Theory and Calculation of X-ray spectra

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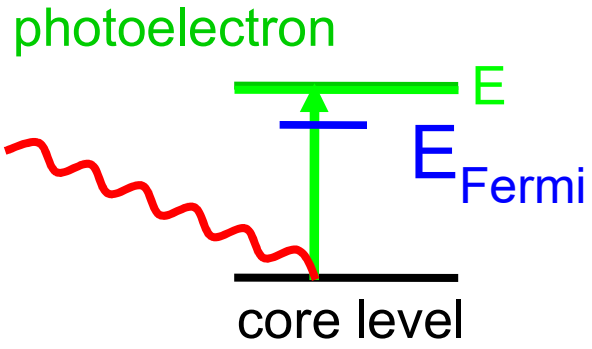
Theoretical Spectroscopy Calculations

- **GOAL**: Next Generation Theory
  for Next Generation X-ray Sources

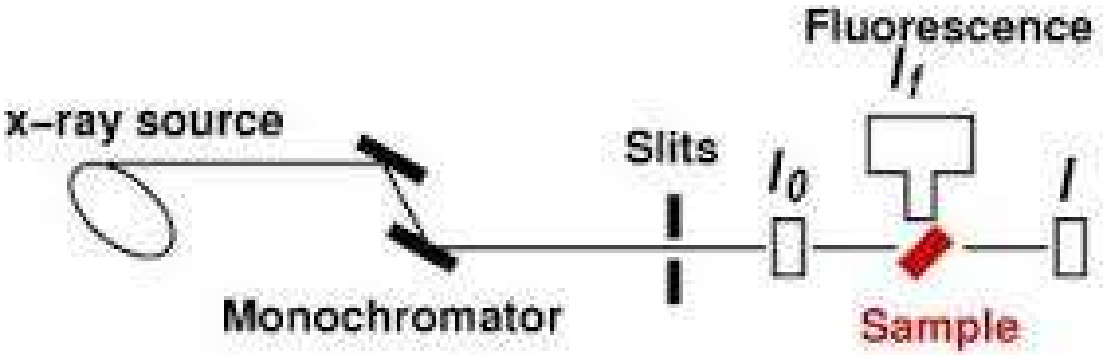
- **TALK**

I Introduction	Current approximations
II State-of-the-art	Ab initio calculations
III Next generation	Multi-electron excitations & strong correlations

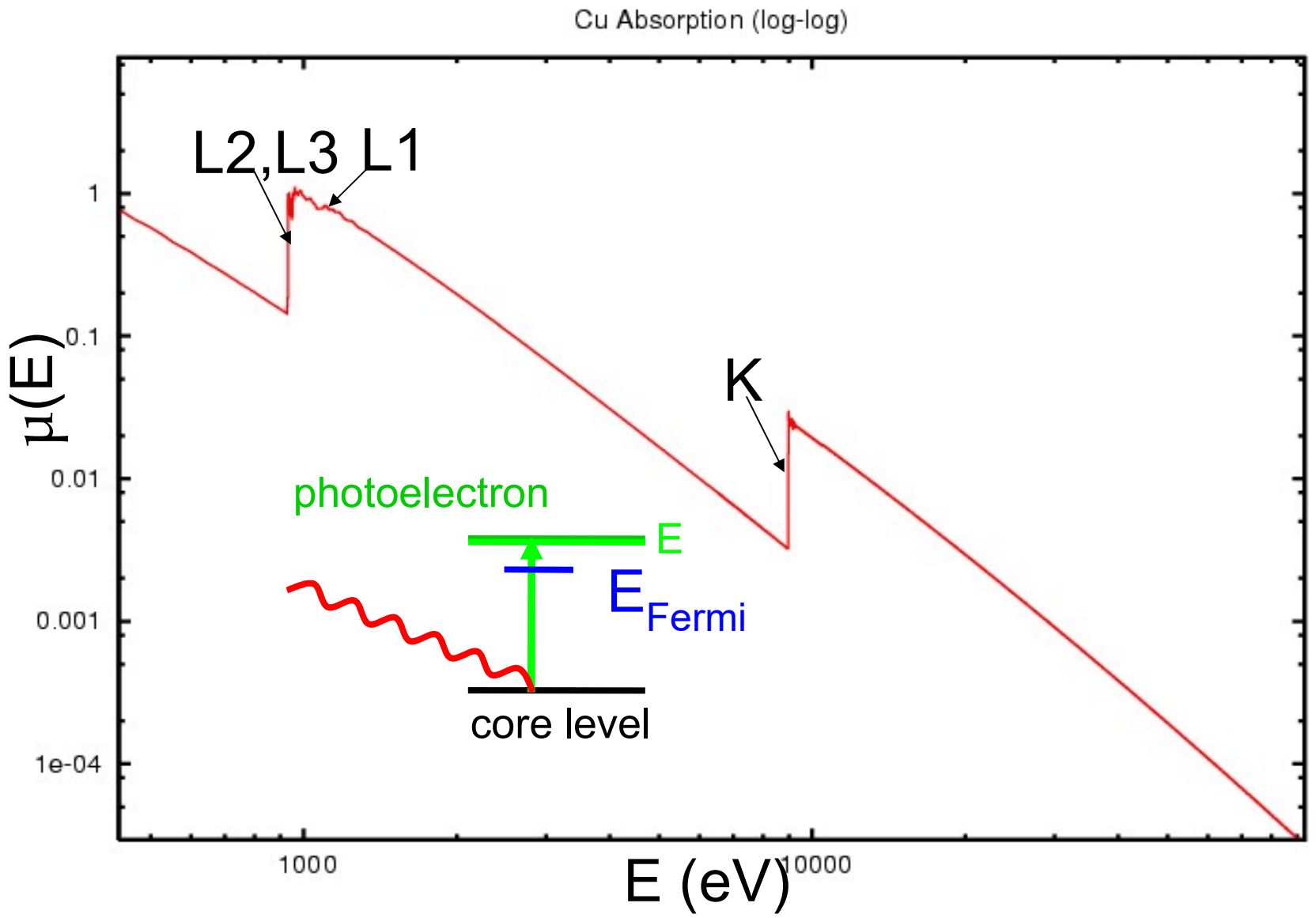
What is x-ray absorption?



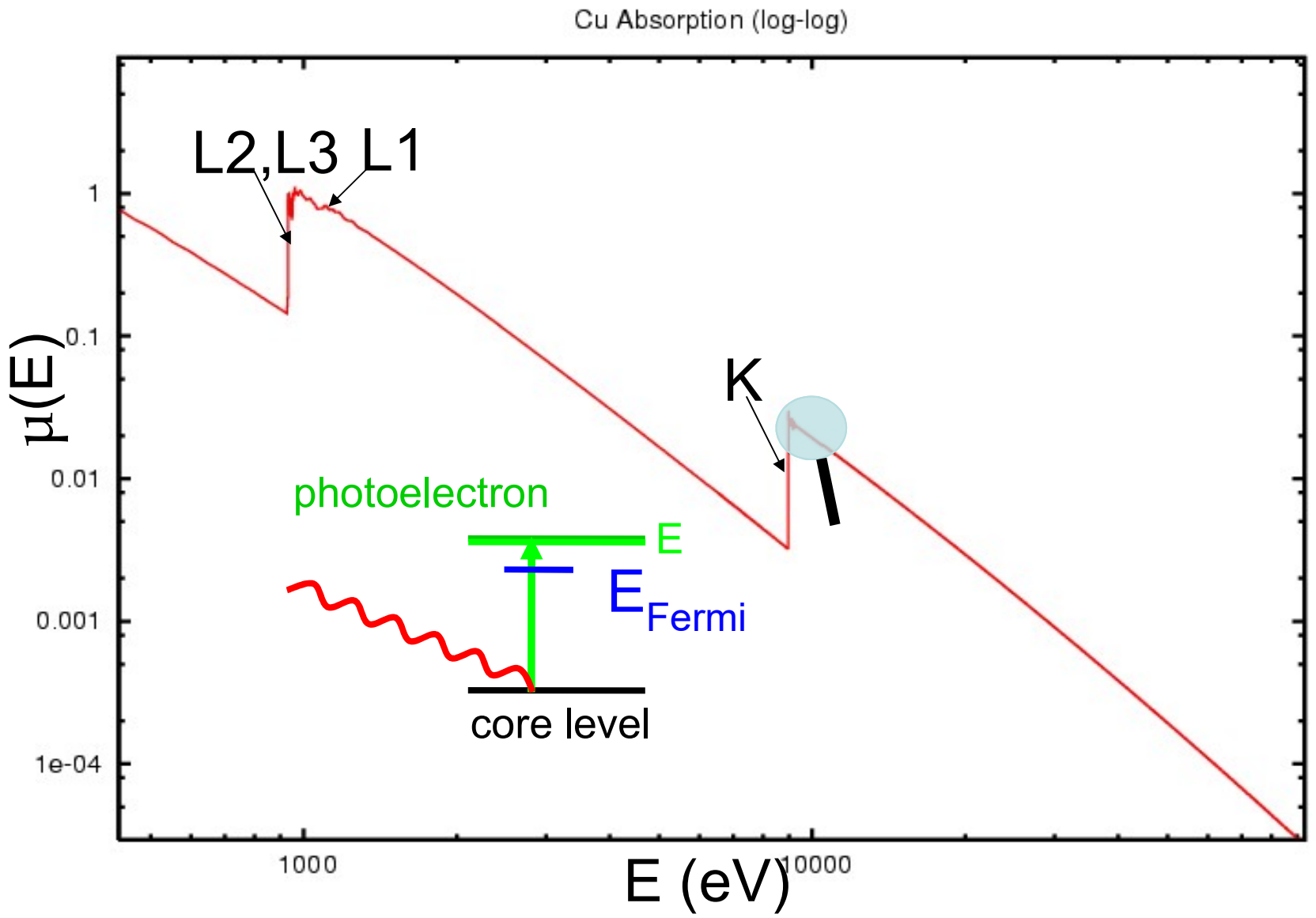
$$I = I_0 e^{-\mu(\omega)x} \Rightarrow \mu(\omega) \propto \mathrm{Log}[I_0 / I]$$



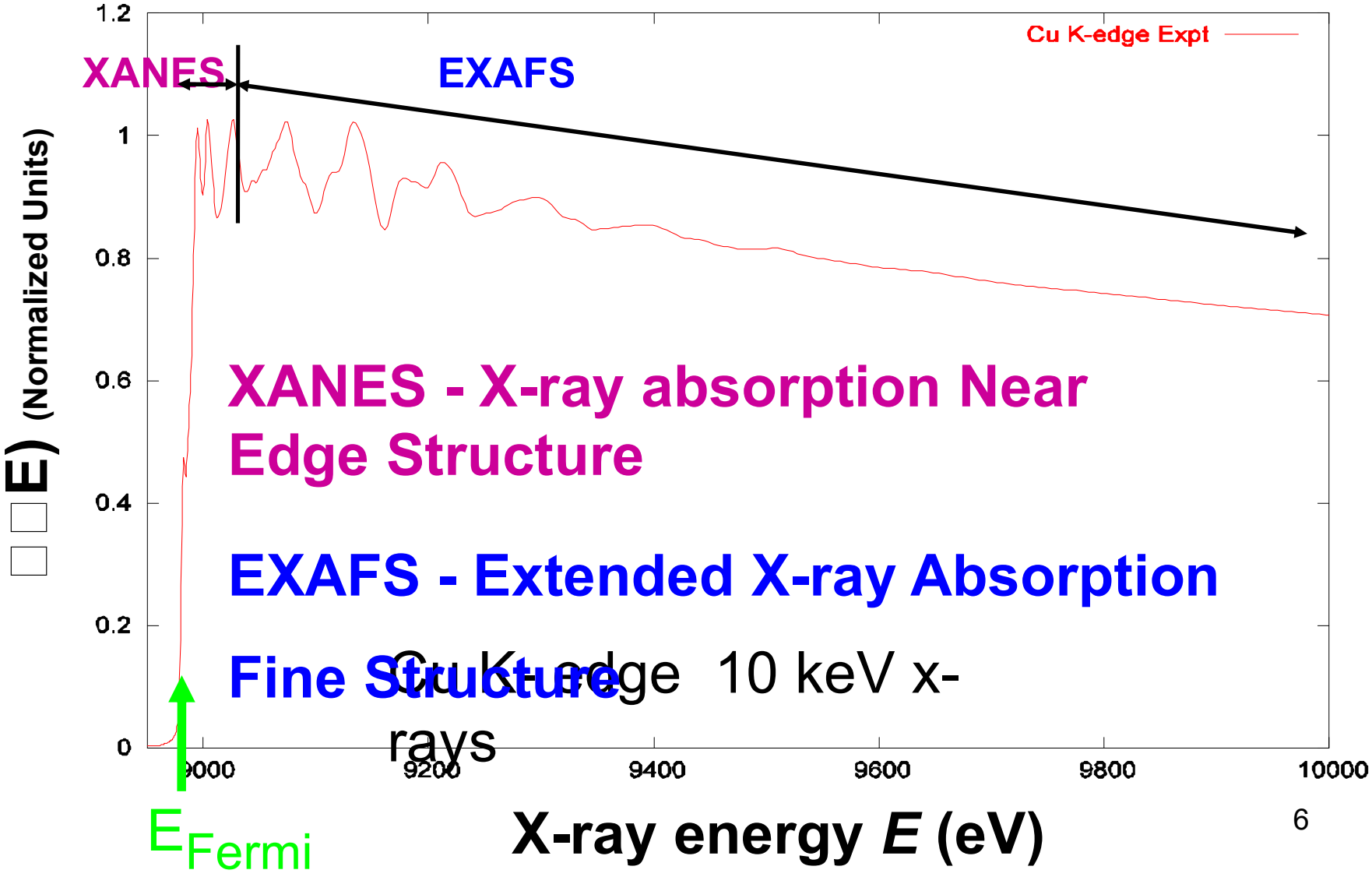
What is x-ray absorption?



What is x-ray absorption?



What is EXAFS?



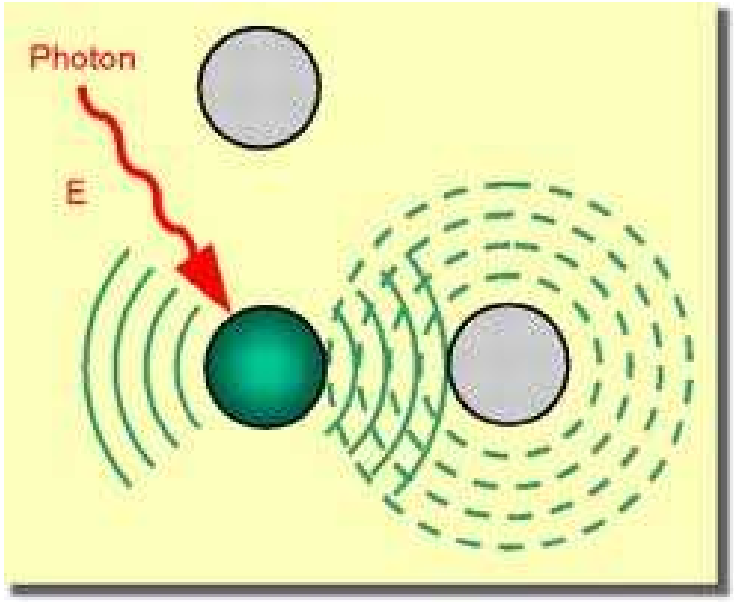
XANES - X-ray absorption Near Edge Structure

EXAFS - Extended X-ray Absorption Fine Structure

Cu K-edge 10 keV x-rays

What is EXAFS?

