High energy electron-ion and photon-ion collisions: Status and challenges

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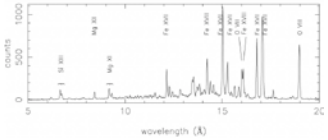
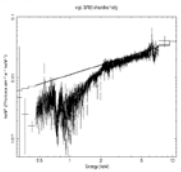
Acronym list

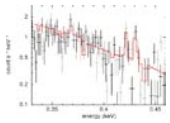
- Electron-ion collisions
  - Electron impact ionization: EII
  - Electron impact excitation: EIE
  - Dielectronic recombination: DR
- Photon-ion collisions
  - Photoioionization: PI
  - A-values/oscillator strengths: PE

Laboratory astrophysics is motivated by observations

- Observations:
  - Ground based
  - Solar
  - X-ray (ASCA, Chandra/XMM..)
  - UV (IUE, HST GHRS, FOS, STIS..)
- Source classes:
  - Coronal →electron-ion processes
  - Photoionized → photon-ion processes
  - Atmospheres → Near-lte







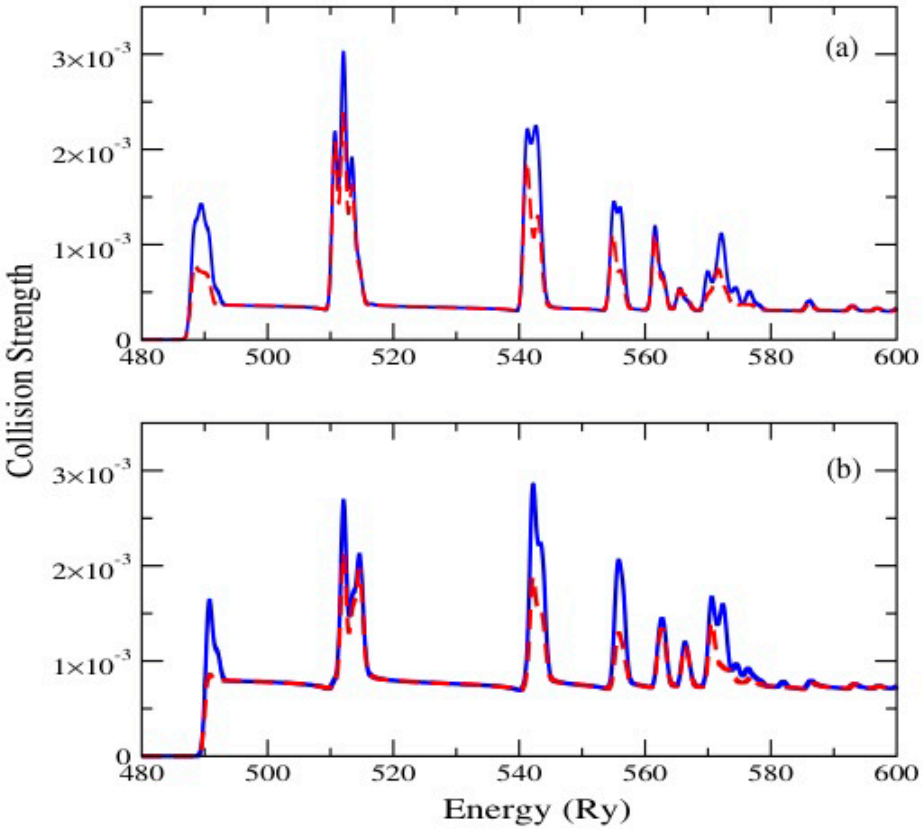
Electron impact excitation (EIE)

$e^- + X_i \rightarrow X_i^*$

- Modeling collisional radiative modeling requires data for many transitions → calculations are key
- This involves calculations of structure and scattering
- lab measurements can serve as important benchmarks
- Distorted wave (DW) remains workhorse for many purposes
- Various useful tools are in use: autostructure, rmatrix, dw, hullac/fac, grasp/darc
- Lab measurements are needed for accurate wavelengths and line IDs

Effect of damping in EIE

- Fe $^{24+}$ $1s^2$ – 1s2s, 1s2p(^{2}P).
- red=with damping, blue=without
- Damping effect is strong for excitation to low n
- Weaker for high n

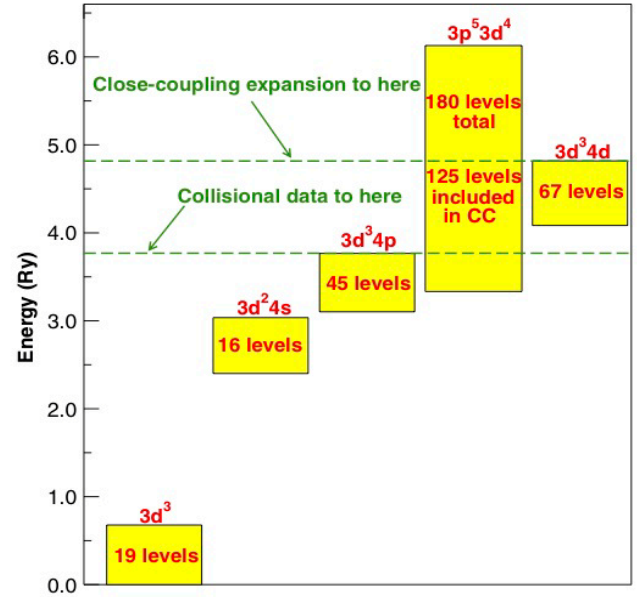


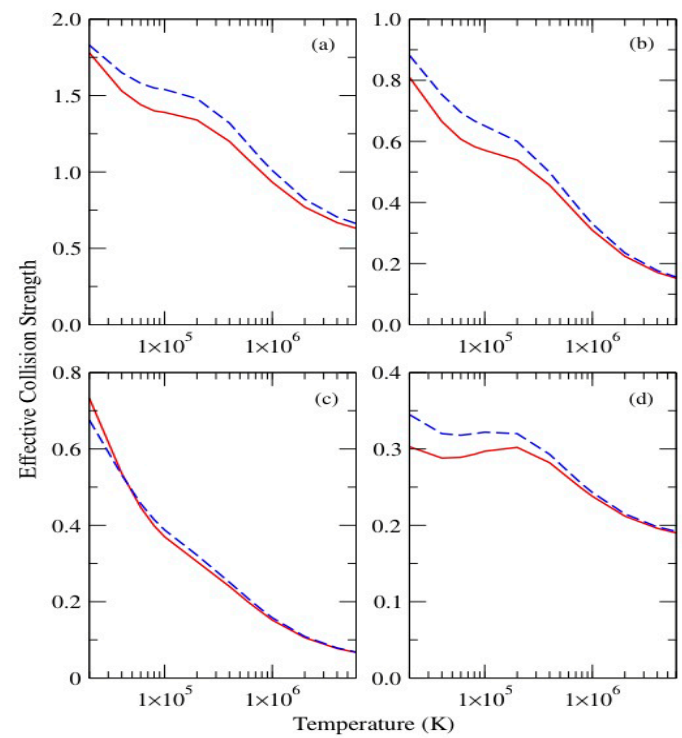
(Griffin and Balance 2009 JPB 42 235201)

Effect of configuration interaction size in EIE

- Dirac R-matrix (DARC) calculation of EIE in Fe^{5+}
- Ground is $3p^6 3d^4$
- 328 levels include 4s + one $3p^5$
- 1728 includes two $3p^4$ configurations
- 328 levels (dashed) vs. 1728 levels (solid)
- Shows ~10% effects on upsilon

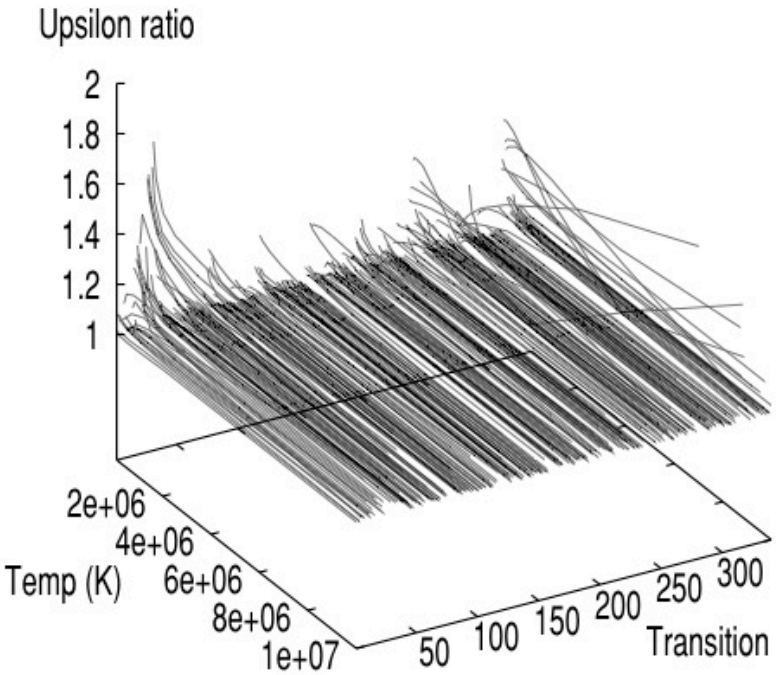
(Ballance and Griffin 2008 JPB 41 195205)





Relativistic effects in EIE

- Dirac vs. BPRM for Fe^{14+}
- Shows the level error associated with BPRM
- Departures show at low temperatures, close to threshold

