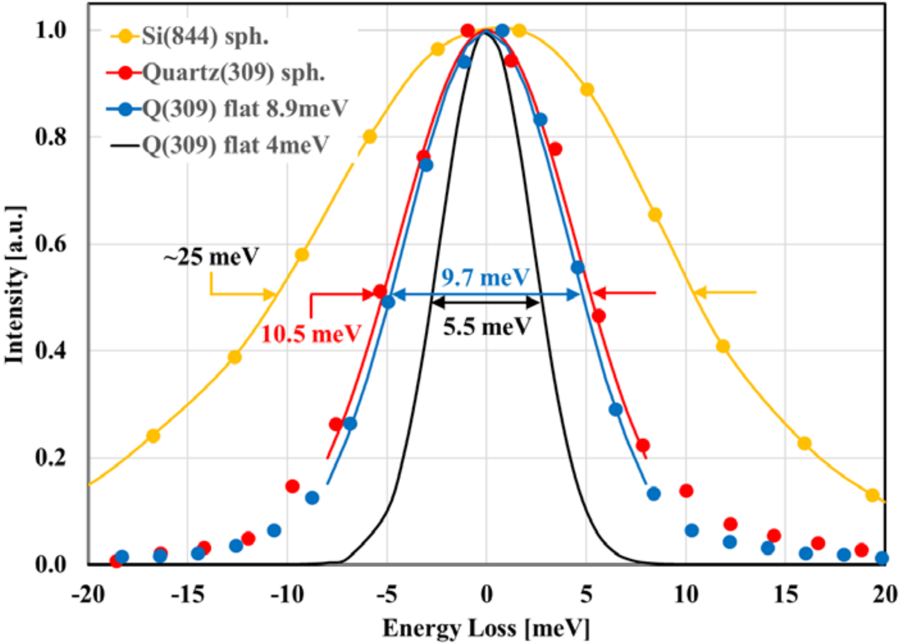


Improved Energy Resolution



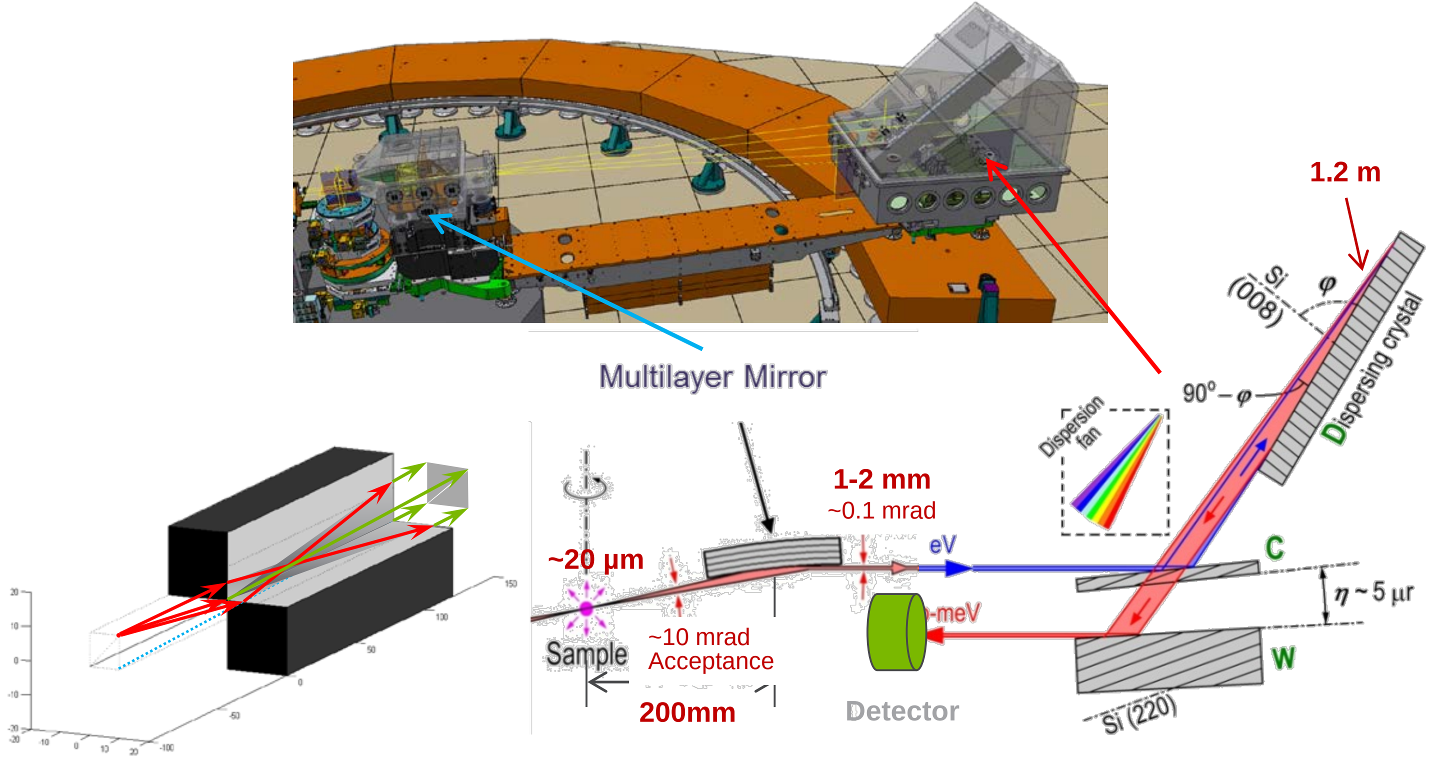
Ang. Acceptance: 10×10 mrad^2 ≈ 100μsrad