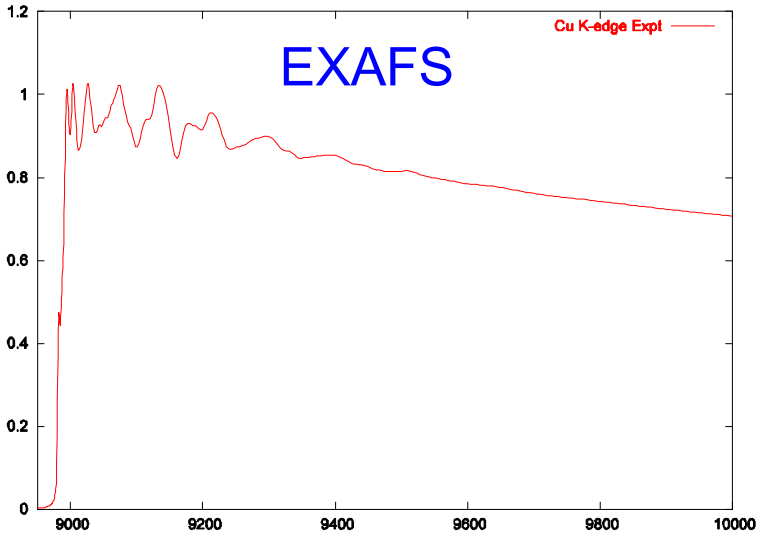
- Quantum interference



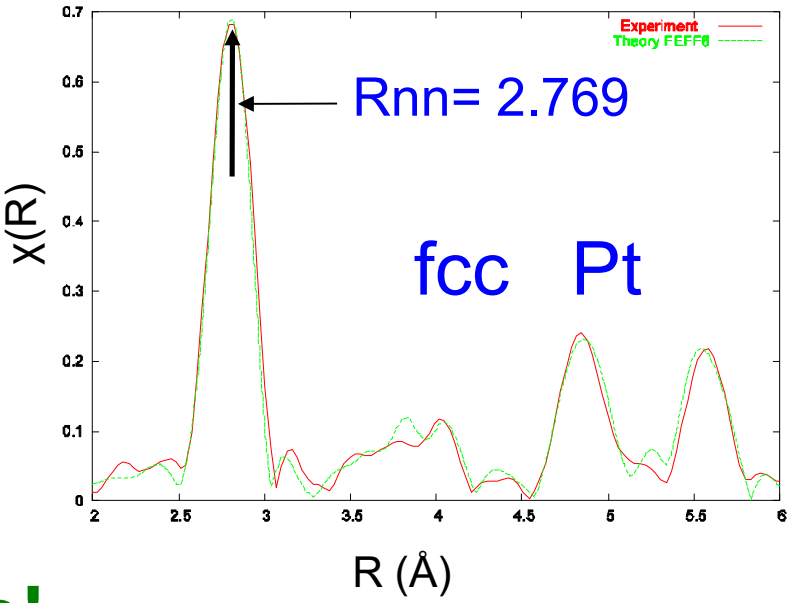
Qualitative Interpretation

D.Sayers Stern & Lytle 1970

Short range order theory



EXAFS Fourier transform – radial distribution function

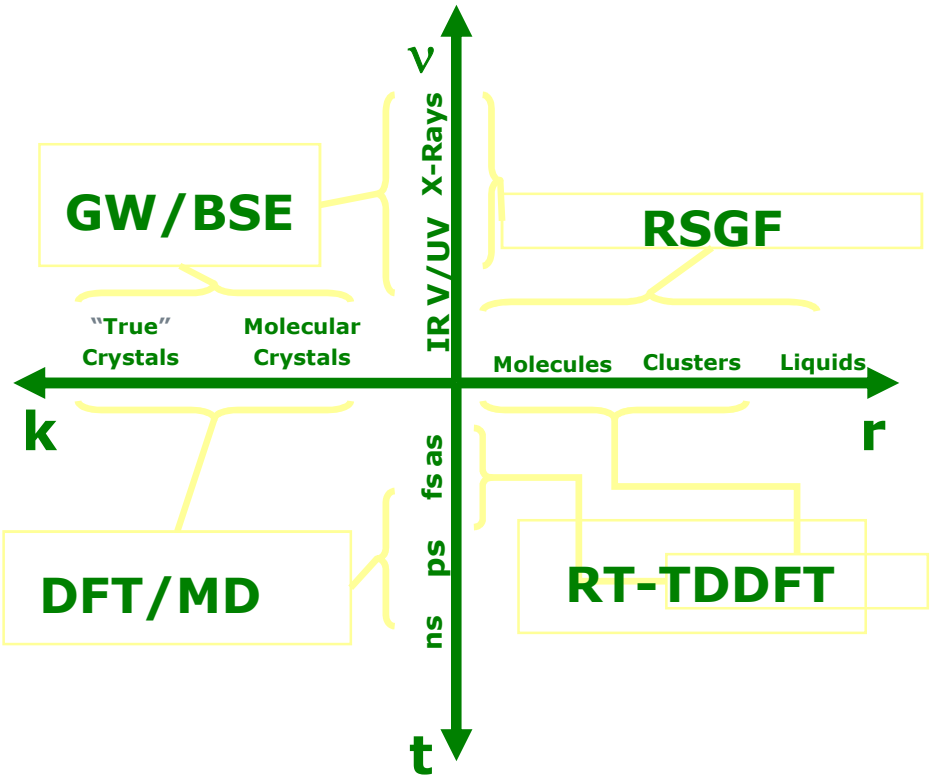


→ **X-ray Microscope!**

Introduction

Promise of Next generation Light sources: NSLSII, LCLS …

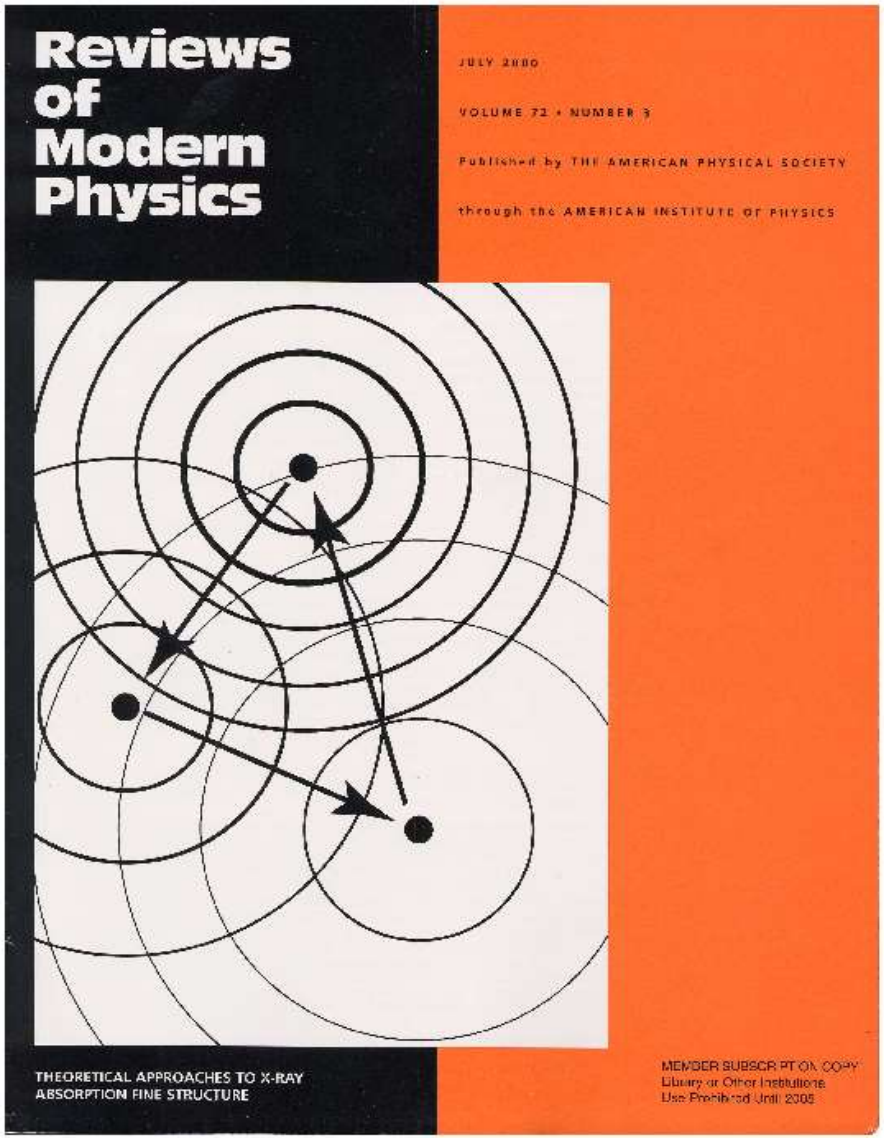
Powerful probes of multiple length and time scales
Partial solution to DOE 5 Grand Challenges, etc.



BUT
Promise cannot be fully exploited without

Next generation theory
& software

I Current methods



EXAFS & XANES

Automated & Integrated

XAS codes

FEFF

> 20 yrs development

J. J. Rehr & R.C. Albers Rev. Mod. Phys. **72**, 621 (2000)

Real-space Green's Function (RSGF)
Theory VIS – X-ray

~~Fermi golden rule via Wave Functions~~

~~$\mu(E) \sim \Sigma_f |\langle i|\hat{\epsilon}\cdot\mathbf{r}|f\rangle|^2 \delta(E - E_f)$~~

Paradigm shift:

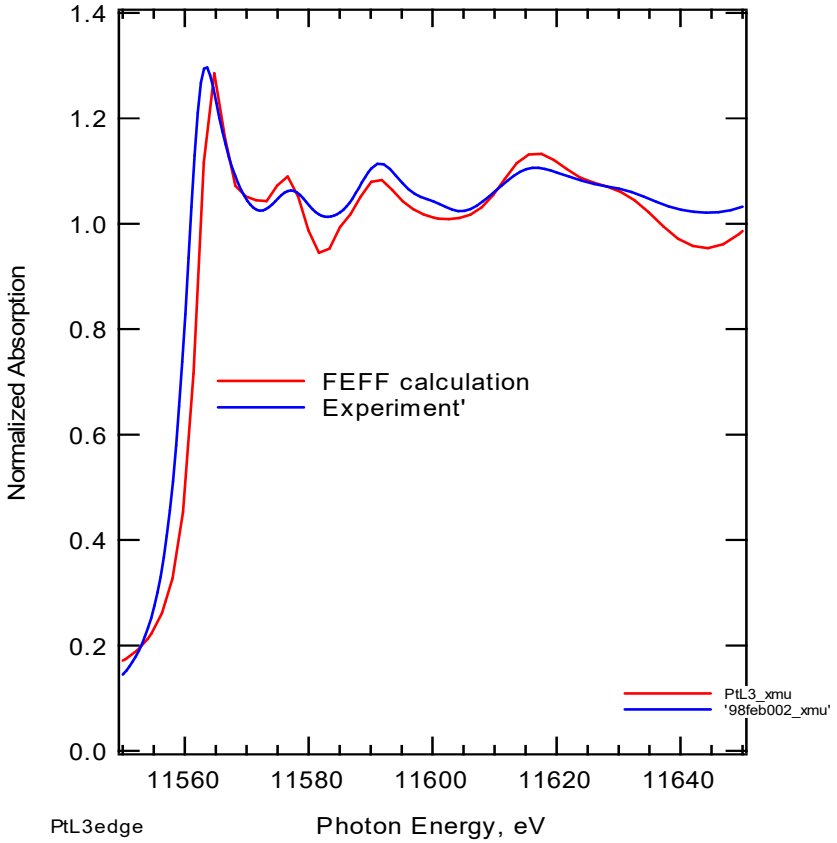
Golden rule via Green's Functions $\mathbf{G} = 1/(E - h - \Sigma)$

$$\mu(E) \sim -\frac{1}{\pi}\mathrm{Im}\,\langle \mathrm{i}|\,\hat{\epsilon}\cdot\mathbf{r}'\,\mathrm{G}(\mathbf{r}',\mathbf{r},\mathrm{E})\,\hat{\epsilon}\cdot\mathbf{r}\,|\mathrm{i}\rangle$$

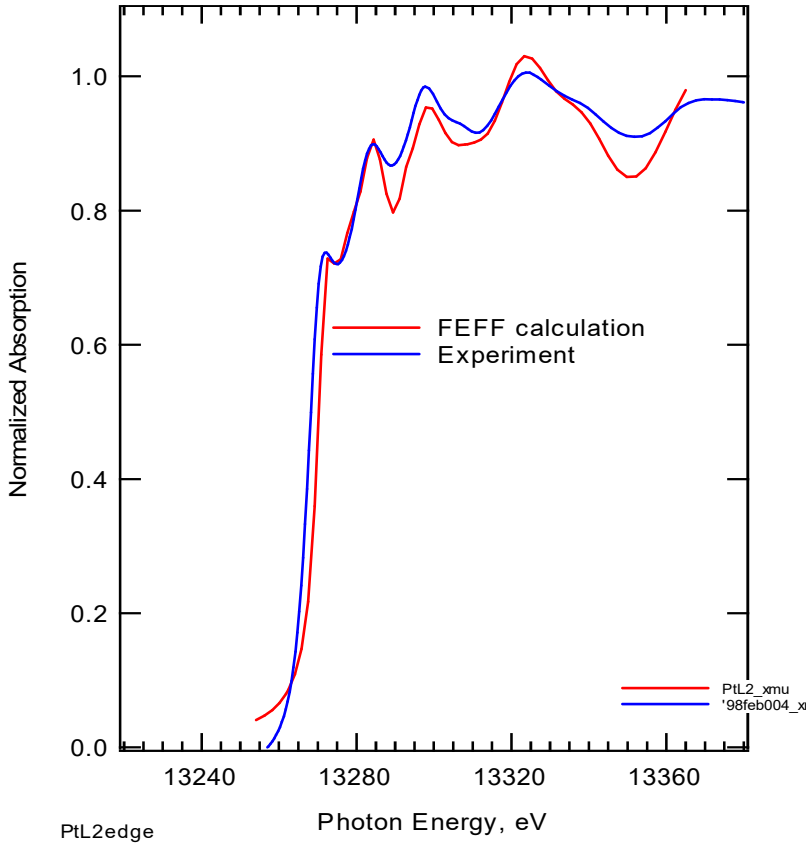
EFFICIENT: ***No sums over final states !***

Example: Pt XANES full multiple-scattering

Pt L_3-edge



Pt L_2-edge **(S. Bare, UOP)**



- Good agreement: *Relativistic* FEFF8 code reproduces all spectral features, ***including absence of white line at L_2-edge***.
- Self-consistency essential: position of Fermi level strongly affects white line intensity.