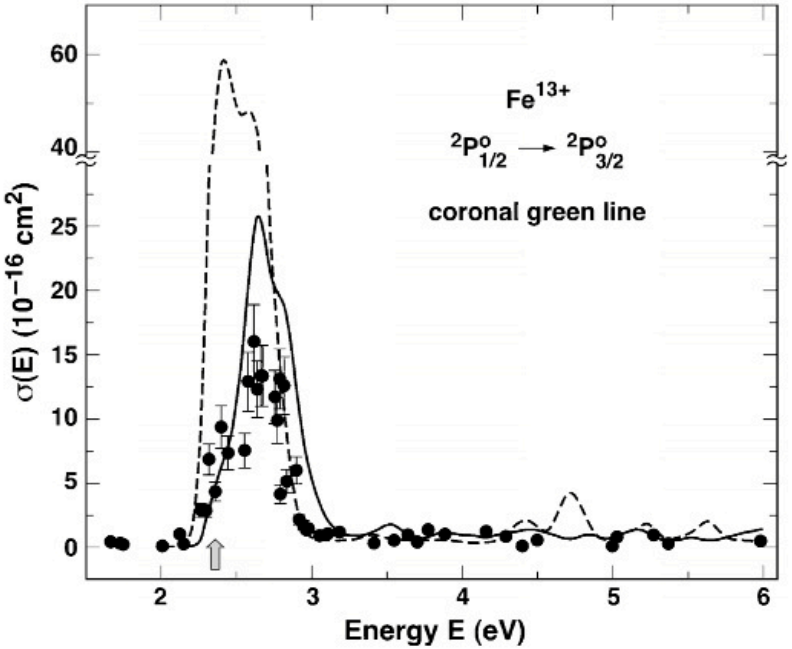


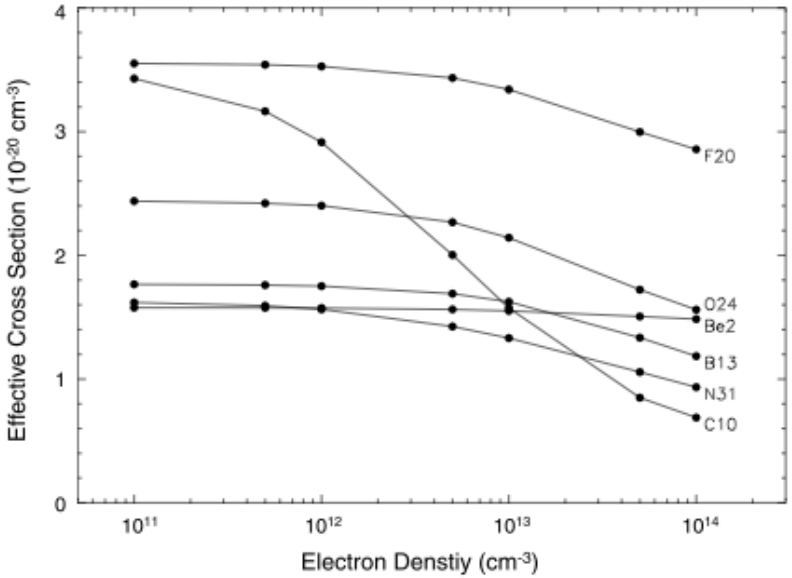
(Berrington et al.2005 JPB 38 1667)

(Hossain et al. 2007 Phys Rev A 75 22709)

Absolute measurements of EIE

- Energy loss measurement in jpl merged beam
- Fe $^{13+}$ coronal green line
- Structure comes from direct excitation resonances
- compared with 135 level BPRM, 14 state ls R-matrix
- Also LLNL EBIT measurements of Fe^{17+} - Fe^{23+}
- Determine absolute cross sections by normalizing to recombination emission

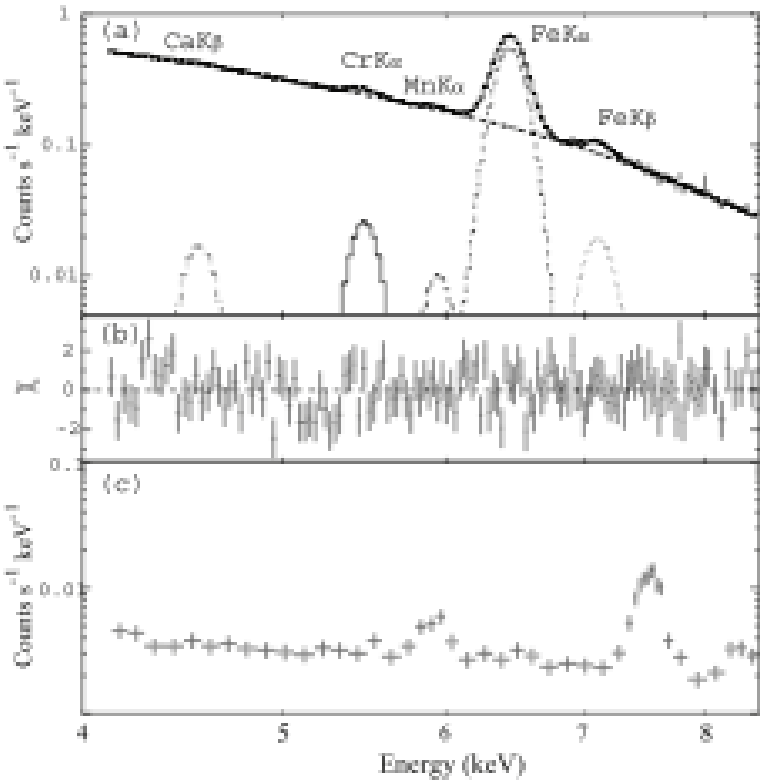




(Chen et al. 2006 Apj 646, 653)

Suzaku spectrum of Tycho SNR

- Detection of Cr, Mn Kα lines is very constraining to SNR models
- Line energies (based on isoelectronic interpolation) → ~Na-like ions
- Implies large NEI effects
- Need for atomic data for EIE of Kα



(Tamagawa et al. 2009 PASJ 61 167)

The frontier: EIE

- Calculations
  - highly-ionized, heavy ions → relativistic effects
  - near-neutral, heavy ions → structure is difficult and large CI is needed
  - Rmatrix challenges: need large CI expansion, resolving resonances, resonances → less accurate at low energy
- Experiment:
  - needed for benchmarking
  - Absolute measurements are challenging
- Inner shells

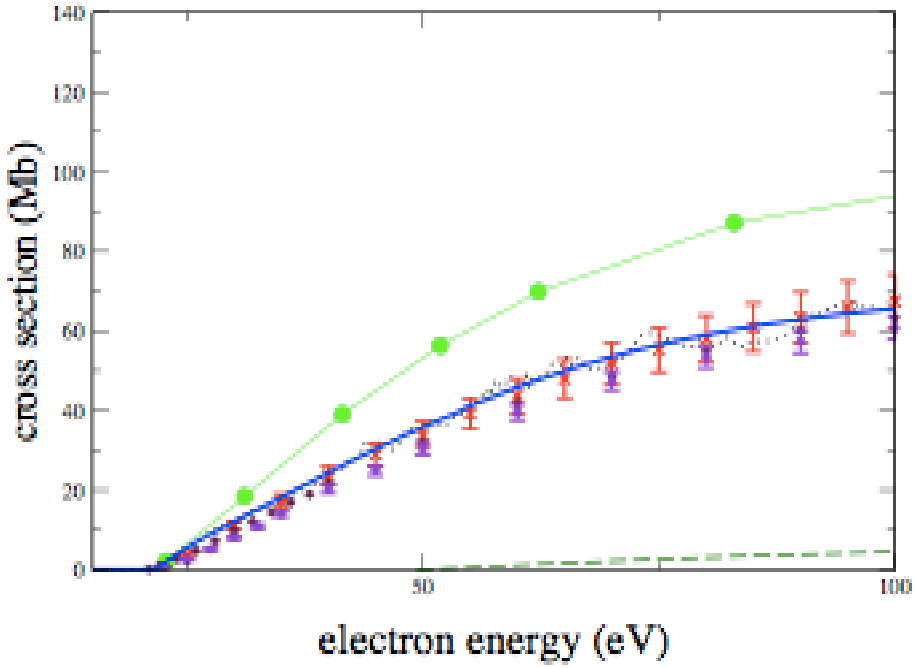
Electron impact ionization (EII)

$e^- + X_i \rightarrow X_{i+1}$

- Important for many astrophysical problems
- Quantity of data needed is limited → experiments can produce all or most
- Many experiments, eg. ORNL
- Compilations by Arnaud and Rothenflug → Dere, rev. by Bryans
  - Motivated by distorted wave (DW) calculations
- Experiments are affected by metastables, excitation-autoionization (EA)

DW overestimates EII for low charge states

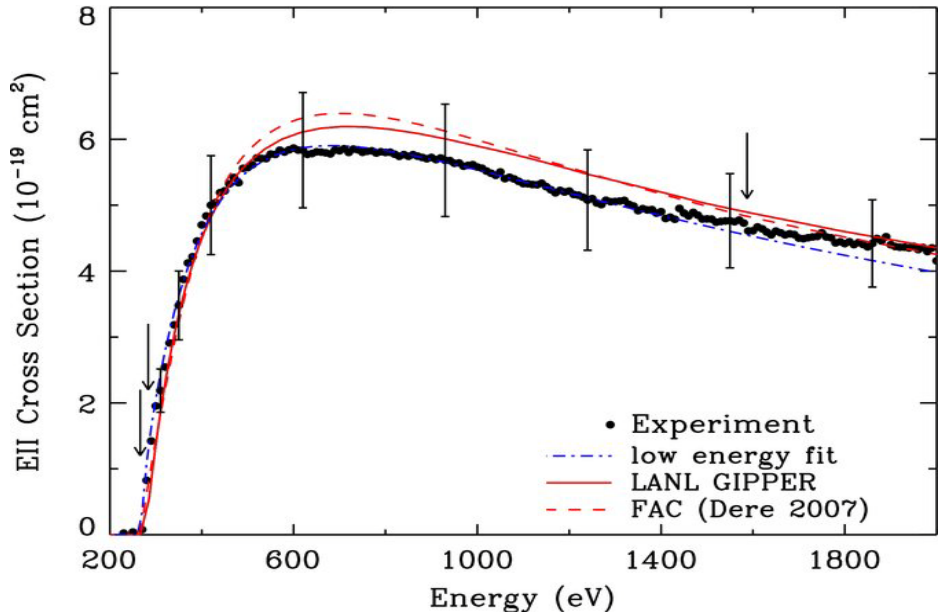
EII of Ne^0
DW (green) +expt +
RMPS (blue)