Ang. Emittance: 100×100 μrad^2



MONTEL-CDW ANALYZER (FROM: YONG CAI)

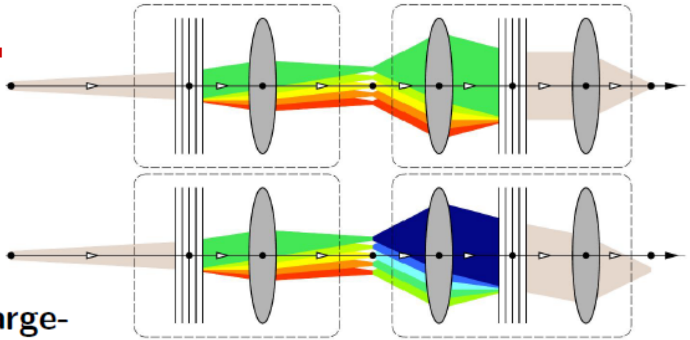
10-ID @ NSLS II



X-ray Echo
Yu. Shvyd'ko

Summary

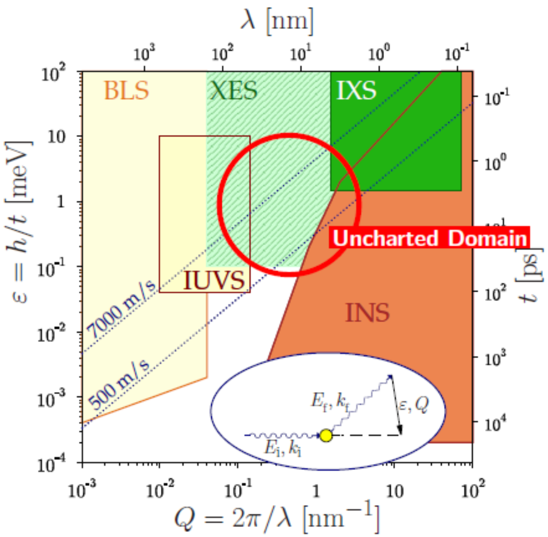
- X-ray echo spectroscopy relies on imaging IXS spectra and does not require x-ray monochromatization, ensuring strong signals along with a very high spectral resolution.



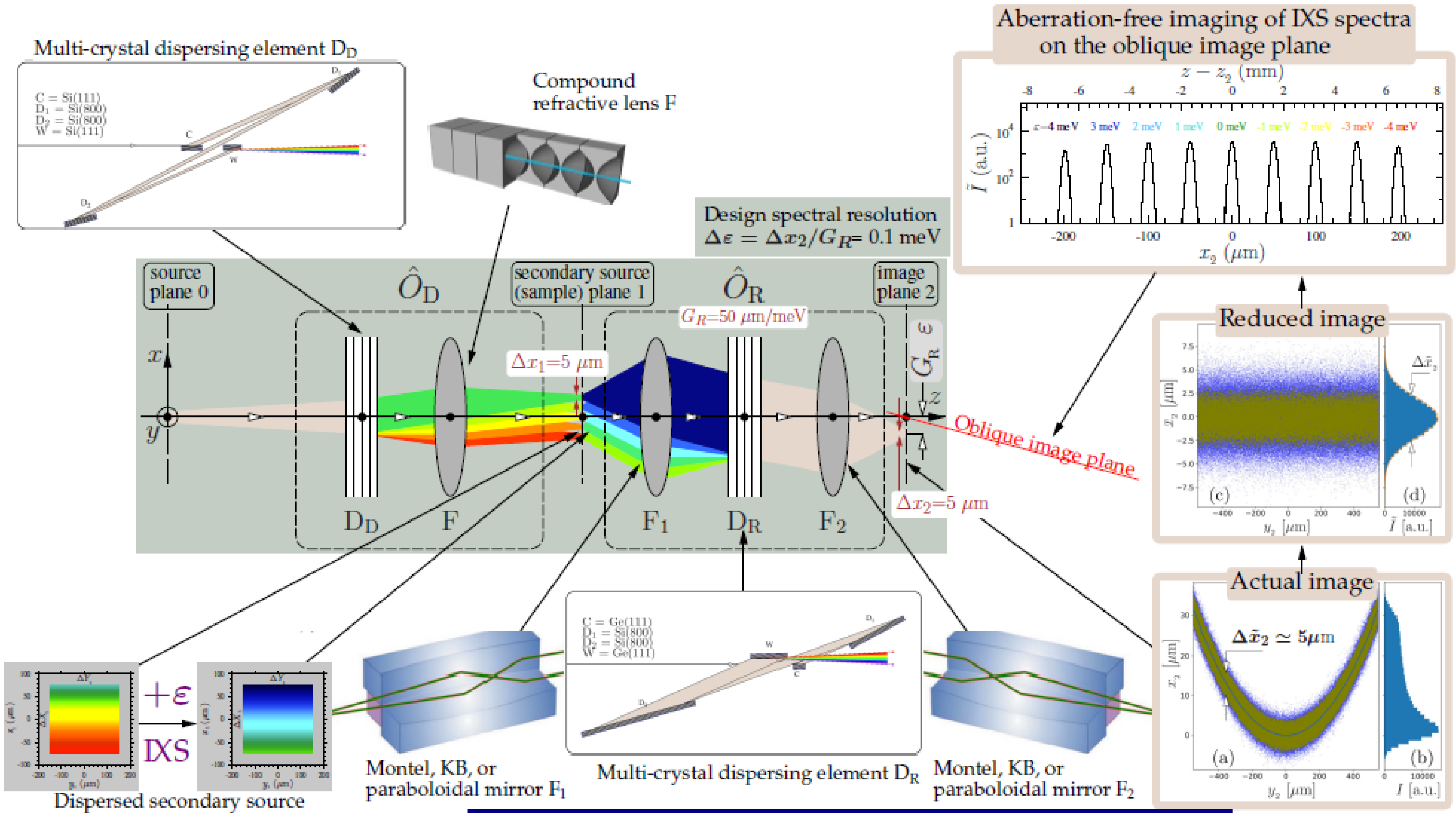
- The hard x-ray optical components (large-dispersion-rate "diffraction gratings", truly imaging optics, etc.) required for the realization of the x-ray echo spectrometers are feasible.