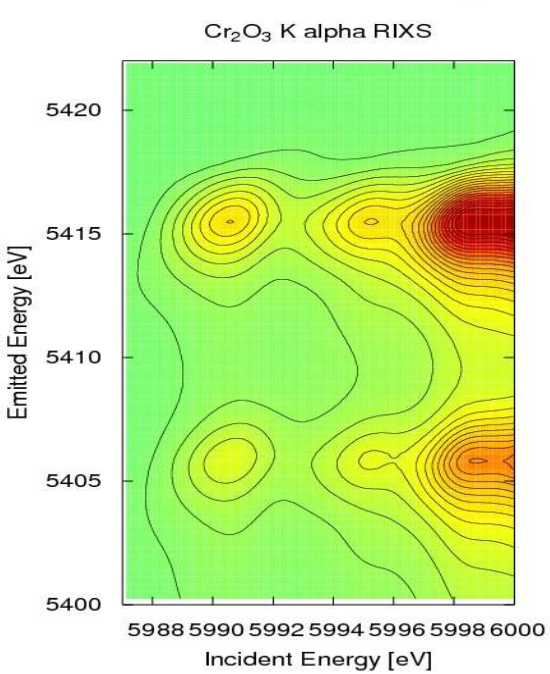
Spectra: RIXS, XES, Compton, …

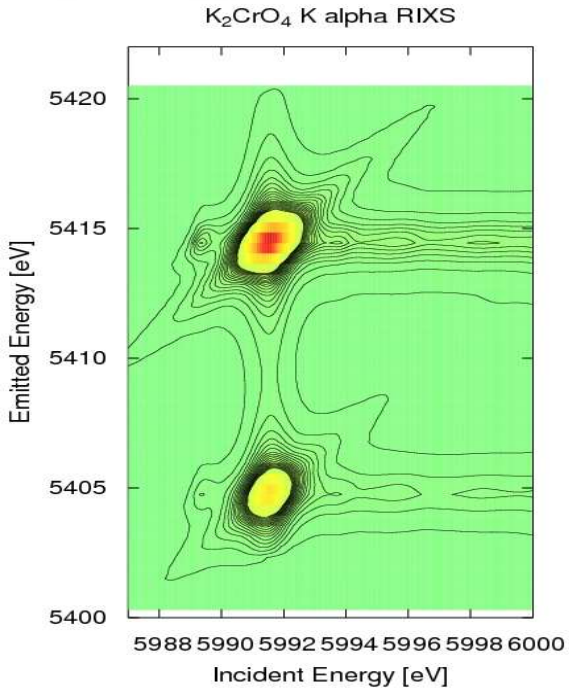
PHYSICAL REVIEW B 83, 235114 (2011)

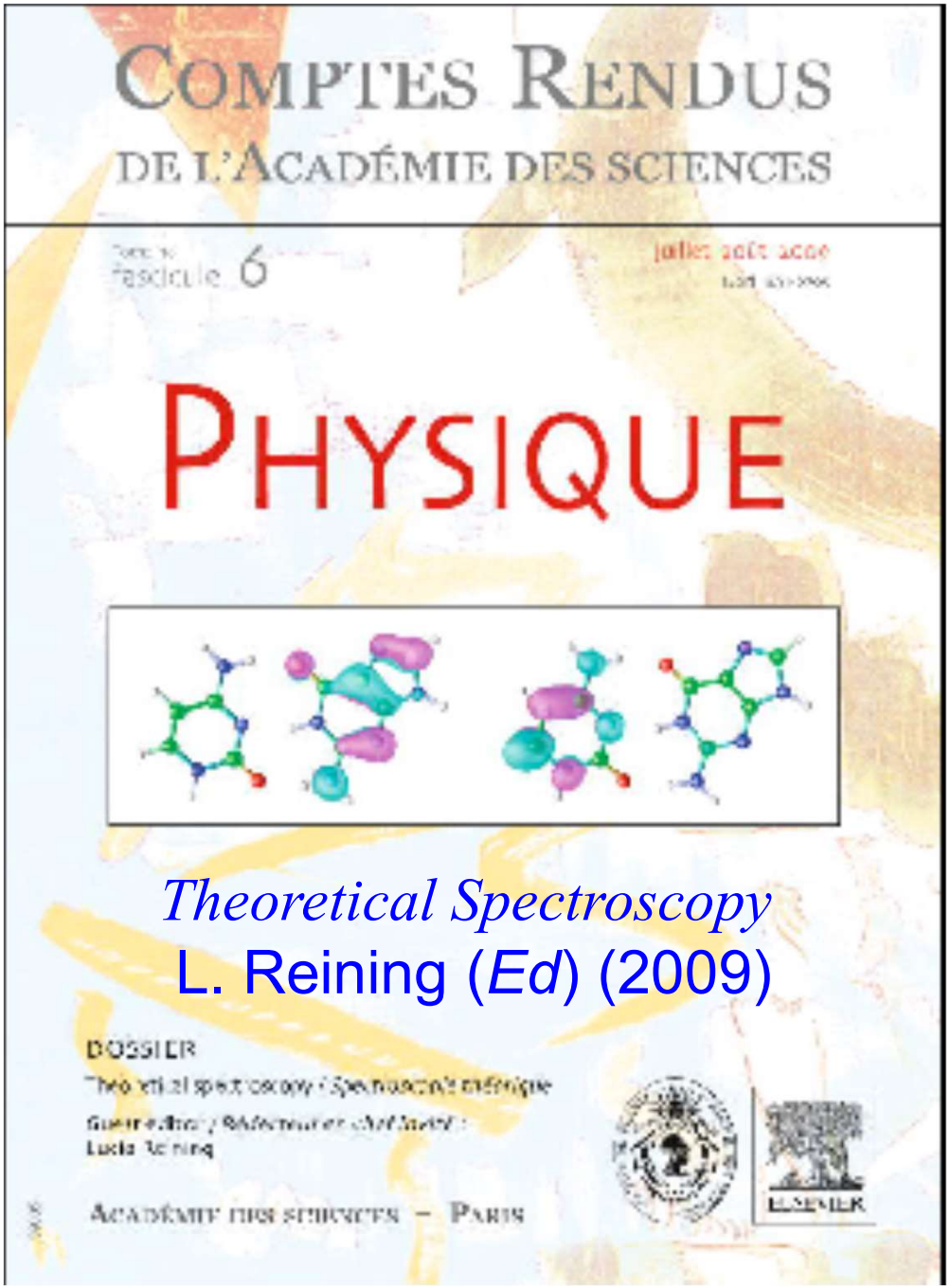
Real-space Green's function approach to resonant inelastic x-ray scattering

J. J. Kas,[1] J. J. Rehr,[1,*] J. A. Soininen,[2] and P. Glatzel[3]
[1]*Department of Physics, Box 351560, University of Washington, Seattle, Washington 98195-1560, USA*
[2]*Department of Physics, P.O. Box 64, University of Helsinki, FI-00014 Helsinki, Finland*
[3]*European Synchrotron Radiation Facility, B.P. 220, F-38043 Grenoble, France*

$$\frac{d^2\sigma}{d\Omega d\omega} \propto \frac{\omega}{\Omega} \int d\omega_1 \frac{\mu_e(\omega_1)\mu(\Omega - \omega - \omega_1 + E_b)}{|\omega - \omega_1 - i\Gamma_b|^2}$$







II. State of the art theory

FEFF9

JJR et al., Comptes Rendus Physique **10**, 548 (2009)

State of the art theory

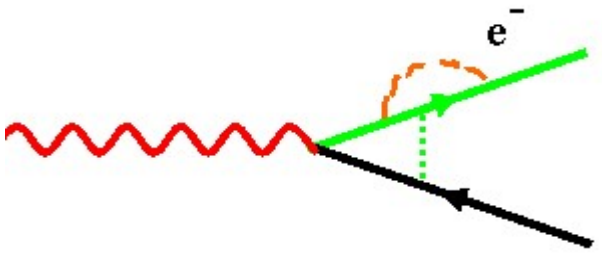
GOAL: ab initio many-body effects

no adjustable parameters

GW Self-energy

Debye Waller factors

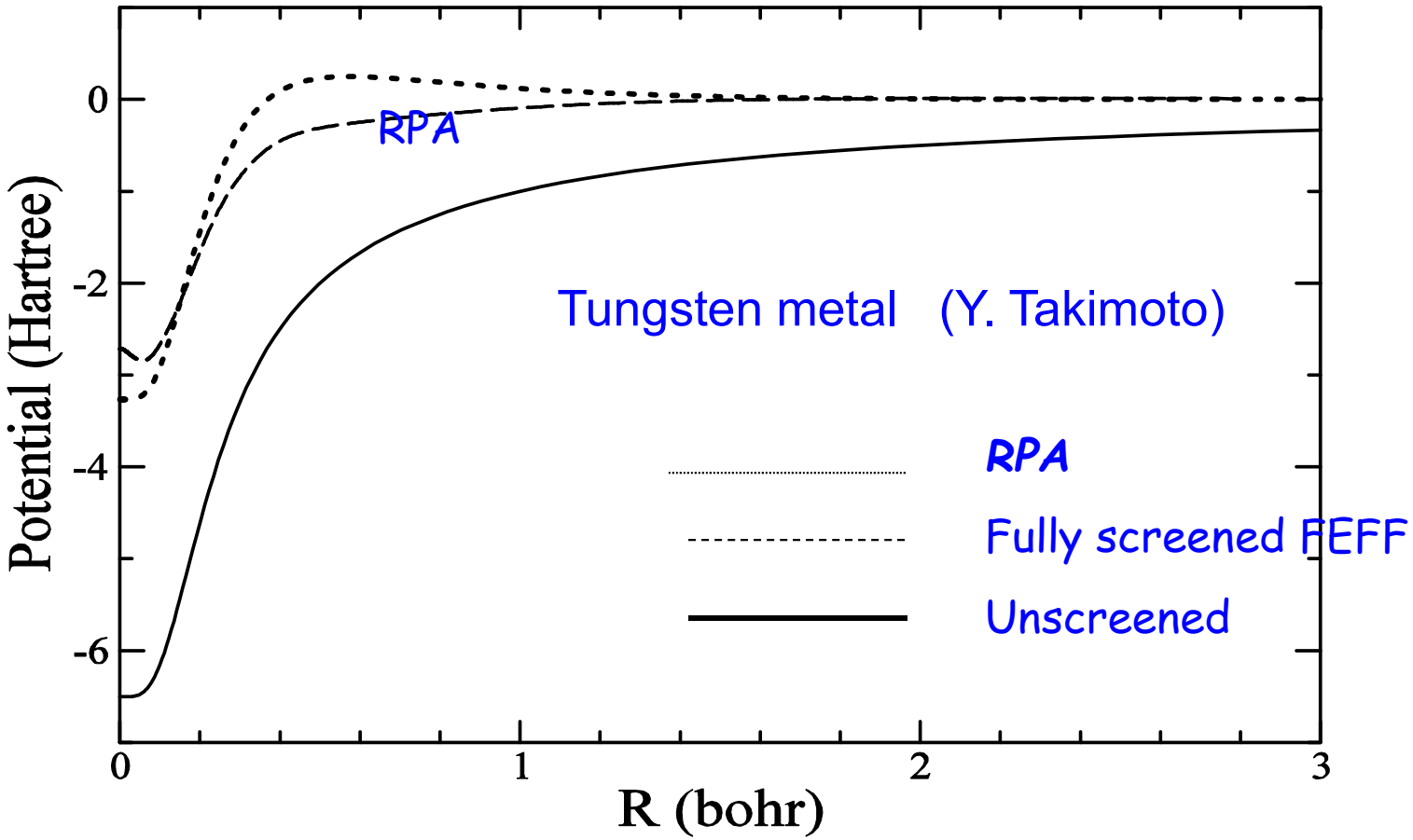
RPA core-hole



Need: **multiple codes**: DFT, self-energy, Phonons

No one group or code can do it all

RPA Core-hole potential



* Also used in BSE

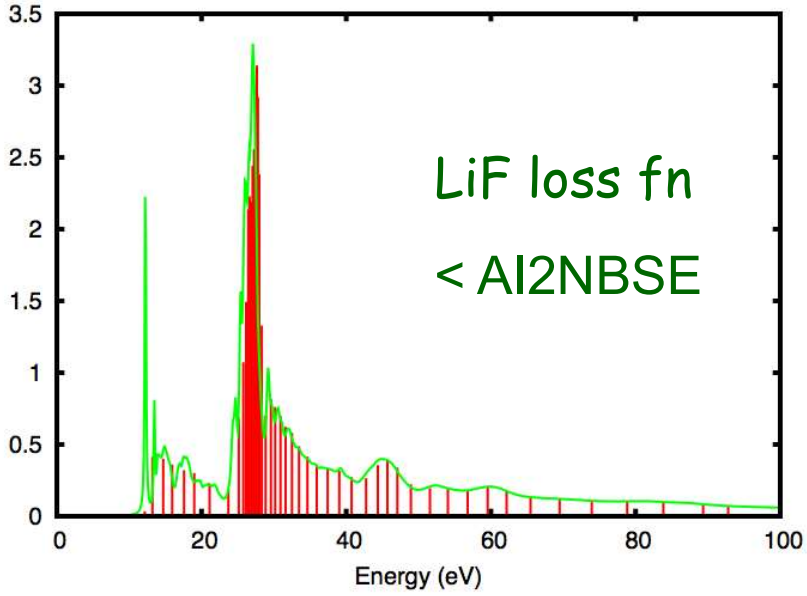
Improves on final state rule, Z+1, half hole

Many-pole GW Self-energy

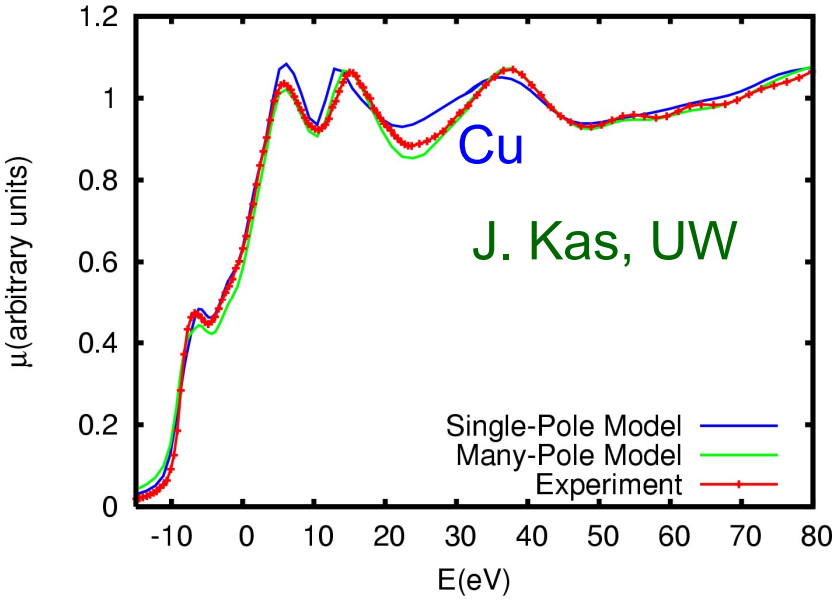
Energy dependent $\Sigma(E)=iGW$ – **replaces V_{xc}**

MFP, energy shifts

cf. Hedin-Lundqvist plasmon-pole



Improved XANES



*J.J. Kas et. al, Phys Rev B **76**, 195116 (2007)

Ab initio XAS Debye Waller Factors * $e^{-2\sigma^2 k^2}$

An Initio Determination of Extended X-Ray Absorption Fine Structure Debye-Waller Factors

Fernando D. Vila, G. Shu, and John J. Rehr
Department of Physics, University of Washington, Seattle, WA 98195

H. H. Rossner and H. J. Krappe
Hahn-Meitner-Institut Berlin, Glienicker Strasse 100, D-14109 Berlin, Germany

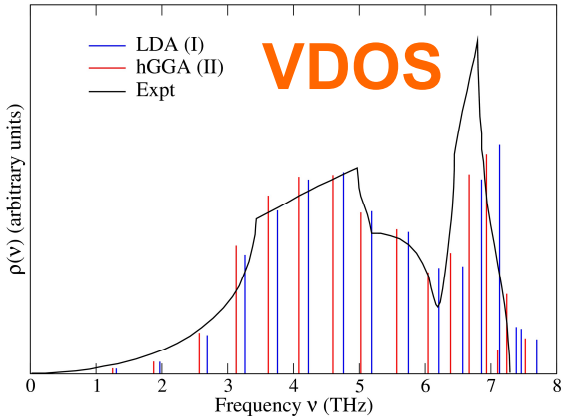
(Dated: August 23, 2005)