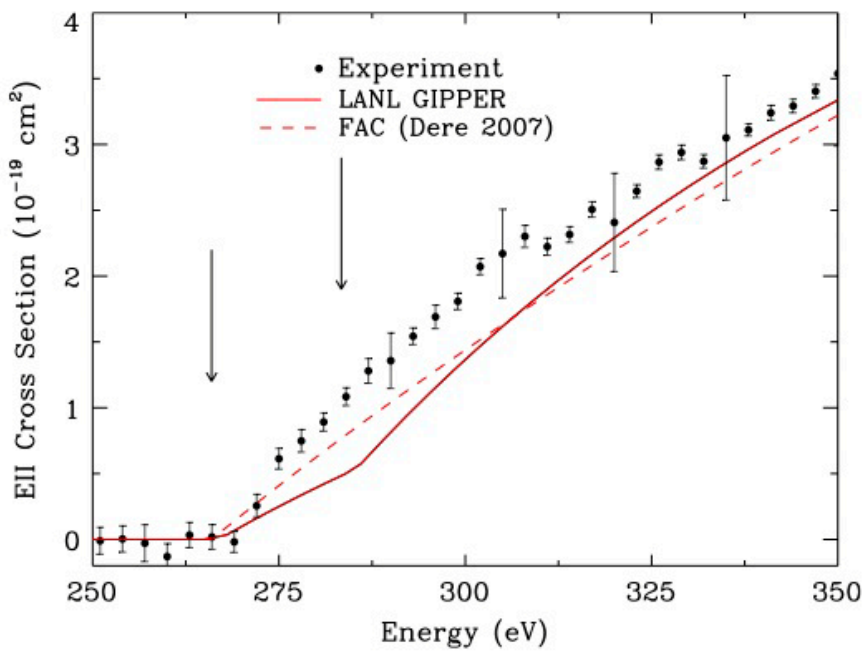


(Ballance et al. 2009 JPB 42 175202)

Measurements of EII with Heidelberg storage ring (TSR)

- $Mg^{7+} \rightarrow Mg^{8+}$
- Campaign to benchmark theory for all isosequences
- Storage ring allows low metastable fraction
- Compare with DW calculations





Hahn et al. 2008 Ap J. 712 1166

The frontier: EII

- Computations:
  - For high charge states, DW results are best available
    - But near-threshold is important
  - challenges for close-coupling methods are being met with new tools: rmps, tdcc
  - Needed for excited states
- Experiment:
  - Most important for low charge states
  - Benchmarking w/o metastables
  - inner shells/NEI conditions
  - excited levels → 3 body recombination
  - Other processes: REDA

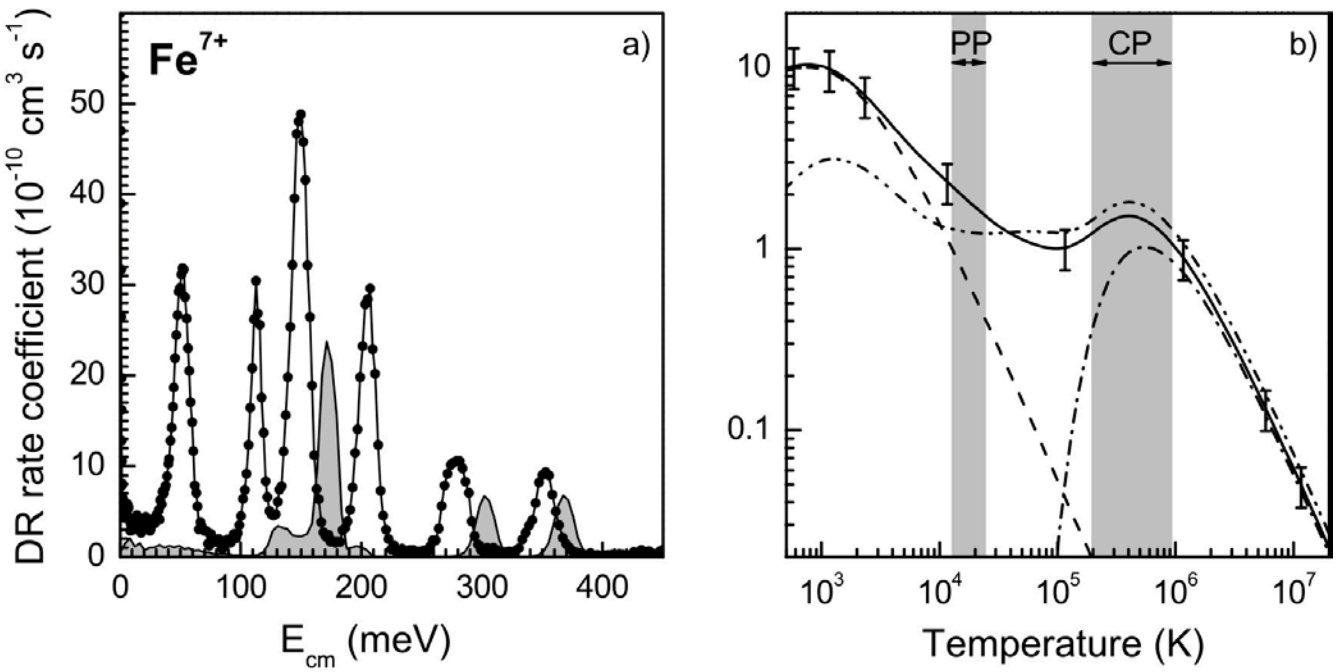
Dielectronic recombination (DR)

$e^- + X_i \rightarrow X_{i-1}^* \rightarrow X_{i-1} + \ldots$

- Traditional calculations are adequate for high temperature plasmas
- Fundamental work by Burgess + compilations
- At low temperature, calculations do not have sufficient precision
- Experiments have proven to be crucial: TSR
- Recent campaign by ADAS

DR measurements using Heidelberg storage ring (TSR)

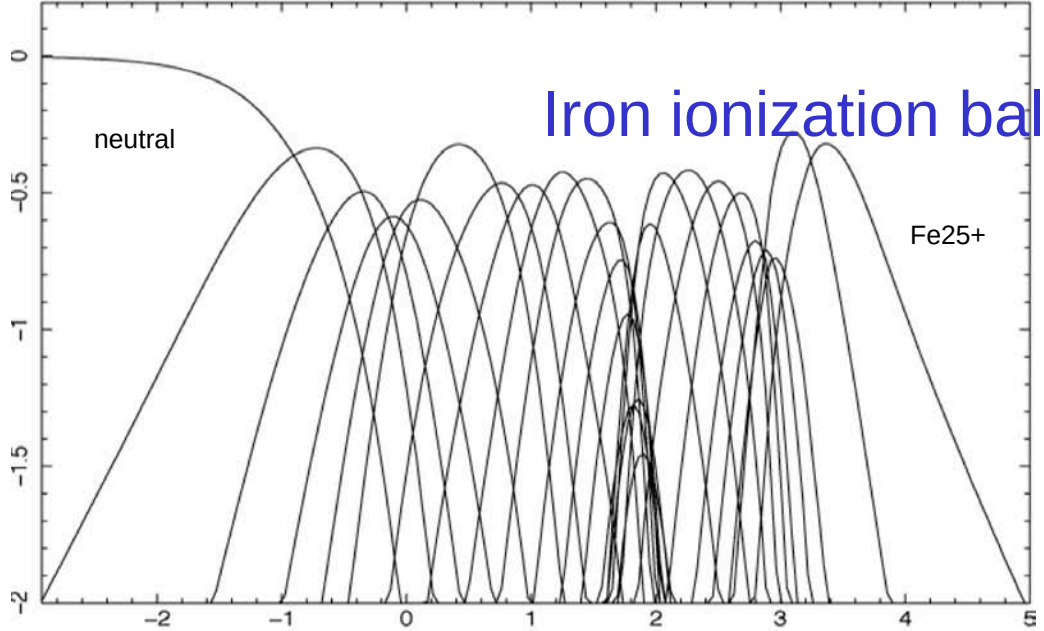
- Measurements provide key validation for calculations
- Low relative speed of ion, e^- allows measurements of near-threshold cross section
- Measurements for Fe are being pushed to low charge
- Have now measured DR for Fe^{7+} - Fe^{10+} using TSR



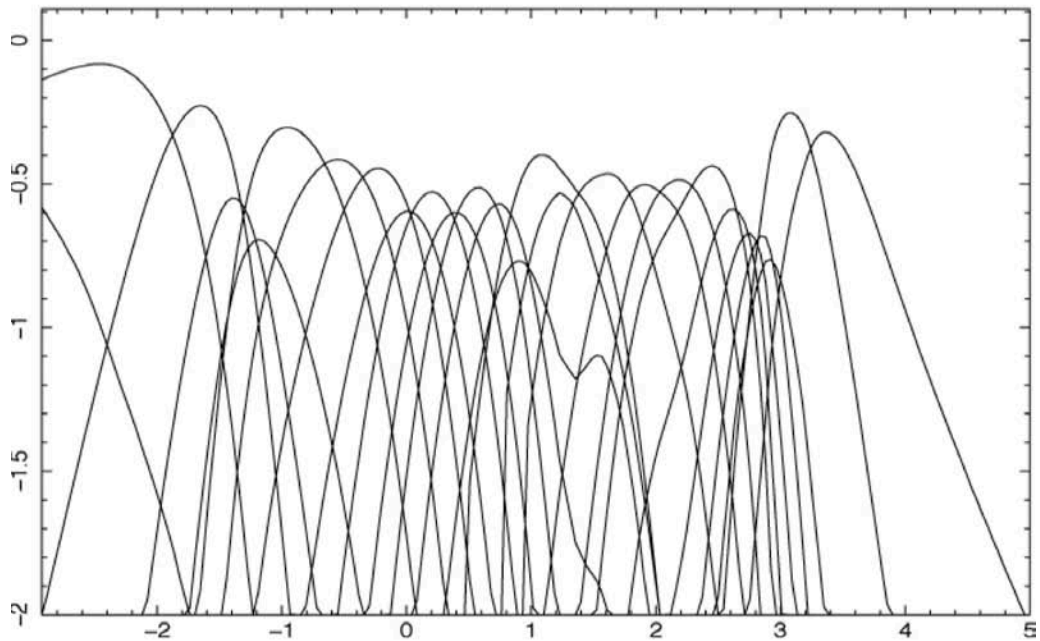
(Schippers et al. 2010 Archiv:1002.35678)