- X-ray echo spectrometers will either enable up to $\simeq$ 1000–fold reduction in measurement time for experiments at presently available $\simeq$1 meV/1 nm^{-1} resolution, or make practical experiments with a $\simeq 0.1$ meV/0.1 nm^{-1} resolution.

- X-ray echo spectrometers (XES) will bridge the gap between the high- and low-frequency inelastic probes and enter the uncharted domain.



X-ray Echo
Yu. Shvyd'ko



Sanchez del Rio, Shvyd'ko *Phys. Rev. A* **99** *(2019) 053839*

Improved Energy Resolution

- Polarization Analysis
- Imaging (of heterogeneous materials)
- Time-Resol
- Improved E
- Novel In sit
- …

- Spherical analyzers: ~10 meV might be the limit due to strain and figure errors
- Flat crystals: everything's possible, but

  flux will become the limit

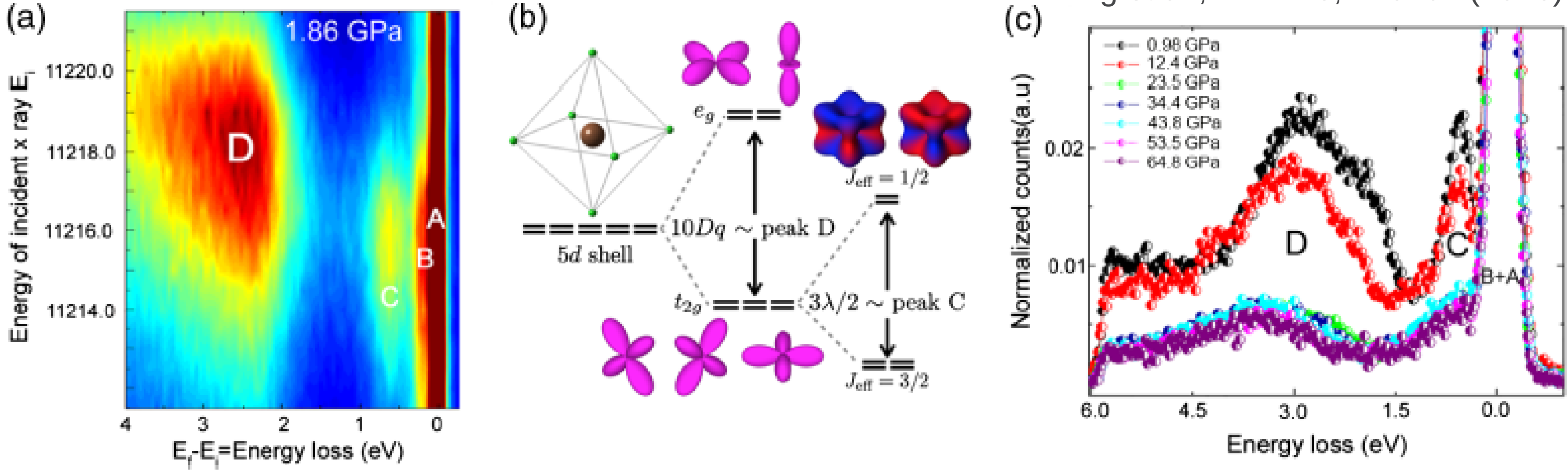
  complexity, stability, ease-of-use will be the issues

New Opportunities for IXS

- Polarization Analysis
- Imaging (of heterogeneous materials)
- Time-Resolved Measurements
- Improved Energy Resolution (in Resonant Techniques)
- Meaningful In situ Sample Environments
  - High-Pressure
  - Magnetic Fields
  - Uniaxial Strain

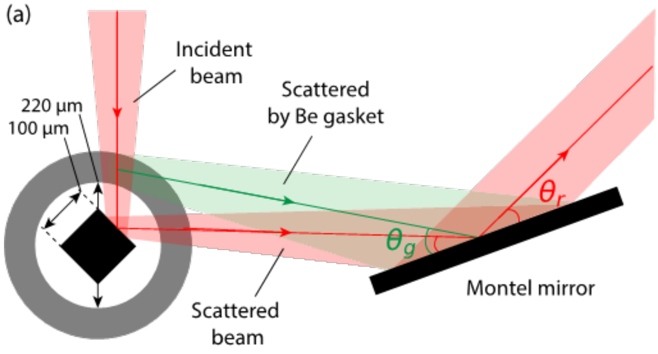
High Pressure

Pressure-Induced Confined Metal from the Mott Insulator $Sr_3Ir_2O_7$
Ding et al., PRL**116**, 216402 (2016)