Many Pole model

for phonons

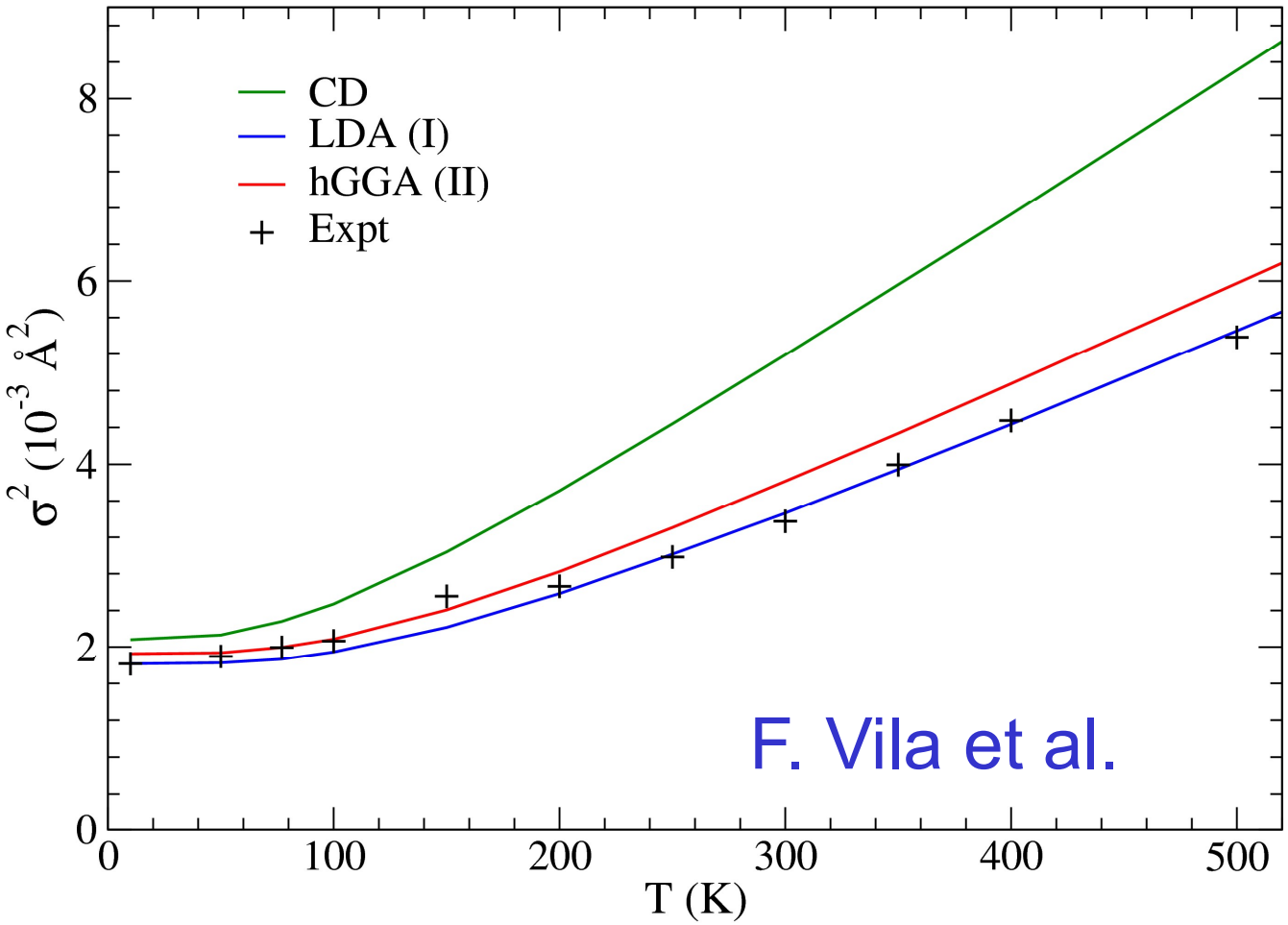
$$\sigma^2 = \frac{\hbar}{\mu_i}\int_0^\infty \rho(\omega^2)\coth\frac{\beta\hbar\omega}{2}\,d\omega$$

$$\rho(\omega^2) = \langle Q_i \,|\delta(\omega^2 - D)|\, Q_i\rangle$$
$$= \{6-\text{step Lanczos recursion}\}$$



*Phys. Rev. B **76,** 014301 (2007)

Example: XAFS Debye-Waller Factor of Ge

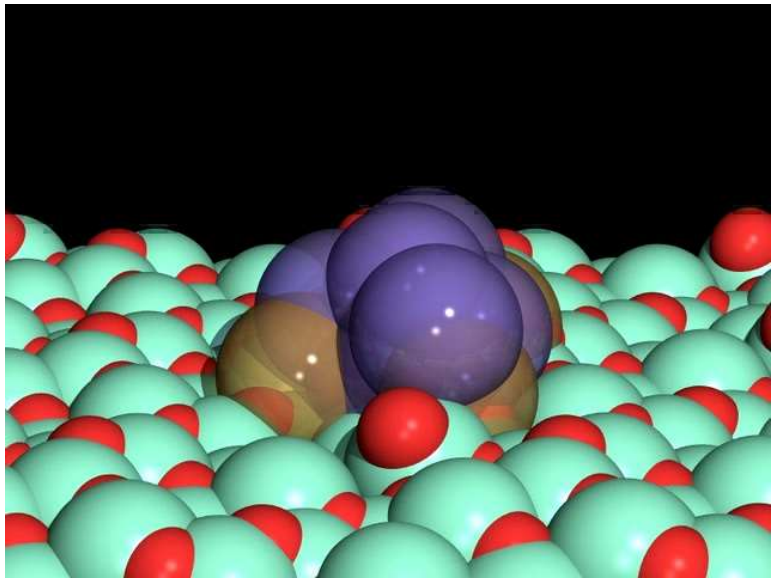


Expt: Dalba *et al.* (1999)

Real-time Finite T DFT-MD / XAS

Nanoscale Pt catalysts*

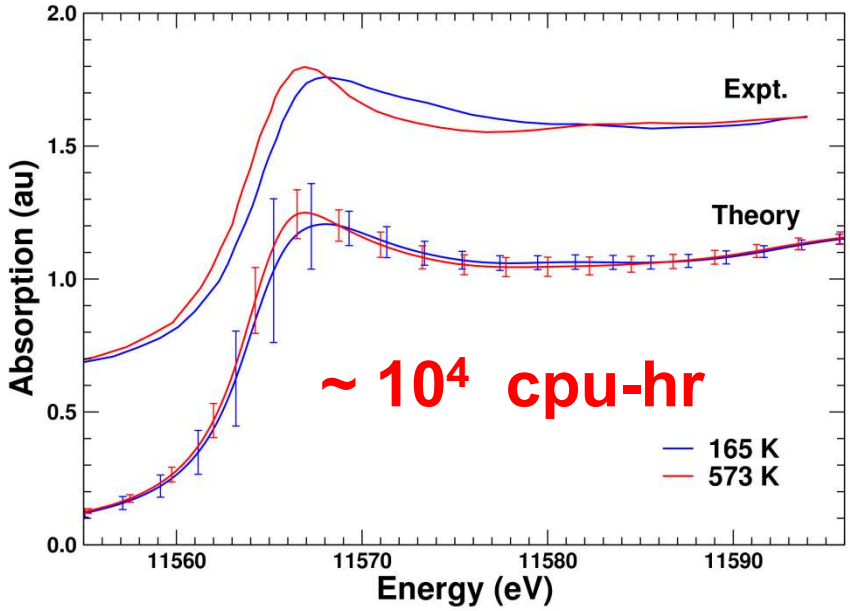
Pt_{10} /γ-Al_2O_3



metallic Pt Al

oxidized Pt O

Expt. vs DFT/MD structure
+ FEFF XAS Theory*



*F. Vila, J.J. Rehr, J. Kas, R.G. Nuzzo, A.I. Frenkel, Phys. Rev. B **78**, 121404(R) (2008)

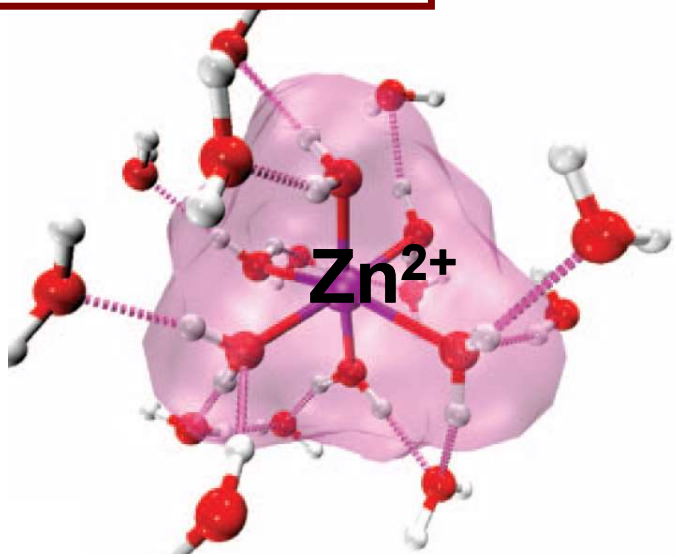
EXAFS and DFT-MD

Aqueous ions

Transition metals, Me^{2+}

Exceptional agreement for:

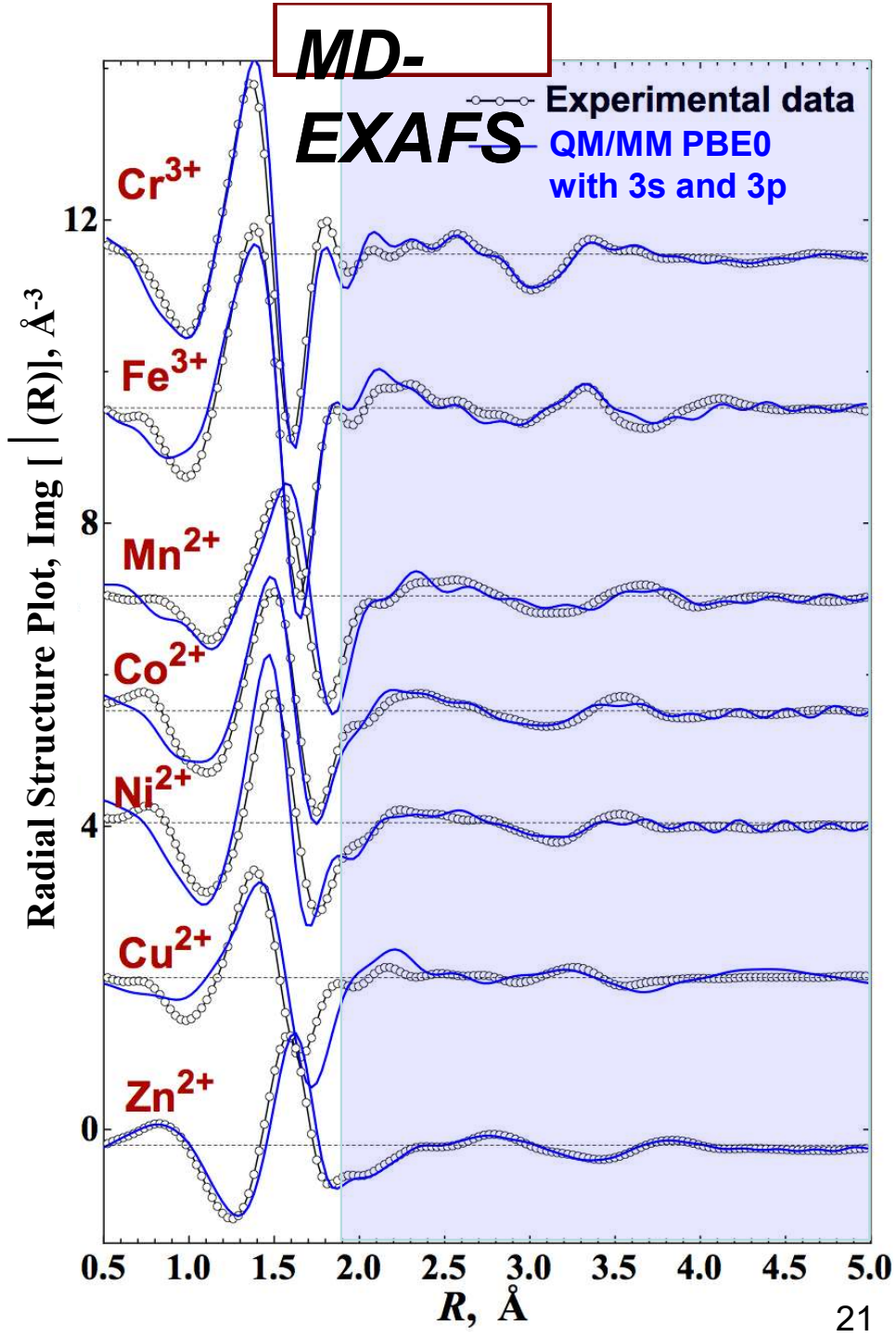
- 1st shell distance and disorder
- Octahedral symmetry
- Angular distribution functions
- Vibrational motions of first shell
- 2nd shell distance and disorder



- QM/MM $Cr^{3+} + 6H_2O$ / 58 H_2O
  DFT PBE0/CPMD MM "SPC/E"
  300K

Fulton, Bylaska, Schenter, et al **JPC Lett.**, 3, 2588 (2012)

24 51.996	25 54.938	26 55.845	27 58.933	28 58.693	29 63.546	30 65.39
Cr	Mn	Fe	Co	Ni	Cu	Zn
CHROMIUM	MANGANESE	IRON	COBALT	NICKEL	COPPER	ZINC



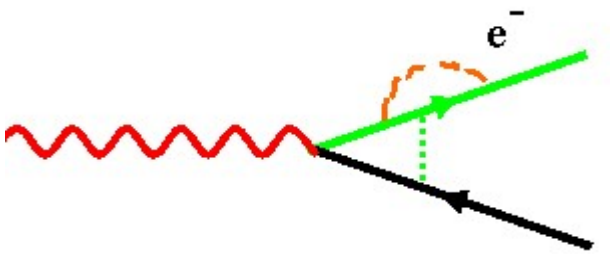
III. Next generation XAS Calculations

- beyond-quasiparticles

Excitonic effects BSE

Multi-electron excitations

Strong correlations



Plus integrated Codes: DFT, GW/BSE, Real-time

etc.