Iron ionization balance

New DR
(ADAS, TSR)



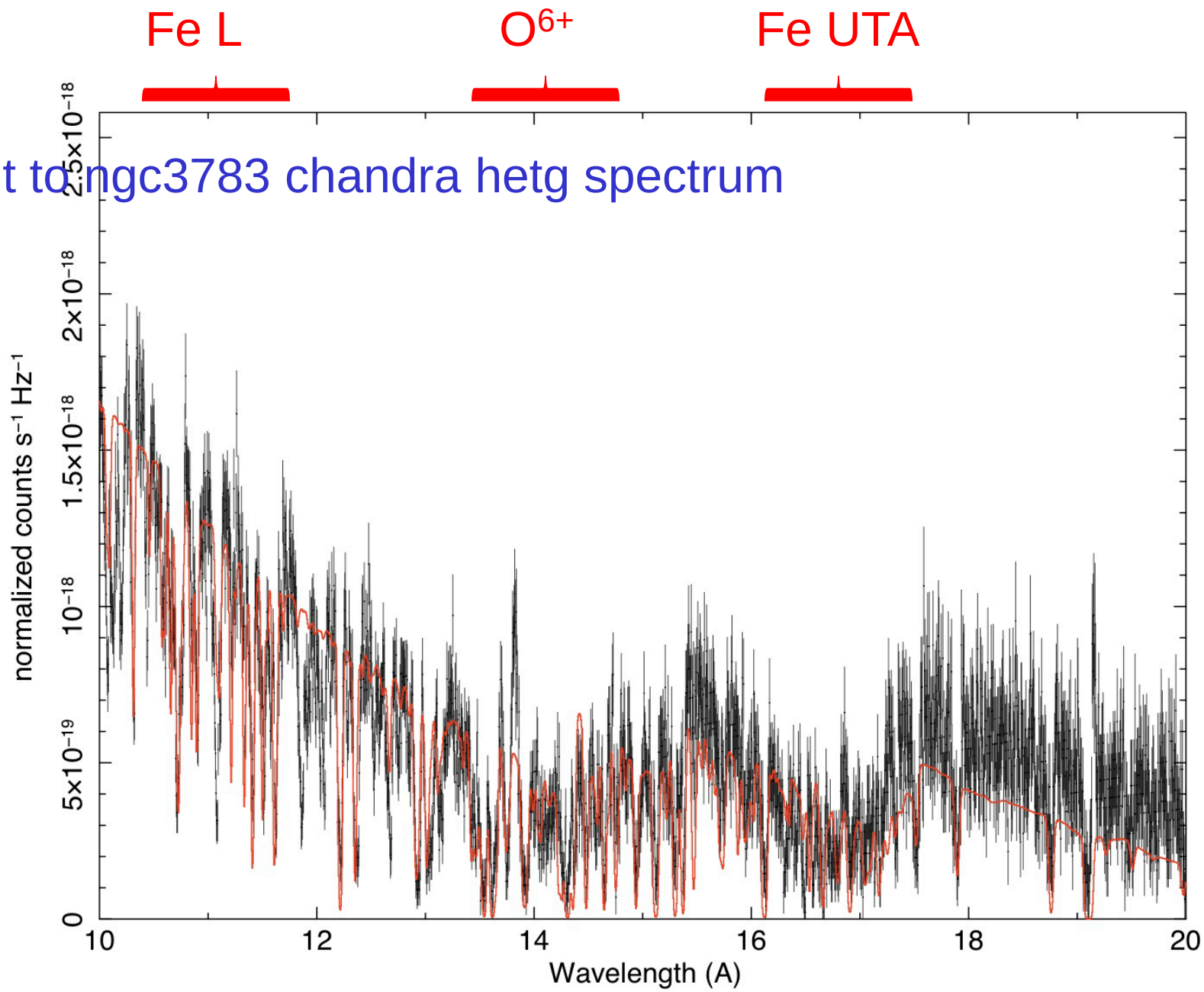
Old DR



logξ

ξ~x-ray flux/gas density

Fit to ngc3783 chandra hetg spectrum



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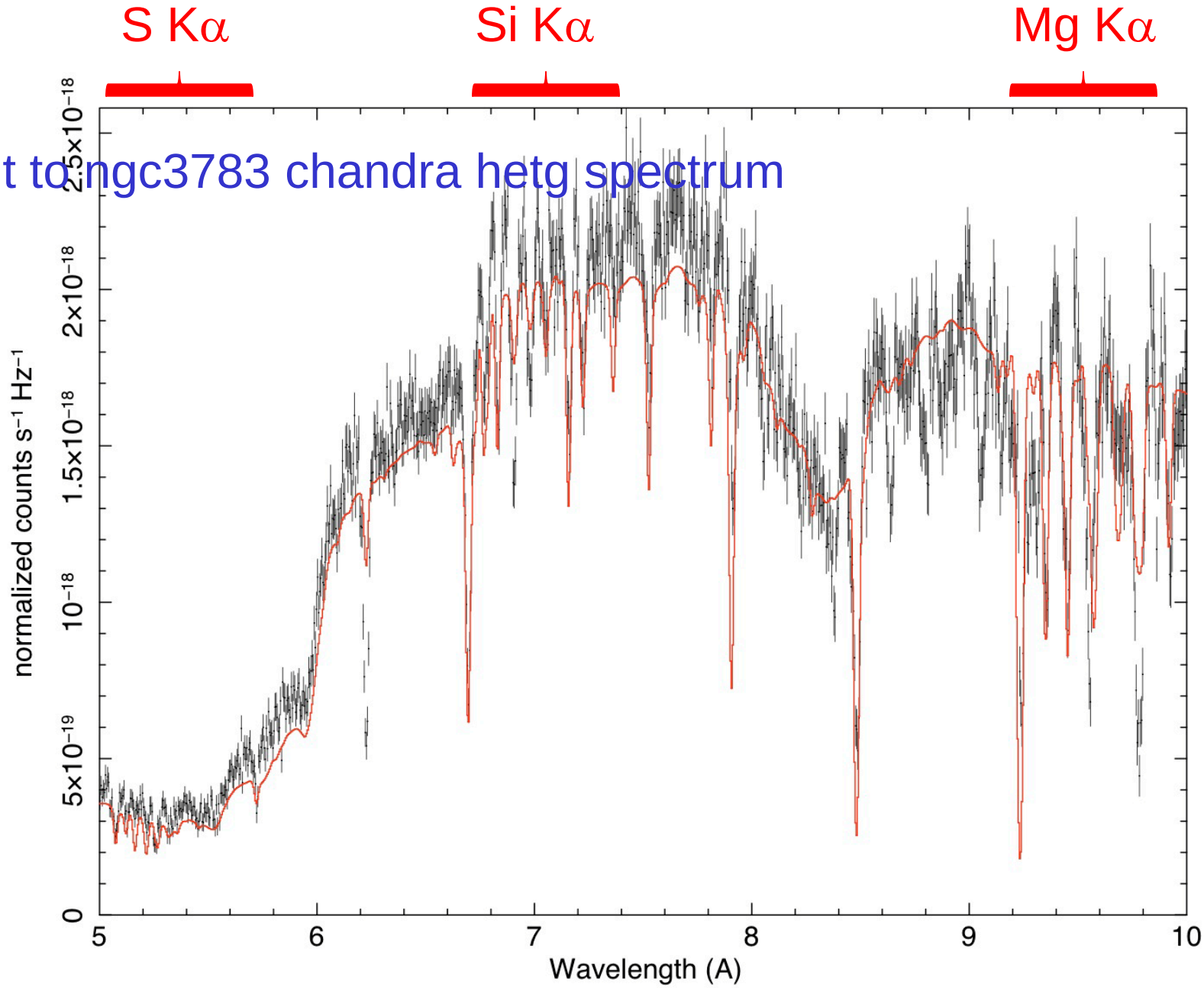


The frontier: DR

- High temperature DR is ~adequately represented by burgess formula
- For low T DR:
  - low charge states still challenging
- The frontier:
  - NEI conditions
  - Other elements (fe peak)