- Confined metal at 59.5 GPa: metallicity in ab-Plane, insulating along c axis
- No collapse of spin-orbit coupling, rather: first-order structural change
- Intricate interplay between structural and electronic properties in $Sr_3Ir_2O_7$

High Pressure



Post sample collimating resonant inelastic x-ray scattering spectrometers for studying low-energy excitation spectrum under high pressure
Jin-Kwang Kim et al., in preparation

Field of view at focal point of Montel mirror is small enough to see sample but discriminate scattering from surrounding environment

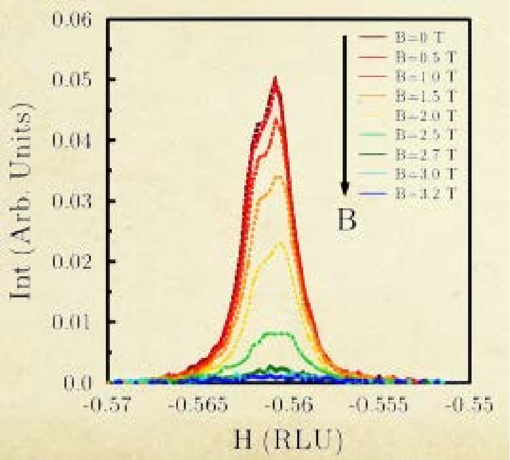
New Opportunities for IXS

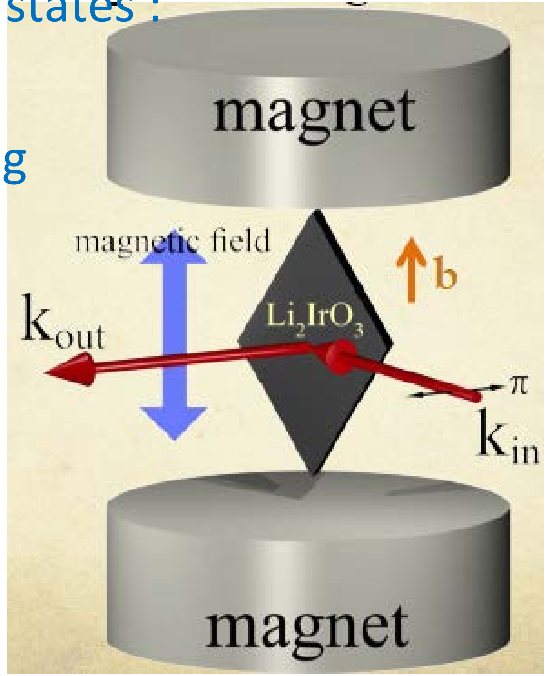
- Polarization Analysis
- Imaging (of heterogeneous materials)
- Time-Resolved Measurements
- Improved Energy Resolution (in Resonant Techniques)
- Meaningful In situ Sample Environments
  - High-Pressure
  - Magnetic Fields
  - Uniaxial Strain

Magnetic Fields

From: Alejandro Ruiz, Alex Frañó, et al., UCSD

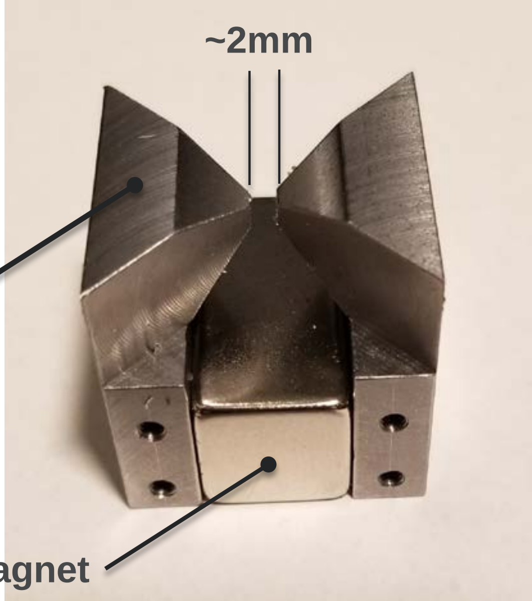
- Unconventional magnetism in 5d materials with strong SOC
- Honeycomb-Li_2IrO_3 promising Kitaev material -> QSL ground state (?)
- Ext. magnetic field -> degeneracy of magnetic ground states : incommensurate spiral, commensurate zig-zag phase
- Dispersing magnon identified for both spiral and zigzag
- First results with B≠0 (≤ 2T): softening of zigzag, hardening of spiral

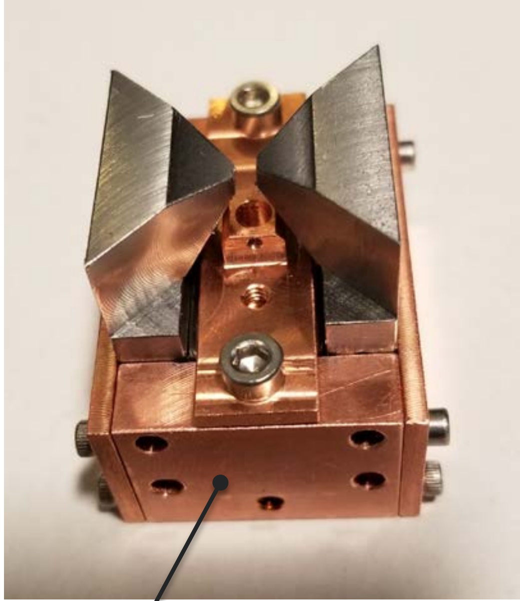




Magnetic Fields

- Small magnet assemblies for use in closed-cycle cryostats
- 1.5 … 2 … 3 T(?)