GW Bethe-Salpeter Equation

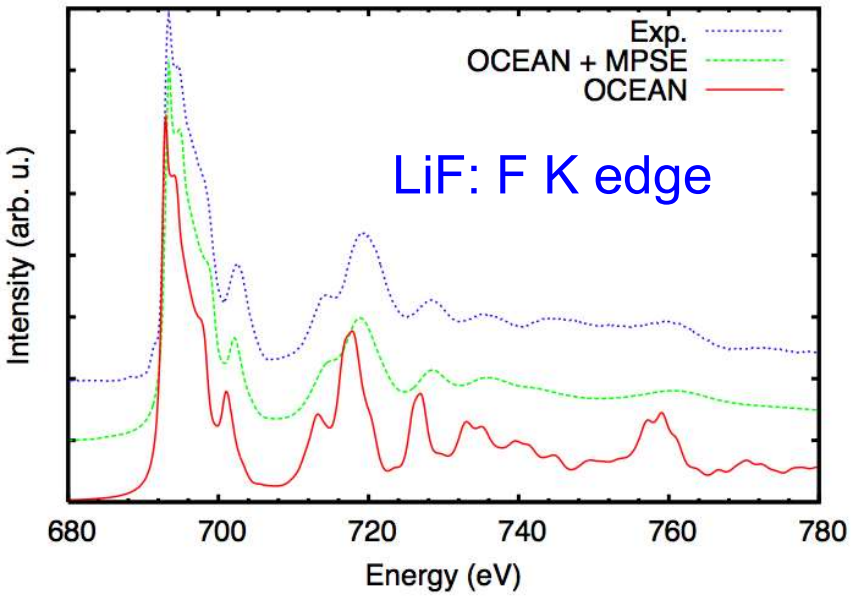
Bethe-Salpeter equation calculations of core excitation spectra

J. Vinson, J. J. Rehr, and J. J. Kas
Department of Physics, University of Washington, Seattle, Washington 98195, USA

E. L. Shirley
National Institute of Standards and Technology (NIST), Gaithersburg, Maryland 20899, USA
(Received 29 September 2010; published 4 March 2011)

We present a hybrid approach for Bethe-Salpeter equation (BSE) calculations of core excitation spectra including x-ray absorption (XAS), electron energy loss spectra (EELS), and nonresonant inelastic x-ray scattering (NRIXS). The method is based on *ab initio* wave functions from the plane-wave pseudopotential code ABINIT atomic core-level states and projector augmented wave (PAW) transition matrix elements; the NIST core-leve BSE solver; and a many-pole self-energy model to account for final-state broadening and self-energy shifts Multiplet effects are also approximately accounted for. The approach is implemented using an interface dubbec OCEAN (Obtaining Core Excitations using ABINIT and NBSE). To demonstrate the utility of the code we presen results for the K edges in LiF as probed by XAS and NRIXS, the K edges of KCl as probed by XAS, the Ti $L_{2,3}$ edge in $SrTiO_3$ as probed by XAS, and the Mg $L_{2,3}$ edge in MgO as probed by XAS. These results are compared with experiment and with other theoretical approaches.

BSE
OCEAN*



Phys. Rev. B83, 115106 (2011)

*Obtaining Core Excitations from ab initio NBSE

Plane-wave, pseudo- potential + PAW + MPSE

cf. EXC, EXC!TING, BerkeleyGW

Many-body Amplitudes in XAS S_0^2

- Many-body X*S ≈ Convolution

$$\mu(\omega) = \int_0^\infty d\omega' \tilde{A}(\omega, \omega') \mu_{qp}(\omega - \omega')$$

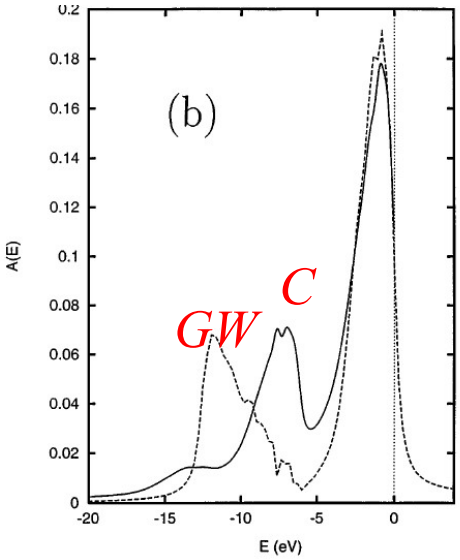
$$\equiv \langle \mu_{qp}(\omega) \rangle$$

- Source: multi-electron excitations

- Spectral function ~ XPS

$$A = - \mathrm{Im}\ G$$

Na XPS



Which Green's function ? *GW* vs Cumulant

J. Phys.: Condens. Matter 11 (1999) R489–R528

On correlation effects in electron spectroscopies and the *GW* approximation

Lars Hedin
Department of Theoretical Physics, Lund University, Sölvegatan 14A, 223 62 Lund, Sweden

$$\Sigma = i\,GW\Gamma$$

$$W = \epsilon^{-1} v$$

GW	**Cumulant**
$G(\omega) = G_0 + G_0\,\Sigma\,G$	$G(t) = G_0(t)\,e^{C(t)}$
$\Gamma = 1 \qquad \Sigma^{GW} = iGW$	$C \sim \mathrm{Im}\,\Sigma^{GW}$

Similar ingredients; all many-body effects in Σ^{GW}

Test: Satellites in XPS of simple metals*

Multiple Plasmon Satellites in Na and Al Spectral Functions from *Ab Initio* Cumulant Expansion

F. Aryasetiawan,[1,2] L. Hedin,[1] and K. Karlsson[3]

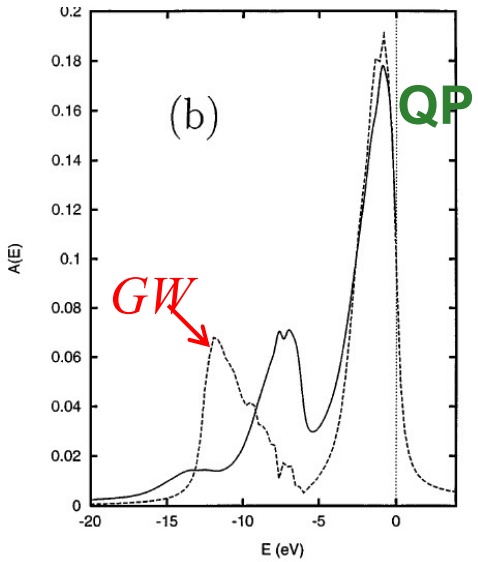
Phys Rev Lett **77**, 2268 (1996)

Good news: *GW* quasi-particle peak agrees with XPS

Bad news: *GW* has ***one*** satellite @ wrong energy

XPS has multiple satellites

Na XPS

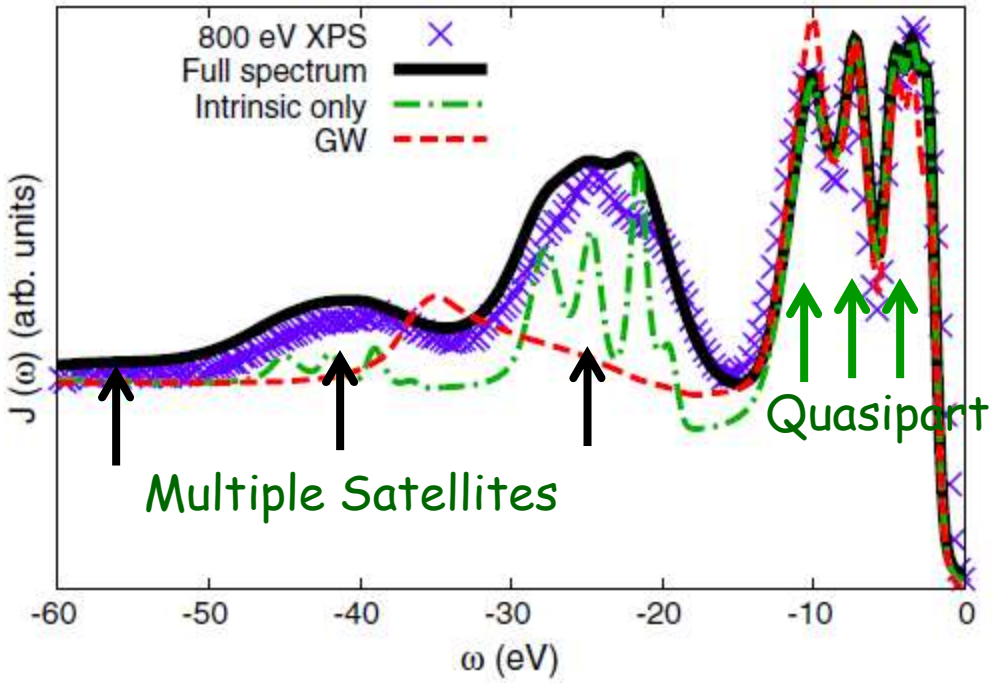


Test 2: Multiple Satellites in XPS of Si

PRL 107, 166401 (2011) PHYSICAL REVIEW LETTERS week ending 14 OCTOBER 2011

Valence Electron Photoemission Spectrum of Semiconductors: *Ab Initio* Description of Multiple Satellites

Matteo Guzzo,[1,2,*] Giovanna Lani,[1,2] Francesco Sottile,[1,2] Pina Romaniello,[3,2] Matteo Gatti,[4,2] Joshua J. Kas,[5] John J. Rehr,[5,2] Mathieu G. Silly,[6] Fausto Sirotti,[6] and Lucia Reining[1,2,†]



Lucia Reining

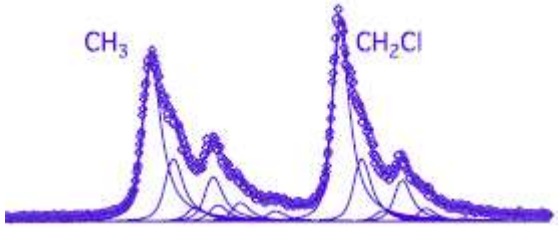
XPS Intensity Ratios in Molecules

PRL 108, 193005 (2012) PHYSICAL REVIEW LETTERS week ending 11 MAY 2012

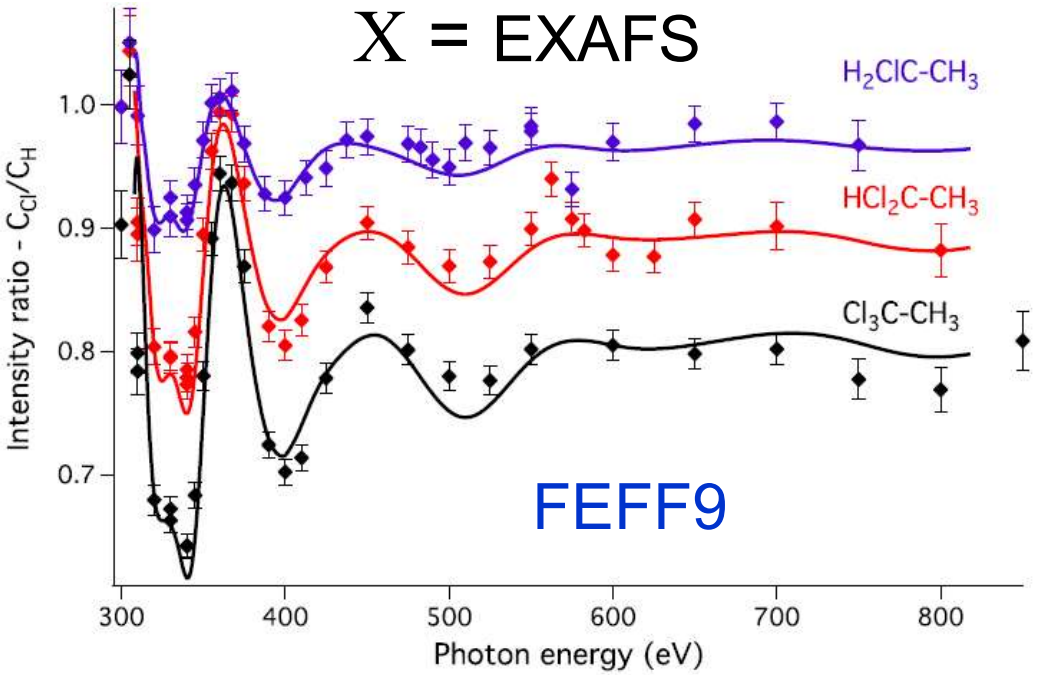
Nonstoichiometric Intensities in Core Photoelectron Spectroscopy

J. Söderström,[1] N. Mårtensson,[1] O. Travnikova,[2] M. Patanen,[2] C. Miron,[2] L. J. Sæthre,[3] K. J. Børve,[3] J. J. Rehr,[4] J. J. Kas,[4] F. D. Vila,[4] T. D. Thomas,[5] and S. Svensson[1]

$$R = \frac{\mu_{C_a}}{\mu_{C_H}} = \frac{\mu_{0C_a} Z_{C_a} \left(1 + X_{C_a}\right)}{\mu_{0C_H} Z_{C_H} \left(1 + X_{C_H}\right)} \approx R_0 \left(1 + X_R\right)$$



X = EXAFS



FEFF9

<XPS> = XAS

Intensity ratio ~ Z

including all losses explains non-stoichiometric ratios

Question: Can the cumulant method work for CT satellites in correlated systems ?

Hedin's answer * MAYBE

"Calculation similar to core case … but with more complicated fluctuation potentials …

… not question of principle, but of computational work..."

* L. Hedin, J. Phys.: Condens. Matter **11,** R489 (1999)

Approach: Cumulant expansion in real-time

Real time cumulant approach for charge transfer satellites in x-ray photoemission spectra

J. J. Kas,[1] F. D. Vila,[1] J. J. Rehr,[1] and S. Chambers[2]

[1] *Dept. of Physics, Univ. of Washington, Seattle, WA 98195-1560*

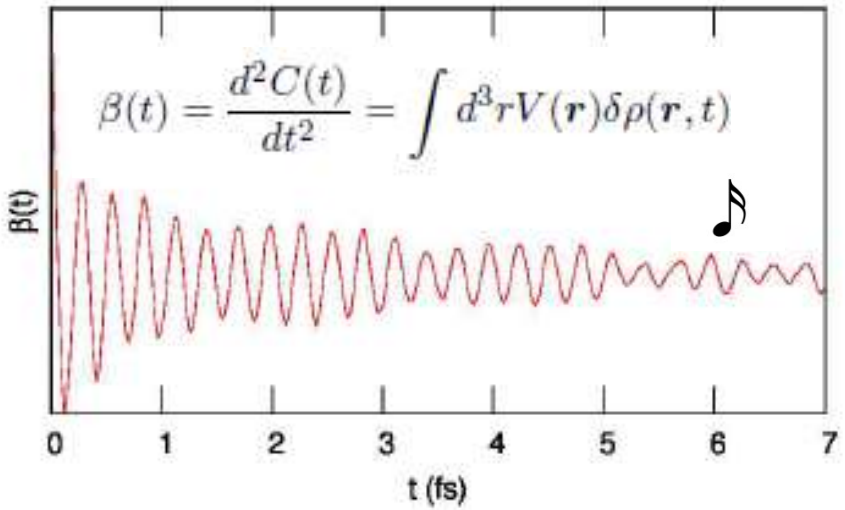
[2] *Physical Sciences Division, Pacific Northwest National Laboratory, Richland, WA 99352*