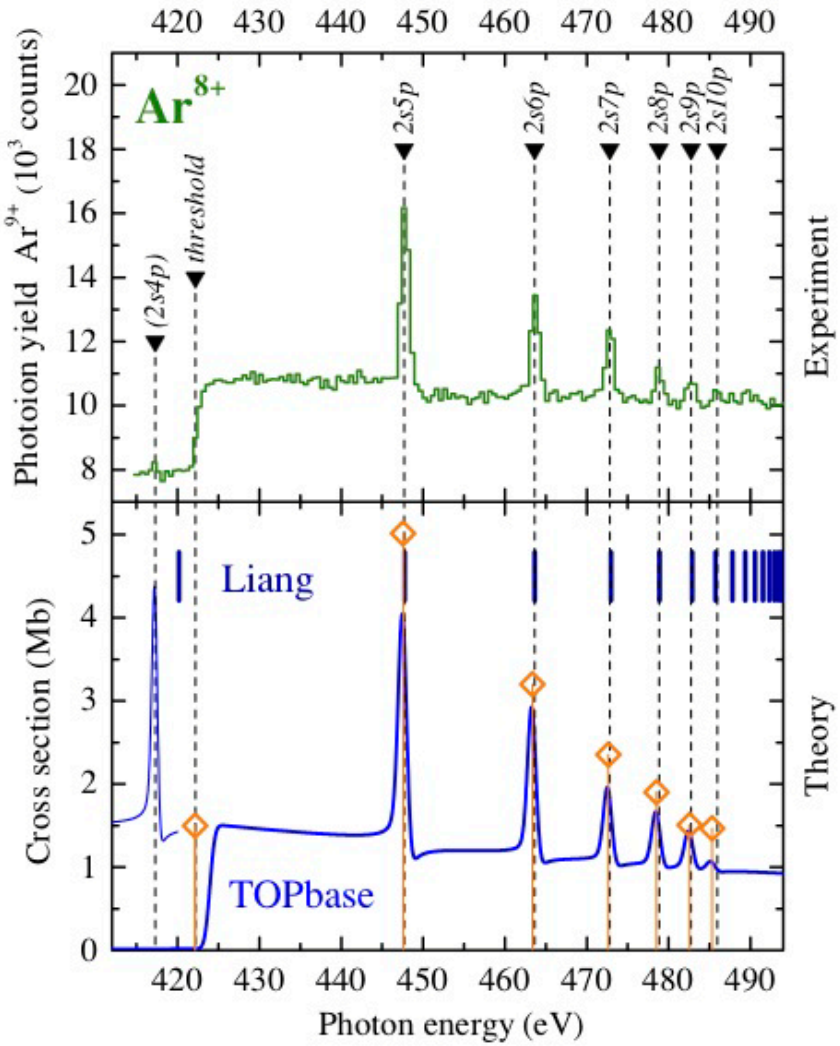
Photoionization (PI)

$h\nu + X_i \rightarrow X_{i+1}$

- The rate coefficient (can) sample all parts of cross section
- Campaign of calculations by opacity project (OP)
- +inner shells, intermediate coupling
- High resolution experiments are coming

Ebit measurements of PI in Ar^{8+}

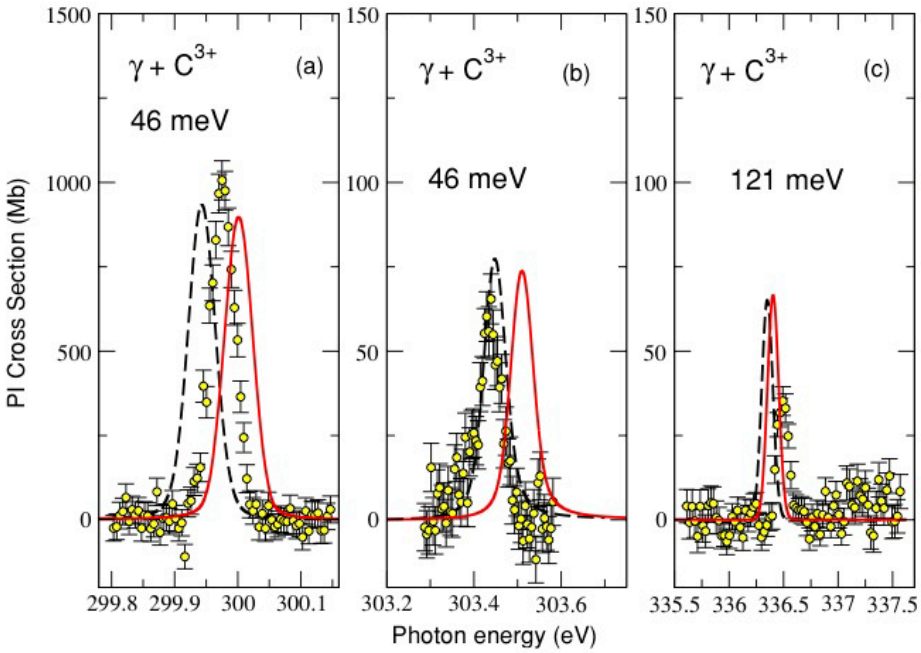
- 'portable' ebit at Hamburg light source
- Direct measurement of photoionization
- compare with mcdf calculations
  - Test for threshold
  - Resonance energies
  - strengths
- Anticipate more measurements at ICSLS



(Simon et al. 2010 JPB 43 065003)

K shell PI in C^{3+}

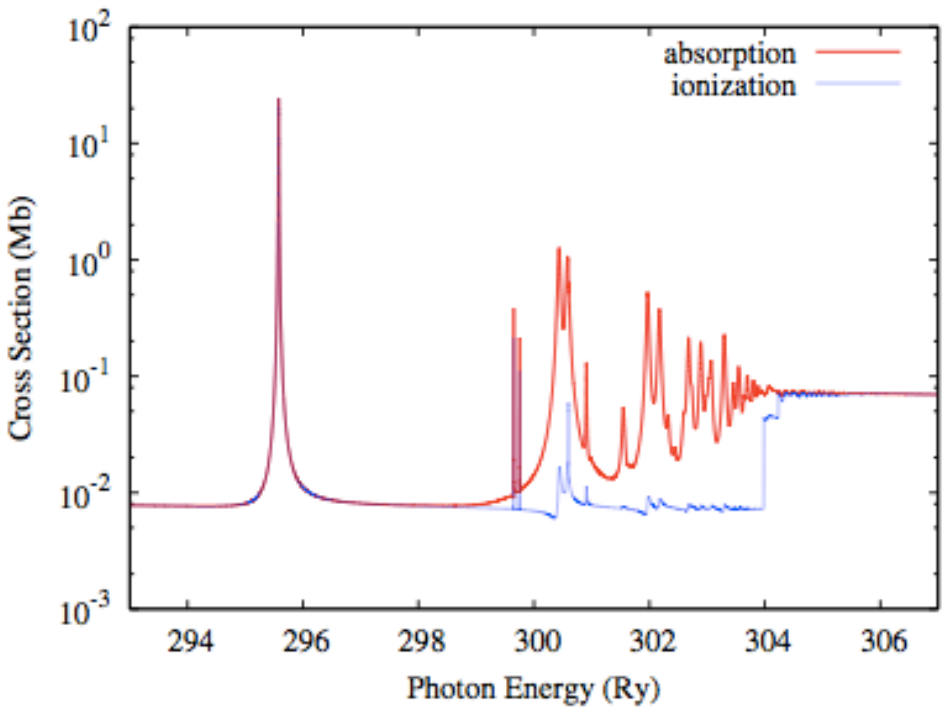
- ALS IPB experiment
- Allows measurement of autoionizing width → challenges to calculations
- Provides independent check on resonant position/width from storage ring expts.
- Measurements have been made on other light ions
- Limitation comes from ALS beam energy



(Muller et al. 2009 JPB 42 235602)

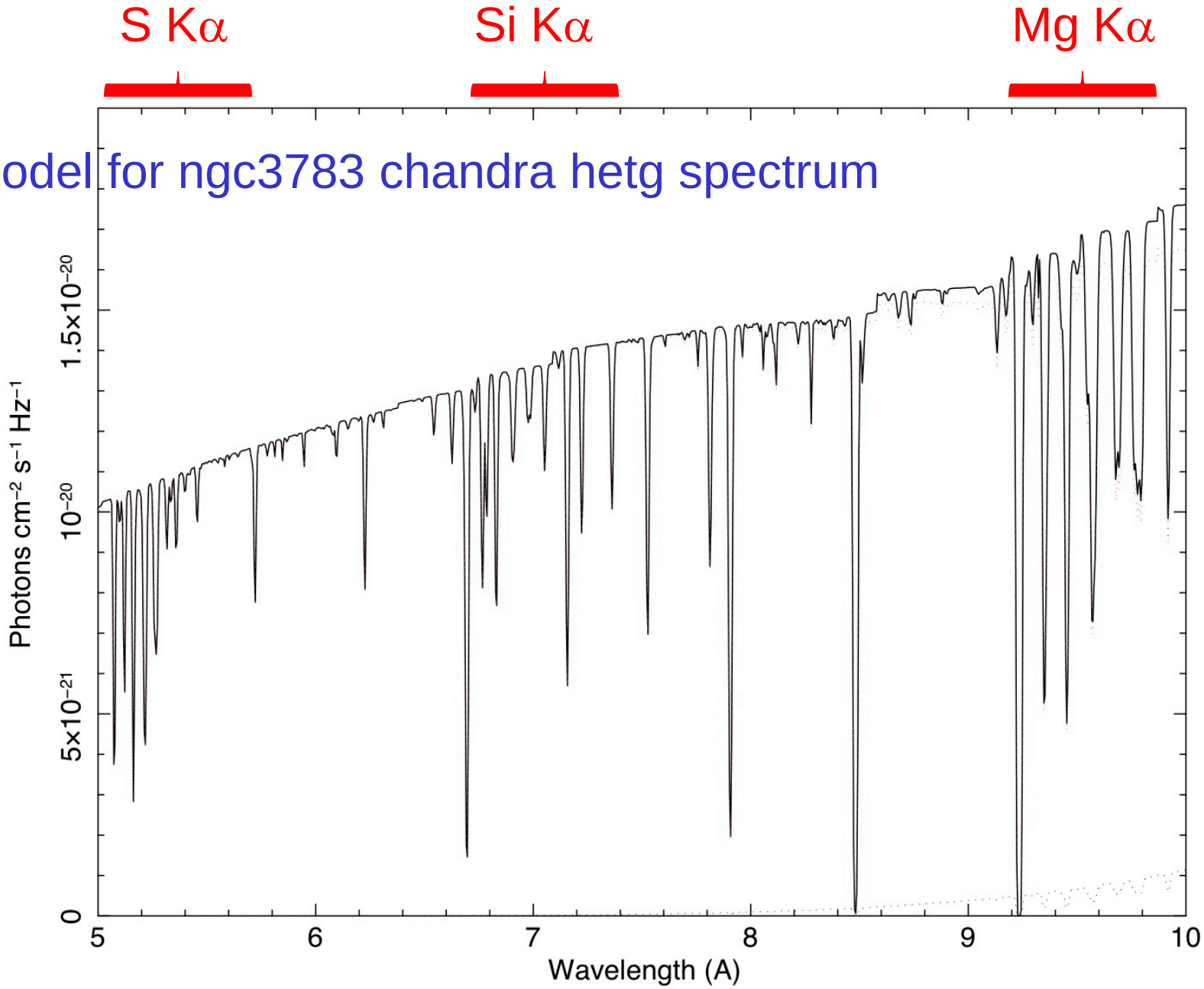
Effects of damping in near-threshold K shell PI