Magnetic Fields

- Pulsed, DC magnets on 6-ID @ APS
- Trapped-field magnets

  (Z. Islam, APS)

New Opportunities for IXS

- Polarization Analysis
- Imaging (of heterogeneous materials)
- Time-Resolved Measurements
- Improved Energy Resolution (in Resonant Techniques)
- Meaningful In situ Sample Environments
  - High-Pressure
  - Magnetic Fields
  - Uniaxial Strain

Uniaxial Strain

Uniaxial pressure control of competing orders in a high-temperature superconductor

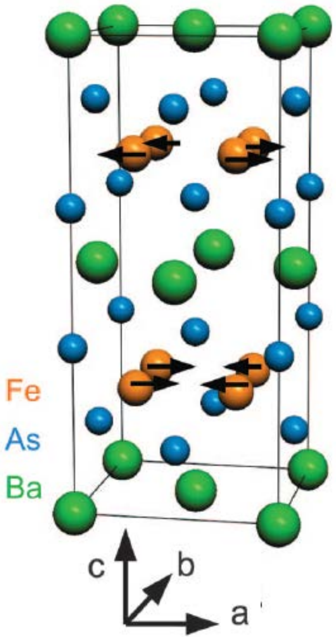
H.-H. Kim et al., Science 362 1040 (2018)

- Ground states of TMOs (High Tc, CDW, …) can be tuned by doping, external fields
- Tuning might introduce disorder
- Application of strain can distinguish between competing orders

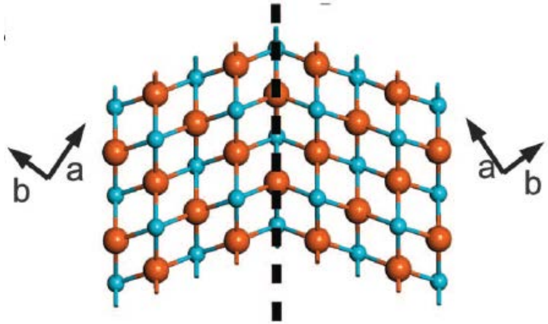
In-Plane Resistivity Anisotropy in an Underdoped Iron Arsenide Superconductor

J.-H. Chu et al., Science 329 824 (2010)

- Application of strain can remove twinning

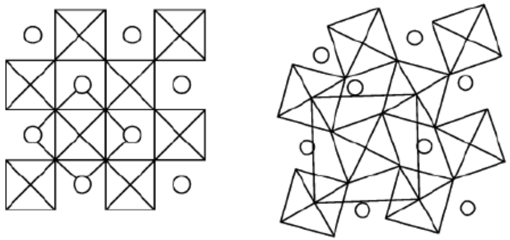


$BaFe_2As_2$



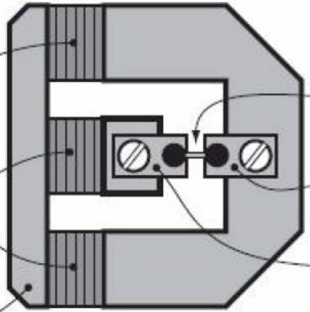
Uniaxial Strain

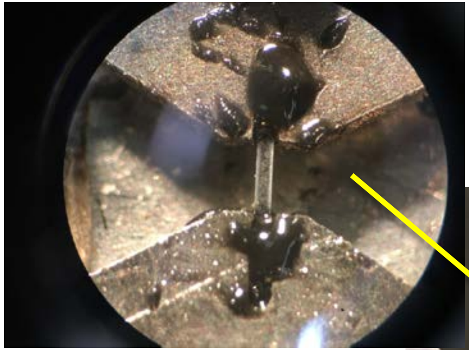
- W. Jin et al.: RIXS in Sr_2IrO_4
- Suppression of structural phase transition in STO



(a) (b)

High T/ Low T





from: Wentao Jin, U Toronto

Conclusions

- IXS has come a long way as a practical, efficient probe of elementary excitations in complex materials
- => Novel materials discovery, characterization
- Efficient polarization analysis possible and will further enhance IXS
- Imaging and time-resolved (ps,ns) measurements at Synchrotrons possible
- As probe of magnetic excitations, RIXS energy resolution has been greatly improved (~ 10 meV)
- … but needs to improve even further (~< ~~5~~ 1 meV) to be on "equal" footing with Inelastic Neutron Scattering
- Novel flat crystals optics and special spherical analyzers provide path to ultra-high resolution

Conclusions

- New multilayer optics / flat-crystal on the horizon / being implemented
- Meaningful in-situ sample environments