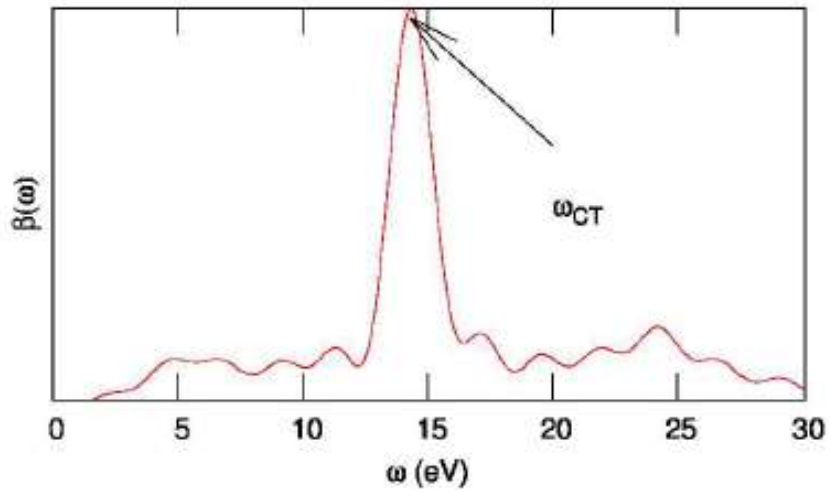
(Dated: August 7, 2014)

arXiv:1408.2508

Langreth $$C(t) = \sum_{q,q'} V_q^* V_{q'} \int d\omega S(q,q',\omega) \frac{e^{i\omega t} - i\omega t - 1}{\omega^2} = \int d\omega \beta(\omega) \frac{e^{i\omega t} - i\omega t - 1}{\omega^2}$$

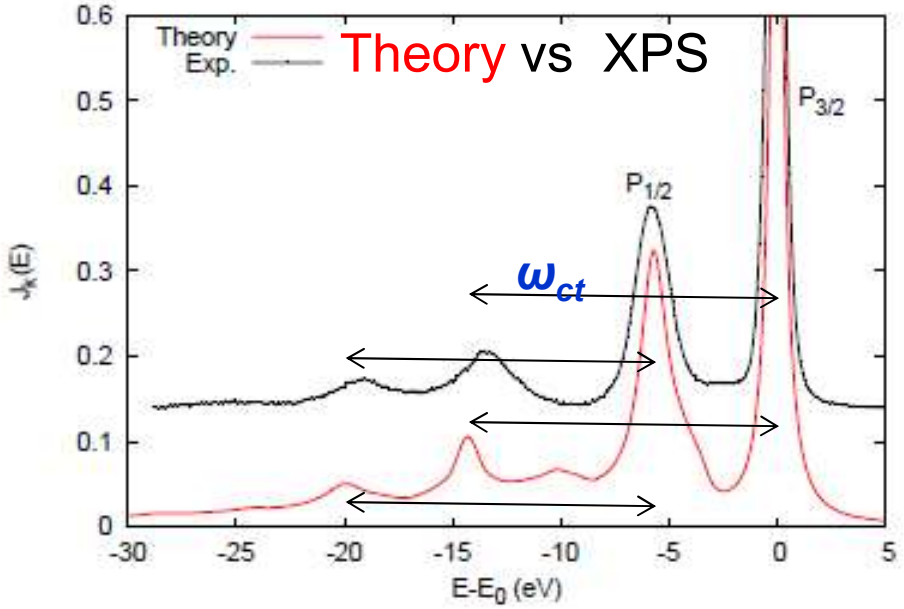
RT Cumulant: RT-TDDFT $$S(q,q',\omega) = \int \frac{dt}{2\pi} e^{i\omega t} \langle \rho_q(t) \rho_{q'}(0) \rangle$$



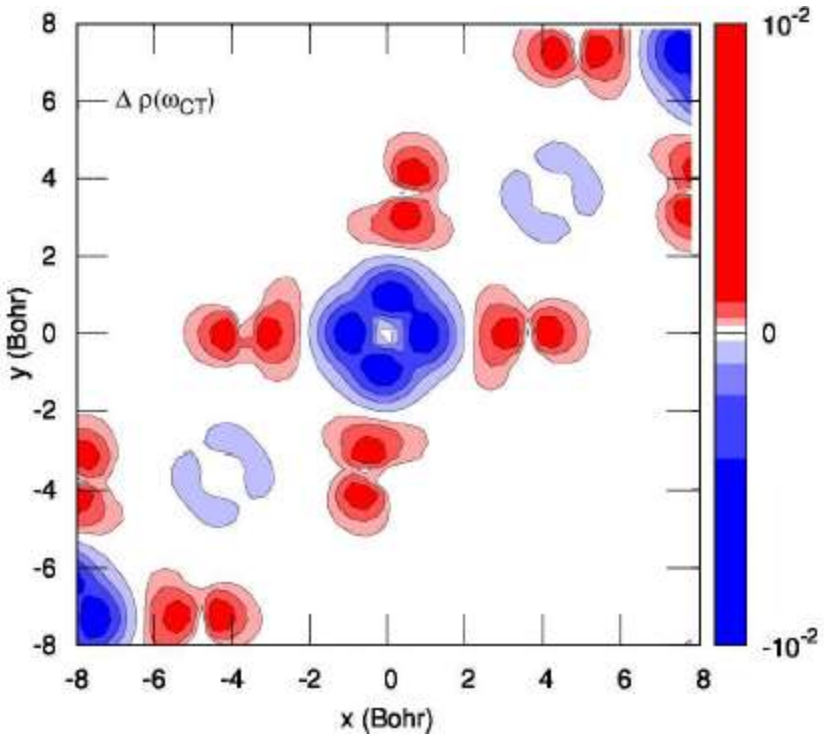


XPS & Real-space Interpretation

RT TDDFT Cumulant



Charge Fluctuations



Interpretation: satellites due to local ligand-metal charge fluctuations at frequency ~ ω_{ct} in response to transient core-hole potential

JJ Kas, FD Vila, JJR & S.Chambers **arXiv:1408.2508**

Conclusions and Outlook

EXAFS - well understood with current methods

RSGF + DFT/MD

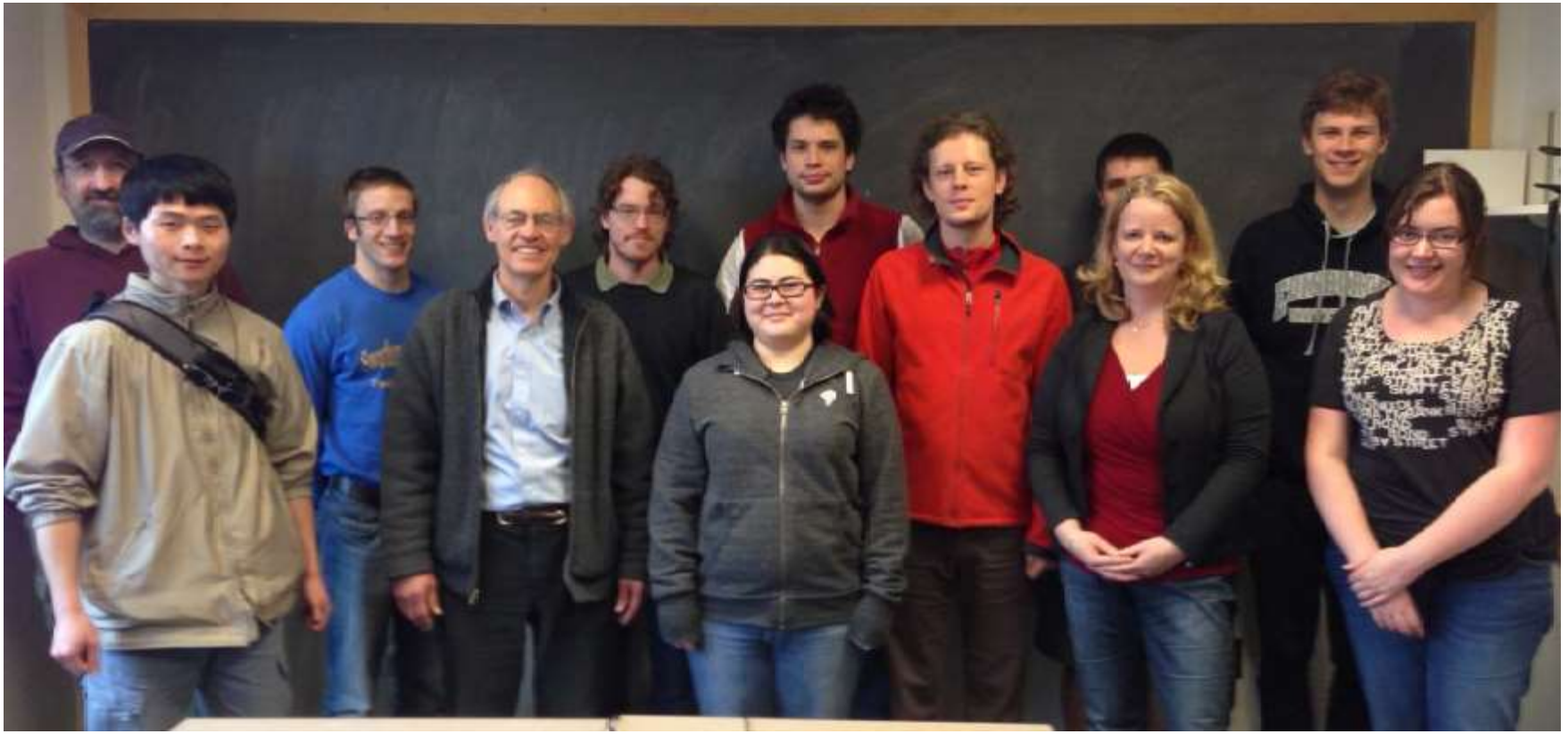
XANES – semi-quantitative state of the art theory

GW, GW/BSE, DW factors, …

XAS, XPS - Multi-electron excitations & correlations via *quasi-boson/cumulant theory*

Full spectrum calculations possible in arbitrary materials with NG theory and codes.

Rehr group & collaborators



Thanks for Listening!

Many Success Stories

XAS of doped SiC

M Ohkubo et al., Sci. Rep., **2**, 831 (2012)

OPEN

SUBJECT AREAS:
PHYSICS
MATERIALS SCIENCE
SPECTROSCOPY
ANALYTICAL CHEMISTRY

X-ray absorption near edge spectroscopy with a superconducting detector for nitrogen dopants in SiC

M. Ohkubo[1], S. Shiki[1], M. Ukibe[1], N. Matsubayashi[1], Y. Kitajima[2] & S. Nagamachi[3]

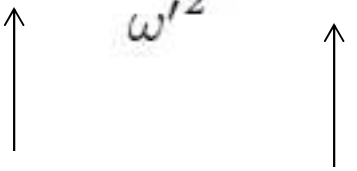
"FEFF8.4 played an important role in analysis of XANES spectra of N-doped SiC. I appreciate your effort for developing this fantastic software …"

Masataka Ohkubo

Cumulant Expansion & Spectral Function

$$G_k(t) = e^{i\epsilon_k^0 t} e^{C(t)}$$

$$C(t) = \int d\omega' \beta(\omega') \frac{e^{i\omega' t} - i\omega' t - 1}{\omega'^2}$$



Spectral Function

$$A_k(\omega) = \int \frac{dt}{2\pi} e^{i(\omega - \epsilon_k)t} \exp\left\{ \int d\omega' \beta(\omega') \frac{e^{i\omega' t} - i\omega' t - 1}{\omega'^2} \right\}$$

*see L. Hedin, J. Phys.: Condens. Matter **11,** R489 (1999)
cf. D.C. Langreth *Phys. Rev.* B **1,** 471 (1970) (Linked cluster theorem)

Other properties

Kernel: $\beta(\omega) = |\mathrm{Im}\,\Sigma_k(\omega)|$ ~ Im ε^{-1} ~ loss function

Peaks in $A(\omega)$ ~ Peaks in loss function

$$Z = \mathrm{e}^{-\overline{n}} \qquad \overline{n} = \sum_q g_q^2/\omega_q^2 = \int \beta(\omega)/\omega^2 \, \mathrm{d}\omega.$$

$\overline{n} = 0.201 r_s^{3/4}$ mean number of shake-up bosons

Dimensionless measure of correlation strength

n ~ 0.3 to 0.4 **even in s-p systems !**

IV. Problems with Cumulant Expansion*

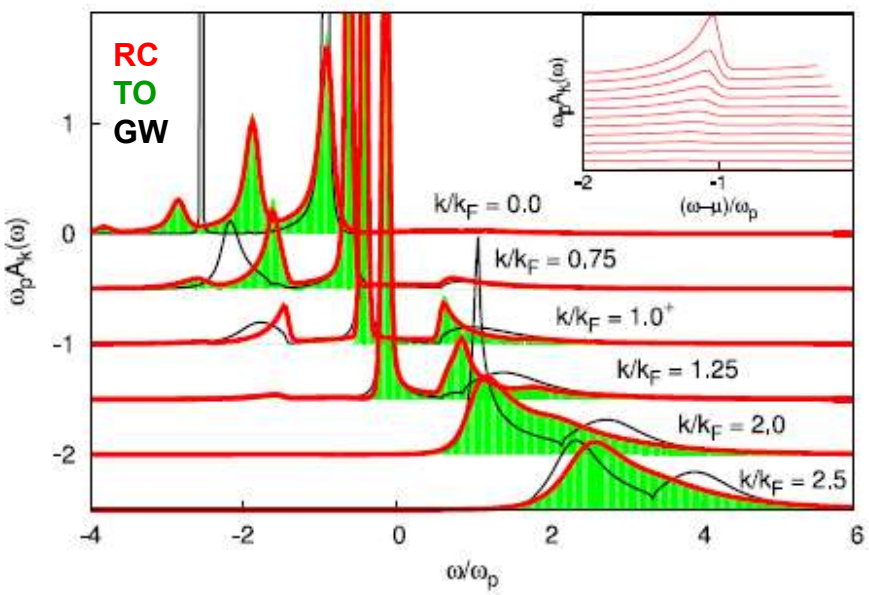
BAD: Pathologies at Fermi energy*

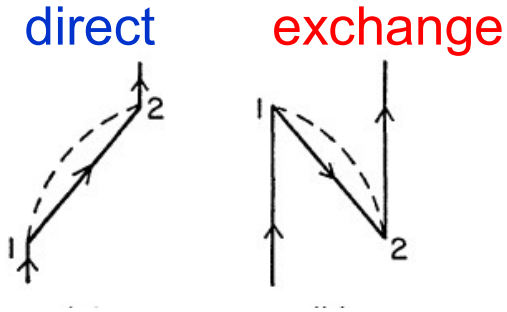
Time-ordered GF (TO) lacks satellites on both sides of QP peak near Fermi energy

GW lacks multiple satellites

Source: recoil approximation: neglect of "exchange diagrams" in time-ordered cumulant