- Inner shell PI affected by photoexcitation to np levels
- These can decay via Auger involving L shell electrons
- 'spectator' Auger leads to a series of broad closely spaced resonances near threshold
- These are apparent in photoabsorption (red) vs photoionization (blue)
- Auger decay leads to ionized final state
- Example shown is Ca^{3+}

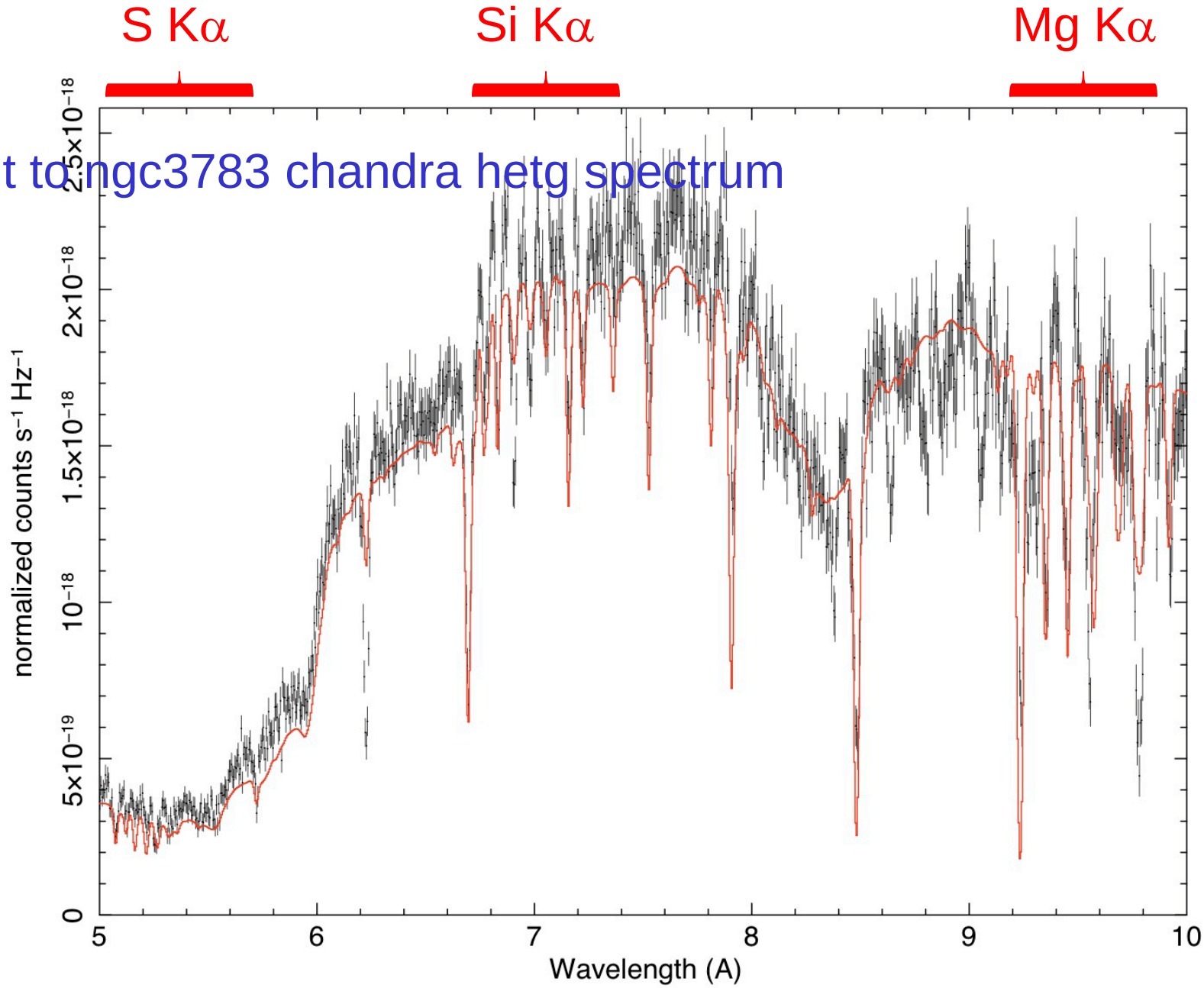


(Witthoeft et al. 2010 Archiv:1010.3734)