People

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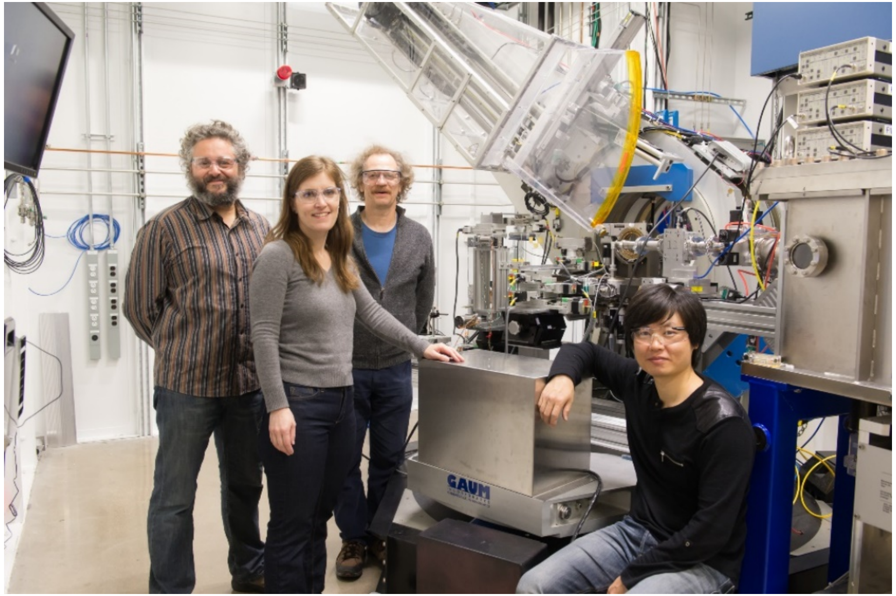

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Ahmet Alatas, XianRong Huang, Jinkwang Kim

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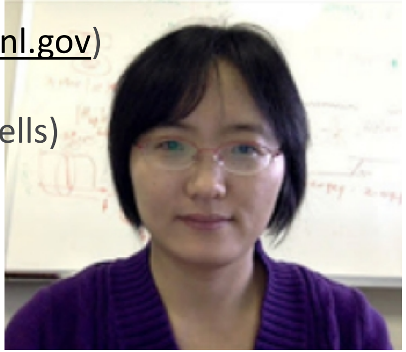
(High Pressure,
Diamond Anvil Cells)



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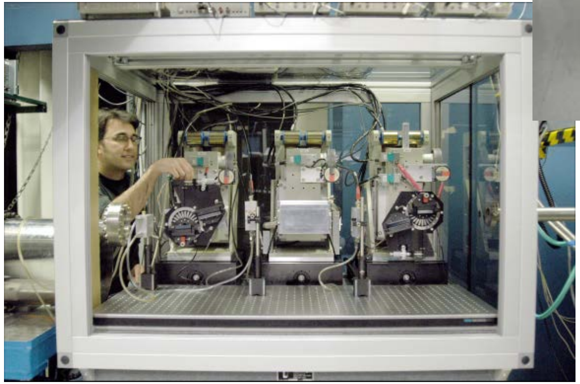
(Spherical Analyzers)



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Rick Krakora
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(Scientific Assc.)

People

XSD-IXN group

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W. Bi
D. Casa
T. Gog
M. Hu
J. Kim
T. Toellner
M. Upton
J. Zhao