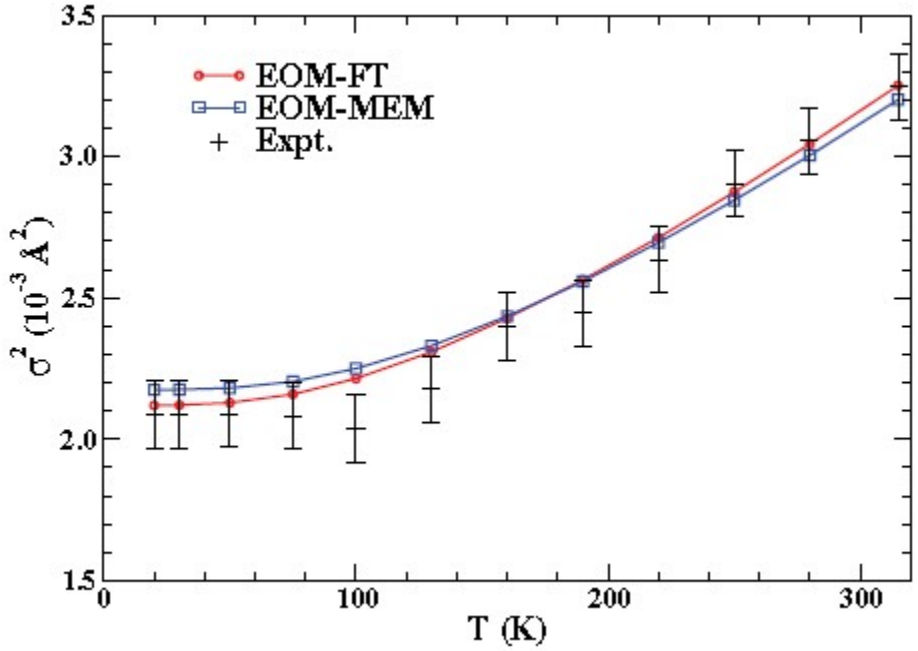
Electron spectral function

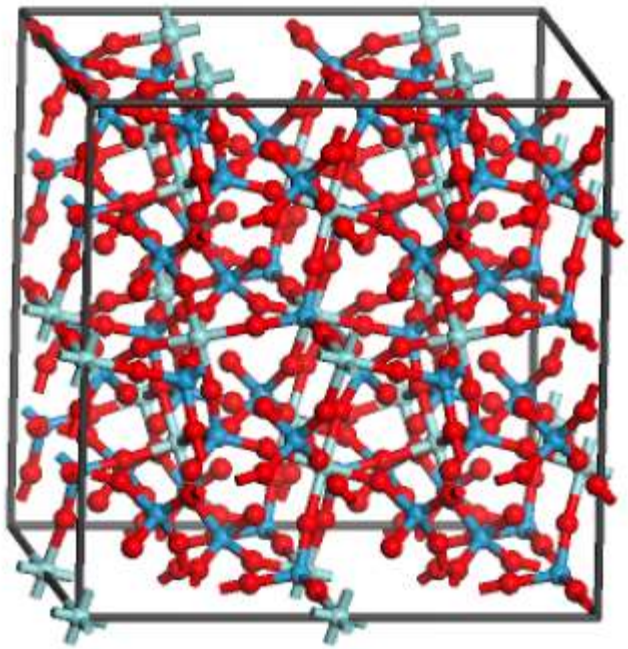




*arXiv:1402.0022

Debye-Waller factors σ^2 in Zr tungstate





FIX: Retarded Cumulant expansion*

PHYSICAL REVIEW B **00**, 005100 (2014)

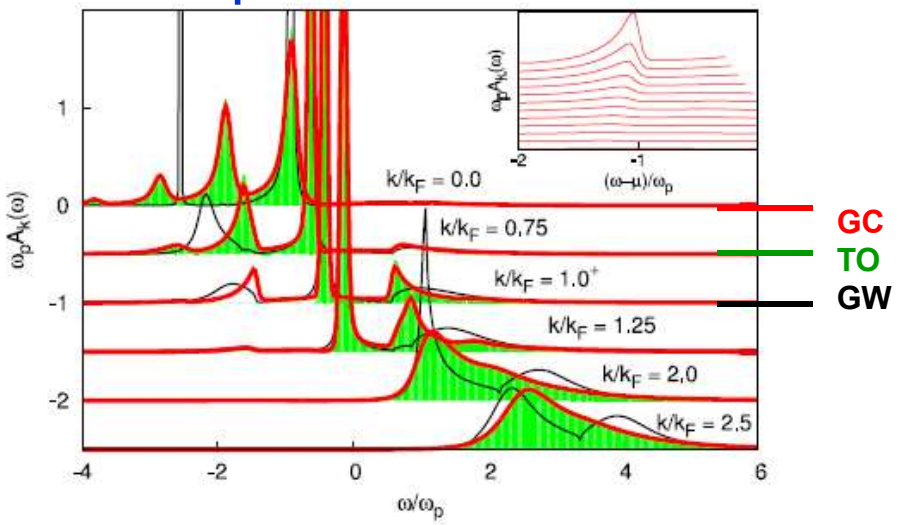
Cumulant expansion of the retarded one-electron Green function

J. J. Kas,[1,*] J. J. Rehr,[1,2,†] and L. Reining[3,2,‡]
[1]*Department of Physics, University of Washington, Seattle, Washington 98195, USA*
[2]*European Theoretical Spectroscopy Facility (ETSF)*
[3]*Laboratoire des Solides Irradiés, École Polytechnique, CNRS, CEA-DSM, F-91128 Palaiseau, France*
(Received 31 January 2014; revised manuscript received 28 July 2014; published xxxxxx)

Retarded formalism

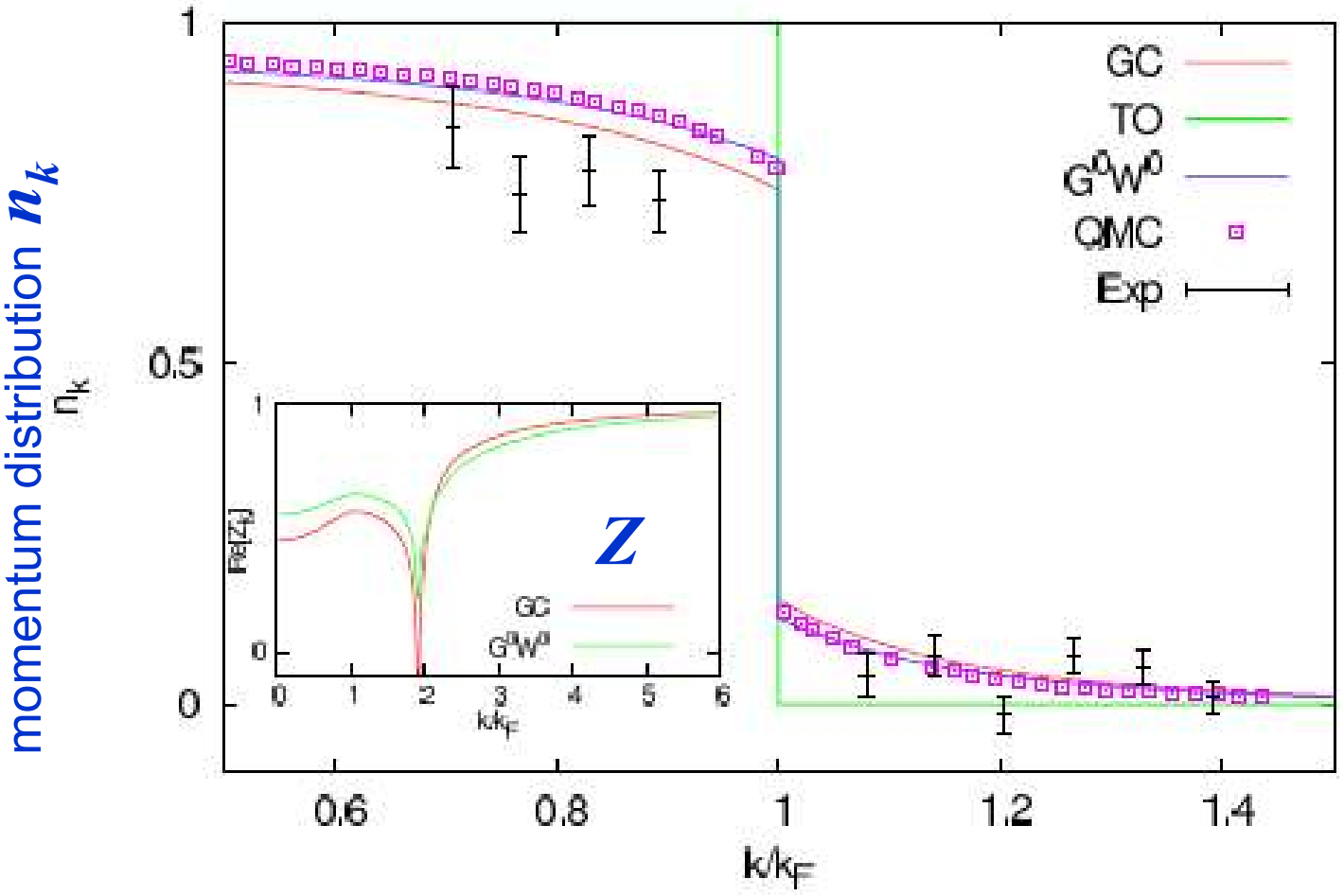
$$G_k^R(t) = -i\theta(t)e^{-i\epsilon_k^{HF}t}e^{\tilde{C}_k^R(t)},$$
$$\tilde{C}_k^R(t) = \int d\omega \frac{\beta_k(\omega)}{\omega^2}(e^{-i\omega t} + i\omega t - 1),$$
$$\beta_k(\omega) = \frac{1}{\pi}\left|\mathrm{Im}\,\Sigma_k^R(\omega + \epsilon_k)\right|,$$

Spectral function



*Phys. Rev. B. (in press, Aug. 2014); arXiv:1402.0022

Retarded Cumulant (GC) gives **GOOD** quasi-particle properties



Many-body Amplitudes in X-ray Spectra

- Many-body X*S ≈ Convolution

$$\mu(\omega) = \int_0^\infty d\omega' \tilde{A}(\omega, \omega') \mu_{qp}(\omega - \omega')$$

$$\equiv \langle \mu_{qp}(\omega) \rangle$$

- Explains crossover: **adiabatic**

to sudden transition

$$|g_q|^2 = |g_q^{ext}|^2 + |g_q^{intrin}|^2 - 2\, g_q^{ext}\, g_q^{intrin}$$

Interference reduces loss!

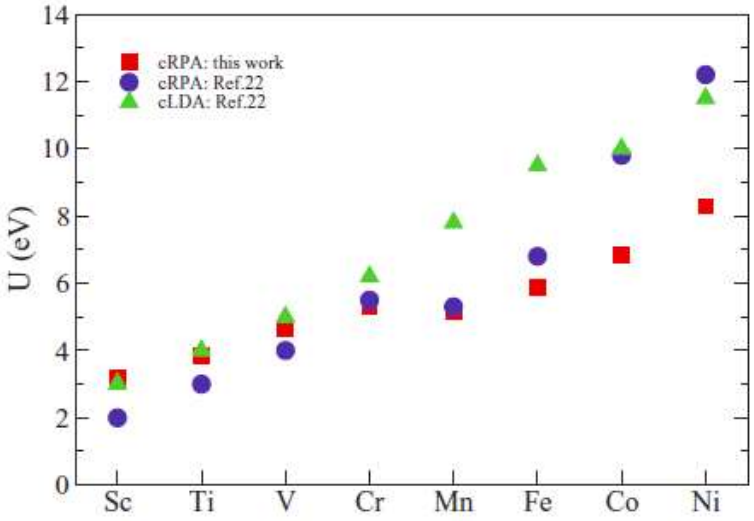
Strong correlation effects: 1. Hubbard corrections

PHYSICAL REVIEW B **85**, 165123 (2012)

Hubbard model corrections in real-space x-ray spectroscopy theory

Towfiq Ahmed, J. J. Kas, and J. J. Rehr

cRPA calculated U



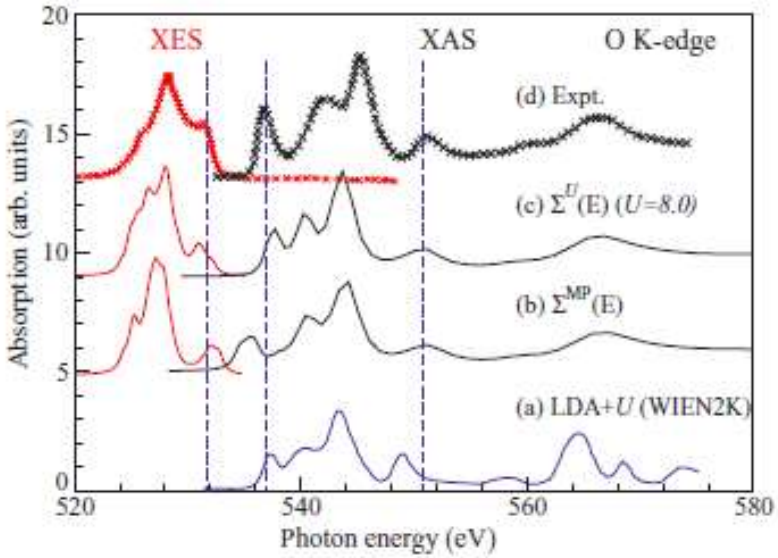


FIG. 1. (Color online) Results of our cRPA calculations of U (re

FIX: Next generation approach

Quasi-Boson Approximation

IDEA: Neutral Excitations - plasmons, phonons, electron-hole pairs, magnons are **bosons** γ *

Many-body Model: $|N\rangle = |e^-, h, \gamma\rangle$

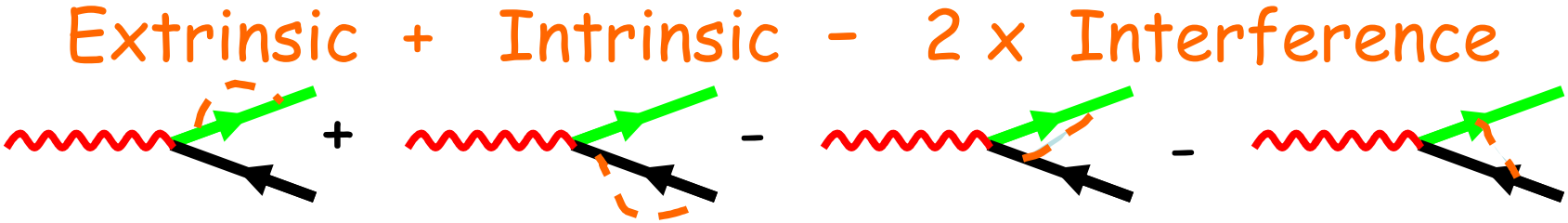
- Excitations: $H_v = \Sigma_n \omega_n a_n^\dagger a_n$
- Electrons: $h' = \Sigma_k \epsilon_k c_k^\dagger c_k$
- e-boson coupling $V_{pv} = \Sigma_{nkk'} \left[V_{kk'}^n a_n^\dagger + (V_{kk'}^n)^* a_n \right] c_k^\dagger c_{k'}$
- Core-hole-boson coupling: $V_{vc} = -\Sigma_n V_{bb}^n \left(a_n^\dagger + a_n \right)$

$V^n \rightarrow$ **-Im** $\varepsilon^{-1}(\omega_n, q_n)$ "fluctuation potentials"

* L. Hedin, J. Phys.: Condens. Matter **11,** R489 (1999)

GW++: Effective Green's Function - perturbation theory*

$$g_{eff}(\omega) = e^{-a}\left[g'(\omega) + \Sigma_n \left(\frac{V^n_{bb}}{\omega_n}\right)^2 g'(\omega-\omega_n) - 2\Sigma_n \frac{V^n_{bb}}{\omega_n} g'(\omega-\omega_n) V^n g'(\omega)\right]$$



Leading term: $g'(\omega)$ damped Green's function in presence of core-hole (~ final state rule!)

$$g'(\omega) \equiv [\omega - h' - \Sigma(\omega) + i\gamma]^{-1}$$

*L. Campbell, L. Hedin, J. J. Rehr, and W. Bardyszewski, Phys. Rev. B **65**, 064107 (2002)

2. Multiplets a la GW/BSE

Phys. Rev. B **86**, 195135 (2012)

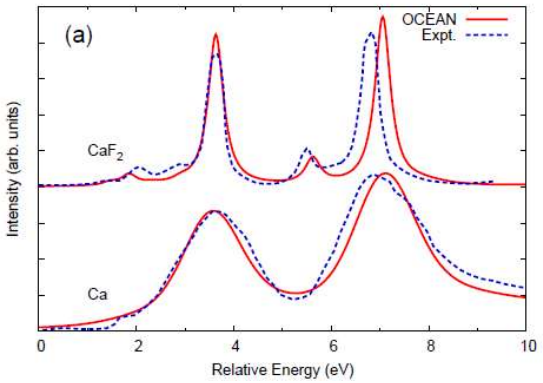
BSE calculations of transition metal L-shell spectra

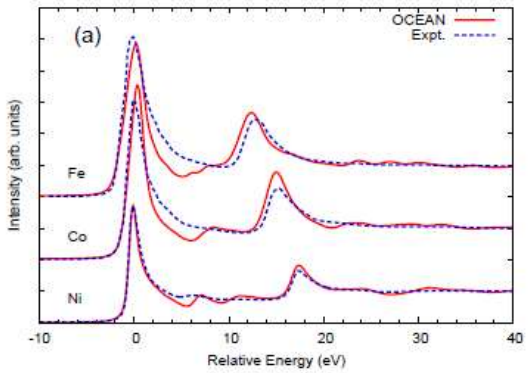
J. Vinson and J. J. Rehr
Dept. of Physics, Univ. of Washington Seattle, WA 98195
(Dated: July 3, 2012)

We present *ab initio* Bethe-Salpeter equation (BSE) calculations of the $L_{2,3}$ edges of several insulating and metallic compounds containing Ca, V, Fe, Co, Ni, and Cu, spanning a range of *3d*-electron occupations. Our approach includes the key ingredients of a unified treatment of both extended states and atomic multiplet effects, i.e., self-consistent crystal potentials, ground-state magnetism, *GW* self-energy corrections, spin-orbit terms, and Coulomb interactions between the L_2 and L_3 states. The method is implemented in the OCEAN package, which uses plane-wave pseudopotential wave functions from ABINIT as a basis, a PAW construction for transition matrix elements, and a resolvent formalism for the BSE calculation. The results are in near quantitative agreement with experiment, including both fine-structure at the edges and the non-statistical L_3/L_2 ratios observed in these systems.