Model for ngc3783 chandra hetg spectrum

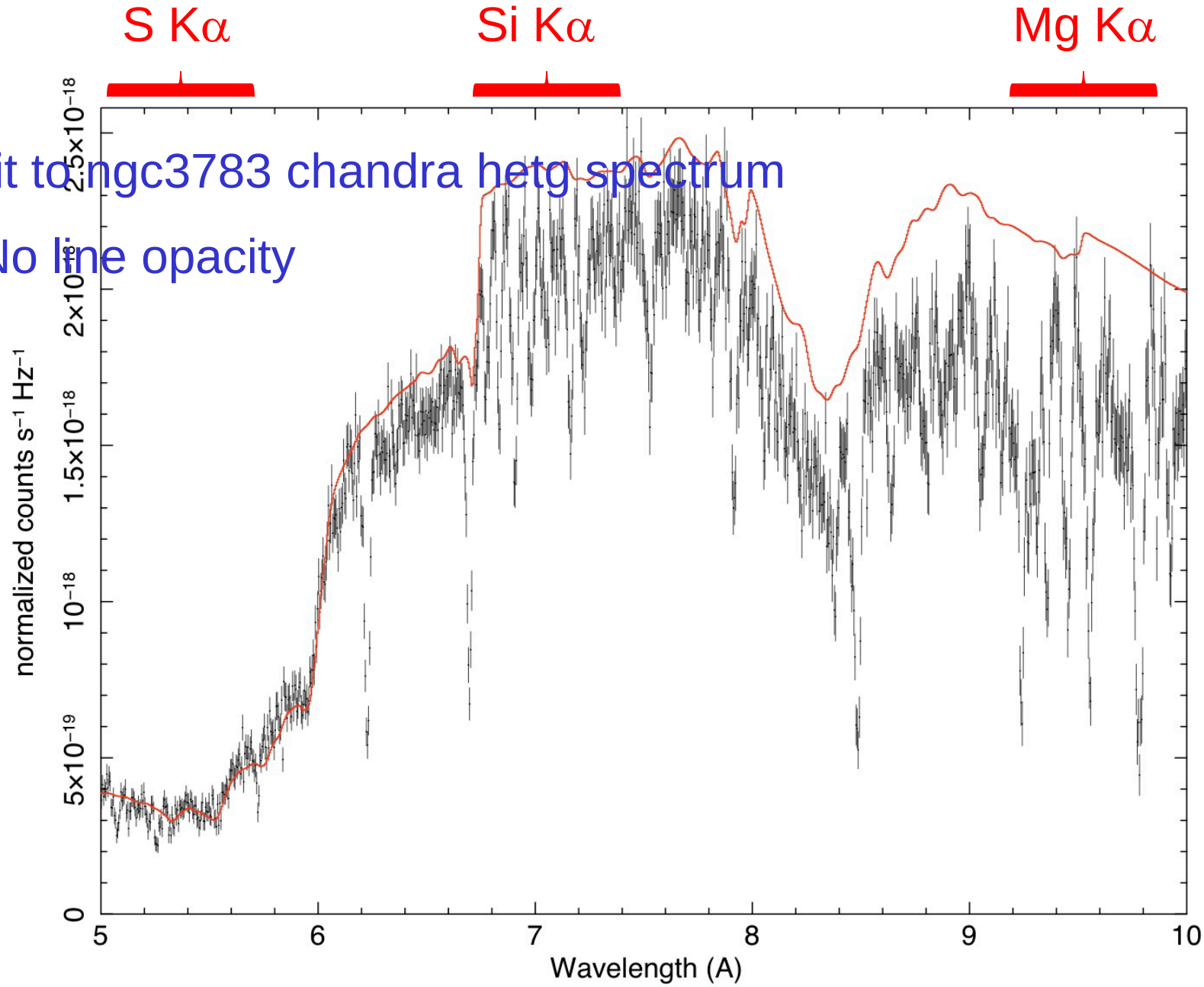


Fit to ngc3783 chandra hetg spectrum



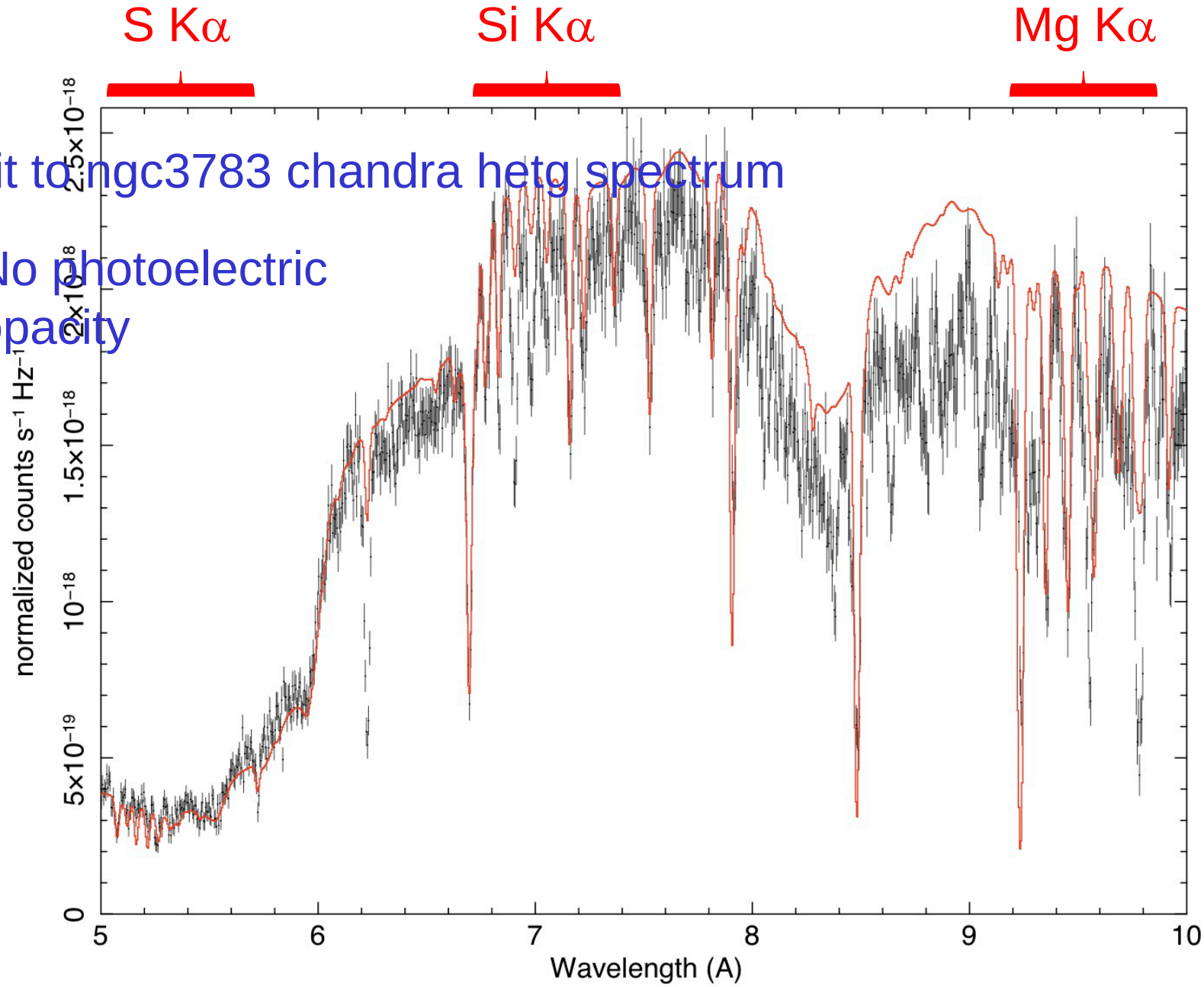
Fit to ngc3783 chandra hetg spectrum

No line opacity



Fit to ngc3783 chandra hetg spectrum

No photoelectric opacity



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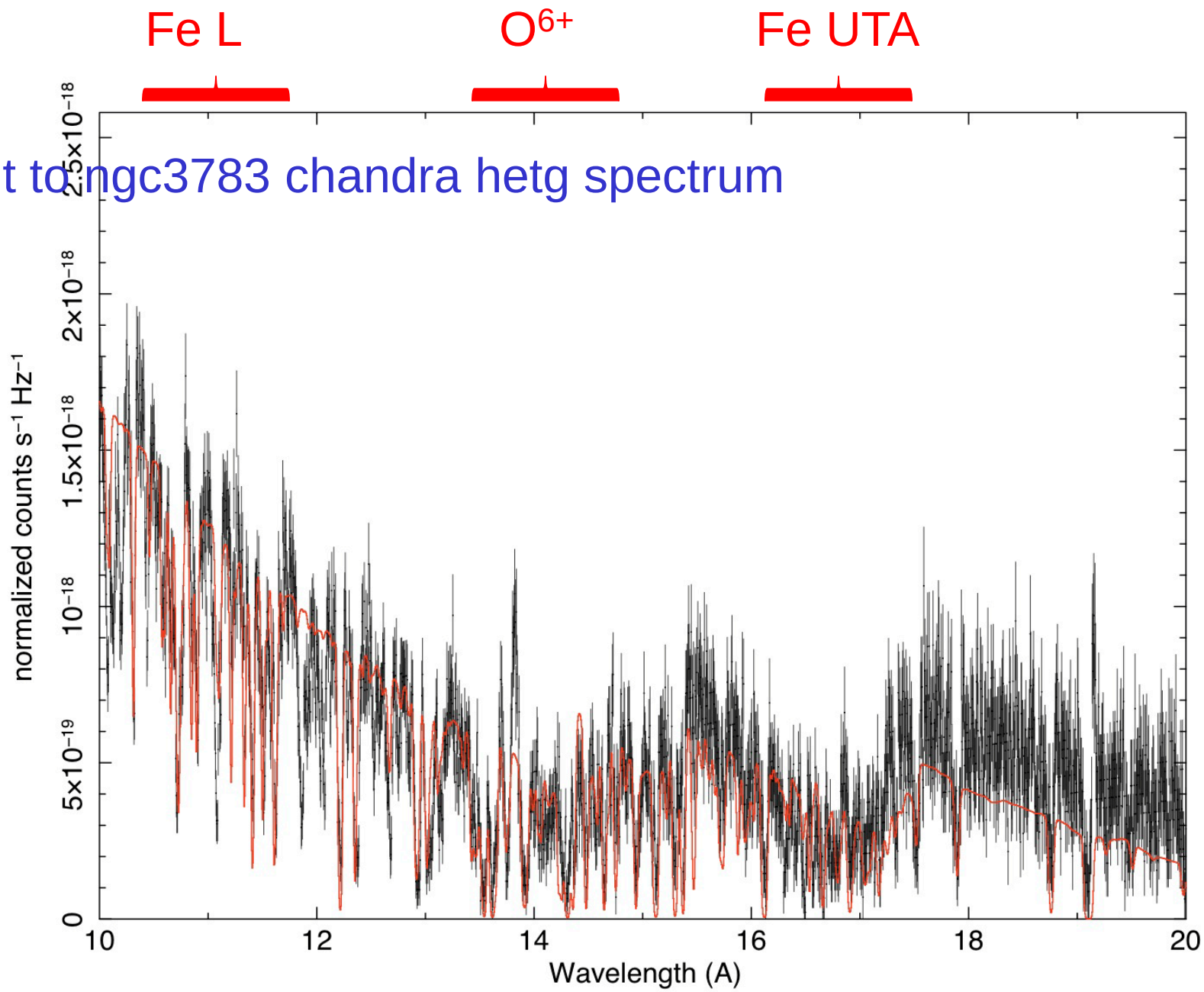
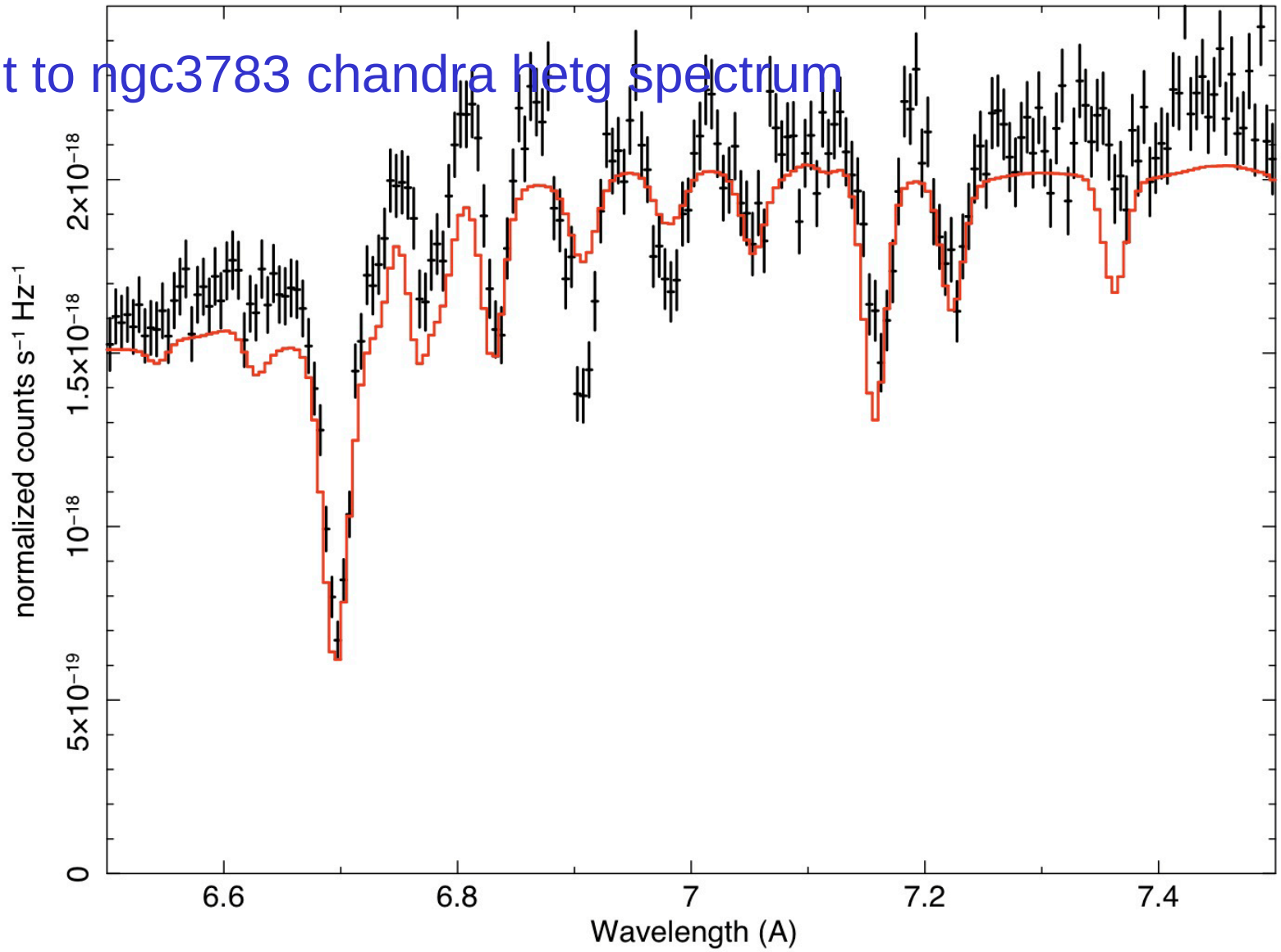