XSD-OPT

X. Huang
E. Kasman
J. Qian
B. Shi
M. Wieczorek

CNM

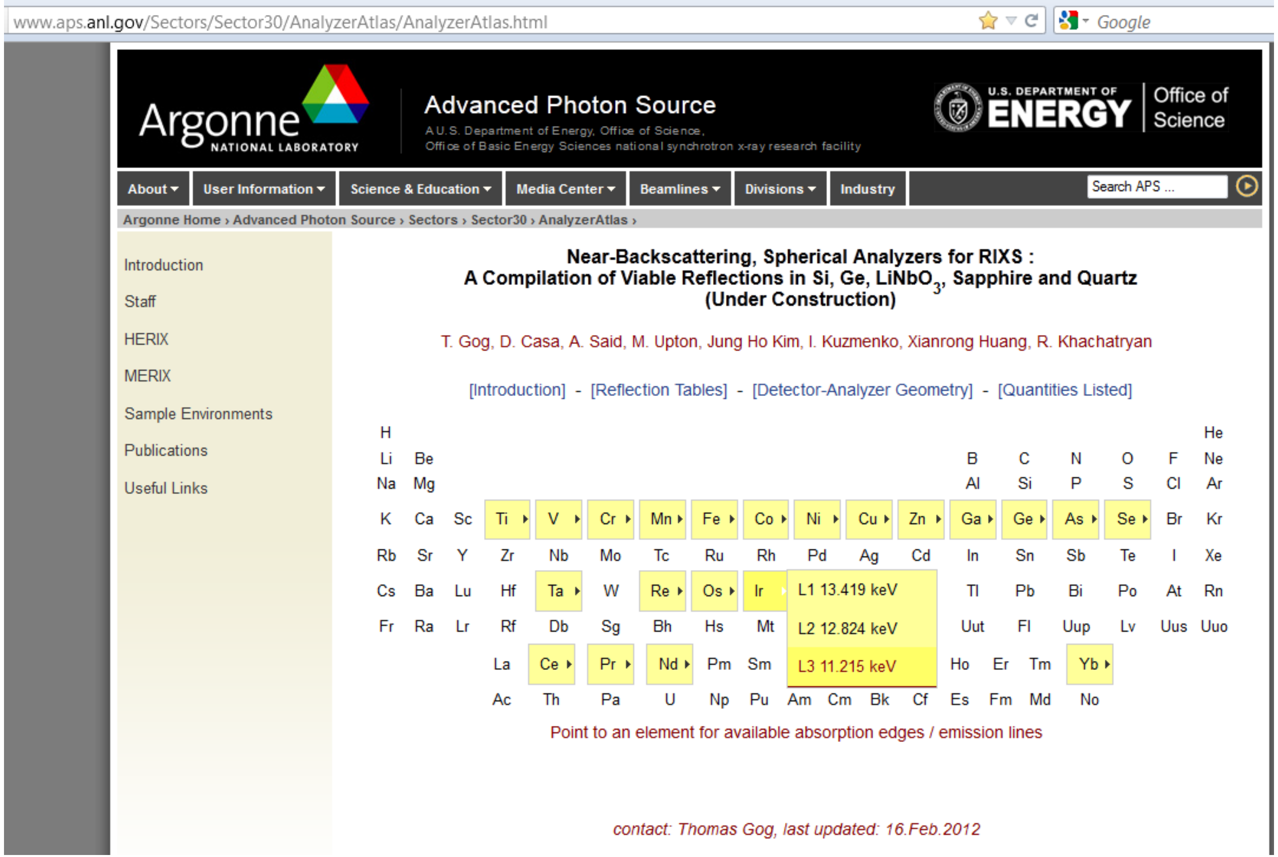
R. Divan
S. Miller

Thank you

Path to Ultra-High Energy Resolution

Compilation of viable Reflections in Si, Ge, Sapphire, Lithium Niobate, Quartz

www.aps.anl.gov/Analyzer-Atlas/Analyzer-Atlas



Path to Ultra-High Energy Resolution

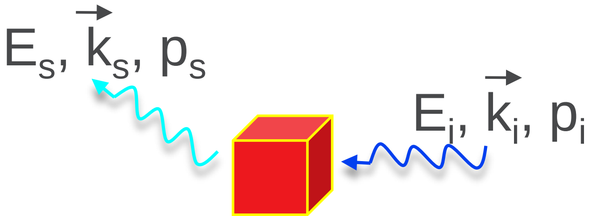
Compilation of viable
Reflections in Si, Ge
Sapphire, Lithium N
Quartz

www.aps.anl.gov/A
-Atlas/Analyzer-Atl

www.aps.anl.gov/Sectors/Sector30/AnalyzerAtlas/AnalyzerAtlas.html

Ei = Cryst	8.9805 Refl (h,k,l)	keV EB [keV]	ΘB [°]	∫IR dΘ [µrad]	Width [µrad]	Ei cotΘ [meV/µrad]	ΔE [meV]	ΔEg 2m, 50µm [meV]	ΔEt 2m, 50µm [meV]
Ge	(3,3,7)	8.969	87.14	80.2	81.5	0.448	36.51	5.6	36.94
Ge	(0,0,8)	8.766	77.46	30.3	28.2	1.998	56.34	24.97	61.62
Si	(2,4,6)	8.542	72.02	13.1	11.5	2.915	33.48	36.44	49.48
Si	(1,3,7)	8.768	77.5	11.8	10.8	1.991	21.56	24.89	32.93
	Equiv. Refl.: (3,5,5)								
LiNbO3	(1,5,-10)	8.941	84.6	58.1	55.8	0.85	47.45	10.62	48.62
	Equiv. Refl.: (5,-6,-10), (6,-5,-10), (-1,6,-10), (-5,-1,-10), (-6,1,-10)								
LiNbO3	(1,-6,10)	8.941	84.6	56.4	55.8	0.85	47.45	10.62	48.62
	Equiv. Refl.: (5,1,10), (6,-1,10), (-1,-5,10), (-5,6,10), (-6,5,10)								
Quartz	(-4,6,4)	8.972	87.44	37.5	34.4	0.401	13.78	5.01	14.66
	Equiv. Refl.: (-4,-2,-4)								
Quartz	(6,-2,4)	8.972	87.44	37.4	34.4	0.401	13.77	5.01	14.65
	Equiv. Refl.: (6,-4,-4), (-2,6,-4), (-2,-4,4)								
Quartz	(4,-6,-4)	8.972	87.44	36.3	34.4	0.401	13.78	5.01	14.66
Quartz	(2,4,-4)	8.972	87.44	36.2	34.4	0.401	13.77	5.01	14.66
	Equiv. Refl.: (2,-6,4), (4,2,4), (-6,2,-4), (-6,4,4)								
Quartz	(6,-2,-4)	8.972	87.44	28.5	26.9	0.401	10.79	5.01	11.89