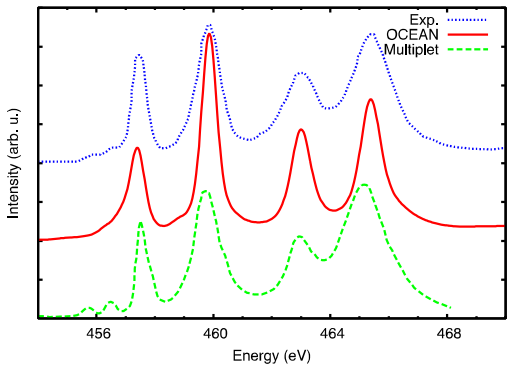
GW/BSE
+ Spin & SO
+ MPSE
+ Slater ***F, G***

Transition metal oxides





Multiplets in $SrTiO_3$



3. Charge Transfer Satellites

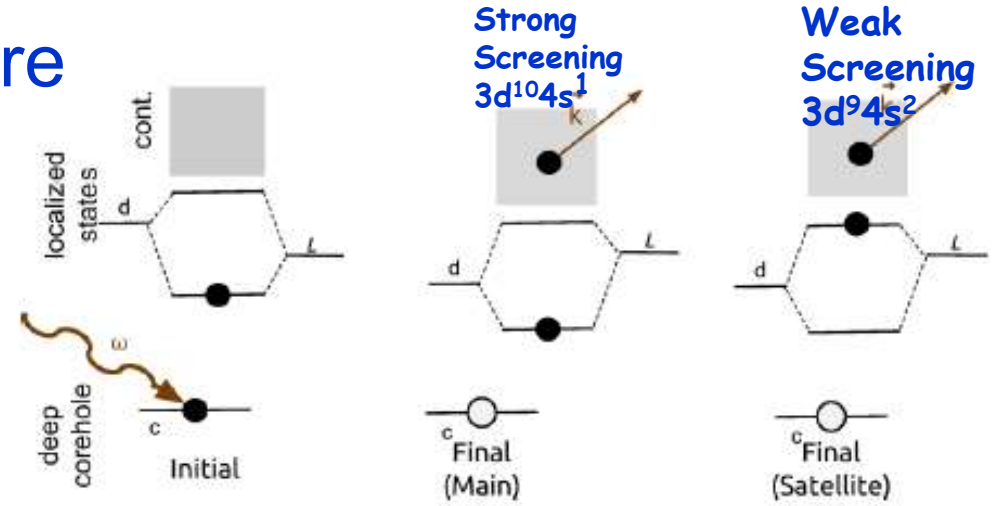
PHYSICAL REVIEW B VOLUME 60, NUMBER 11 15 SEPTEMBER 1999-I

Transition from the adiabatic to the sudden limit in core-level photoemission: A model study of a localized system

J. D. Lee and O. Gunnarsson
Max-Planck Institut für Festkörperforschung, Heisenbergstrasse 1, D-70569 Stuttgart, Germany

L. Hedin
Max-Planck Institut für Festkörperforschung, Heisenbergstrasse 1, D-70569 Stuttgart, Germany and Department of Theoretical Physics, University of Lund, Sölvegatan 14 A, S-223 62 Lund, Sweden

2-state picture



Approaches: Anderson impurity, DMFT, multiplets, ….

+ Lots of **Sound & Fury +** millions of cpu hrs

BUT still no satisfactory 1st principles theory …

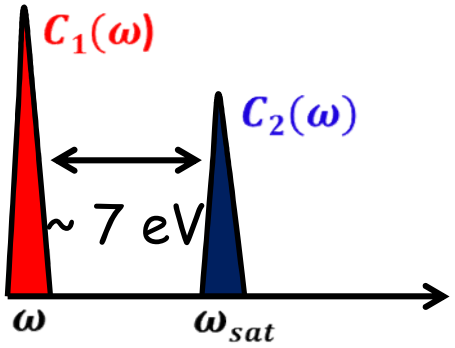
Simple picture: 2-state model of LGH*

PHYSICAL REVIEW B 89, 085123 (2014)

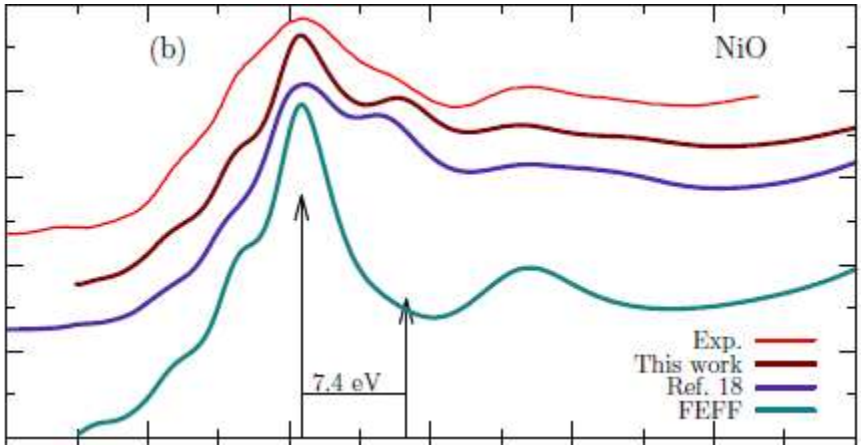
Charge transfer satellites in x-ray spectra of transition metal oxides

E. Klevak, J. J. Kas, and J. J. Rehr
Department of Physics, University of Washington, Seattle, Washington 98195, USA

$$H = \sum_{i\sigma} \varepsilon_{i\sigma}^{DFT} n_{i\sigma} + \sum_{ij} U_{ij} n_{i\uparrow} n_{j\downarrow} + t(c_{3d}^{\dagger} c_{4s} + c_{4s}^{\dagger} c_{3d})$$

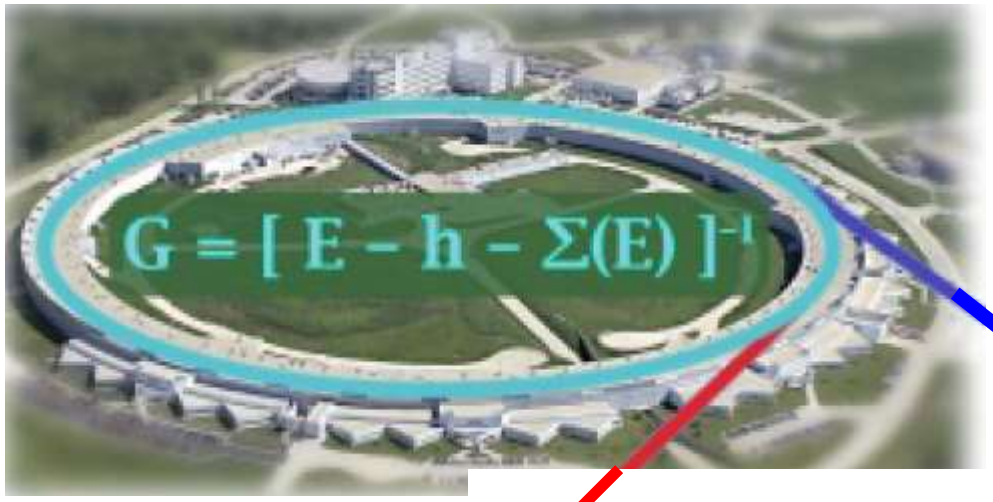


XAS NiO



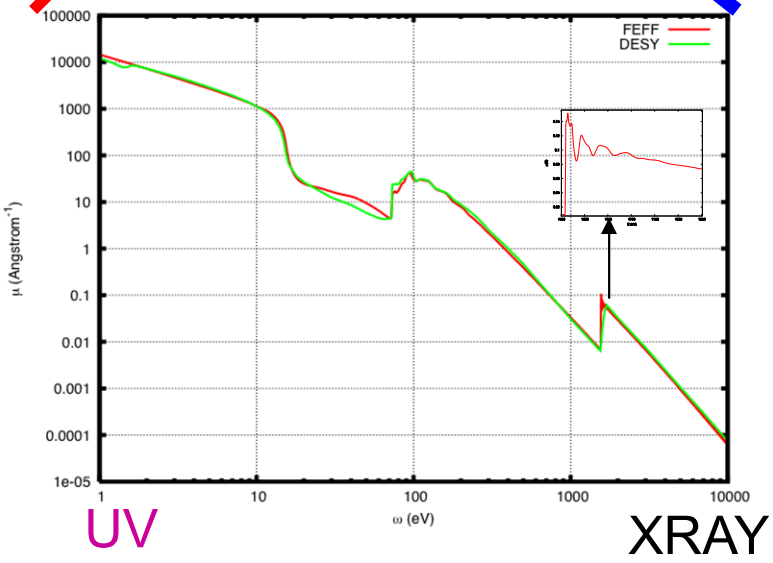
*Lee, Gunnarsson & Hedin, Phys Rev B **60**, 8034 (1999)

Goal: X-ray Spectroscopy Beamline



XAS
XES
XMCD
NRIXS
RIXS
etc.

Full spectrum theoretical tools

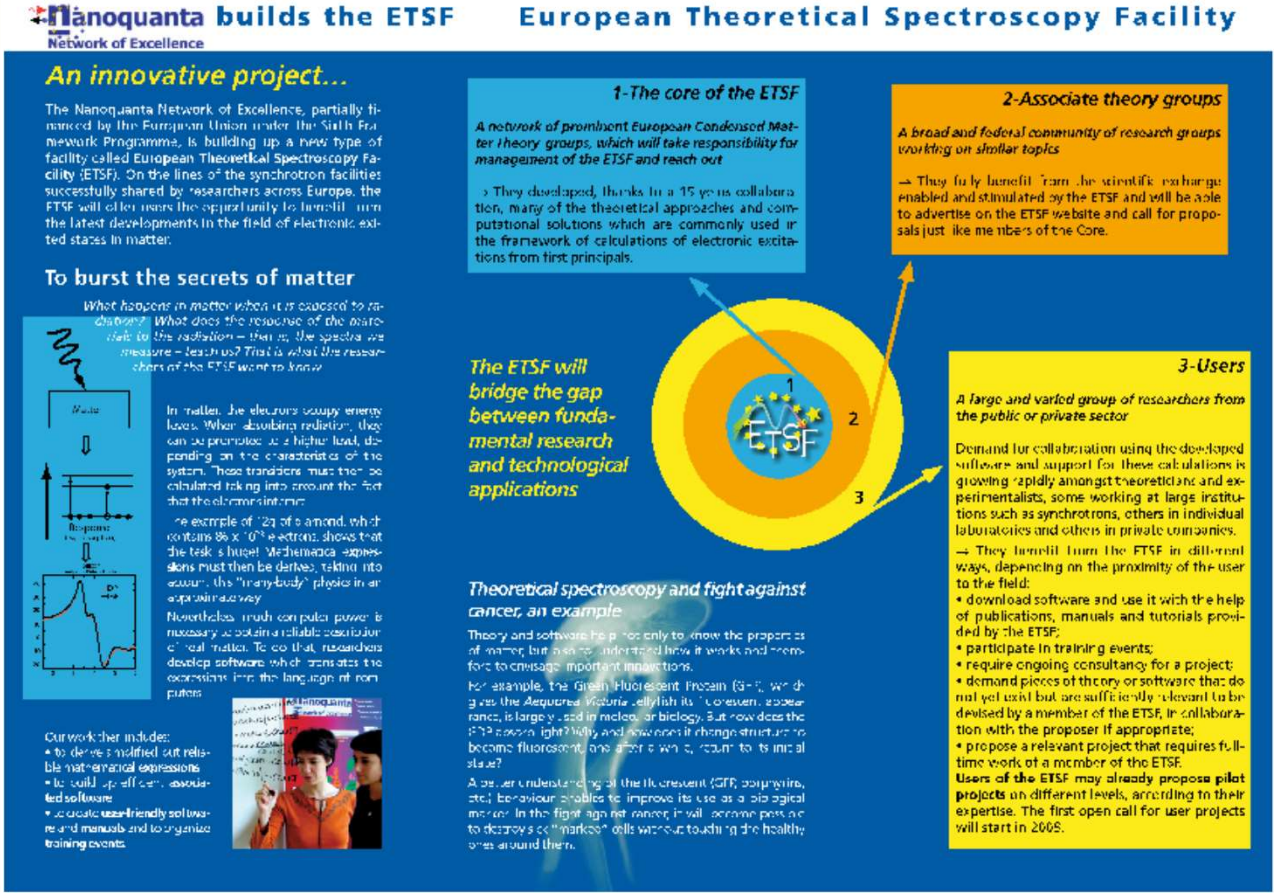


UV XRAY

EU Model

European Theoretical Spectroscopy Facility

www.etsf.eu



Networked “theoretical beamlines”

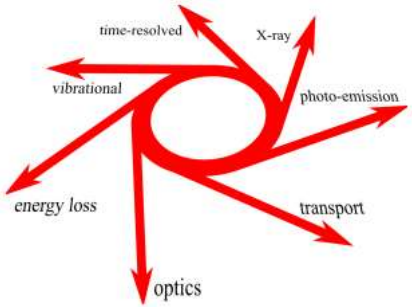
Home

Beamlines

The ETSF is divided into 7 beamlines, each of which is concerned with a specific scientific topic. A beamline coordinator is responsible for the contact with the users of each line. He/She also serves as the contact person for users who want to submit a proposal to the ETSF.

Further details are available on the beamlines' description.

Beamlines and Coordinators



Optics

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Quantum Transport

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Time-resolved Spectroscopy

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Photo-emission Spectroscopy

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Vibrational Spectroscopy

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X-Rays Spectroscopy

Prof. John Rehr
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