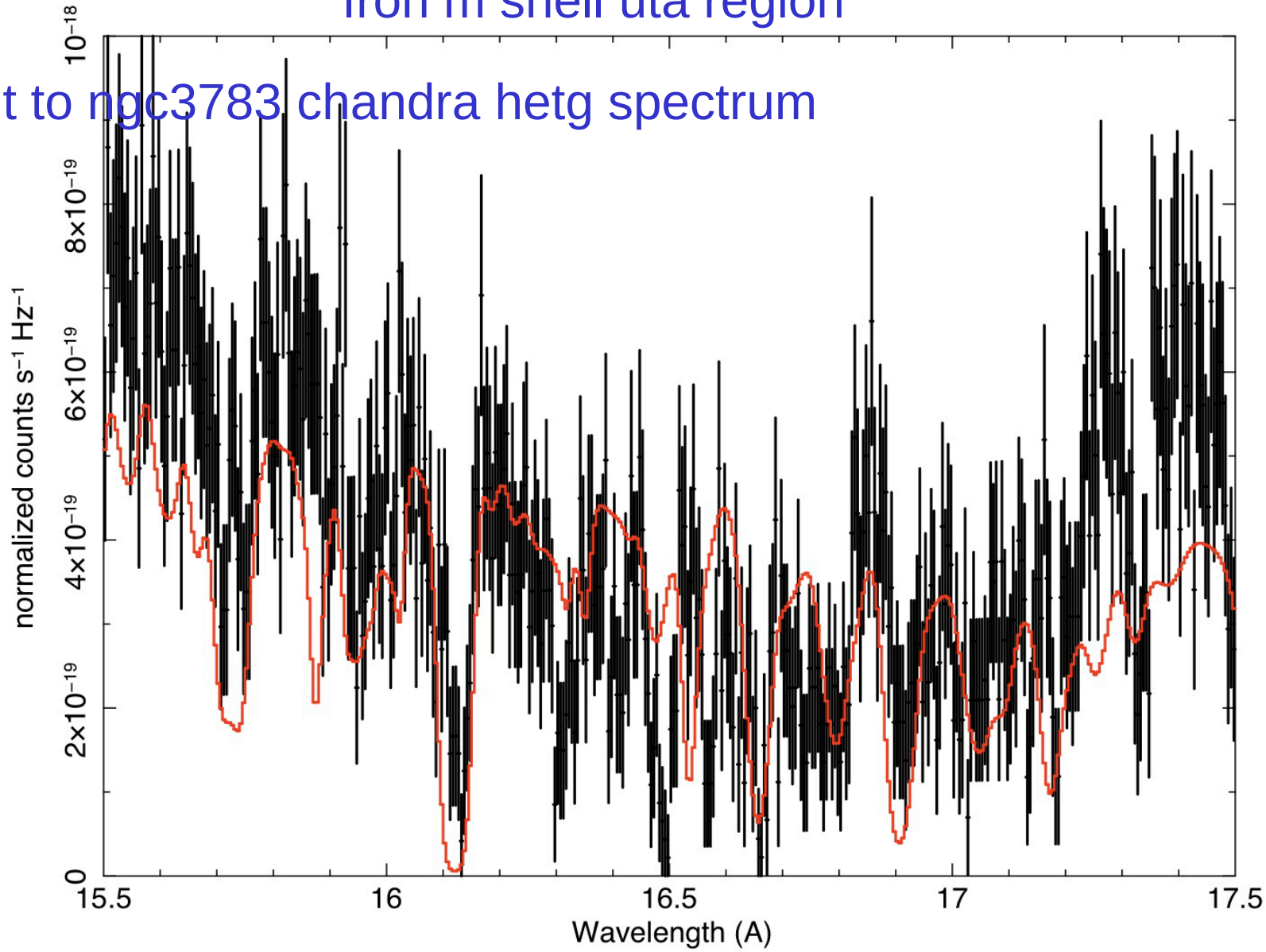
Si Kα region

Fit to ngc3783 chandra hetg spectrum



Iron m shell uta region

Fit to ngc3783 chandra hetg spectrum

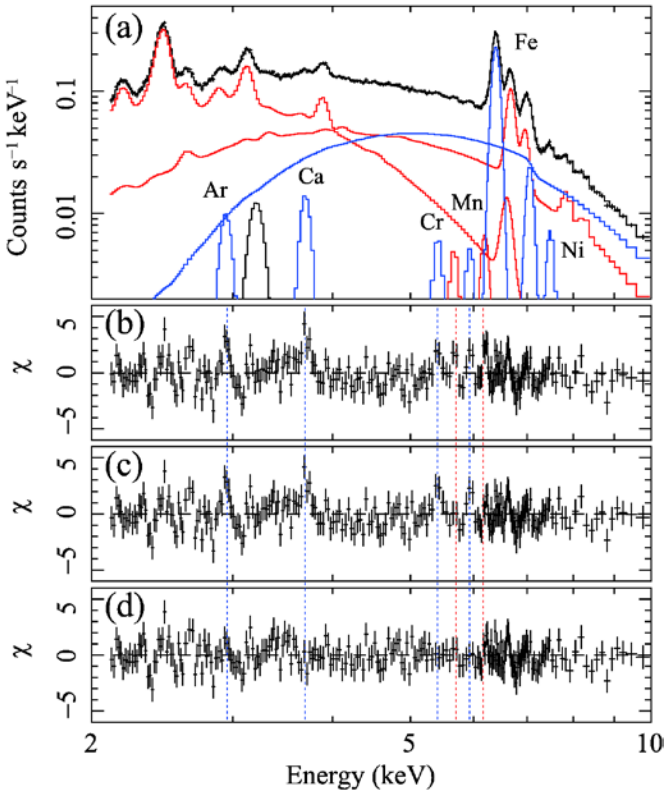


The frontier: PI

- Challenges to computations:
  - Relativistic effects
  - CI size
- Excited level cross sections are needed
  - for RR, line emission
- Inner shells are important
  - Spectator resonances
  - core relaxation, non-orthogonal orbitals, large CI
- Experimental benchmarking is taking off, due to new light sources → surprises
- Plus: we still need accurate transition wavelengths! We can't make use of diagnostics, eg. M shell UTA
- Neutrals: cf. ISM
  - Challenging to computations

Detection of iron peak lines from galactic center

- Suzaku observations find statistically significant features in Fe K region
- Absence of strong photoionizing source suggests either fossil of past outburst or cosmic ray production
- Suggests enrichment by 1.5-4 depending on excitation mechanism

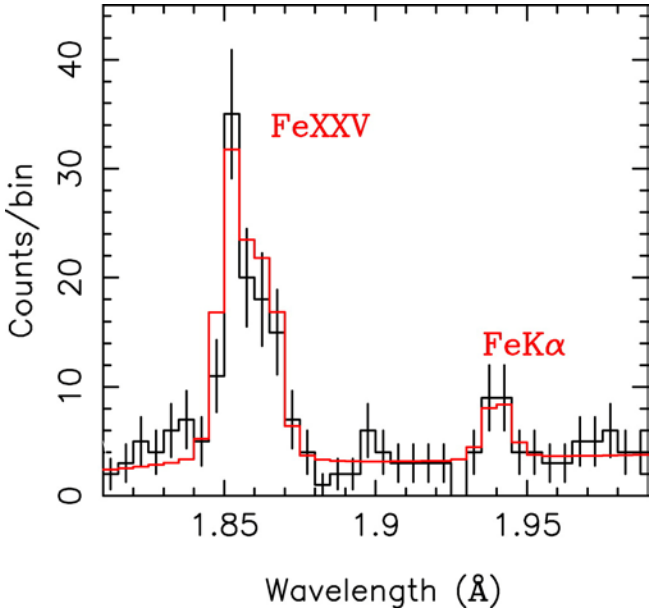


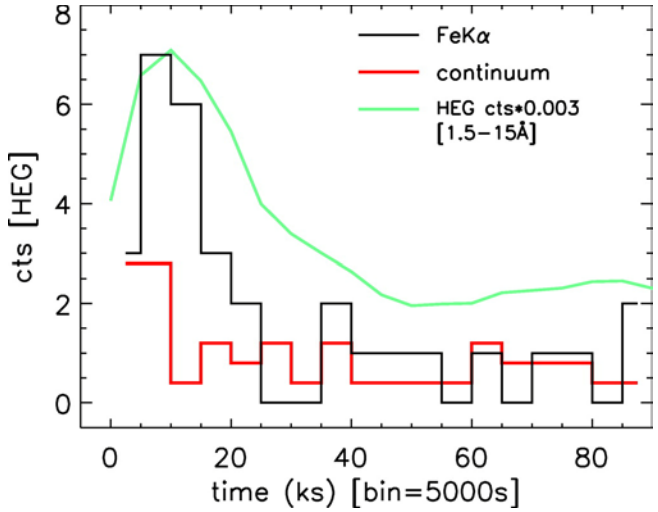
(Nobukawa et al. 2009)

nobukawa2010PASJ...62..423N

Chandra HETG observations of stellar flares

- Observe Fe Kα during flare from HR9024
- Chandra hetg
- suggests strong X-ray heating of photosphere
- Alternative scenarios are energetically unattractive
- Provides us a ‘star’s eye view’ of a flare…





(Testa et al. 2009)

Other important topics

- Databases have been key so far
  - Chianti, ‘adam’db, ADAS, uadb
- Future missions
  - IXO, ASTRO-H,
- There is data which has not yet been fully explored..
  - Chandra, hst, xmm

Challenges

- More elements (iron peak, some odd-z)
- Large scale calculations
  - More states → iron peak valence shell
- Non-equilibrium
  - Evidence from SNRs
- Molecules
  - Must be in every observed X-ray spectrum!
- Inner shells
  - Most opacities use OP or equivalent
- Protons
  - Eg. Need diagnostics of nt particles vs. photons