Introduction

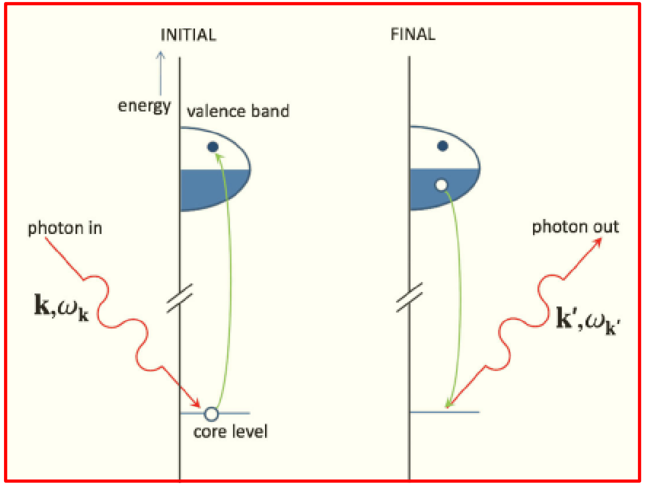


Inelastic Scattering Cross Section

$$\frac{d^2\sigma}{d\Omega d\omega} \propto \left| \langle f \mid H_{int} \mid i \rangle + \sum_{|n\rangle} \frac{\langle f \mid H_{int} \mid n \rangle \langle n \mid H_{int} \mid i \rangle}{E_i - E_n + i\Gamma} \right|^2$$

Non-Resonant (weak)

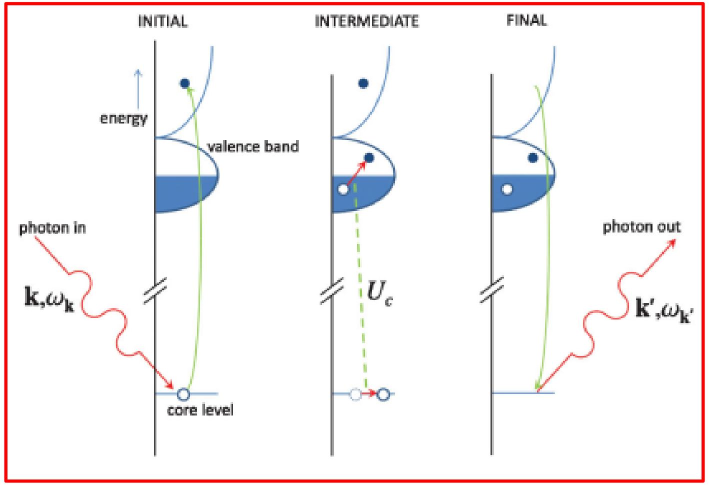
Resonant Enhancement (x 50 … 100)



RIXS Processes

direct

Indirect



Ament, van Veenendaal, Devereaux, Hill, van den Brink, Rev. Mod. Phys. **83**, 705 (2011)

People

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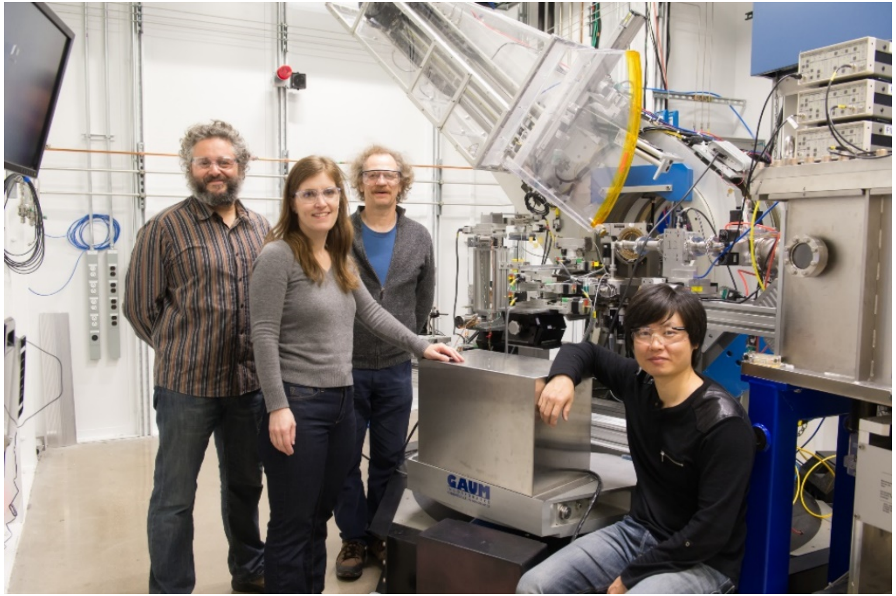

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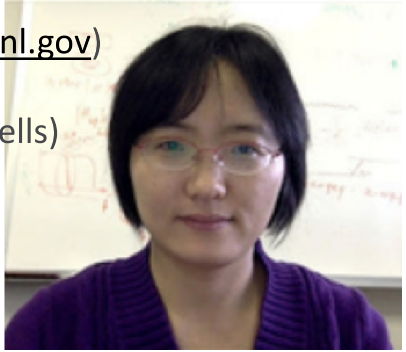

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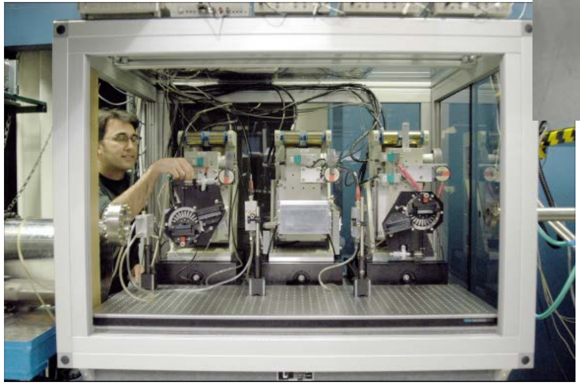

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